

AN INVESTIGATION OF AUDITORY ICONS AND BRAKE
RESPONSE TIMES IN A COMMERCIAL TRUCK-CAB
ENVIRONMENT

by

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(ABSTRACT)

In the driving task, vision, hearing, and the haptic senses are all used by the driver to gather required information. Future Intelligent Transportation Systems components are likely to further increase the volume of information available to or required by the driver, particularly in the case of commercial vehicle operators. The use of alternate modalities to present in-vehicle information is a possible solution to the potential overload of the visual channel. Auditory icons have been shown to improve operator performance and decrease learning and response times, not only in industrial applications, but also as emergency braking warnings. The use of auditory icons in commercial truck cabs has the potential to increase the number of auditory displays that can be distinguished and understood by commercial vehicle operators, and this experiment sought to determine the utility of auditory icons in that situation.

Nine auditory icons were evaluated by commercial vehicle operators as they drove an experimental vehicle over public roads. A comparison of the data collected in the truck-cab environment to data collected in a laboratory study on the same auditory icons revealed some differences in the perceived meaning, perceived urgency, and association with the auditory icons' intended meanings between the two conditions. The presence of these differences indicates that driver evaluations of auditory icons can be affected by the environment, and testing should therefore be conducted in a situation that approximates the end-user environment as closely as possible.

A comparison of the drivers' brake response times across the three warning conditions (no warning, auditory icon, and soft braking) was also conducted on a closed, secure handling course. Dependent measures included overall brake reaction time and its components, steering response time, time to initial driver action, and categorical measures of driver responses (steering, swerving, braking, and stopping).

The results indicated numerically shorter mean response times (on the order of 0.5 seconds for Total Brake Response Time) for the two conditions with warnings, but the differences were not statistically significant. The most likely reason for this lack of significance is the extreme between-subject variability in response times in the no warning condition. An analysis of the response time variance across the three conditions did indicate significantly less variability in operator responses in the two warning conditions. Two of the five dependent measures (Brake Pedal Contact Time and Total Brake Response Time) exhibited significantly reduced variance in the auditory icon warning condition compared to the no warning condition. The soft braking warning condition exhibited significantly reduced variance for four of the dependent measures (Accelerator Reaction Time, Brake Pedal Contact Time, Total Brake Response Time, and First Reaction Time). These results indicate that a soft braking stimulus like that used in this study could potentially prove to be a more effective emergency braking warning than simple auditory warnings alone.

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“For a man may do his work with wisdom, knowledge, and skill, and then he must leave all he owns to someone who has not worked for it. This too is meaningless and a great misfortune.”

Ecclesiastes 2:21

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But the greatest thanks and praise are due to my Lord and Savior, Jesus Christ. Although I am the worst of sinners, loved me so much that He gave His life and died an excruciating death that I may come to know Him and have the eternal and abundant life that He promises to all who call upon His name.

“Of making many books there is no end, and much study wearies the body.

Now all has been heard; here is the conclusion of the matter:

Fear God and keep his commandments, for this is the whole duty of man.”

Ecclesiastes 12:12b - 13

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LIST OF MULTIMEDIA OBJECTS

<u>File Name</u>	<u>Description</u>	<u>Type of Object</u>
1-automatic_toll_payment.wav	Auditory Icon #1	.wav file
2-children_ahead.wav	Auditory Icon #2	.wav file
3-emer_braking_wrng.wav	Auditory Icon #3	.wav file
4-hi_engine_temp.wav	Auditory Icon #4	.wav file
5-rr_xing_ahead.wav	Auditory Icon #5	.wav file
6-roadwork_ahead.wav	Auditory Icon #6	.wav file
7-emer_vehicle_appr.wav	Auditory Icon #7	.wav file
8-incoming_voice_msg.wav	Auditory Icon #8	.wav file
9-roadside_mowing_ahead.wav	Auditory Icon #9	.wav file
Low_fuel.wav	Sample Auditory Icon	.wav file

INTRODUCTION

In 1944, the U.S. Congress authorized the construction of what would become the Interstate Highway System. Among the purposes behind the creation of these new highways were reduced travel time, increased fuel efficiency, and improved safety. These benefits would combine to give greater mobility to the general public and provide for national defense. As a whole, the road network was intended to meet the nation's anticipated transportation needs twenty years into the future (FHWA, 1984).

Much of today's Interstate System includes previously constructed roadways, but completion has required more time than originally envisioned. Originally scheduled to be completed by 1972, factors such as increased construction costs and difficulties in obtaining needed land delayed construction significantly. As traffic has increased over the years, the completion of new highways and the expansion and repair of existing road systems have struggled to keep pace with demand. During the 1970's and 1980's, total U.S. road mileage increased only four percent; yet over that same period, the number of vehicles using those roadways increased by 78 percent, and miles traveled increased by more than 91 percent (FHWA, 1992).

To cope with congestion, technological innovations have been gradually added to road systems. Improvements include programmable and vehicle-sensitive traffic signals, variable message signs, and high-occupancy vehicle lanes (Whelan, 1995). These approaches to traffic control, however, rely solely on predictions based primarily on established traffic patterns and lack the ability to respond to a dynamic traffic system in real-time.

Just as the focus of the Federal government has changed from construction to maintenance and repair, the approach to increasing traffic throughput has also shifted. Instead of increasing the size of current roadways, programs in the United States and other countries are seeking to use technology to increase the amount of traffic that can be fed through a fixed number of lanes. The implementation of these solutions will require changes in both highway infrastructure and vehicle components. National standards must

also be defined and agreed upon by both the government and private sectors (Hancock, Maze, and Waggoner, 1996).

Some of the new technologies being developed to fit these changing transportation needs are nearing implementation. New imaging sensors will have the ability to detect obstacles in a vehicle's path and are hoped one day to lead to the reallocation of the guidance function from the domain of the human to that of the machine. As more information is becoming available to the traveler while in the vehicle, in-car navigation aids are becoming more accepted and even demanded by the public sector, and are especially prevalent in Japan. In-vehicle and in-road sensors will collect data to be passed on to traffic management centers, where advanced traffic algorithms will allow a more accurate prediction of traffic trends and thereby avoid or minimize bottlenecks and gridlock. These advances have the potential to continue the goal of the Interstate System – to reduce travel time, improve safety, and increase fuel efficiency.

COMMERCIAL VEHICLE OPERATIONS

A primary use of the U.S. highway system has always been the transportation of freight, generally by commercial carriers. Although its share has declined in recent years, the transportation of freight still accounted for 17.9% of the highway system's total revenue ton-miles of freight in 1990. In the case of rural interstates, 16% of the traffic volume is made up of heavy (five-axle or more) trucks (FHWA, 1992).

Keeping the nation's highways clear and available for the transport of commercial goods is a critical factor in maintaining economic growth. Commercial vehicles often face delays not encountered by non-commercial users. Delays ranging from a few minutes to half an hour or more are often caused by stops for weigh stations, safety inspections, and state or national border crossings (Boehm-Davis and Mast, 1992). If these delays can be reduced, transportation times and costs can be reduced for the trucking industry.

Workload

Workload is typically defined as a multidimensional measure of the load on an operator's resources and is used to express the demand a task places on an individual, the individual's ability to meet that demand, and the capacity of the individual to meet the performance requirements of the task (Schlegel, 1993; Verwey, 1993). An unsafe level of workload is reached when the demands of the task cannot be met by the operator, such as when a driver fails to notice or is unable to properly respond to an important stimulus such as caution lights or an auditory warning or display.

In performing the driving task, commercial vehicle operators are forced to deal with a highly variable workload. Workload can approach dangerously high levels in congested areas. When driving long distances, however, the driver workload may fall to levels that induce boredom and promote inattention to the primary task of driving (Bowers-Carnahan, 1991). Each of these factors will be addressed in the discussion session.

High workload. Due to the size and handling characteristics of heavy trucks, a commercial vehicle operator must allocate more attentional resources to the surrounding environment than the typical automobile driver. The size and weight of heavy trucks require that drivers anticipate far in advance those situations requiring slowing or stopping. A typical tractor-trailer combination may require 110 feet to come to a stop from a speed of only thirty miles per hour (Alliance Tractor-Trailer Training Centers, 1981). The size of most commercial vehicles, including buses, straight trucks, and tractor-trailer combinations, also reduces the drivers' visibility, requiring them to devote greater mental resources to keep track of surrounding traffic.

Tasks secondary to the driving task itself are also significant contributors to workload. A multitude of internal truck systems must be monitored, such as air and oil pressures, fuel level, water level, and engine temperature (The Maintenance Council, 1992). Unlike the majority of private automobiles, most commercial vehicles are outfitted with communications equipment such as CB radios, computers, and global

positioning systems (GPS) to allow the driver to maintain contact with his or her employers. While continued practice within this multiple-task environment will typically lead to more efficient time-sharing and better performance (Wickens, 1992), the need to monitor multiple systems can still overwhelm the driver (Bowers-Carnahan, 1991).

Low workload. In the case of the long-haul truck driver, it is possible for workload to be low enough to hamper performance. Reduced traffic and unchanging road conditions give the driver little to occupy his or her attention. The long-haul driving task becomes repetitious and includes a monotonous pattern of sensory stimulation. According to O'Hanlon (1981), these factors promote boredom in the driver, the onset of which can occur mere minutes after the start of such repetitive and frequently experienced activities. Driving is, potentially, a highly monotonous activity and boredom can create dangerous side effects such as a deterioration in lateral road tracking (O'Hanlon, 1981). Lateral road tracking is particularly crucial for the commercial vehicle operator due to the weight and length of combination trucks.

Other workload factors. Along with changes in workload, other occupational characteristics can affect the commercial vehicle operator as well. Operators typically drive for long periods of time, often during late night and early morning hours. These conditions tend to promote fatigue in the long-haul commercial driver (Miller and Mackie, 1979), which is a major factor in accidents involving heavy trucks (Sanders and McCormick, 1993).

Driver performance can also be influenced by familiarity with the vehicle being operated. Commercial drivers may not always drive one particular vehicle, but instead may drive different vehicles from their employer's fleet (Boehm-Davis and Mast, 1992). Lack of familiarity with a particular vehicle's controls and handling characteristics may cause increased reaction times and poorer driving performance. Inexperience with the layout of the displays and controls may also cause the driver to revert to behavior patterns typical of a novice driver, such as infrequent visual sampling of the external

environment, failure to attend to all internal displays, and failure to look at the roadway ahead of the vehicle an appropriate distance (Schlegel, 1993).

The commercial vehicle operator may also be distracted from the driving task by the navigation task. Navigation tends to be more difficult for the commercial driver than for the operator of a private vehicle because truck drivers are frequently called upon to drive in unfamiliar areas. The navigation task can require constant scanning of the environment and the construction of a mental map (Schlegel, 1993). Secondary tasks such as these have the potential to lower the level of performance for the primary driving task.

Accident Statistics

The fatality rate on the nation's highways has been in an almost continual decline, falling from 20 fatalities per 100 million miles of travel in 1925 (Seiff, 1985) to approximately 2 fatalities per 100 million miles in 1991. The Interstate Highway System is safer still, with a fatality rate approximately half of that of the overall road system (FHWA, 1992).

According to data presented by Seiff (1985), in 1983 the accident rates for cars and combination trucks were similar, with the rate for cars being only slightly higher. The fatality rates, however, demonstrate a great disparity between cars and combination vehicles. While the fatality rate for cars was approximately 2.5 per hundred million miles, the rate for combination vehicles was over two and a half times higher, almost 6.5 fatalities per hundred million vehicle miles. Of the 42,584 highway fatalities in 1983, 5,475 of the fatalities involved accidents with medium or heavy trucks. But of the truck-related fatalities, a mere 18% were truck occupants. The vast majority of fatalities were occupants of other vehicles. This data has shown relative consistency over the years. Information provided by the Federal Highway Administration (1992) indicates that of the 44,529 highway fatalities in 1990, 5,254 were in truck-related accidents. Of those fatalities truck occupants accounted for only 13.4%. This drop may be a demonstration

of either increased protection for truck drivers or the decreased protection offered by the smaller cars on the road in 1990.

Using police reports and on-scene investigations, Treat, Tumbas, McDonald, Shinar, Hume, Mayer, Stanisfer, and Castellan (1979) examined the causes of traffic accidents. They concluded that “human factors” were the most frequent cause of accidents, totaling 93%. Within the human factors category, the two primary causes were inattention and internal distractions. The second highest cause, environmental factors, contributed to only 34% of the accidents studied. These findings are supported by Wierwille (1995), who found that accident rate increases with an increase in the visual demand of a vehicle’s interior. In the case of truck accidents, Seiff (1985) found the driver to be the highest contributing factor in 64% of all heavy truck accidents. The most frequent specific causes were driving too fast, failure to stay in a lane, and carelessness or inattention.

Driver Information Needs

Commercial vehicle operators require a great deal of information to successfully perform their jobs, much of which is unnecessary to the typical private-vehicle driver. The additional information may either relate to truck equipment and subsystems not found in automobiles or concern routing information. This information adds to the workload of the driver due to the cognitive resources required for attention, comprehension, and integration.

The great number of subsystems in heavy trucks requires that the driver monitor a larger number of gauges. Cross (1995) states that a recent Volvo GM cab display includes 14 dial gauges to monitor engine- and vehicle-related functions. This display scheme includes a warning buzzer and an indicator lamp for each gauge, all of which must be monitored by the driver.

Information to be monitored by the driver may also originate outside the truck. In order for a commercial trucking company to be profitable, it must maximize the time each truck spends on the road while minimizing the miles each truck travels (White,

1995). Accomplishing this task requires communication between the driver and the dispatcher. In a survey of the trucking industry, Stone and Ervin (1990) found that 83% of their respondents considered two-way communication between driver and dispatcher either “important” or “very important.”

Audition in the Truck Cab

The need for two-way communication between driver and dispatcher is but one of many operator functions related to audition. Both the hearing capabilities of the driver and the acoustic characteristics of the truck cab influence the effectiveness of communications devices such as CB and private-band radios. These factors can gain even more importance as future efforts to lessen driver workload may increase the number of auditory displays in the truck cab.

Working environment. Noise in the truck cab can be caused by wind, cooling fans, road surfaces, the engine, vibrations, tires, and exhaust (Mortimer, 1994; van den Heever and Roets, 1996). A study performed by Reif, Moore, and Steevensz (1980) found that the noise exposure in truck cabs may be high enough to cause permanent hearing loss. These high noise levels may also lower performance on driver tasks through distraction or masking of critical sounds (Sanders and McCormick, 1993). These measurements, however, were performed in trucks manufactured in the 1960’s or 1970’s. A more recent study involving newer trucks determined that the risk of noise-induced hearing loss, while lower than before, still exists (van den Heever and Roets, 1996). Additionally, interviews with truck drivers suggest that while there is variation between individual vehicles, most newer trucks are not as loud as older models. The noise level in most trucks, however, is still loud enough to mask warning signals that originate either inside or outside of the cab (Robinson, Casali, and Lee, 1997).

Auditory needs of drivers. While the driving task is primarily visual, the driver must also attend to auditory cues to perform his or her job safely. A task analysis of truck and bus drivers by Moe, Kelley, and Farlow (1973) was adapted by Micheal (1995) to include modality information. While the majority of critical tasks use the visual

modality, the auditory modality remains important in dealing with events such as blowouts, brake failures, and emergency vehicles. Driver hearing is also critical to the detection of mechanical problems, communication, and the driving task in general (Robinson et al., 1997). A quieter truck cab will help to preserve driver hearing and improve the understandability of internal auditory messages. Unfortunately, as truck cabs become quieter, the added insulation may reduce the volume of external sounds (tire blowouts, sirens, train horns, etc.) to inaudible levels.

Auditory warnings in today's truck cab. In the modern truck cab, auditory displays are primarily used to present warning signals. Among those found in most cabs are warning buzzers for low air pressure, low oil, and engine shutdown (B. Meyer, personal communication, May 17, 1996). The purpose of these warnings is comparable to that of the “attenson,” defined by Patterson (1982, p. 9) as a warning sound “required to indicate the arrival of a low-priority alert or other information on a visual display.”

While some auditory warnings in a truck cab may signal events of a more urgent nature than those proposed by Patterson (1982), the principle is similar. Deatherage (1972) states that warning signals and information that must be presented independent of head position are better suited for the auditory modality than for visual display. Hereford and Winn (1994) state that sound is useful in signaling alarms in need of immediate action and it provides information that can be used to direct the eyes. Events such as loss of oil pressure or an imminent engine shutdown require the driver's immediate attention, regardless of where the driver is currently directing his or her visual resources. As warning devices, these signals serve to alert the driver to the presence of a condition needing attention.

As currently implemented, however, auditory warnings have deficiencies. Even if the spectral characteristics and presentation levels are such that masking by environmental noises is avoided, deeper problems remain. Current alarms fall short when evaluated according to the design principles outlined by Begault (1994). The auditory warnings used in trucks are frequently loud and repetitive, fail to convey any

real information about the situation, are of low quality due to hardware constraints, and do little to increase the driver's ability to operate a truck effectively.

Differences also exist between trucks. What one truck manufacturer chooses as a low oil warning buzzer may be drastically different from what other manufacturers select. Such discrepancies have the potential to increase error, increase the time required to determine the cause of the warning, and make it difficult for a driver to form a stereotypical response to the warning sounds.

It is also unlikely that the set of warnings used in a particular truck cab were developed as a group. Individually, the warnings for each function may be audible and consistent across manufacturers, but they may still promote confusion. Following a study of operating rooms and intensive care units, Momtahan, Hetu, and Tansley (1993) created a set of guidelines for auditory alarms. Included in these guidelines was the recommendation that alarms should be distinctive enough to avoid confusion. The only reliable method to eliminate confusion between alarms is to develop the set of alarms as a whole, a task that has yet to be performed for most truck cab warnings.

INTELLIGENT TRANSPORTATION SYSTEMS

In an effort to coordinate and encourage the development of advanced transportation technologies in the U.S., the Intelligent Vehicle Highway Society of America (IVHS America) was formed in August of 1990 (IVHS America, 1992). IVHS America was created to be a partnership between the private sector and government agencies to coordinate the use of technology in improving transportation. Since then, the organization has been renamed the Intelligent Transportation Society of America (ITS America), and has been designated as a utilized Federal Advisory Committee by the Department of Transportation. The group's purpose, however, remains the same – to improve the effectiveness and safety of the surface transportation system of the United States.

The activities comprising current ITS programs have their roots in projects begun in the 1980's. Although they are currently considered by the U.S. Department of Transportation to be a continuation of the construction of the Interstate System, these projects were not typically initiated at the federal level. Most ITS activities were started at the local level in an effort to diminish localized traffic problems (Whelan, 1995).

Pressure on ITS Industry

As a unit, the ITS industry in the U.S. is under pressure from sources on both the private and public sides of the ITS partnership. The stress caused by constantly increasing traffic volume in already congested urban areas requires that the ITS industry focus efforts on increasing the number of vehicles that can safely pass through a given corridor in a given period of time. A number of potential solutions to such problems are available due to the decreasing costs and increasing power of information technology (Chen and Ervin, 1990). It is believed that the technologies necessary to make ITS a reality, if not currently available, are achievable in the near future through research and design (IVHS America, 1992). Added to these forces is the catalyst of international competition; research and implementation efforts are underway in Europe and Japan just as they are in the U.S. (Chen and Ervin, 1990).

ITS Implementation

Development of national architecture. The Federal Highway Administration (FHWA) has been working with the ITS community to increase the effectiveness of the ITS program. The FHWA has sought to ensure that each project will be able to interact with other projects, thus making the whole greater than the sum of the individual pieces (IVHS America, 1992). The effective implementation of ITS in the United States depends on the ability of individual systems and projects to complement one another and to easily exchange information. The first step in this process was taken in September 1993 when the FHWA awarded a set of contracts to develop national system architecture concepts (Whelan, 1995).

ITS projects are typically grouped into one of six functional categories. The four categories defined initially were Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), and Commercial Vehicle Operations (CVO) (IVHS America, 1992). Two additional functional categories, Advanced Public Transportation Systems (APTS) and Advanced Rural Transportation System (ARTS), were later created to address areas not specifically defined as a part of the first four groups (Whelan, 1995).

The system architecture dictates a set of guidelines to follow in the development of ITS programs. The development stage is followed by a multiple-level integration of the six separate, but often overlapping, functional categories. Systems must be integrated to allow them to communicate. The systems are also integrated in that they combine to form a multi-modal surface transportation system. The ITS plan includes a variety of transportation modes, ranging from personal and commercial vehicles to public transit systems. The integration phase is followed by the actual deployment or implementation of ITS systems. Without deployment on a large scale, ITS will do little to achieve its goals of increasing safety and mobility while reducing congestion (IVHS America, 1992).

In-vehicle equipment. In order to effectively provide information to drivers, in-vehicle equipment must be vastly improved. The information provided may pertain to the state of the vehicle and its subsystems or to the vehicle's environment. The amount of equipment needed to accomplish this is staggering. For example, equipping a vehicle with a navigation system alone may require the addition of a visual display and its associated controls, a CD-ROM drive for a map database, global positioning system (GPS) equipment, geomagnetic sensors, wheel sensors, and a local beacon signal receiver (Hirata, Hara, and Kishore, 1993; Matsuda, Fujita, and Kobayashi, 1991). To fully install the VORAD (Vehicle On-board Radar) Vehicle Collision Warning System, steering and brake sensors, a speedometer connection, a driver display control unit, an audio speaker, a "blind spot" sensor and display, central processor assembly, and antenna transmitter and receiver must be added to the vehicle (Bulkeley, 1993).

Additional in-vehicle components will be required to gather information as well. At present, one of the greatest weaknesses in implementing ITS is the lack of accurate and timely traffic information (Robinson, 1996). It is anticipated that the most effective way to gather current traffic information is to collect it from vehicles on the road. The TravTek navigation system operational field test in Orlando, for example, included the use of “probe cars” to collect such information (Fleischman, 1991).

Infrastructure. To collect information and distribute it to all drivers, a national ITS infrastructure must be completed. Some of the necessary equipment is already in place, such as the GPS satellite network used by most navigation systems. Additional requirements include traffic management centers such as the one used in the TravTek demonstration (Fleischman, 1991) and, potentially, roadside beacons similar to those used in Japan’s Vehicle Information Communication System (VICS) to provide accurate vehicle location data (Hirata et al., 1993).

Goal of ITS

The stated goal of the ITS program is to address on a fundamental level the issues of safety, congestion, mobility, environment, and energy (IVHS America, 1992). Under the ITS initiative, these problems are to be solved not through constructing more roadways, but through information and automation (Mele, 1990). Information that is timely and more complete will allow drivers to make more intelligent decisions, and automation should help reduce workload and decrease reaction time (Michon, 1993).

Information. Early automobiles had perhaps two gauges for the driver to monitor – speed and oil pressure. Drivers of today’s vehicles have become accustomed to having information about numerous vehicle systems displayed, either continuously or intermittently (Ethington, Streelman, and Clark, 1989). Driver workload will increase as the information available to the driver expands to include updates on traffic and weather, vehicle headway information, and route guidance. Additional information may concern roadside services, advanced vehicle diagnostics, or the presence of a vehicle in the driver’s blind spot. To offset this increase of information and to improve safety, future

vehicle display systems must filter, interpret, integrate, and prioritize the information before it is presented (Michon and Smiley, 1993).

Automation. Machines have long been recognized as having shorter response times than humans and to be better at monitoring for infrequent events (Woodson, 1981). These principles are now being applied in the ITS field to improve the safety and speed of travel. In an effort to reduce the likelihood and severity of collisions, numerous projects are underway to allow vehicles to brake automatically when an obstacle is detected ahead. Some of these systems are designed to simply react when an obstacle is detected, and others are part of an overall Intelligent Cruise Control (ICC) system (Belohoubek, 1982; Hagleitner, 1994; Kikuchi, Ishiyama, Nakajima, and Tasaka, 1995). While the options available may detect distances using infrared sensors, radar, LEDs, or lasers (Ajluni, 1995; Bulkeley, 1993; Zelubowski, 1994), the purpose of each is the same.

Problem Areas

Modality allocation. The driving task is primarily visual, but it involves the use of the auditory and haptic pathways as well. Perhaps because of the predominance of the visual modality in driving, the majority of research into information presentation to the driver has dealt with visual displays (Harteman and Favre, 1990; Popp and Farber, 1991; Wierwille, 1993). In recent years, however, studies have examined the potential for presenting information to the driver through auditory or haptic means. The bulk of this work has concerned the various combinations of maps and verbal messages in navigation systems.

Labiale (1989) found that drivers preferred to receive auditory guidance as a complement to an in-car map display. The map was presented using a small video display unit mounted on top of the dashboard. The map and auditory message option was preferred over the use of the map alone or use of written instructions and the map. The study concluded that concise auditory messages should be used along with the map when the car was in motion. Similar recommendations have been made in studies dealing with functions other than navigation. Following a test of in-car visual displays, Graham and

Mitchell (1994) suggested an auditory complement to visual displays for weather, road, and traffic information. The research in this area has begun to point back to the suggestion made by Patterson (1982) to use the auditory modality to draw attention to complex visual messages.

Visual display problems. Reconfigurable visual displays, such as CRTs and flat-panel displays, seem to be an extremely popular option for presenting information to the driver. They have distinct advantages over dials, LEDs, and dot matrix displays in that they are more easily altered to display information of different forms or from different sources. Yet such displays may require the driver to remove his or her eyes from the path of the vehicle for an extended period of time. Reducing the amount of time the driver spends looking at the roadway ahead will produce a comparable decrease in safety (Paley and Tepas, 1994; Wierwille, 1995).

The use of a visual display may also increase the risk to the driver if the display is additionally used as a touch-screen to receive input from the driver. Here visual displays again have an advantage over other options in that a touch-screen display can automatically be reconfigured to be used with a variety of vehicle functions. The smoothness of the screen and lack of other tactile feedback complicate the driver's task of locating and using buttons on a touch-screen display (Zwahlen, Adams, and DeBald, 1988).

Changing levels of workload. The workload produced by the driving task has been found to be influenced partially by driver experience, but the primary source of variation appears to be traffic situation (Verwey, 1991). Therefore, since the vehicle-driver interface should be designed to optimize driver workload, that interface should be adaptable across drivers and driving situations. While the characteristics of the driver may not change from instant to instant, the driver's familiarity with the environment may change, producing a subsequent change in workload. Rothengatter, Alm, Kuiken, Michon, and Verwey (1993) claim that the driver's momentary workload is what determines the appropriate type of driver support. Satisfying this requirement demands

that driver workload be continuously sampled or measured. Furthermore, the vehicle-driver interface must be designed so that its changes are automatic and not controlled by the driver, as this would only serve to add to the operator's workload. "An optimal interface," says Kantowitz (1989, p. 55), "would degrade gracefully under excessive workload demands instead of failing precipitously. The interface would sense when either the human or machine intelligence was [sic] overloaded and automatically transfer system functions to the component that had the most spare capacity." In the driving situation, it is possible that the machine intelligence would never approach overload. But the principles outlined by Kantowitz (1989) are still valid in this situation as the interface must prevent driver workload from reaching levels low enough to decrease vigilance and safety (O'Hanlon, 1981).

Benefits for CVO

While the implementation of ITS will bring numerous benefits to the driving population, certain ITS features will have specific application to commercial vehicle operations. Most of the applications of ITS within the CVO functional category are expected to have been initially developed as part of ATMS, ATIS, or AVCS projects. Due to its operating requirements, the trucking industry is likely to be one of the first recipients of these new technologies. The operational characteristics of commercial vehicles call for safer and more reliable designs and specialized road information required by truck drivers (IVHS America, 1992). Ervin (1992) sees specific applications of ITS to the trucking industry in business communications, mobile debiting, regulatory issues, location-based functions, and safety enhancements.

Specific to CVO. The Transportation Research Board (1993) lists seven categories of CVO-specific technologies: Automatic Vehicle Identification (AVI), Weigh in Motion (WIM), Automatic Vehicle Classification (AVC), Automatic Vehicle Location (AVL), Two-Way Communications (TWC), Automatic Clearance Sensing (ACS), and Electronic placarding / bill of lading. Features such as ACS, WIM, and AVI will serve to eliminate or greatly lessen the down-time of commercial vehicles, increasing productivity

and profitability. Numerous trucking companies have already begun to use satellite networks to incorporate Two-Way Communications and Automatic Vehicle Location into their fleets. The use of these systems provides trucking companies with up-to-the-minute information on the locations of all of their trucks, allowing for more efficient dispatching. Real-time communication allows dispatchers and drivers to contact one another instantly across the country with information about route and delivery time changes and emergency situations (Dollar, 1995; White, 1995).

ATIS. Nearly every identified ATIS function has an application in the realm of commercial vehicle operations in addition to the private-transportation arena. A set of ATIS functions relevant to CVO is shown in Table 1. Lee, Morgan, Raby, and Wheeler (1994) suggest that commercial operators will find standard ATIS functions such as hazard notification, approaching emergency vehicle warnings, navigation information, and parking availability updates helpful. Projects such as the TRANSCOM network in the New York / New Jersey area are already providing information to truck drivers on lane closings due to accidents, breakdowns, maintenance, and construction, increasing productivity and customer service while reducing costs (Batz, 1991). While both commercial vehicle operators and private-vehicle drivers may find such ATIS functions helpful, the assistance rendered by these programs will be amplified in the case of commercial vehicle operators in that the average combination truck is driven approximately 60,000 miles per year compared to the 11,000 miles per year traveled by the typical passenger car (FWHA, 1993).

The profitability of ATIS programs will be greater for the CVO industry than for the general public, but not only because of greater frequency of use. A larger percentage of ATIS-related information is more relevant to truck drivers than to the private-vehicle driver. While ATIS functions like cargo monitoring systems and automated toll payments (Lee et al., 1994) may be useful to some members of the general public, they will assist and speed the travel of nearly all commercial vehicles. Other ATIS

TABLE 1

Summary of ATIS/CVO Functions (adapted from Lee, Morgan, Raby, and Wheeler, 1994)

IRANS (In-Vehicle Routing and Navigation System)
Trip planning
Multi-mode travel coordination and planning
Pre-drive route and destination selection
Dynamic route selection
Route navigation
Automated toll collection
IMSIS (In-Vehicle Motorist Information System)
Broadcast services/attractions
Services/attractions directory
Destination coordination
Message transfer
ISIS (In-Vehicle Signing Information System)
Roadway guidance sign information
Roadway notification sign information
Roadway regulatory sign information
CVO-specific (Road restriction information)
IVSAWS (In-Vehicle Safety and Warning Systems)
Immediate hazard warning
Road condition information
Automatic aid request
Manual aid request
Vehicle condition monitoring
CVO-specific (Cargo and Vehicle Monitoring)
CVO-Specific
Fleet resource management
Dispatch
Regulatory administration
Regulatory enforcement

applications of greater value to the truck driver include road restriction information and customer contact phone number (Stone and Ervin, 1990).

COLLISION AVOIDANCE

The continuing decline in traffic fatalities in the United States has been due primarily to improvements in vehicle design. The addition of air bags, greater vehicle crashworthiness, and advances in road design have combined with increased use of seat belts and a decrease in alcohol-impaired driving to bring traffic-related fatalities to their lowest rates in history (Leasure, 1994). But recent technological advances have opened the door for vast improvements in the ability of vehicles and drivers to avoid crashes instead of merely surviving them.

Capabilities

Specific ITS technologies are being developed as countermeasures to nearly all types of collisions. Since nearly one quarter of all police-reported traffic accidents are rear-end collisions (Tijerina, 1995), this type of collision has received the majority of the attention. Collision avoidance technologies are typically grouped in six categories. The categories dealing with rear-end collisions are collision warning and adaptive cruise control (ACC) (Leasure, 1994). Systems in both categories include radar sensing technologies to determine the distance between the intelligent vehicle and other vehicles. The difference between the two systems lies in how the system responds to other traffic. Collision warning systems notify the driver of obstacles in the path of the vehicle and may include automatic braking, where adaptive cruise control systems, on the other hand, will automatically adjust the speed of the vehicle based on the local traffic and parameters set by the driver.

Collision avoidance systems that help the driver keep the vehicle in the proper lane are referred to as lane position monitors or run-off-road warning systems (Leasure, 1994; Najm, 1994). These systems are intended to lower the frequency of single vehicle roadway departures (SVRD), which are the most common type of traffic accident after

rear-end crashes (Tijerina, 1995). In an effort to prevent backing crashes, near object detection systems (NODS) are being developed (Leasure, 1994). These systems use many of the same technologies as collision warning and ACC systems to detect hazards in a vehicle's path.

Cooperative intersection systems are also under development (Leasure, 1994). These systems typically include more out-of-vehicle equipment than CASs in the other five categories, such as roadside beacons, transponders, and cameras (Najm, 1994). The final category of CAS technology deals with the enhancement of the driver's vision (Leasure, 1994). Among the methods under development to aid drivers in this area are infrared and radar imaging and ultraviolet headlights (Najm, 1994).

Variations

Task allocation. Depending on the level of task allocation, collision avoidance systems (CASs) may be placed in one of three categories. At the most basic level, the system can simply warn the driver of an impending collision through either an alert or by providing a view of the driver's blind spots (Mele, 1990). The system may also be completely automated and, using a preset criterion, decide that a collision is imminent and take action to avoid the collision independent of the driver. The third category represents a compromise between these two extremes. The collision avoidance system may be designed to initiate an action in response to a detected obstacle or impending collision, and then give the driver the option of continuing or aborting the action (Nilsson, Alm, and Janssen, 1991). While the automatic system may prevent the most accidents, it is also the system with the greatest designer liability risk (Hagleitner, 1994).

Criteria for activation. Nearly all collision avoidance systems use one of three separate criteria to determine the point of activation. The criterion may be fixed in time, activating the CAS whenever an obstacle is a specific time range ahead of the vehicle. This criterion treats each obstacle as a "brick wall" and does not account for the speed of the obstacle. The second criterion is the time-to-collision (TTC) criterion, which will activate the CAS if, accounting for speed, a collision will occur in a set time period if all

speeds and headings remain constant. The final criterion is similar to, but more conservative than, the TTC criterion. A CAS using this conditional criterion will be activated if a collision will occur within a specific interval if the vehicle ahead were to suddenly apply full braking power (Verwey, Alm, Groeger, Janssen, Kuiken, Schraagen, Schumann, van Winsum, and Wontorra, 1993).

Other factors. A vehicle's CAS may also be designed to include continuously updated data on the vehicle's headway. A system developed by Daimler-Benz uses a radar sensor to measure distance to the vehicle ahead and displays relative motion and distance on the instrument panel (Ulke, Adomat, Butscher, and Lauer, 1994). Another possibility for continuous display of CAS information is the E-Meter, described by Owens, Helmers, and Sivak (1993). The E-Meter can replace the conventional speedometer and provide instead a relative measure of the vehicle's kinetic energy. Kinetic energy is a truer measure of the damage possible in a collision than is the velocity of the vehicle since the force of the collision is directly related to the vehicle's amount of (kinetic) energy, which must be dispersed.

Methods of Warning

Following task allocation, the next most significant variation between collision avoidance systems is the method by which the system warns the driver. Warnings are not typically present for systems on the intervention level, but warning and suggestive systems can use a variety of means to provide information to the driver. Warnings may be presented using one or any combination of the visual, auditory, and haptic modalities.

Visual warnings. The visual modality is frequently chosen to present collision avoidance warnings. Such displays typically consist of a light or set of lights that are illuminated to signal a warning. The Sideminder collision avoidance system, for example, lights an LED array in the rear- and side-view mirrors when an object is in the driver's blind spot (Ajluni, 1995). Eaton Corporation's VORAD Vehicle Collision Warning System also uses a visual display. The VORAD interface, however, has advantages over Sideminder in two areas. First, VORAD's visual display includes green,

yellow, and red warning lights, informing the driver of the severity of the situation. Second, VORAD uses auditory warnings in combination with its visual display (Bulkeley, 1993).

Other visual display options include a car-shaped LCD display of changing color and size, a set of LEDs to indicate following distance in seconds, and a set of multi-colored bars that illuminate according to headway (Najm, 1994). Overall, visual displays are advantageous in that there is no threat of masking as is the case for auditory displays and that the visual modality is more suited to presenting integrated information about a collision situation. When immediate action is required, however, auditory and haptic displays are superior (Lerner, Kotwal, Lyons, and Gardner-Bonneau, 1993).

Auditory warnings. Auditory warnings typically take the form of simple beeps or verbal messages (Najm, 1994). They are recommended for use as imminent crash avoidance warnings, and should be presented to appear to come from the direction of the hazard. Advances in 3-D sound technology have increased the potential of auditory warnings in CAS interfaces (Lerner et al., 1993).

The previously mentioned VORAD system uses auditory warnings to notify the driver of potential hazards in front of the vehicle. Unfortunately for the driving public, the development of such warning systems for passenger vehicles is in a much less advanced stage (Bulkeley, 1993; Horowitz and Dingus, 1992). Different forms of auditory warnings have been tested in Europe as part of the PROMETHEUS (Programme for European Transport and Traffic with Highest Efficiency and Unprecedented Safety) program (Graham, Hirst, and Carter, 1995), and will be discussed in a later section.

Haptic warnings. Haptic warnings have received less attention than auditory and visual warnings (Lerner et al., 1993), yet they share many of the advantages of auditory displays. Haptic displays can be used for temporal information in the same way as auditory displays, and are expected to possibly produce shorter reaction times and place less mental load on the driver than other display options. When a tactile display is used

and applied specifically to the driver, it has the added advantage that passengers in the vehicle will be unaware of the message (Onken, 1994).

While not in extensive use, tactile displays are varied in application. The accelerator is frequently employed to transmit tactile feedback to the driver. The accelerator may provide force feedback to the driver, either steadily or in pulsed form (Najm, 1994; Nilsson et al., 1991). One drawback of the use of the accelerator pedal to convey information to the driver is that the foot must be in contact with the pedal for the driver to receive the signal. The first problem with this is that brake response times may be reduced if the driver is allowed to keep his or her foot near the brake pedal instead of on the accelerator. Hogema, van der Horst, and Janssen (1994) found that drivers simply didn't like this type of display due to the foot placement requirement. A later study compared two intelligent cruise control (ICC) systems that differed only in that one required that the driver keep one foot on the accelerator pedal to keep the system active. While driving performance measures for the two ICC systems were not significantly different, questionnaire results heavily favored the foot-off-pedal system (Hogema and Janssen, 1996).

The steering wheel has also been used to provide information to the driver. A German driver-monitoring device used torque feedback in the steering wheel to inform the driver of lane excursions. This force output had a vibration signal imposed in order to distinguish it from normal road impacts. This form of display was easily detected and recognized by drivers and received favorable recommendations (Onken, 1994).

One of the most recent collision avoidance systems developed is Delco Electronics' FOREWARN Collision Warning System. In an effort to reduce detrimental effects of false alarms, the FOREWARN system includes both "caution" and "emergency" warning levels. Auditory and visual cues are used for both warning levels, but a brake pulse is included in the "emergency" level warning. The implementation of an automatic brake pulse allows the buildup of brake pressure at the same time that the "emergency" level warning is given, starts to slow the vehicle, and provides the driver

with an intuitive cue to slow down. While both the brake pulse and the previously discussed accelerator pedal feedback provide a tactile cue, the brake pulse also stimulates the vestibular organs, making the cue a proprioceptive one (Landau, 1995). It has been suggested that the use of a proprioceptive cue will allow the driver to naturally associate the warning with the collision avoidance situation and the appropriate action to be taken, thereby reducing the response time (Lerner et al., 1993). Four principles were chosen for the development of the FOREWARN system: (1) simultaneous presentation of brake pulse and auditory warning; (2) no startle effects from brake pulse due to intensity or rate of onset of the deceleration; (3) no interference with the ability of the driver to control the vehicle; and (4) the length of the brake cue should be approximately 300 ms, with other variables determined through experimentation (Landau, 1995).

Combined modality displays. A collision avoidance system may also provide warnings to the driver through multiple modalities. One reason for this is that a message presented simultaneously in multiple modalities is more likely to be noticed than a message presented in only one modality. Second, different modalities may be used to present different types of information. The visual domain is vastly superior to other options for the presentation of complex messages or information that must later be referenced. The auditory domain, on the other hand, lends itself to the presentation of information that requires immediate action (Deatherage, 1972). The best modality for information presentation in a CAS depends on the type of information provided by the CAS. Those collision avoidance systems that provide information about continuous quantities such as headway should present that information through visual displays. Since haptic and auditory warnings produce shorter reaction times, these types of signals should be used to give the driver cautionary or imminent collision warnings (Horowitz and Dingus, 1992; Lerner et al., 1993).

Brake Reaction Times

Accurately measuring the effectiveness of a collision avoidance system requires measures of the likelihood of accurate driver response and latency of response. Under

the assumption that the driver fully and accurately complies with the CAS warning, the best measure of CAS effectiveness then becomes the speed of the driver's response (Tijerina, 1995). Using the brake response time (BRT) to evaluate the stimulus effectively removes vehicle-specific factors from the evaluation of the system. Its use as a yardstick for CAS comparison is not without flaws, however, as it is unaffected by factors such as potential changes in driving habits due to use of the system (Tijerina, 1995). A study cited by Tijerina (1995) found that the use of BRT for comparison between studies may also be risky due to variations caused by differences in methods, subjects, and field settings.

Definitions. Due to variations in equipment and experimental designs, a variety of operational definitions has been used for BRT measurement. The majority of recent research measuring brake response times occurred during the testing, introduction, and subsequent retesting of the center high-mounted stop lamp (CHMSL). The effectiveness of the CHMSL was typically measured by recording the response time of unsuspecting motorists to the activation of the brake lights. The most frequently used procedure involved the use of lead and monitoring vehicles to surround the unsuspecting subject's vehicle. The operational definition for BRT used in these studies was the interval between the first detectable onset of the brake lights of the lead vehicle and the first detectable onset of the brake lights of the subject vehicle (Sivak, Post, Olson, and Donohue, 1981). Even though this method allows the collection of large amounts of real-world data in a shorter period of time than other BRT estimation methods, its utility is limited. This method may only be used to measure driver reactions to brake lights and does not allow the overall response to be broken into the component intervals required for a full understanding of the braking response.

Simulator-based tests have used other definitions of brake response time. In testing a new brake indicator, Flannagan and Sivak (1989) placed subjects in a car mockup complete with steering wheel and brake and accelerator pedals. The subjects were asked to respond to a brake light by releasing the accelerator and pressing the brake

pedal as quickly as possible. The BRT was measured as the time it took the subject to release his or her foot from the accelerator pedal after the brake light was energized. This operational definition of BRT was again used by Theeuwes and Alferdinck (1995) to test new CHMSL arrangements. While the use of a simulator allows the braking response to be broken into specific intervals and large amounts of data can be collected, the subjects are typically more focused on the braking stimulus than when driving an actual vehicle. A drawback found in the execution of most of the studies using this definition is that the driving tasks used to occupy the driver are frequently unrealistic and not representative of an actual driving environment.

More recent research in the collision avoidance system arena by Graham et al. (1995) measured driver reaction time to different CAS stimuli. Subjects were instructed to respond to the CAS stimuli by pressing the brake pedal as soon as possible. But the design of this experiment differed from much of the previously related work in that some of the CAS activations were false alarms. Subjects were asked to respond to the CAS warning only if the accompanying driving video sequence required braking. Brake response time was measured as the interval from the beginning of the warning sound to the depression of the brake pedal.

In a simulator study of reaction times to unexpected obstacles, Broen and Chiang (1996) defined brake response time as the sum of reaction time and movement time. Braking response time was recorded in response to pedestrians stepping into the lane of traffic. The operational definition of reaction time was the interval beginning when the pedestrians entered the lane of traffic and ending with the complete release of the accelerator pedal. Movement time was defined as the interval between accelerator pedal release and the first depression of the brake pedal.

Simulators vs. real-world testing. While measuring BRTs in a real-world environment may be highly realistic, the use of a simulator has several advantages. As seen in the previous studies, simulator studies permit more accurate measurement of more quantities, such as the location and velocities of all traffic participants. This

advantage, however, is irrelevant in a comparison of most of the examples given here due to the low degree and fidelity of the driving simulations. The use of a simulator also permits more precise control of the driving environment, and allows the testing of maneuvers too dangerous to be regularly attempted with naïve subjects in real-world driving (van Winsum and van Wolffelaar, 1993). The gap between simulator and real-world testing in these two areas, however, can be narrowed with careful design and execution of a real-world scenario.

Unfortunately, valid results may not always be attainable through simulator testing. When driving a simulator, the subject's expectancy of a collision situation tends to be higher. This increased expectancy could significantly affect response times. Johansson and Rumar (1971) compared brake reaction times in anticipated and surprise situations. Each unexpected reaction time was longer than the reaction times in the expected situations, and the mean reaction times were found to differ by 0.3 seconds. The authors calculated a correction factor of 1.35 to convert data from the anticipation situation to a surprise condition. Despite these results, the authors stressed that the conversion factor they calculated would be valid for only simple reactions and that it is important to take measurements that are applicable to actual traffic situations.

AUDITORY WARNINGS AND INFORMATION

Traditional Auditory Warnings

While warnings from a system conceivably could be transmitted to the user through any sensory modality, the auditory modality is usually the optimal choice. The temporal nature of sound is what gives it this advantage in the transmission of warnings (Deatherage, 1972). Unfortunately, auditory alarms and warnings are frequently designed improperly. Warnings are commonly masked by background noise, or if they are loud enough to be detected, this is usually due to the fact the volume of the warning was set high enough to drown out all other noises (Patterson, 1990).

Technological advances have in recent years increased both the economy and potential of auditory warnings in the work environment. Included in these advances is the ability to use prerecorded or synthesized speech to warn or present hazard information (Simpson and Williams, 1980). Voice and other auditory warnings are frequently used in combination with visual warnings. These types of dual-modality warnings have been shown to be safer and to produce shorter reaction times than warnings using only a visual cue (Patterson, 1990; Simpson and Williams, 1980).

Speech warnings have obvious benefits over tonal or other non-speech warnings in the amount of information that can be conveyed. Synthesized speech can be used to present a variety of verbal messages, but studies have found synthesized speech to be less intelligible than natural speech (Logan, Greene, and Pisoni, 1989), and the rate of intelligibility can degrade rapidly when other noise is present (Morrison and Casali, 1994). The use of speech displays is especially limited if there is other speech in the work environment (Momtahan et al., 1993), as is the case with commercial vehicles equipped with CB radios. When poorly designed, auditory warnings can frequently be confused with one another and environmental sounds (Patterson, 1990).

The sound level of auditory warnings may be increased to overcome background noise, but warnings that are too loud can, in fact, be dangerous. A warning may be loud enough to drown out all other auditory messages, such as critical crew communication. As crew communication is most important in emergency situations, the alarm signaling a danger may actually prevent the crew from responding properly. If a warning is too loud or has a rapid onset rate (reaches full volume quickly), it may produce a startle reaction in the operator. When startled, the operator is likely to experience a break in his or her cognitive processes. Such a reaction can be dangerous for the operator in any situation, but risks are increased if the situation is hazardous enough to warrant an alarm. Some aircraft alarm systems have in fact been so intrusive to the crew that upon hearing the alarm, the crew will devote their entire attention to simply turning off the alarm, and

once the alarm is silenced, they fail to address the situation that triggered the alarm (Patterson, 1982).

Example environments. There are countless environments in which auditory warnings are beneficial, but the areas with the most related research are factories, the flight decks of aircraft, and power plants (Momtahan et al., 1993). Operators in each of these situations are involved in processes which require their attention to be directed to numerous functions. The temporal nature of these processes makes the use of auditory warnings advantageous to the operators' understanding and control. Of these three example situations, the case of the aircraft flight deck has the most to offer to the ITS and CVO arenas due to the common background in transportation.

The decade of the 1980's saw great advances in the design of auditory alarms for aircraft. A review of extant systems by Patterson (1982) revealed that perfect identification of all the alarms required excessive amounts of training and retraining. One of the surveyed systems included 16 different alarms, which was demonstrated to be too many for the crew to remember and identify. Alarms were also commonly too loud and too long to allow crew communication and failed to communicate the urgency of the situation. In a study using naïve listeners, Patterson (1982) found that the first four to six alarms of a set of ten could be learned quickly, and all ten could be learned within one hour. Most of the alarm systems of the day, however, used more than ten separate sounds. Using lessons learned from these systems, new alarm sets were developed for other situations (Patterson, 1982; Hellier, Edworthy, and Dennis, 1993; Patterson, 1982). Patterson (1990) outlines changes made to auditory displays for fixed-wing aircraft, helicopters, and trackside railroad personnel. Among those changes were the addition of auditory warnings for critical information previously presented only visually, a reduction in the overall number of auditory messages, and alteration of sounds to allow them to be audible in a variety of noise environments.

The guidelines for the design of auditory warnings in the hospital environment have more in common with the guidelines used in aircraft than the basic issues of

audibility and identification. Speech alarms are undesirable for hospital equipment since, just as in aircraft, they have the potential to disrupt inter-operator communication. The use of speech alarms in hospitals is also discouraged in order to prevent patients from understanding the content of messages intended for hospital personnel (Momtahan et al., 1993).

Without the prospect of using speech alarms, hospital intensive care units and operating rooms were often reduced to a “cacophony of buzzers and bells” (Patterson, 1990, p.43). A study by Momtahan et al. (1993) tested hospital personnel on the knowledge of auditory alarms in their workplace, testing equipment from operating rooms and intensive care units. Although each of the alarms was intended to be distinguishable from all others, the researchers found that hospital personnel could identify only an average of 40 percent of the alarms. The study cited previously (Momtahan et al., 1993) compared these percentages to the findings of earlier studies and found their results to be comparable, but slightly higher.

Design guidelines. In designing a set of auditory alarms, it is advisable to avoid loud warnings and warnings with sharp onsets so as to prevent the disruption of communication and cognitive functions (Patterson, 1982). Momtahan et al. (1993) suggest a set of principles to be used in the ergonomic design of alarms. The alarms should be audible and distinctive enough to avoid confusion. A limit of ten alarms is suggested to allow each alarm to be easily remembered. Finally, the guidelines state that each alarm should convey a level of urgency appropriate to the situation signaled by the alarm. Momtahan et al. (1993) also suggest that while alarms specific to the hospital environment need not sound urgent in and of themselves, the perceived urgency of the alarms should be correlated with the urgency of the message conveyed.

Patterson (1982) recommends that the ideal number of auditory alarms for an operator to recall ranges from four to nine. The overall number of alarms that an operator must memorize to effectively perform his or her task may be reduced by selecting one or two sounds to serve as “attensons” to inform the operator of the type of

warning and that more information is available. Patterson (1982) suggests that there be four specific warning sounds and two attentions signaling different levels of urgency. These recommendations are echoed by Momtahan et al. (1993), who suggest two alarm levels, “critical” and “caution.” These alarms can be designed to draw the attention of hospital personnel to a central console, where information on the specific nature of the alarm and patient number is available.

Perceived urgency. Different warnings will be associated with differing levels of urgency based on their acoustic parameters. Unfortunately, this is a feature that is rarely used to advantage in the design of auditory alarms. Most evaluations of extant systems have shown that there is a low level of correlation between the psychoacoustic urgency of alarms and the situations they announce (Hellier et al., 1993; Hellier, Edworthy, and Dennis, 1995).

Failure to apply the principle of scaled urgency in the design of a system of alarms can seriously hamper an operator’s performance. This problem is magnified when the number of alarms is such that the operator is unable to accurately remember the meaning of each alarm. Without knowing what an alarm means, the operator is left only with the perceived urgency of the alarm to determine the timing of his or her response (Sorkin, Kantowitz, and Kantowitz, 1988). If the urgencies of the alarms have not been properly scaled, the operator may disregard a critical alarm because it sounds routine or choose to neglect a critical function to respond to an alarm that sounds urgent but signals a routine situation (Hellier et al., 1995).

The urgency of warnings is not a topic that has completely escaped the notice of researchers. Patterson (1982) realized the importance of urgency and remarked that pulsed sounds seem more urgent than continuous sounds. But while the urgencies of sounds have been rated and compared for years, the prediction and manipulation of urgency is a relatively new topic. Recent research has focused on quantification of the effects that different acoustic parameters have on perceived urgency. Specifically, an attempt is being made to apply Stevens’ Power Law to allow urgencies of alarms to be

manipulated or predicted (Hellier et al., 1993; Hellier et al., 1995). Hellier et al. (1993) tested the effects of speed (pulse rate), fundamental frequency, repetition units, and inharmonicity on perceived urgency, and then scaled the results for comparison. The stimuli created for these experiments were based on the guidelines of Patterson (1982). Pitch (fundamental frequency) was found to have too small a range to be economical in the scaling of urgency, and was thought to be best employed as a discriminator between sounds. Speed was found to be the most economical parameter to change due to the significant changes in urgency produced by small changes in speed.

The scaling of the perceived urgency of alarms has the potential to provide operators with additional information that they can use to respond to the situation in the most efficient manner. A properly designed set of alarms will signal functions with urgencies comparable to the perceived urgency of the associated alarm. These qualities can be used by the operators to determine how and when to respond to the situation. The scaling of urgency will be beneficial in the common binary alarm systems, in which alarms are either present or absent. But the application of these principles has even greater potential in the case of alarm displays that vary the urgency of a given alarm based on the current urgency of the situation (Sorkin et al., 1988).

A potential problem with these likelihood alarm displays (LADs) is that the benefit gained by the added knowledge of system state will be outweighed by the added cognitive load of extracting that information. Sorkin et al. (1988) tested both visual and speech LADs to determine whether or not the advantages outweighed the disadvantages. The results of the study showed that for a demanding task, operator performance was better in the four-level LAD condition as compared to a binary alarm condition.

Auditory Icons

A recurring problem in the design of auditory warning systems has been the selection or mapping of sounds so that as a group they are both distinguishable and easily remembered. One solution offered by Patterson (1982) and Momtahan et al. (1993) has been to reduce the number of sounds used in a system. This tactic, however, tends to

limit the amount of information that can be presented via the auditory channel to ten or fewer separate messages. A second solution may be found in advances in the design of sound interfaces for computer workstations over the last decade. The development of earcons and auditory icons may provide a way for an alarm system or any other system with auditory output to present a greater variety of messages to operators.

Gaver (1986) defines the auditory icon as a caricature of a naturally occurring sound. Since they are nothing more than everyday sounds, auditory icons are representational in nature. Similar to the auditory icon is the earcon, which also represents the sound of an unseen object, but is metaphorical or symbolic instead of representational. Due to this difference, the definition and mapping of earcons are more arbitrary than that of auditory icons (Hereford and Winn, 1994).

Auditory icons are based on a different definition of sound than has been normally used in auditory interfaces. Sounds are historically defined or described by the physical components of frequency, intensity, spatial location, duration, and attack (Hereford and Winn, 1994). These factors combine to define the proximal stimulus of a sound. An auditory icon, however, is defined by the distal stimulus – the object or action that created the sound (Mynatt, 1994). The meaning is based partially on stereotype and experience, but is primarily determined by the distal stimulus (Gaver, 1986). The identification of auditory icons requires “everyday listening,” which is “the experience of listening to determine the source itself” (Gaver, 1994, p. 419).

The majority of research into auditory icons has involved their use in computer interfaces. Gaver, Smith, and O’Shea (1991) concluded that auditory icons can present information efficiently and assist an operator in the integration of information into a coherent whole. Their simulation of a bottling plant, using auditory icons at control stations, found that relatively untrained subjects could effectively manage the plant despite the fact that as many as 14 auditory icons could be presented at once. The number of auditory icons that could be understood and remembered in this study is especially significant when it is compared to the established limits of non-

representational sounds remembered by operators of aircraft and hospital equipment (Momtahan et al., 1993; Patterson, 1982).

The greater number of sounds discernible by operators of interfaces using auditory icons is a demonstration of the ease and rapidity with which a novice operator can learn auditory icons as opposed to non-representational sounds. Begault (1994) claimed that auditory icons can be classified, identified, and categorized by operators without musical training more efficiently than non-representational sounds. This implies that the use of everyday sounds instead of earcons in a human interface can reduce the time required to learn and use the interface.

Categorization and identification were some of the greatest problems identified in Momtahan et al.'s (1993) examination of hospital operating rooms and intensive care units. With the application of auditory icons to this situation, the recognition rates of the different alarms could potentially be raised from their current level in the thirty percent range. But recognition and discernibility are not the only problems related to auditory warnings. The greatest failure by the subjects in the simulation performed by Gaver et al. (1991) was the neglect of important tasks to deal with relatively minor problems. After rating the urgency of the different sounds, this deficiency was found to be due to a poor correlation between the urgency of the auditory icons and the urgency of the information they presented.

Applications. The bottling plant simulation by Gaver et al. (1991) was designed to test the effect of the implementation of a set of auditory icons on performance of a complex task. The plant was operated by two subjects at separate control stations from which they had control over the nine machines involved in the bottling process. Each machine was equipped with an on/off switch and rate control. The subjects were instructed to produce the most bottled cola with the least amount of waste possible. Subjects operated the simulated plant both with and without the aid of the auditory icons. When operating in the auditory icon condition, each machine made sounds chosen to represent the purpose and activity of the machine. The sounds were presented in

repeated bursts instead of as continuous sounds to decrease the likelihood that all sounds would be presented simultaneously. The rhythm of the sounds changed with the speed with which the machines were operated.

The auditory representation of the status of each machine allowed the operators to effectively monitor all plant functions at the same time. The knowledge of events in all parts of the plant permitted the operators to allocate their attention and time in an economical manner. Collaboration between subjects also improved with the introduction of the auditory icons to the simulation.

A study discussed by Begault (1994) examined the effects of auditory icons in the use of touch-screens in aircraft multi-functional displays. The auditory icons were presented to the subjects through headphones to signify the activation of a system function. The activation of fuel pumps was signaled to the operators by the playback of the closing of a high-quality door-lock mechanism. Recorded versions of the push-in and release of actual in-cockpit switches were used to indicate the activation and deactivation of other buttons. The changing of the displayed menu was originally accompanied by the sound of the shuffling of cards. This particular auditory icon was changed to a simple clicking noise, however, after it was discovered that the shuffling noise was too long. While the second auditory icon used for this function was more abstract in relation to the function, it was found to be preferred by the operators. The addition of auditory feedback was found to increase operator performance, and may even be able to overcome the lack of tactile feedback through cross-modality sensory substitution.

The U.S. Army's Battlefield Combat Identification System (BCIS) was created to provide the operators of aircraft, tanks, and other vehicles with information on the identity of nearby vehicles. As originally designed, the BCIS presented this information to the operator through a set of five non-representational auditory signals. In an effort to improve the user interface of the BCIS by decreasing reaction times and errors, the original signals were compared to a new set of auditory icons intended to be more associated with their functions by the users, U.S. Army infantrymen.

Following the construction of the set of new auditory icons, subjects were presented with both the original signals and auditory icons and asked to rate the association of the sounds with the intended functions. A significant difference in the two sets of signals was found for only the “friend-in-sector” function. While the tested infantrymen failed to have an overwhelming preference for either set of signals, the use of the auditory icon set would still be preferred. The auditory icon set had a statistically significant advantage over the original set for only one of the five functions, but in an environment as critical as the battlefield, all possible steps should be taken to increase the safety of the operators.

One unexpected shortcoming revealed by the experiment was the dislike the subjects had for the doorbell auditory icon chosen to represent the “friend” function. The subjects felt that particular sound was unsuitable for use in a combat environment. This problem was not revealed in the pilot study, perhaps due to the failure of the researchers to present the pilot study auditory icons to the subjects in the appropriate environment (Haas and Schmidt, 1995).

While Haas and Schmidt (1995) succeeded in determining the levels of association between different sounds and their intended meanings, they made no attempt to measure the urgency of the auditory icons used in the study. The different messages were undoubtedly at differing levels of importance or urgency. If a target is interrogated by the BCIS and found to be “unknown,” then the operator may have to engage that target. If the target has instead been identified as a “friend,” the operator should continue searching for other targets. The “unknown” signal should therefore be more urgent, compelling the operator to either engage the target or seek positive identification. The “friend” signal, on the other hand, should be designed to be less urgent and encourage the operator to relax and seek other targets.

Graham et al. (1995) performed a simulator-based experiment to evaluate the effectiveness of auditory icons in a collision warning scenario. Two auditory icons, the sound of a car horn and screeching tires, were tested along with tonal and speech

warnings. The subjects were not given a training session with the warning sounds, but were instead asked to determine from the driving scene projected before them whether or not braking was required and to press the brake pedal as soon as possible. The dependent variables measured included time to press the brake pedal, percent of correct activations, and subjective ratings of the different warning sounds.

The results of the study demonstrated the utility of auditory icons by showing that the auditory icons produced significantly faster response times than the other stimuli. Graham et al. (1995) believed that this difference was due to the greater urgency of the auditory icons. While all sounds were presented at the same intensity, other factors such as frequency and pitch could have influenced the perceived urgency. According to the subjective evaluations, the horn sound was the most appropriate warning sound of the four tested.

A potential harmful effect of the use of auditory icons was revealed by the higher incorrect response rate for the auditory icons when compared to the tonal and voice warnings. It appeared that by responding faster to these warnings, subjects failed to spend an adequate amount of time assessing the driving situation. This effect, however, may not be a problem for actual CAS warning systems. The improper responses could be a function of the simulation, which required the driver to be focused on the dashboard of the car performing a tracking task. In an actual driving situation, the driver would not have this constraint. Secondly, the false positive responses may have been elicited by a quality of the particular auditory icons used that could be eliminated without increasing response times. Finally, false alarms from CAS warning systems are expected to become less and less frequent as advances are made in sensing technologies and warning initiation criteria selection.

Selection and use. Since auditory icons are defined by the object or action that they represent rather than a set of acoustic parameters (Gaver, 1986; Mynatt, 1994), methods for their creation and selection will differ from methods concerning non-representational sounds. Gaver (1994) suggested that auditory icons be created and

controlled by manipulation of characteristics of their perceived sources such as material, size, and force. Two of the best sources for auditory icons are sound effect collections and the sampling of actual events, but using samples such as these has disadvantages. While the acoustic attributes of tonal and other non-representational sounds may be easily altered to change their meanings, the meanings of auditory icons can only be changed by manipulating the object or action that creates the sound (Gaver, 1994).

Just as with other auditory interfaces, each sound must be evaluated in context with other sounds. Hereford and Winn (1994) address this in their set of guidelines for the use of earcons. These principles are similarly useful in constructing and evaluating sets of auditory icons. Among their suggestions are the variation of as many dimensions of the sound as possible if three or more earcons are used and making warnings and alarms different enough from other system or environmental sounds to attract immediate attention.

The functions or meanings to which auditory icons are assigned should be carefully chosen. While it appears that mappings between complex functions and auditory icons can be learned (Gaver et al., 1991), there is some evidence to the contrary. The auditory icons used in the BCIS evaluation represented not only complex functions, but sometimes included multiple messages. Haas and Schmidt (1995) believe that the associations between auditory icons and BCIS functions were not higher due to the fact that it is difficult to describe complex ideas and multiple concepts with one non-speech signal. The complexity of the function, however, may simply be a function of operator experience and can be reduced with increased familiarity with the overall system.

RECAPITULATION

In comparison to private-vehicle drivers, commercial vehicle operators are required to devote more attention to the driving task and to process more information to perform adequately. These demands, when combined with the reduced visibility and maneuverability of heavy trucks, can increase the rate of human error. Human error has

been shown to be the leading cause of accidents in commercial vehicle operations (Treat et al., 1979). Safety problems in heavy trucks are exacerbated by the failure of current auditory warnings to conform to the proper guidelines (Begault, 1994; Hereford and Winn, 1994; Momtahan et al., 1993).

ITS programs seek to increase the mobility and safety of transportation (IVHS America, 1992) – goals which will be primarily met through information and automation (Mele, 1990). It is expected that commercial vehicle operators will see an even greater increase in amount of information available than private-vehicle drivers. ITS designers are faced with the dilemma of improving safety while increasing information. The added information is frequently presented through the visual modality, but increased visual attention to the interior of the vehicle can lead to a decrease in safety (Wierwille, 1995; Zwahlen et al., 1988). Other sensory modalities must therefore be explored as alternatives to the visual pathway.

Advances in vehicle crashworthiness have increased safety and reduced fatalities, but the returns in this area are diminishing. More promise seems to lie in helping drivers to avoid accidents altogether instead of only to survive them (Leasure, 1994; Najm, 1994). Collision avoidance systems (CASs) may be designed to only alert the driver to a hazard, initiate a reaction and permit the driver to override the response, or execute and complete a response without input from the driver. Due to factors such as manufacturer liability and the human desire to be in control, the first two options are preferable to total machine control (Hagleitner, 1994; Nilsson et al., 1991). These two options both require that the CAS alert the driver of the impending hazard. Due to the shorter reaction times produced, the auditory and haptic modalities are favored over visual warnings (Horowitz and Dingus, 1992; Lerner et al., 1993; Onken, 1994). If auditory warnings are to be used, they should be designed in compliance with accepted guidelines (Hereford and Winn, 1994; Patterson, 1982, 1990). Similarly, the choice of haptic displays is limited by factors such as driver acceptability (Hogema and Janssen, 1996; Hogema et al., 1994; Onken, 1994).

The best measure of the effectiveness of a collision avoidance warning is the change in driver reaction time (Tijerina, 1995). To compare warnings, BRT must be defined in precise operational terms. To fully understand how a change in warning may reduce BRT, the driver's response must be divided into specific intervals. A decrease in overall BRT may be attributed to a warning if the difference is due to a smaller reaction time while movement and response completion times remain relatively unchanged.

Auditory icons, while originally designed for use in human-computer interfaces (Gaver, 1986), show great potential for reducing the workload and improving the performance of commercial vehicle operators. This reduction may be accomplished through the use of the auditory modality instead of the visual modality, by the integration of complex information into short messages, and through shorter training periods (Gaver et al., 1991; Janssen, Alm, Michon, and Smiley, 1993; Momtahan et al., 1993; Mynatt, 1994). The auditory messages may transmit information in and of themselves or may be designed to alert an operator to complex visual displays (Graham and Mitchell, 1994; Labiale, 1989; Patterson, 1982). If used to transmit information, the auditory icons should be designed to have a perceived urgency comparable to the information represented (Momtahan et al., 1993). The use of auditory icons instead of speech and tonal warnings has also been shown to reduce driver reaction time to a CAS braking stimulus (Graham et al., 1995).

RESEARCH OBJECTIVES

As shown in the previous overview of the literature, commercial vehicle accidents are more frequent and more severe than private vehicle accidents. This difference is primarily due to the size and handling characteristics of commercial vehicles and the greater workload of the commercial vehicle operator. The truck driver currently has a variety of functions to monitor, and this number has the potential to increase greatly with the addition of ITS technologies to the truck cab.

A potential solution to the dilemma of truck driver workload is the use of the auditory modality to present information, a tactic already used with success in other transportation areas (Graham et al., 1995; Haas and Schmidt, 1995; Patterson, 1990). Auditory messages show particular promise in the CVO arena due to the nature of the messages the driver must receive and their compatibility with guidelines for the use of the auditory modality formed by Deatherage (1972). The current poor designs in the human-machine interface of the commercial vehicle may be dramatically improved through the use of auditory messages. The ability of a set of auditory icons to present complex information may be estimated through simulation of the environment in which they will be used. Operator responses in the actual environment, however, may be different from reactions in simulations (Haas and Schmidt, 1995). It is for this reason that auditory icons intended for use in a heavy truck cab should ultimately be evaluated on-road and not by simulation.

Emergency braking warnings such as those used in collision avoidance systems are temporal in nature. It is therefore expected that they will be best presented through the auditory modality, the haptic modality, or a potential combination of the two. To demonstrate their effectiveness, auditory icons and haptic cues must reduce the time required by the driver to react when compared to other stimuli. The overall brake response time is important, but the most crucial measure is the change in reaction time, the time between stimulus presentation and the initiation of the driver's response.

This study investigated the use of auditory icons in the truck cab environment for the ITS applications of traveler information and collision avoidance. The specific aims of the study were to:

1. Examine the use of auditory icons to present information to the commercial vehicle operator.
2. Examine the effect of an auditory icon cue on commercial vehicle operator response to an unexpected collision event.

3. Examine the effect of the haptic cue of soft braking on commercial vehicle operator response to an unexpected collision event.
4. Determine the baseline response (i.e., with no warning) of a commercial vehicle operator to an unexpected collision event.

Additional objectives of the study included gathering information concerning the perceived urgencies of the informational auditory icons used in the study, information which may be used in subsequent research to compare perceived urgencies to the actual urgency of the information presented or functions represented. The study also served to test a set of auditory icons that may be used to provide information to the commercial vehicle operator. Information gained from testing these auditory icons in the truck cab environment allows for an evaluation of the methodology developed to select the set of auditory icons.

EXPERIMENTAL METHOD AND DESIGN

Experimental Design

The information presentation portion of the in-truck sessions used a single-factor within-subjects design with nine levels of auditory icon. The obstacle response portion used a single-factor between-subjects design. Due to various equipment difficulties that are typically encountered with full-scale vehicle testing, mis-timed warnings, and incompatible subject behavior, valid data obstacle response data was recorded from only 25 of the 41 subjects. Ten subjects received no warning, seven received an auditory warning, and eight received a haptic warning. An equal number of subjects were planned to be tested within each condition, but the time allotted for data collection expired before the desired number of valid tests could be completed.

Independent variables. The independent variable for the information presentation portion was auditory icon. Fifty-one candidate auditory icons were evaluated in a pilot study. Eleven auditory icons were originally selected for on-road

testing, but two were eliminated due to spectral similarities with the background noise of the truck cab. The auditory icons used in the on-road testing are shown in Table 2.

TABLE 2

Descriptions and Intended Meanings of Auditory Icons

Number	Description of Auditory Icon	Intended Meaning
1	Coin falling into slot	Automatic Toll Payment Completed
2	Giggling children	Children Playing Ahead
3	Tire skid	Emergency Braking Warning
4	Teapot whistling	High Engine Temperature
5	Train crossing bell	Railroad Crossing Ahead
6	Jackhammer	Roadside Construction Ahead
7	Ambulance siren (wail)	Emergency Vehicle Approaching
8	Digital telephone ringing	Incoming Voice Message
9	Lawnmower	Roadside Mowing Ahead
*	Rain with thunder roll	Bad Weather Conditions Ahead
*	Foghorn (2-tone)	Fog Ahead

Note: Auditory icons designated by an * were deleted from the test set due to spectral similarities with truck noise.

The independent variable for the obstacle response portion of the experiment was warning type. Three levels of warning were tested: (1) no warning, (2) auditory icon warning, and (3) soft braking (haptic) warning. It was originally intended to also test a combination auditory icon and soft braking warning, but this condition was eliminated during the course of testing due to limited subject availability and experimental equipment problems. To properly simulate the acquisition time of a real-world collision warning system, the warnings were designed to be triggered 300 ± 100 ms after the obstacle became visible. The auditory warning, the sound of a tire skid, was selected on the basis of the results of the pilot study. The soft braking warning consisted of a temporary automatic braking of the vehicle. Operationally, this warning consisted of an additional 75 psi on the truck's front brake lines for a duration of 1.0 seconds. The experience of the driver was one of a short "pulse" of the brakes, well short of causing

tire skid or profound vehicle nose dive. This warning was not accompanied by any pedal or steering wheel feedback. Since these tests were intended to be a “proof of concept” evaluation of the soft braking warning, the duration of the soft braking warning was selected to be considerably longer than the 300 ms “brake pulse” warning discussed by Landau (1995).

Despite the lack of conventional tactile feedback, the soft braking warning is still classified as a haptic warning. Haptic perception is defined to include cutaneous information and both afferent and efferent kinesthetic information (Boff and Lincoln, 1988). When the soft braking stimulus is presented, the driver feels pressure on his or her hands (from the steering wheel), thighs (from the seat), and from the shoulder belt. Additionally, there is proprioceptive feedback as the driver is forced to push against the steering wheel to combat the force of deceleration.

Dependent variables. Four subjective measures were obtained for each auditory icon tested: perceived meaning, perceived urgency, association with the specified meaning or function, and recall of intended meaning. The perceived meaning measure consisted of the subjects’ estimation of what each auditory icon would mean or what function each would represent if used to present information to a commercial vehicle driver. The subject responses to perceived meaning were not restrained to any uniform set of answers. Subjects were allowed to respond freely, and similar responses were grouped to form specific categories at the conclusion of the study. To facilitate comparison with the results of the pilot study, responses were assigned to categories developed during the pilot study whenever possible. When no adequate matches were possible, additional response categories were defined. The urgency and association ratings were made using free-modulus magnitude estimation. Each auditory icon was rated by the subjects on two non-consecutive presentations and the average of the two responses was used as the dependent measure. For the ratings of association, the experimenter informed the subject of the intended meaning of the auditory icon and then presented the auditory icon. The subject was then asked to rate the level of association

between the auditory icon and its intended meaning. Following the association ratings, the drivers had heard each of the nine auditory icons a total of five times, with the last two presentations paired with the intended meaning of the individual auditory icon. The recall measure defined the ability of the subjects to properly recall the intended meaning of the individual auditory icons following the association presentations. This measure was only recorded for eight of the auditory icons; the emergency braking auditory icon was not tested to prevent biasing the subjects. Due to time constraints, a set of five different randomly-selected auditory icons was tested with each participant instead of the full set of eight.

Multiple dependent variables were measured during the obstacle response portion of the study. Accelerator Reaction Time, Brake Pedal Contact Time, Total Brake Response Time, Steering Reaction Time, First Reaction Time, and Maximum Brake Pedal Activation were all recorded. All driver reaction times were measured with respect to the frame on the front-view videotape in which the obstacle first became visible. The frame number was used in conjunction with the data file recorded by the ICAR data collection program to determine the time at which the obstacle appeared.

Total Brake Response Time (TBRT) and its components are shown graphically in Figure 1. Accelerator Reaction Time (ART) was defined as the time required for the subject to begin lifting his foot from the accelerator following the appearance of the obstacle. Movement Time is the time required for the driver's foot to move from the accelerator to the brake pedal. The operational definition of Movement Time used was the interval between the initial movement of the driver's foot from the accelerator to the initial depression of the brake pedal. The final component of TBRT was the Response Completion Time, which was defined as the time required for the driver to achieve maximum depression of the brake pedal after his foot made contact with the pedal.

These components of TBRT differ from the BRT components presented by Broen and Chiang (1996) due to the selection of initiation of driver foot movement rather than accelerator pedal release as the point of transition between Accelerator Reaction Time

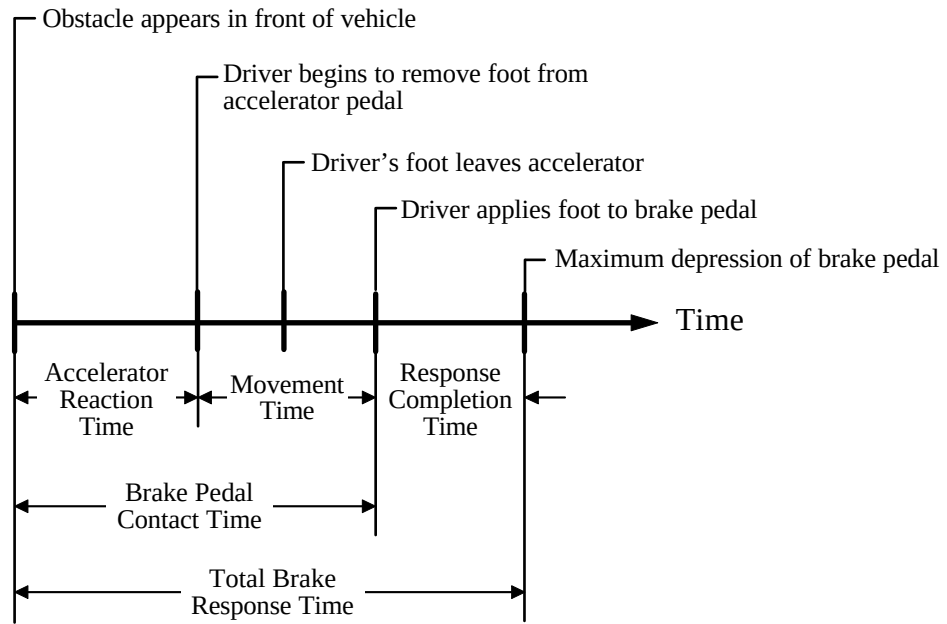


Figure 1. Components of Total Brake Response Time (TBRT).

and Movement Time. These particular intervals were chosen due to the difficulty in accurately determining the time at which the driver's foot actually leaves the accelerator.

Brake Pedal Contact Time (BPCT) was also calculated for each driver. BPCT was defined as the time from the appearance of the obstacle to the point at which the driver's foot made contact with the brake pedal, or the sum of the Accelerator Reaction Time and Movement Time. This additional metric was used to complement TBRT since it was discovered that different drivers appeared to have different strategies for bringing the truck to a complete stop. While some drivers would simply depress the brake pedal as far and as fast as possible, other drivers "pumped" the brake pedal, depressing it, easing slightly, and then applying maximum pressure. This may have been due to lack of driver experience with anti-lock truck brakes, even though all drivers held commercial licenses. Comparing BPCT across conditions eliminated the variability in TBRT produced by the variability in drivers' response strategies.

Steering Reaction Time was also calculated. A steering reaction was defined as a dramatic, rapid shift in steering wheel angle in response to the obstacles. In the case of small but rapid changes in steering wheel angle, the videotapes of driver reaction were used to help determine whether or not the movement was in response to the obstacles. A "swerve" was defined as a steering deviation of 20 degrees or more from the position of the wheel at the start of the reaction. This criterion was selected since it is twice the upper limit of steering wheel play that commercial drivers are to look for during a pre-trip inspection (Virginia Department of Motor Vehicles, 1997). To account for the fact that some drivers may have a personal tendency to either steer or brake, artificially lengthening the time they required to steer or remove their foot from the accelerator, First Reaction Time was also calculated. This measure consisted of the smaller of the two reaction times - either the Accelerator Reaction Time or the Steering Reaction Time.

In an effort to determine whether or not one of the warning conditions caused a more severe braking reaction, Maximum Brake Pedal Activation (MBPA) was also calculated. This value consisted of the maximum point to which the driver depressed the

brake pedal. Normalized (unitless) brake pedal position ranged from 0.0000 (fully up) to 1.0000 (fully depressed). Further comparison of the warning conditions was made possible through the examination of contingency data. Categorization was made on the basis of whether or not the participant had a steering reaction, whether or not he “swerved,” whether or not he braked, and whether or not he brought the truck to a complete stop.

Failure to respond to the obstacle was defined as an initial reaction more than 2.5 seconds after the presentation of the warning or obstacle. This criterion was partially based on the 1.5 second interval used by Theeuwes and Alferdinck (1995). The interval was increased since Theeuwes and Alferdinck (1995) were measuring responses to the expected activation of brake lights and not an unexpected stimulus. Furthermore, in a study of the braking reaction times of 100 drivers to an unexpected obstacle, the longest brake reaction time recorded was 2.44 seconds (Broen and Chiang, 1996). (The definition of BRT employed by Broen and Chiang (1996) is the equivalent of Brake Pedal Contact Time in the current study.) Of the 41 drivers, one participant in the no warning condition failed to notice or respond to the obstacle, and his obstacle response data were therefore discarded. While the failure to respond to the obstacle within this interval or an improperly timed warning necessitated the elimination of an individual subject’s data, the subjective data collected during auditory icon presentation for those subjects was not discarded.

Pilot Study

In preparation for the on-road experiment, a pilot study was performed to establish a set of auditory icons suitable for use in a commercial truck cab. An initial set of 51 auditory icons was created to represent information available in current truck cabs and information potentially available through future ITS technologies. A subset of those auditory icons was used for this experiment. An overview of the pilot study and its results has been included in Appendix A. The criteria used to select the subset of auditory icons for the on-road study included: (1) subject free responses to perceived

meaning; (2) ratings of the association between the auditory icons and their intended meanings; (3) perceived urgency scores of the auditory icons, and, in the case that too many auditory icons satisfied the previous criteria; (4) utility of the function or information represented by the auditory icon. Using these criteria, 11 of the 51 auditory icons were selected for use in the on-road testing. The spectral patterns of two of these auditory icons, a foghorn and rainfall with thunder, were very similar to the pattern of truck noise. This, combined with the poor quality of the original samples, necessitated the elimination of these auditory icons from the study. The pilot study also served to test the data-collection methods to be used in the in-truck portion of the study.

Loudness Equalization

The sound files containing the auditory icons were converted from Macintosh System 7 Sound format to wave format for use with a laptop PC. Although these auditory icons had already been set to equal loudness to avoid biasing the perceived urgency ratings, the loudness of the converted auditory icons was equalized to account for differences between the pilot and on-road studies. For the pilot study, all auditory icons had been presented via headphones from a Macintosh Powerbook in a quiet laboratory environment. The equalization process was designed to provide as close an approximation of on-road conditions as possible, including the presence of background truck noise.

The equalization process was carried out using the Virginia Tech Commercial Vehicle Driving Simulator. The auditory icons were presented from a Gateway 2000 laptop computer through an AudioControl octave-band equalizer, an Adcom model GFP-555II preamplifier, an Adcom model GFA-545II amplifier, and a pair of Optimus XTS 25 speakers. The loudspeakers, identical to those to be used in the on-road study, were mounted behind and to either side of the truck seat's headrest in the simulator. All sound levels were measured using a Larson-Davis 3100 real-time spectrum analyzer. At this point it was discovered that the foghorn and rainfall with thunder auditory icons had spectral distributions that were very similar to that of heavy truck cab background noise.

The similarity of the spectra, due to the low signal-to-noise ratios of the original sound samples, would have required an inappropriate amount of amplification of the auditory icons to ensure that they were audible and identifiable in the presence of the truck noise. Since it had been determined that the other auditory icons from the pilot study were not suitable for use in the on-road study, the eliminated auditory icons were not replaced and the on-road set was reduced to the nine auditory icons previously listed in Table 2.

The method of paired comparison was used to equalize the loudness of the nine auditory icons. Using the audio equipment installed in the truck simulator, each possible pair of auditory icons was played in random order for individual listeners. The listeners were asked to state whether or not the two sounds they heard were within ten percent of each other with respect to loudness as they perceived it. Once all of the combinations were played, those combinations that were reported to be different with respect to loudness were played a second time, but with the pair presented in reverse order. If the listener failed to provide the same response as after the first presentation of the pair, the auditory icon pair was considered to be of equal loudness. After three listeners had compared all of the auditory icons, the levels of individual auditory icons were adjusted according to the listeners' responses. A second group of three listeners was then used to evaluate the adjustments of the auditory icons. At this point, no consistent differences in loudness were found for the auditory icons.

The master volume and sound file gain settings of the laptop PC were adjusted such that all nine of the auditory icons met the 1/3 octave band criteria of ISO standard 7731, "Danger signals in work places - Auditory danger signals." ISO 7731 states that the level in at least one 1/3 octave-band of a signal must be 13 dB or greater than its masked threshold in the 300 to 3000 Hz range (the 315 to 3150 Hz 1/3 octave bands) (ISO, 1986).

The loudness equalization process was used again, but this time the auditory icons were presented in continuous truck noise. This noise had been recorded during a previous research project and was the same noise used in the operation of the Virginia

Tech Commercial Driving Simulator. Three listeners from the previous group were used to compare the loudness of the sounds. Only very minor differences in loudness were reported by the listeners, and the required modifications were made to the individual sound files.

The noise levels in the truck to be used in the on-road testing were measured under conditions identical to those to be encountered in the experiment. The same route was traveled (four-lane, hilly road) at the appropriate speed (55 mph). The sound levels were measured by continuous calculation of 5-second L_{eq} 's over a period of thirty minutes using a RION SA-27 one-third octave band real-time analyzer. Two sets of measurements were recorded, one with the truck's air conditioning system off and one with the fan set on the second lowest of four settings. During a portion of the route driven for the measurements, the speed limit dropped to 45 mph. The L_{eq} 's for both the overall route and the portion of the route with the 55 mph speed limit were calculated. According to ISO 7731, the level of an auditory warning should be set with consideration given to the maximum background noise levels. The measurements taken during the 55 mph portion of the route with the air conditioning system off were found to be slightly higher than those taken under the other conditions and were therefore used for the masked threshold calculations. The noise levels measured in the different conditions and the resulting criterion level are shown in Table 3.

To ensure that all of the auditory icons were presented at an audible and intelligible level, the in-truck amplifier was adjusted before each day's testing so that the 1/3 octave band level of the quietest of the nine auditory icons (Roadside Mowing Ahead) exceeded the ISO 7731 criteria in at least one 1/3 octave band between 315 and 3150 Hz. Graphs comparing the spectral patterns of this and all other auditory icons to the spectral pattern of the measured truck cab background noise have been included in Appendix B.

TABLE 3
One-Third Octave Band In-Truck (Volvo VN) Noise Levels (dB)

1/3 OB cf [Hz]	Fan on		Fan off		ISO 7731 1/3 OB criteria
	Overall L _{eq}	55 mph L _{eq}	Overall L _{eq}	55 mph L _{eq}	
25	84.6	83.8	84.7	84.5	97.5
31.5	83.7	83.2	82.9	83.7	96.7
40	80.5	80.9	80.5	81.1	94.2
50	79.4	79.3	80.0	80.4	93.4
63	76.8	76.4	78.9	79.0	92.0
80	77.4	77.0	79.0	80.1	93.1
100	75.1	74.6	76.3	76.2	90.6
125	70.6	70.4	71.4	71.6	88.1
160	73.2	72.9	72.5	72.9	85.9
200	70.3	70.1	71.0	71.2	84.2
250	67.4	67.0	69.4	69.3	82.3
315	65.4	65.4	65.9	66.3	79.8
400	66.9	66.7	66.5	66.8	79.8
500	64.8	64.8	64.1	64.5	77.5
630	63.2	63.3	62.9	63.3	76.3
800	61.8	61.9	62.4	62.8	75.8
1000	60.3	60.2	60.6	61.0	74.0
1250	57.4	57.3	58.1	58.6	71.6
1600	55.2	55.0	55.2	55.6	69.1
2000	53.7	53.6	53.9	54.2	67.2
2500	52.4	52.1	52.1	52.3	65.3
3150	49.2	48.7	49.0	49.2	62.8
4000	47.0	46.5	46.7	46.9	60.3
5000	43.9	43.3	43.4	43.6	57.8
6300	41.5	41.0	40.9	41.1	55.3
8000	38.6	37.3	37.4	37.5	52.8
10000	36.2	34.2	34.9	34.9	50.3
12500	31.4	31.2	30.9	30.9	47.8
16000	29.3	29.4	28.5	28.4	45.3
20000	25.3	25.1	25.0	24.8	42.8

Test Facilities and Apparatus

Audiometric screening. A Beltone 119 portable audiometer (Figure 2) with TDH50 headphones was used to present the audiometric tones. All tests were performed in an IAC 250-LP portable audiometric booth (Figure 3). Inside the booth, ambient sound levels were measured to ensure they were consistent with the requirements set forth in the OSHA Hearing Conservation Amendment (OSHA, 1990).

Heavy truck. All of the testing for the in-truck portion of the study took place as the participant drove a 1997 Volvo VN (Figure 4) donated to the Virginia Tech Center for Transportation Research (CTR) by the Volvo GM Heavy Truck Corporation. To reduce the potential risks to the participant and experimenter, the cab was operated without a trailer attached. The addition of a trailer was not anticipated to affect the subjective or objective responses of the participants, and the use of the trailer may have unnecessarily and undesirably increased the stopping distance of the vehicle during the collision avoidance warning test.

Auditory icon presentation. The sound files for the nine auditory icons presented to the subjects in the truck cab were contained on a Gateway 2000 laptop computer, the same computer used in the loudness equalization process. The presentation of each sound was initiated by the experimenter riding with the subject. The sounds were presented to the driver through a pair of Optimus XTS 25 speakers, located behind and to either side of the truck seat's headrest as shown in Figure 5. The auditory icon used as an emergency braking warning was also stored on the laptop computer, but was triggered by a direct memory access wave file player which played the emergency braking warning sound file when it received a signal from the in-truck control laptop. This sound file was identical to the file used to present this auditory icon during the subjective data presentations. The speakers were driven by Denon model PMA-525R stereo amplifier installed in the vehicle. The amplifier was wired to receive input from the laptop computer's line-out jack.



Figure 2. Belton 119 Portable Audiometer.



Figure 3. IAC Portable Audiometric Booth.



Figure 4. 1997 Volvo VN.



Figure 5. Optimus XTS 25 speakers.

Obstacle presentation. In order to avoid adverse consequences of the potential collision between obstacle and vehicle, the obstacle had to be chosen carefully. The obstacle had to be sturdy enough not to shatter or break apart upon collision with the truck, yet must also not damage the truck. The nature of the obstacle should be such that the driver would be compelled to apply the truck's brakes as soon as the obstacle entered the truck's path.

It was decided to use plastic construction barrels as the obstacle. Construction barrels were chosen since they are designed both to resist impact and to be sturdy enough that a driver would be motivated to avoid a collision. These barrels were modified slightly in that their bottom rims were cut off to enable them to roll freely. Cardboard disks were taped inside the barrels to help them maintain their shape yet collapse if caught underneath the truck. Four barrels were used to provide a more persuasive obstacle than a single barrel. If only one or two barrels were to be used, it would be possible for them to roll completely across the path of the truck before the truck reached them, eliminating the need for the driver to take evasive action. Additionally, a smaller number of barrels might not register as a sufficient obstacle to the drivers.

Lerner (1993) states that having an object enter the vehicle's path is preferred to stationary objects in the roadway or other line-of-sight techniques due to the increased alertness of drivers when roadway sight distance is reduced. A similar procedure was used in a study reported by Rice and Dell'Amico (1974). While driving on a specially-constructed handling course, a 20 gallon plastic container was ejected into the path of the vehicle. The ejection of the obstacle was triggered by a trip switch located 100 feet up-track from the ejection point. Approach speed for the 34 drivers ranged from 37 to 62 mph. The mean values for approach velocity and reaction time (braking or steering) were 55 mph and 0.65 seconds, respectively. A common problem experienced in the reported study was that the ejection mechanism would frequently under- or overshoot the center of the roadway, and data generated in those runs had to be discarded. It was hoped

that the use of a set of plastic barrels in the current study would prevent or reduce such problems.

To produce a valid simulation of the emergency braking stimulus of an emergency braking system, the auditory and haptic warnings must be presented after the obstacle is ejected in front of the vehicle. A delay of 300 ms was selected to simulate the time required by an actual emergency braking warning system to detect an obstacle and distinguish it from other non-threatening objects. Due to timing variations caused by factors such as the speed and path of the truck, equipment response time, and time required for the barrels to roll from behind their place of concealment, warnings presented 200 to 400 ms after the appearance of the barrels were ruled to be acceptable approximations.

The obstacle presentation was performed in a closed parking lot, a map of which is shown in Figure 6. (A map of the course itself is shown in Figure 17.) The inclusion of the handling course allowed the experimenters to inform the participants that there would be some risk, even though the exact nature of the risk was not revealed beforehand, avoiding bias and anticipation effects. Secondly, it was hoped that the presence of the traffic cones outlining the course, defining a straight path for the vehicle, would encourage the participant to react to the obstacle by braking or braking and evasive steering rather than evasive steering alone. In previous research (Lerner, 1993), nearly half of the subjects failed to brake at the sight of an obstacle. The low speed of the truck at the time of the presentation would reduce the effectiveness of steering in avoiding the obstacle, which could also increase the percentage of recordable brake responses.

The release of the construction barrels was triggered by an infrared sensor located 50'-10" away from the barrels. This point was selected since it provided enough time for the truck to avoid contact with the barrels only if the driver activated the brakes within a few tenths of a second after the appearance of the barrels. When testing began, the release of the barrels was instead controlled by a ControLaser 200 laser range-finder

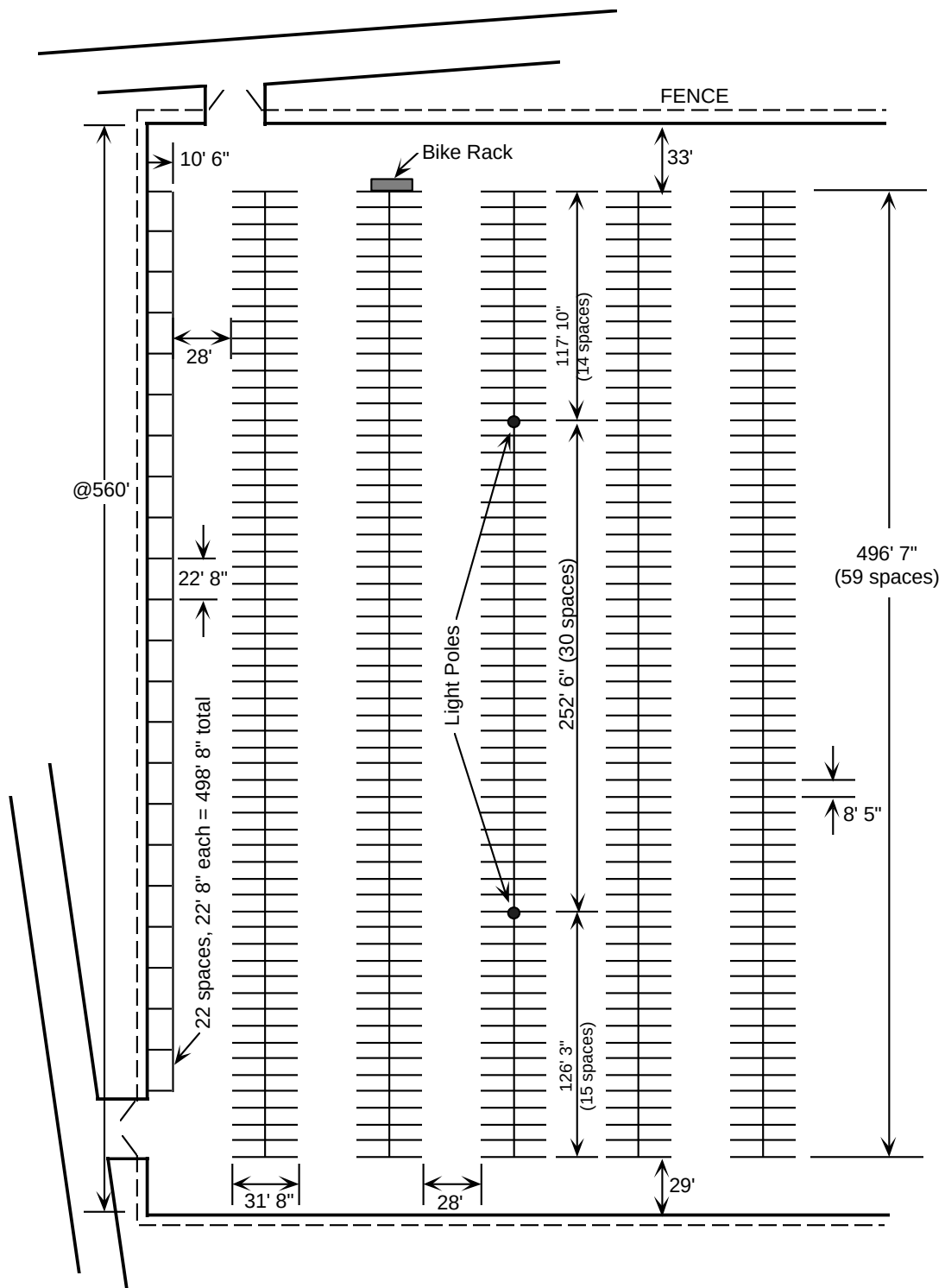


Figure 6. Layout and dimensions of parking lot for obstacle course.

capable of outputting the speed of the detected object. From the measured speed and position of the truck, the release of the barrels would be triggered when the truck (assuming constant velocity) was a predetermined time away from the location at which the barrels would appear. By triggering the release of the barrels using a time-to-collision (TTC) criterion instead of a strict distance criterion, the potential variability in driver reaction due to variability in TTC across trials would be eliminated. The range-finder, however, was found to have an insufficient reliable detection range and to be too inconsistent in its time between readings to provide accurate truck velocity data. Without an accurate reading of the truck's velocity, it was impossible to continuously calculate an accurate TTC. It was determined that the variability introduced by the use of the laser range-finder was greater than the expected variability in driver speeds, so a strict distance criterion was instead used to trigger the obstacles. If each participant were to drive the course at an identical speed, there would be no variation in TTC across trials.

Through an analysis of videotape of the barrel presentation, it was determined that the operational TTC for the experimental setup was approximately 1.9 seconds. At a constant speed of 15 mph (22 feet/second), a vehicle would require 2.3 seconds to reach the point at which the barrels appeared after passing the trigger sensor. The 0.4 second discrepancy is accounted for by delays inherent in the sensor itself and the time required for the barrels to gain velocity and roll out of their concealed position.

While TTC is often a useful metric, additional measures must be used to make comparisons across different vehicle speeds. In situations that do not involve swerving to avoid an obstacle, the urgency of the potential collision is better measured by the rate of deceleration required to bring the vehicle to a stop before contact is made with the obstacle. The Required Deceleration is calculated by the following formula:

$$RD = \frac{V}{2 \times TTC}$$

where V is the vehicle speed.

Even though the TTC selected for this project is short in comparison to other studies, the Required Deceleration for the collision scenario is either comparable to or

much less than that of most other studies. With respect to the amount of vehicle deceleration required to avoid the obstacle, this TTC value would be equivalent to a TTC of almost 6 seconds if the truck were to be traveling at a speed of 45 mph. A comparison of TTC and Required Deceleration values for this study and previously published simulator research is shown in Table 4. A metric similar to Required Deceleration, Actual Degree of Emergency, was used by Lechner and Malaterre (1991). Their calculations, however, included the subtraction of a constant correction factor from the TTC to account for driver reaction time. If such a correction factor were to be used, the value for the current study would become even smaller in relation to previous values.

The barrels used as the obstacle were placed on a wooden ramp approximately three feet to the right of the straight entrance to the handling course (Figure 7). The ramp and barrels were concealed by the trailer used to store the obstacle course equipment and four stacks of additional barrels, as shown in Figure 8. The parking lot used for the obstacle course had a natural slope in the same direction as the ramp. The slope of the parking lot combined with the slope of the ramp to incline the barrels at an angle of 23 degrees.

The barrels were restrained by the small wooden gate shown in Figure 9. The weight of the barrels on the gate provided enough force to hold the linkage that propped up the gate in the “closed” position. The lower linkage bar was connected to a solenoid using high-strength fishing line. When the infrared sensor was activated, it sent a signal to the solenoid to pull on the pin attached to the fishing line. This provided sufficient force to collapse the linkage that held up the gate, allowing the barrels to roll off of the ramp and into the path of the truck, as shown in Figures 10 and 11.

In-truck measurements. An EPS laptop computer located inside the truck cab in an under-bed compartment, as shown in Figure 12, was used to run a customized version of the ICAR In-Car Data Collection Program written and adapted by CTR personnel. This program simultaneously collected continuous data from sensors throughout the truck. The variables recorded included a time-stamp measured from the time the

TABLE 4

Comparison of Required Deceleration with Previous Simulator Studies

Source	TTC [sec]	Vehicle Speed (original units)	Vehicle Speed [ft/s]	Distance to Obstacle [feet]	Required Deceleration [ft/s ²]
Adams, Flannagan, and Sivak (1995)	2.01	55 mph	80.7	162	20.08
Barrett, Kobayashi, and Fox (1968)	2.09	25 mph	36.7	77	8.79
Doi, Nagiri, and Takei (1994)	2.0, 2.5, 3.0	31-37 mph	45.6-54.7	not given	15.16-28.9
Lechner and Mallaterre (1991)	2.0, 2.4, 2.8	56-62 mph	80.7-91.7	114-279	28.8-45.8
Current Study	1.9	15 mph	22	42	11.58



Figure 7. Ramp used to present obstacles.



Figure 8. Concealment of obstacles.



Figure 9. Gate and solenoid mechanism.

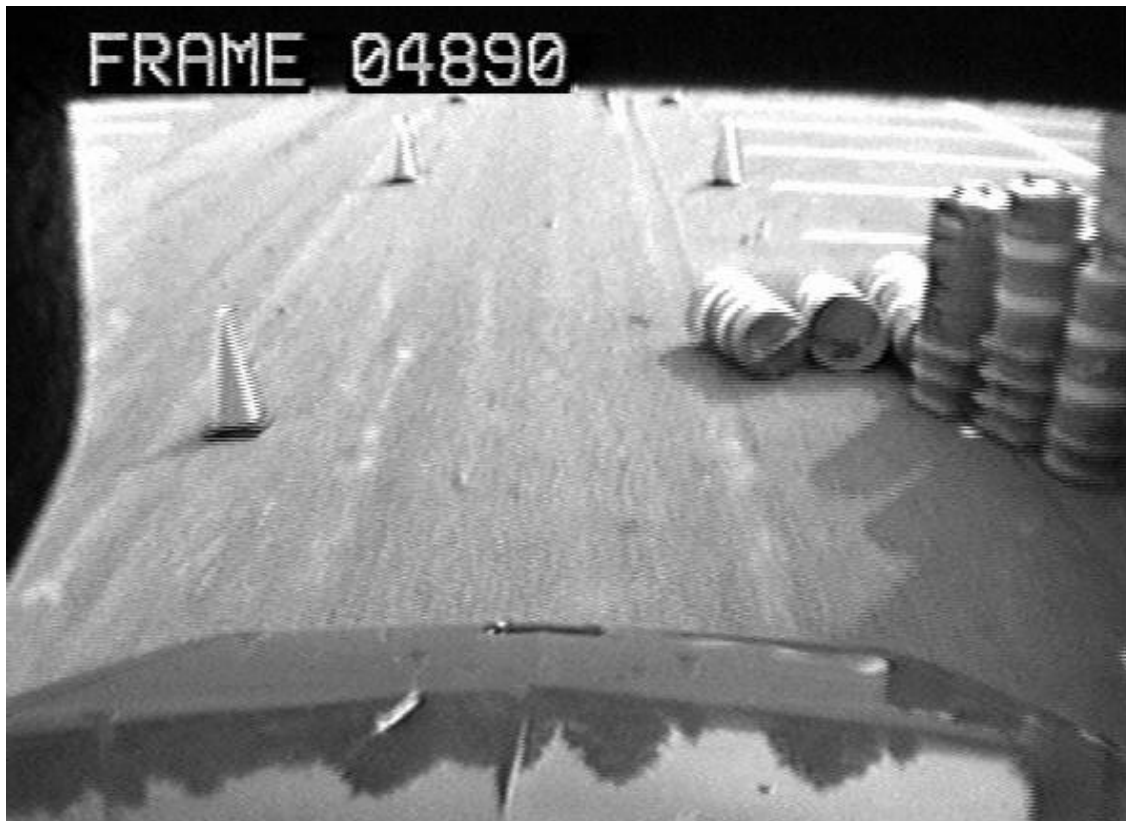


Figure 10. Release of barrels into the path of the truck (driver view).



Figure 11. Release of barrels into the path of the truck.



Figure 12. In-truck control laptop.

program was initiated (measured in milliseconds), a video frame number, steering wheel position, normalized brake and accelerator pedal positions, lateral, longitudinal, and vertical acceleration of the truck cab, speed of the truck, and distance traveled since data collection began. These values were continuously written to a data file on the computer's hard drive. Additional columns in the data file registered the time at which the signal from the infrared sensor was received and the activation of the emergency braking warnings. The ICAR program sampled these attributes at a nominal rate of 30 Hz, but the time interval between samples was typically 50 ms, resulting in an actual rate of 20 Hz. This was due to the fact that there was no change in time stamp for approximately one out of every three entries. While the time stamp did not change, other sampled values were typically updated between each entry. Further information about this system can be found in Gellatly, Petersen, Ahmadian, and Dingus (1997).

Soft braking cue. The soft braking cue consisted of a small amount of automatic braking by the vehicle, providing proprioceptive, kinesthetic, and inertial cues to the driver. A mechanism constructed by CTR personnel, shown in Figure 13, was connected to the truck's front brake lines. When activated, this mechanism introduced an additional 75 psi of air pressure to the front brake lines. To the truck's driver and passengers the cue felt like a short but rapid "pulse" of the brakes. Once the in-truck computer received the signal from the infrared sensor that the barrels were being released, it paused for a predetermined time and activated the soft braking mechanism for a period of 1.0 seconds. A graph of the longitudinal deceleration caused by the activation of the soft braking apparatus is shown in Figure 14.

Videotaping. The truck was also equipped with four miniature video cameras, each measuring approximately one inch square and one-half inch deep. These cameras were used to collect information during the obstacle avoidance portion of the experiment. One camera was directed at the driver to determine where the driver was looking when the obstacle became visible. A second camera was aimed in front of the truck to record the appearance of the obstacle itself. A third camera was used to record the positions of

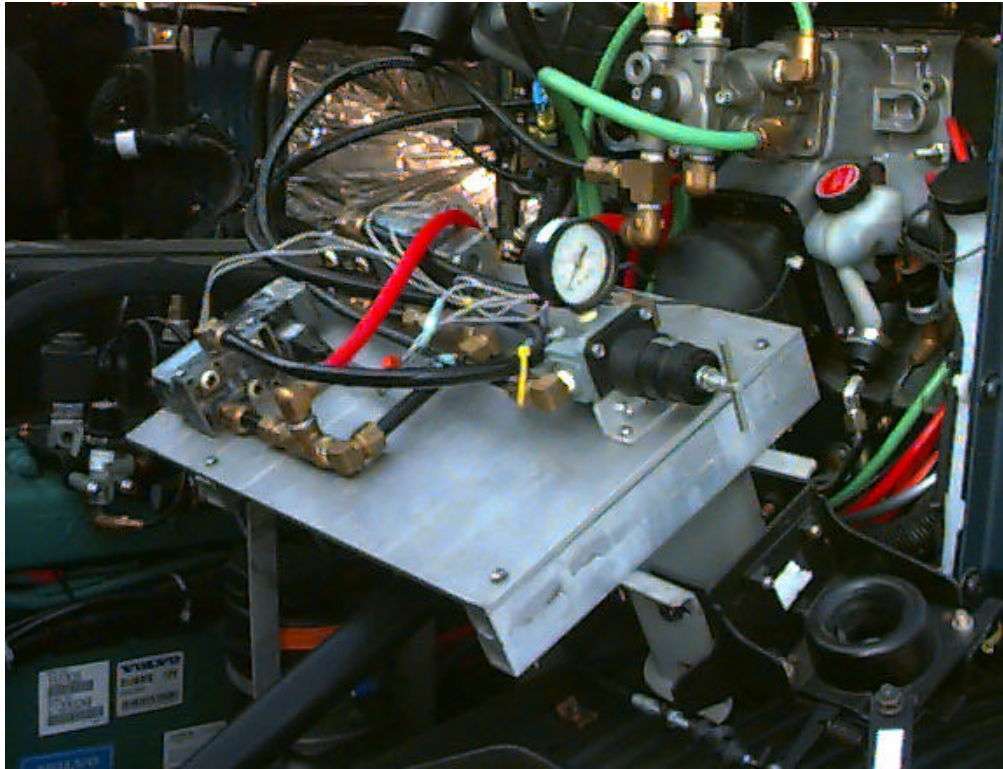


Figure 13. Soft braking mechanism.

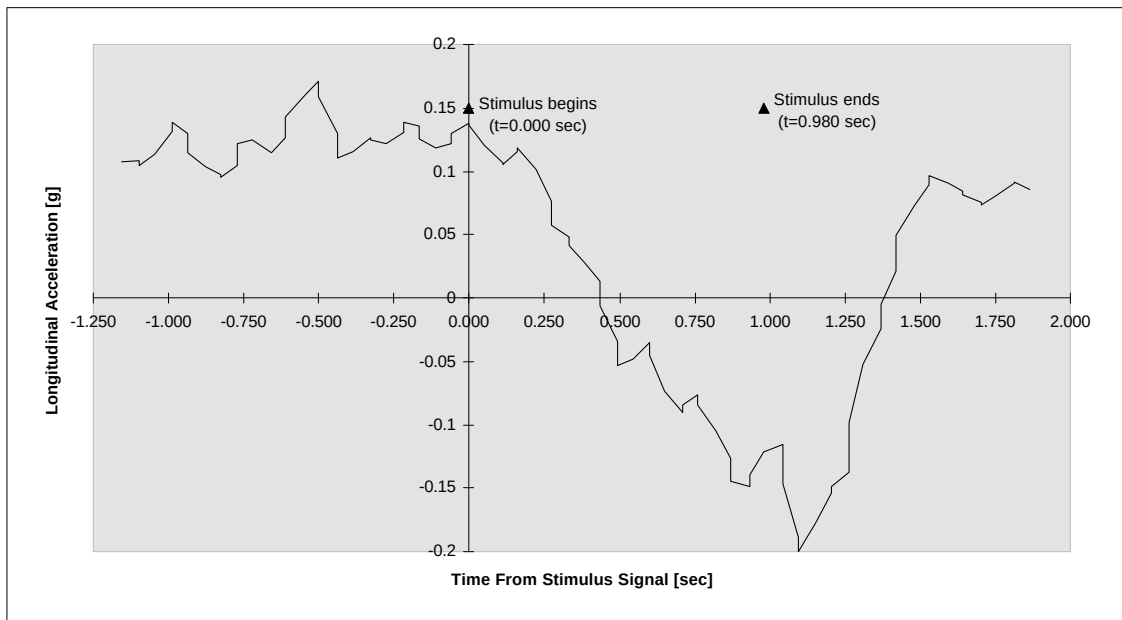


Figure 14. Example of longitudinal deceleration due to soft braking stimulus.

the driver's feet, aiding in the interpretation of brake and accelerator position data. The fourth camera was concealed in the passenger-side exterior convex mirror and provided a view comparable to the driver's view in the mirror.

The small size of these cameras permitted them to be entirely concealed from the view of the driver. The lens of each camera was less than 1/16th of an inch in diameter. The camera providing a view of the driver was concealed within the molding of the driver-side A-pillar. The front-view and pedal cameras did not require concealment as they were not in the driver's field of view. The front-view camera was mounted on the centerline of the truck between a pair of front, overhead, in-cab compartments. The angle of the view provided by this camera differed slightly from the driver's view in that it was higher and closer to the center of the cab. This difference may have caused the barrels to become visible on the recorded videotape at a slightly different time than when the driver could see the barrels. The difference in angle, however, did not significantly affect the measurement of driver responses as any difference would be extremely small and constant across trials. The output of the cameras was mixed by a video splitter and recorded in quad-split format by a Super-VHS VCR. An example of the camera views is shown in Figure 15.

Subjects

The subjects for the in-truck portion of the study were required to possess a Class A commercial driver's license (CDL). This was necessary since the subjects were required to drive a heavy truck on public roads during the experiment. (Only a Class B CDL is required to drive the truck without a trailer, but participants with Class A experience were needed for the data collected concerning auditory icons to be applicable to the Class A CDL population.) Participants were also required to have at least 10,000 miles of commercial driving experience. Only male drivers were recruited; inclusion of female drivers would have required that one of two approaches to be taken – either the percentage of female drivers in each condition would have to be equivalent to the percentage of female drivers in the Class A CDL population or an equal number of male



Figure 15. In-truck camera views.

and female drivers would have to be used. Since current estimates of the percentage of female truck drivers are about five percent, the first option would not justify the inclusion of even one female driver in each condition. The second condition was ruled to be equally unacceptable as it would require the recruitment of an unrealistic number of female truck drivers. Data was collected for a total of 41 paid volunteers. Background information on each of the participants can be found in Appendix C.

Subjects were also required to meet the FHWA motor vehicle driver hearing level criteria for participation found in CFR 391.41 (FHWA, 1994). The FHWA pure-tone criteria require drivers to have a pure-tone average hearing level of 40 dBHL at 500, 1000, and 2000 Hz for the better ear.

Experimental Procedure

Each participant was scheduled to attend one experimental session. For a few subjects, problems with the experimental apparatus were detected after the session had begun, but before the obstacle presentation. These subjects were asked to schedule a second, shorter, session to permit the collection of these data. Useful data were collected for only one of these subjects. All other subjects completed all parts of the testing during a single session.

Prior to each day's testing, the volume of the in-truck amplifier was calibrated using a RION SA-27 one-third octave band real-time spectrum analyzer, with the microphone mounted at the approximate driver head position, as shown in Figure 16. The calibration was performed using the Roadside Mowing Ahead auditory icon, which was the auditory icon with the smallest differential from the recorded level of truck noise. If the amplifier volume was set at a level such that this auditory icon met the requirements of ISO 7731, all other auditory icons would also be at a satisfactory level.

Screening and orientation. Potential participants were greeted at the experimental area and provided with an informed consent document. The informed consent document, Appendix D, included an outline of the portion of the in-truck study dealing with the presentation of auditory icons and subsequent collection of subjective



Figure 16. Calibration of speaker volume level.

data. The obstacle presentation portion of the experiment was not mentioned in the informed consent document to allow the obstacle and warning to be presented in a completely unexpected manner. (This information was covered in a second informed consent document provided to the participants after the completion of the session. This document is included in Appendix E.) Each participant was given a copy of the informed consent document after signing it.

Next, the experimenter administered a partial audiometric screening test to ensure that the participants meet the FHWA hearing requirements. Following the audiogram, the experimenter explained the method of free-modulus magnitude estimation to the participant. The participant then performed a short line-length estimation task to practice the method. Such practice was valuable in preventing confusion during the pilot study and has been shown to stabilize the results of later scaling tasks and decrease the regression effect (Zwislocki, 1983). The instructions given to the participants are listed in Appendix F.

The participant was then escorted to the truck and allowed to familiarize himself with its displays, controls, and other features. Once the participant was familiar with the truck, the experimenter (seated in the passenger seat) directed the participant to drive the truck out of the parking area. At this time, the participant was allowed to drive the truck over a set of low-traffic, 35 mph speed limit roads to become more familiar with the truck's handling characteristics.

Once comfortable with the truck, participants in the no warning or auditory warning conditions were directed to begin the route over which the auditory icons would be presented. Participants scheduled to receive the soft braking stimulus were given the chance to become familiar with that stimulus. The soft braking stimulus was presented five times, the same number of times that each participant would hear the auditory icon intended as an emergency braking warning. In an effort to decrease the emphasis on the soft braking stimulus, the familiarization process was also carried out for an auditory icon not selected for the on-road testing. Similar procedures were followed for the

auditory icon and soft braking stimulus, so the use of the auditory icon also served to acquaint the participant with the procedures before they were performed for the soft braking stimulus.

The auditory icon selected for the familiarization process was the sound of a drain clearing, intended as a Low Fuel Warning. The auditory icon was played twice, and the participant was asked to say what he would expect the sound to mean if he heard it while driving. The sound was played a third time, and the participant was asked to rate its effectiveness as a Low Fuel Warning. The participant was permitted to choose from the following options: Completely Ineffective, Somewhat Ineffective, Somewhat Effective, Completely Effective, and No Opinion. Finally, the auditory icon was played two more times, at which point the participant was asked what could be done to make the sound more effective as a Low Fuel Warning. The responses given by the participants to these questions have been included in Appendix G.

For the soft braking stimulus familiarization process, the participant was instructed to maintain a truck speed between 20 and 25 mph. These speeds were chosen to be close to the speed of the obstacle presentation portion of the testing (15 mph), yet not too slow to impede traffic on the experimental route. As with the auditory icon familiarization process, the soft braking stimulus was presented twice and the participant was asked to say what he would expect it to mean if he felt it while driving. The participant was then given an explanation of the purpose of an Emergency Braking Warning. The stimulus was presented again, and, given the same response options as for the auditory icon, the participant was asked to rate its effectiveness as an Emergency Braking Warning. The participant was also asked to assume that the stimulus would have no harmful side-effects if used under wet or icy road conditions. Finally, the soft braking stimulus was presented two more times, after which the participant was asked if its effectiveness as an Emergency Braking Warning could be improved by changing either its magnitude or duration. The responses provided by all participants who went through the familiarization procedures with the soft braking stimulus can be found in

Appendix G. Only two of the 19 drivers tested under this procedure gave initial responses that could be interpreted as an Emergency Braking Warning. When asked to rate the effectiveness of the stimulus as such a warning, however, 21% considered it to be somewhat effective and 68% thought it would be completely effective.

At this time, the participant was instructed to begin the experimental route. After leaving the Virginia Tech campus, the participant was directed to head west on U.S. 460. This section of road is a rural, hilly, four-lane, divided highway with a speed limit of 55 mph. The participant was instructed to maintain a speed as close to the posted speed limit as practical.

Auditory icon presentation. While operating the truck, the participant was presented with the set of auditory icons. The instructions read to the participant for this portion of the testing have been included in Appendix F. The auditory icons were presented individually and in a different random order for each participant. Each presentation was initiated and controlled by the experimenter seated in the truck's passenger seat. An interval as long as 30 seconds separated the presentation of all auditory icons. Additionally, in order to prevent distraction of the driver, no presentations occurred while the truck was passing another vehicle. Following each presentation, the participant was asked to give the perceived meaning of the sound or describe the function associated with that sound. The participant's response was recorded by the experimenter; if the response was too vague, the experimenter requested a more detailed answer. The complete set of nine auditory icons was presented. The responses given by the participants have been included in Appendix H.

Following a short break while still driving, the set of auditory icons was presented to the participant a second and third time, on non-consecutive occasions, in a different random order each time. Following each presentation, the participant was asked to use free-modulus magnitude estimation to rate the perceived urgency of each sound. The participant was reminded to rate the perceived urgency of the sound itself and not the message or function represented. The two responses given for each sound were averaged

to give the sound's rating. Following the collection of perceived urgency data, the participant was instructed to take the next available opportunity to cross to the opposite side of the highway and begin the return trip.

Once the return trip began, the participant was again presented with the entire set of auditory icons in a different random order. As for perceived urgency, each auditory icon was presented twice on non-consecutive occasions. Prior to each presentation, the experimenter informed the driver of the sound's intended meaning. When necessary, an explanation of the intended meaning was also provided. The participant was asked to use free-modulus magnitude estimation to rate the degree of association between the auditory icon and its intended meaning. The average of the two responses for each sound was used as the participant's rating of the sound's association with its intended meaning.

Following a delay of approximately three minutes, the remainder of the on-highway time required to reach the obstacle presentation area was used to test the participant's recall of the intended meaning of a subset of the auditory icons. A different randomly selected set of five auditory icons was used for each participant. Each auditory icon was presented on two non-consecutive occasions. Only five auditory icons were presented to each participant to permit each presentation to be separated by an interval of at least 30 seconds while ensuring that the entire set could be presented before the return trip was completed. The emergency braking auditory icon was never a part of these presentations to prevent the participant from having an increased awareness of the emergency braking function, which could potentially affect the participant's expectation of an obstacle and thereby contaminate the measured obstacle responses.

The participant was informed that a subset of the auditory icons he had already heard would be played at random times without warning. After each presentation, the participant was to state the intended meaning of the auditory icon as best as he could remember. As in the free response categorization, all responses similar to the intended meaning were recorded as correct. Incorrect responses were also recorded and the

participant was told the auditory icon's correct intended meaning before the next auditory icon was presented.

Obstacle presentation. After completing the return trip, the participant was instructed to drive the truck to a large enclosed parking lot on the Virginia Tech campus where a short handling course had been set up. The route to the parking lot was selected to prevent the participant from seeing the ramp holding the construction barrels that would serve as the unexpected obstacle. This ramp was hidden behind the truck trailer used to store the handling course equipment and the personal vehicle of an additional experimenter who had set up the handling course.

The participant was instructed to stop the truck at the start area of the handling course. At this point, the ICAR data acquisition software was activated. The in-truck experimenter then explained to the participant the route he would be required to take through the handling course (Figure 17). The driver's view at the start point of the handling course is shown in Figure 18. The participant was told that he would make two separate drives through the course; the first trip through the course would be for the purpose of practice and would only cover the initial straight approach and the first slalom course. The second trip would cover the entire course. The primary purpose of these instructions was to permit a second trip through the course if the obstacles failed to be released in front of the truck. All valid data collected were taken during the participants' initial trips through the course.

Each participant had been informed that the purpose of this course was to determine how drivers navigated obstacles and that measures such as steering and braking reactions, as well as eye glance data, would be recorded. Participants wearing sunglasses were asked to remove them at this point to permit their direction of sight to be determined from the videotape. The participants were informed that their two responsibilities in completing the course were to stay within the traffic cones and to maintain a constant speed as close to 15 miles per hour as possible. The participants

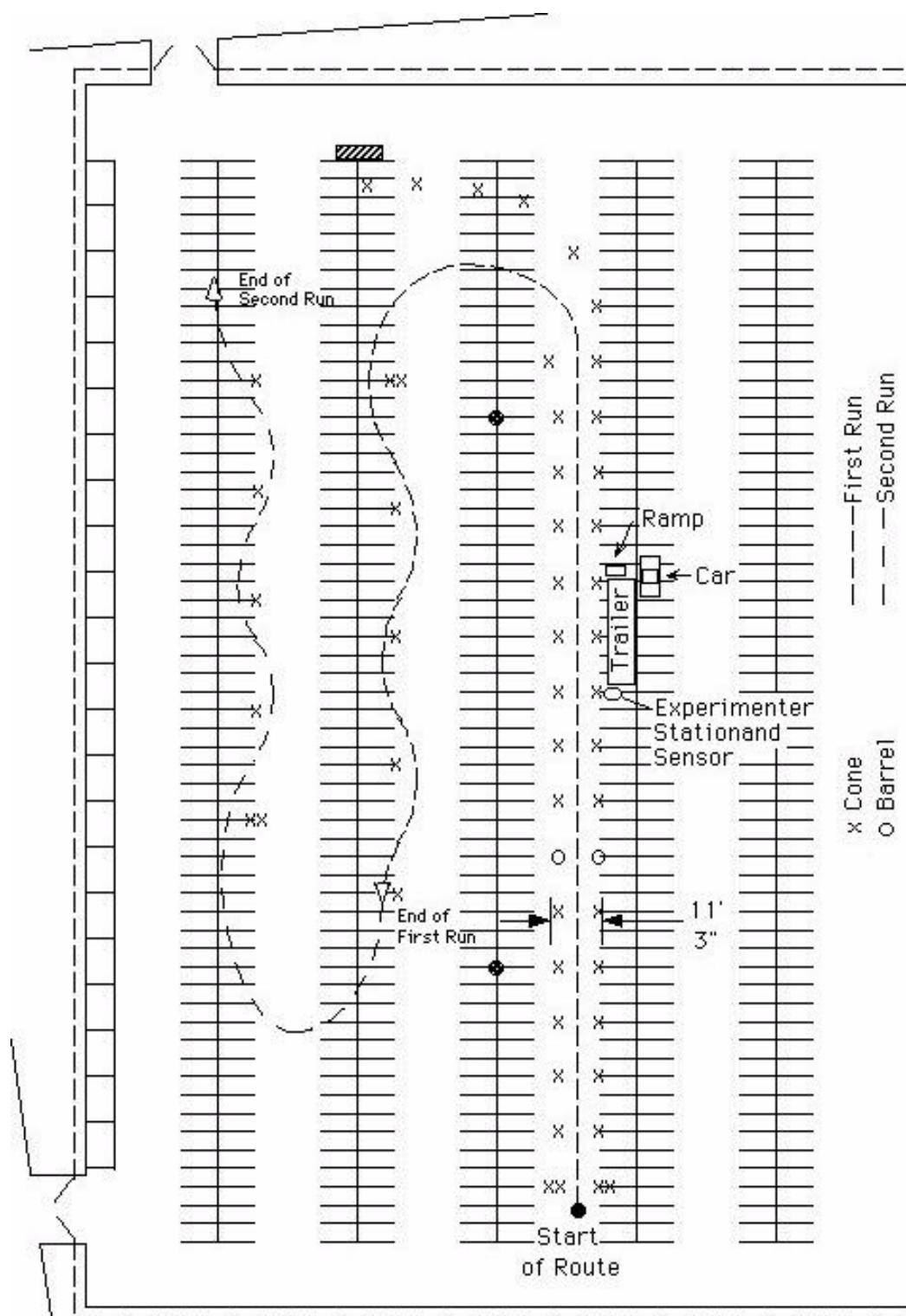


Figure 17. Intended route of truck through obstacle course.



Figure 18. Driver's view of obstacle course from start location.

were also told that they were permitted to slow as much as necessary to safely negotiate the turn at the end of the initial straight section.

As the truck traveled down the initial approach, it passed in front of the infrared sensor. The sensor sent simultaneous signals to equipment within the truck and the servo mechanism attached to the small wooden gate restraining the construction barrels.

As described previously, the in-truck equipment was designed to initiate the emergency braking warnings 300 ms after the barrels became visible. This delay was achieved by causing the in-truck control computer that received the sensor signal to wait an empirically-determined interval before signaling for the warning to be activated. This 300 ms time period was measured between the appearance of the first barrel and the initiation of the individual warnings, not the point at which the warnings were sensed by the driver. While the auditory icon was presented and audible almost immediately after it was triggered, the haptic warning had an inherent delay. This delay was due to the time required to release the additional 75 psi of air pressure into the front brake lines and for the truck to decelerate enough to be discernible from the slight but constant vibration of the truck cab itself.

Debriefing. Following the presentation of the obstacles, the participant was given a brief verbal explanation of the purpose of this study. The experimenter then administered a short verbal questionnaire concerning the safety and authenticity of the obstacle presentation scenario as well as a set of questions about the effectiveness of the warning used, if any. The questionnaire and participant responses are included in Appendix I. Following the completion of the questionnaire, the participant was asked to read and sign a second informed consent document, included as Appendix E, and was also be asked not to discuss the experiment with anyone for the next six months. The participant was then directed to drive the truck back to the building at which the test began. At that point, the participant received \$50 as financial compensation for his time and was given the opportunity to request a copy of the final results of the experiment if desired.

RESULTS

Audiometric Data

The results of each participant's audiogram are listed in Appendix C. The audiometric data were grouped as shown in Table 5 to permit a comparison with expected hearing levels of non noise-exposed males (Ward, 1986). The average threshold levels for each age group are shown in Figures 19 and 20. These figures show evidence of increased hearing thresholds with an increase in age. The overall average threshold levels are shown in Figures 21 and 22.

Also shown in these graphs is a weighted average of the threshold levels for males not exposed to industrial noise (Ward, 1986). These figures demonstrate that at the lower frequencies tested, the participating drivers have hearing thresholds similar to that expected for males not exposed to industrial noise. At 4000 Hz, however, the participants' hearing thresholds are higher than expected. This is possibly an indication of the presence of noise-induced hearing loss, of which a 4000 Hz loss is a common symptom.

TABLE 5

Participant Grouping for Hearing Threshold Comparison

Comparison Age	Participant Ages	Number of Participants in Age Group
20	18-25	4
30	26-35	14
40	36-45	12
50	46-55	8
60	56-65	2
70	66-75	1

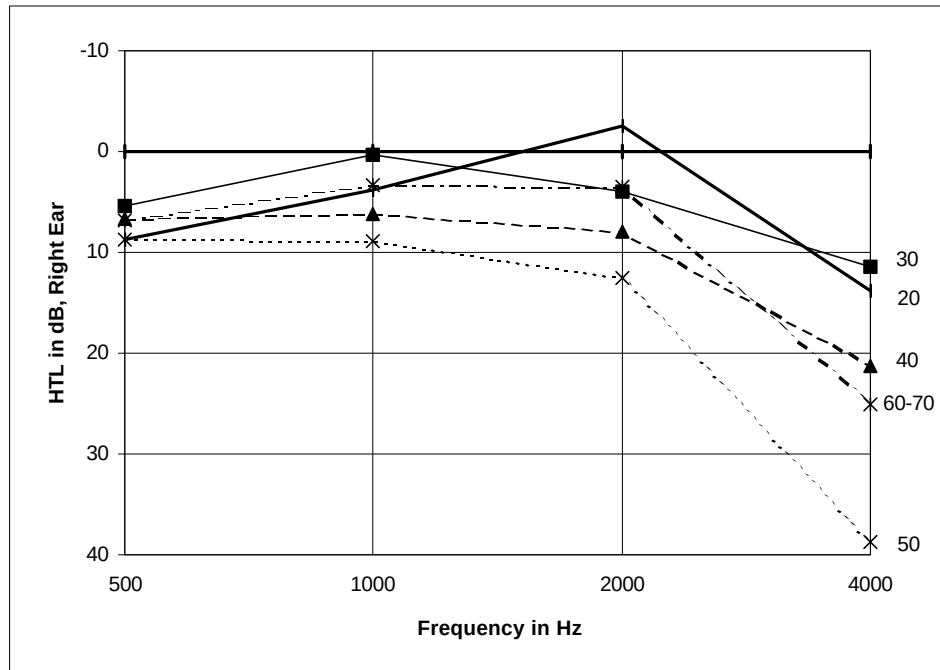


Figure 19. Participant hearing levels by age group, right ear.

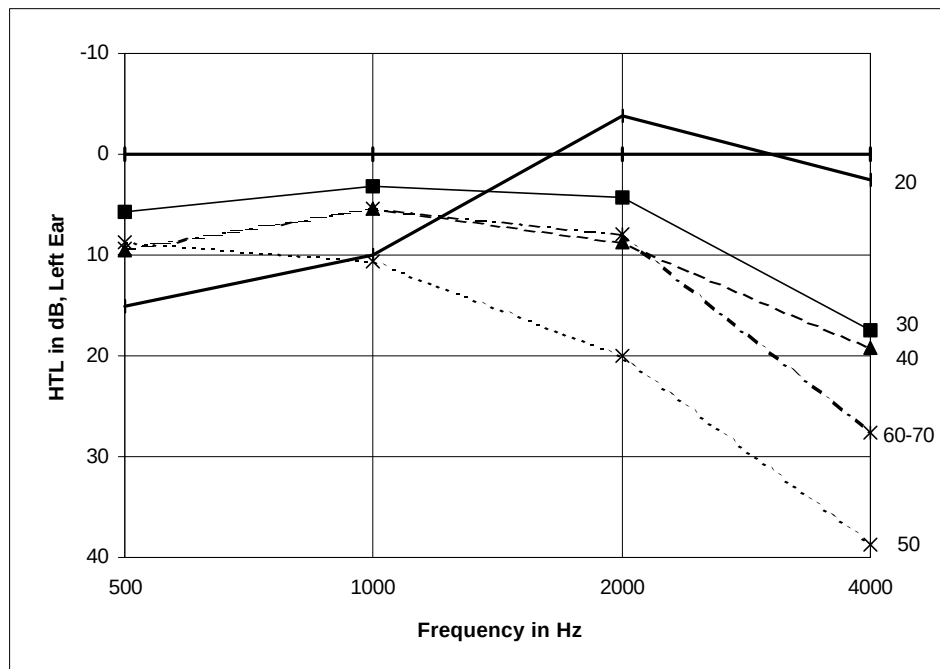


Figure 20. Participant hearing levels by age group, left ear.

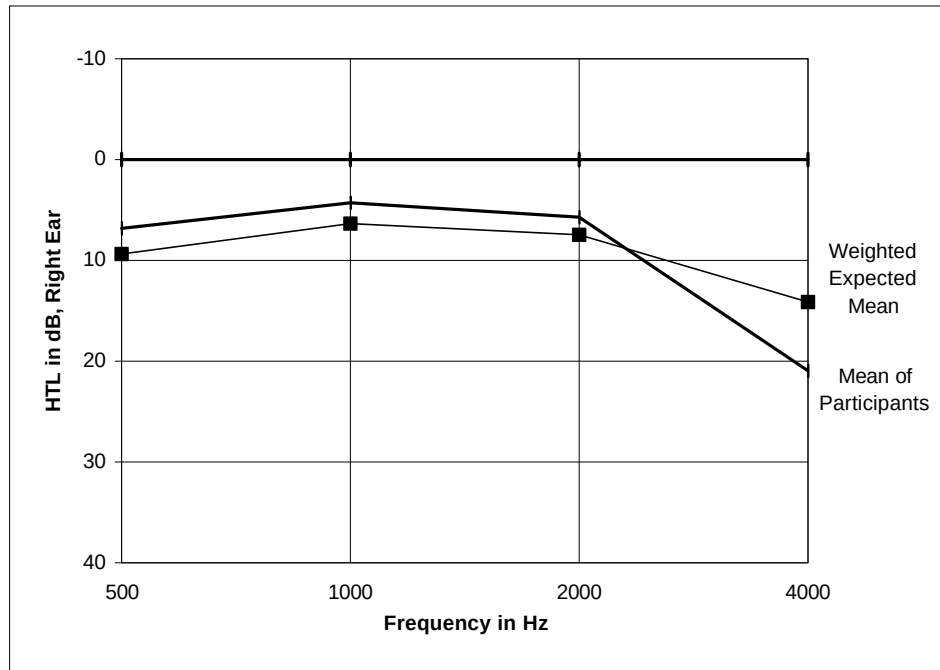


Figure 21. Mean participant hearing level compared to expected thresholds (Ward, 1986), right ear.

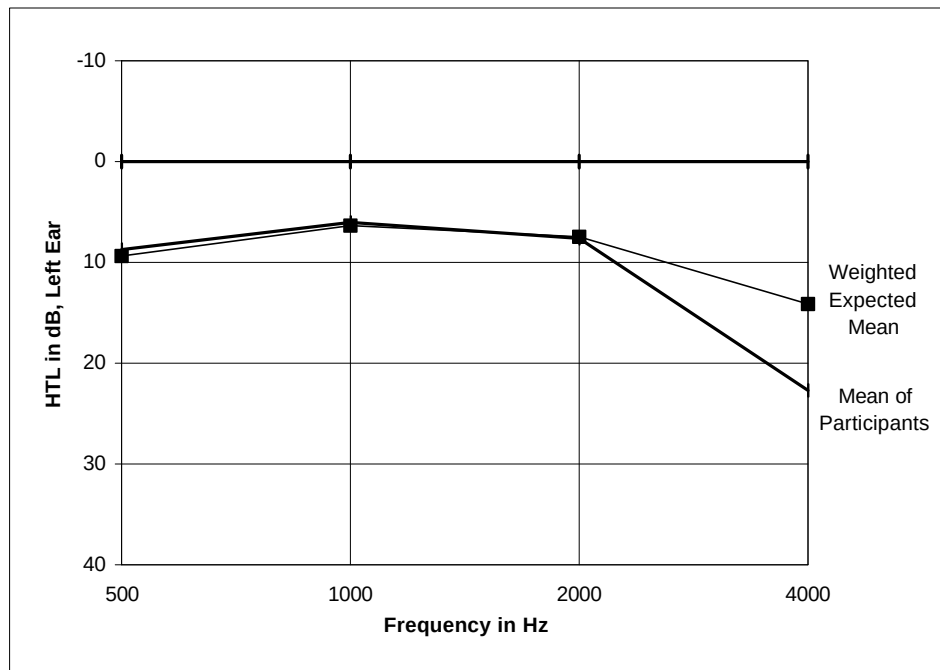


Figure 22. Mean participant hearing level compared to expected thresholds (Ward, 1986), left ear.

Free Responses

During the first presentation of the auditory icons, subjects were asked to state the perceived meaning of each sound. Following the conclusion of all testing, the free response data were grouped into categories based on similarity of response. For example, the responses to Auditory Icon #3 (Emergency Braking Warning) were grouped into categories such as “Emergency Braking Warning,” “Tire Skid,” and “Accident Ahead.” Whenever possible, responses were placed in categories defined at the conclusion of the pilot study to facilitate the comparison of the results of the two studies.

Individual responses that were not sufficiently similar to any other responses given in either study were grouped in a “Miscellaneous” category. The categorized listings of the free responses for each auditory icon, for both the pilot and in-truck studies, are listed in Tables 6 through 14. The original responses have been included in Appendix H. The subjective nature of this classification technique precludes the use of any statistical analysis other than listing the frequency with which responses fell into each category (G. R. Terrell, personal communication, July 8, 1996).

Data Conversion

Since the perceived urgency of the auditory icons and the ratings of association were measured using free-modulus magnitude estimation, conversion to a common modulus was necessary. A technique outlined by Engen (1971) and used by Haas (1993), Hellier et al. (1995), and Haas and Schmidt (1995) eliminates the effect of different moduli on interobserver variance, and also removes intra-observer variability. Engen’s (1971) procedure assumes that each subject makes more than one free-modulus magnitude rating for each item. Since subjects in the current study rated each sound twice, the averaging steps, which eliminate intra-observer variability, are included. An error in Engen’s (1971) instructions has also been corrected, per Haas (1993). The steps in the corrected transformation procedure are presented in Table 15.

TABLE 6

Free Responses, Auditory Icon #1 - Automatic Toll Payment Completed

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Toll Booth Ahead	1	7.1%	11	26.8%	12	21.8%
Load Shift / Fallen Off Vehicle	4	28.6%	7	17.1%	11	20.0%
Engine (Mechanical) Problems	1	7.1%	3	7.3%	4	7.3%
Loose Object in Cab	0	0.0%	4	9.8%	4	7.3%
Hit / Run Over Something	2	14.3%	1	2.4%	3	5.5%
Paid Toll	2	14.3%	0	0.0%	2	3.6%
No Answer	1	7.1%	11	26.8%	12	21.8%
Miscellaneous	3	21.4%	4	9.8%	7	12.7%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Coin Dropped in Slot; Pilot Study Auditory Icon #29

TABLE 7

Free Responses, Auditory Icon #2 - Children Playing Ahead

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Children Ahead / School Zone	14	100.0%	31	75.6%	45	81.8%
No Answer	0	0.0%	4	9.8%	4	7.3%
Miscellaneous	0	0.0%	6	14.6%	6	10.9%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Children Giggling; Pilot Study Auditory Icon #40

TABLE 8

Free Responses, Auditory Icon #3 - Emergency Braking Warning

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Emergency Braking Warning	5	35.7%	18	43.9%	23	41.8%
Nearby Car Skidding / Braking	0	0.0%	10	24.4%	10	18.2%
Hydroplaning / Wet Pavement	2	14.3%	3	7.3%	5	9.1%
Accident Ahead	2	14.3%	2	4.9%	4	7.3%
Tire Skid	2	14.3%	0	0.0%	2	3.6%
Problem with Brakes	2	14.3%	0	0.0%	2	3.6%
No Answer	0	0.0%	6	14.6%	6	10.9%
Miscellaneous	1	7.1%	2	4.9%	3	5.5%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Tire Skid; Pilot Study Auditory Icon #46

TABLE 9

Free Responses, Auditory Icon #4 - High Engine Temperature

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Engine Overheating	8	57.1%	15	36.6%	23	41.8%
General Air Leak or Release	1	7.1%	6	14.6%	7	12.7%
Brake Problem	0	0.0%	5	12.2%	5	9.1%
Engine (Mechanical) Problems	1	7.1%	3	7.3%	4	7.3%
Teapot	2	14.3%	2	4.9%	4	7.3%
Windows Open	0	0.0%	3	7.3%	3	5.5%
No Answer	0	0.0%	3	7.3%	3	5.5%
Miscellaneous	2	14.3%	4	9.8%	6	10.9%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Teapot Whistling; Pilot Study Auditory Icon #6

TABLE 10

Free Responses, Auditory Icon #5 - Railroad Crossing Ahead

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Train / Railroad Crossing	13	92.9%	38	92.7%	51	92.7%
No Answer	0	0.0%	1	2.4%	1	1.8%
Miscellaneous	1	7.1%	2	4.9%	3	5.5%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Train Crossing Bell; Pilot Study Auditory Icon #38

TABLE 11

Free Responses, Auditory Icon #6 - Road Construction Ahead

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Construction Ahead	12	85.7%	25	61.0%	37	67.3%
Train / Railroad Crossing	0	0.0%	5	12.2%	5	9.1%
Engine (Mechanical) Problems	0	0.0%	3	7.3%	3	5.5%
Object Dragging	0	0.0%	2	4.9%	2	3.6%
No Answer	0	0.0%	3	7.3%	3	5.5%
Miscellaneous	2	14.3%	3	7.3%	5	9.1%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Jackhammer; Pilot Study Auditory Icon #33

TABLE 12

Free Responses, Auditory Icon #7 - Emergency Vehicle Approaching

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Emergency Vehicle Approaching	13	92.9%	32	78.0%	45	81.8%
Pull Over (Police)	0	0.0%	7	17.1%	7	12.7%
Going Too Fast / Slow Down	1	7.1%	2	4.9%	3	5.5%
No Answer	0	0.0%	0	0.0%	0	0.0%
Miscellaneous	0	0.0%	0	0.0%	0	0.0%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Siren-Wail; Pilot Study Auditory Icon #30

TABLE 13

Free Responses, Auditory Icon #8 - Incoming Voice Message

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Incoming Call	13	92.9%	33	80.5%	46	83.6%
Incoming Computer Message	0	0.0%	4	9.8%	4	7.3%
General Alarm / Reminder	0	0.0%	2	4.9%	2	3.6%
You Need to Make a Phone Call	1	7.1%	1	2.4%	2	3.6%
No Answer	0	0.0%	0	0.0%	0	0.0%
Miscellaneous	0	0.0%	1	2.4%	1	1.8%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Digital Ringer; Pilot Study Auditory Icon #17

TABLE 14

Free Responses, Auditory Icon #9 - Roadside Mowing Ahead

Free Responses	Pilot Study		In-Truck		Total	
	Number	Percent	Number	Percent	Number	Percent
Construction Ahead	1	7.1%	19	46.3%	20	36.4%
Lawnmower (Roadside Mowing)	11	78.6%	6	14.6%	17	30.9%
Engine (Mechanical) Problems	1	7.1%	5	12.2%	6	10.9%
Jake Brake (Engine Brake) Is On	0	0.0%	4	9.8%	4	7.3%
No Answer	0	0.0%	3	7.3%	3	5.5%
Miscellaneous	1	7.1%	4	9.8%	5	9.1%
Total	14	100.0%	41	100.0%	55	100.0%

Note: Sound of Lawnmower-Low Pitch; Pilot Study Auditory Icon #36

The data collected during the current study were combined with the raw data collected in the pilot study to permit comparison of the two data sets. The free-modulus magnitude estimation data provided by one of the participants in the pilot study were discarded due to difficulties that individual had with the practice line-length estimation task. According to Zwislocki (1983), individuals with poor rating skills for one set of stimuli commonly exhibit similar behavior for other types of stimuli. The total number of participants in the pilot study group was 13, while valid data were collected from 41 participants over the course of the in-truck testing.

Perceived Urgency

The means of the transformed perceived urgency ratings for the pilot and in-truck studies are presented in Table 16. The goal of the comparison of these two data sets was to determine whether or not the different procedures used affected the participants' ratings. Two-sample, unequal- n t -tests were used on the transformed data. The Bartlett test for homogeneity of variance was used to determine the type of t -test to be used for each individual auditory icon. If no significant difference in variance was found at the $\alpha=0.05$ level, the standard Student's t -distribution was used to compare the data sets. The Cochran and Cox Adjusted t Formula was used for auditory icons with heterogeneity of variance between the pilot study and in-truck data. The results of these analyses are presented in Table 17. Significant differences were found between the population means for only two auditory icons. Auditory Icons #2 (Children Playing Ahead) and #5 (Railroad Crossing Ahead) were rated significantly more urgent in the in-truck situation.

Perceived Association

The means of the transformed ratings for perceived association with intended meaning for the pilot and in-truck studies are presented in Table 18. As with perceived urgency, the goal of the comparison of these two data sets was to determine whether or not the different procedures used affected the participants' ratings. Again, two-sample t -tests were used on the transformed data. The Bartlett test for homogeneity of variance

TABLE 15

Steps for Free-Modulus Magnitude Estimation Data Transformation

1.	Convert each response value to its logarithm.
2.	Calculate the arithmetic mean of the logarithms of the two responses made by each observer to each auditory icon. This value is equal to the logarithm of the geometric mean of the observer's responses to each auditory icon.
3.	Tabulate the values such that subjects are listed by column, and auditory icon is listed by row.
4.	Calculate the arithmetic mean of the logarithmic responses in each row. This is equal to the logarithm of the geometric mean of each observer's responses to all the auditory icons.
5.	The arithmetic mean of all the values obtained in step 4 will be obtained. This is equal to the logarithmic value of the grand mean of all the responses for all observers to all auditory icons in the original data matrix.
6.	Subtract the value obtained in step 5, the grand mean log response, from each of the arithmetic individual mean log responses determined in step 4.
7.	Subtract the value obtained in step 6 from the row of original response values.
8.	Take the antilog of each transformed response value.

TABLE 16

Mean Transformed Ratings of Auditory Icon Perceived Urgency

Auditory Icon	Pilot Study		In-Truck Study		Total	
	Number	Mean	Number	Mean	Number	Mean
1	13	5.15	41	7.04	54	6.58
2	13	7.30	41	10.86	54	10.01
3	13	13.10	41	13.15	54	13.14
4	13	12.13	41	9.34	54	10.01
5	13	11.42	41	14.13	54	13.48
6	13	9.24	41	9.15	54	9.17
7	13	14.38	41	15.75	54	15.42
8	13	7.42	41	5.75	54	6.16
9	13	8.64	41	7.52	54	7.79

Note: Auditory icon #1 is Automatic Toll Payment Completed, 2 is Children Playing Ahead, 3 is Emergency Braking Warning, 4 is High Engine Temperature, 5 is Railroad Crossing Ahead, 6 is Roadside Construction Ahead, 7 is Emergency Vehicle Approaching, 8 is Incoming Voice Message, and 9 is Roadside Mowing Ahead.

TABLE 17

Auditory Icon Perceived Urgency Rating Comparison

Auditory Icon	Bartlett Test		<i>t</i> -test		Mean rating	
	χ^2_{observed}	<i>p</i>	<i>t</i> _{tabled}	<i>t</i> _{observed}	Pilot	In-Truck
1	4.188	0.041	2.06	1.483	5.15	7.04
2	8.925	0.003	2.05	2.441*	7.30	10.86
3	0.007	0.933	2.01	0.028	13.10	13.15
4	3.320	0.068	2.01	1.773	12.13	9.34
5	10.716	0.001	2.04	2.206*	11.42	14.13
6	0.019	0.890	2.01	0.081	9.24	9.15
7	2.297	0.130	2.01	0.755	14.38	15.75
8	0.206	0.650	2.01	1.436	7.42	5.75
9	1.831	0.176	2.01	0.986	8.64	7.52

Note: * denotes significance at the $\alpha=0.05$ level. Values in boldface indicate a significantly higher rating.

was performed for each auditory icon, and the Cochran and Cox Adjusted t Formula was used when appropriate. The results of these analyses are presented in Table 19.

Significant differences were found between the population means for two auditory icons. Auditory Icons #5 (Railroad Crossing Ahead) and #7 (Emergency Vehicle Approaching) were rated significantly more urgent in the in-truck situation.

Participant Recall of Intended Meaning

Following the conclusion of the perceived association ratings, two consecutive sets of recall measures were taken. For each incorrect response given by the participant, the correct answer was provided. Table 20 displays the results of the recall tasks. The percent of correct responses during the initial free response trials is included for comparison.

Overall, 91.3% of the participant responses were correct after the first recall presentation, and this number increased to 96.6% after the second recall presentation. For individual auditory icons, the percent correct in the free response trials ranged from 0% to 93%, but percentages increased to 62% to 100% during the first recall phase. Three of the eight auditory icons tested had scores of 100%. Individual auditory icons showed improvements of as great as 88% over the free response scores. Percentages in the second recall set were even higher. The lowest score for an auditory icon during these trials was 87%, and five of the eight auditory icons had scores of 100% recognition. The changes in percent correct across the different trials are shown graphically in Figure 23.

Obstacle Response Data

Data collected during the obstacle response portion of the testing included various reaction times, level of brake pedal activation, and contingency data defining the individual participant's response. Reaction time and brake pedal data for the 25 participants with valid trials are listed in Table 21 along with the mean values for each condition. Graphs of the accelerator, brake pedal, and steering wheel positions for each

TABLE 18

Mean Transformed Ratings of Auditory Icon Perceived Association

Auditory Icon	Pilot Study		In-Truck Study		Total	
	Number	Mean	Number	Mean	Number	Mean
1	13	11.48	41	9.97	54	10.33
2	13	13.52	41	15.38	54	14.93
3	13	11.90	41	13.04	54	12.77
4	13	12.79	41	13.47	54	13.31
5	13	13.47	41	17.79	54	16.75
6	13	12.29	41	12.56	54	12.50
7	13	14.26	41	18.05	54	17.14
8	13	11.93	41	12.23	54	12.16
9	13	12.26	41	10.06	54	10.59

Note: Auditory icon #1 is Automatic Toll Payment Completed, 2 is Children Playing Ahead, 3 is Emergency Braking Warning, 4 is High Engine Temperature, 5 is Railroad Crossing Ahead, 6 is Roadside Construction Ahead, 7 is Emergency Vehicle Approaching, 8 is Incoming Voice Message, and 9 is Roadside Mowing Ahead.

TABLE 19

Auditory Icon Perceived Association Rating Comparison

Auditory Icon	Bartlett Test		<i>t</i> -test		Mean rating	
	χ^2_{observed}	<i>p</i>	<i>t</i> _{tabled}	<i>t</i> _{observed}	Pilot	In-Truck
1	9.071	0.003	2.05	1.714	11.48	9.97
2	6.926	0.008	2.05	1.583	13.52	15.38
3	2.981	0.084	2.01	0.791	11.90	13.04
4	4.218	0.040	2.06	0.643	12.79	13.47
5	12.814	<0.001	2.04	3.881*	13.47	17.79
6	5.778	0.016	2.05	0.358	12.29	12.56
7	15.069	<0.001	2.03	2.934*	14.26	18.05
8	2.480	0.115	2.01	0.206	11.93	12.23
9	1.453	0.228	2.007	2.005	12.26	10.06

Note: * denotes significance at the $\alpha=0.05$ level. Values in boldface indicate a significantly higher rating.

TABLE 20

Results of Recall of Intended Meaning

	Response	1		2		4		5		6		7		8		9	
		Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers	Total Answers	Percent Answers
First Presentation	1	21	87.5%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	2	0	0.0%	24	100%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	3	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	4	0	0.0%	0	0.0%	22	95.7%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	5	0	0.0%	0	0.0%	0	0.0%	24	100%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	6	2	8.3%	0	0.0%	0	0.0%	0	0.0%	23	92.0%	0	0.0%	0	0.0%	12	38.7%
	7	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	27	100%	0	0.0%	0	0.0%
	8	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	28	96.6%	0	0.0%
	9	0	0.0%	0	0.0%	0	0.0%	0	0.0%	2	8.0%	0	0.0%	0	0.0%	19	61.3%
	Other	1	4.2%	0	0.0%	1	4.3%	0	0.0%	0	0.0%	0	0.0%	1	3.4%	0	0.0%
Second Presentation	1	23	92.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	2	0	0.0%	24	100%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	3	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	4	0	0.0%	0	0.0%	23	100%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	5	0	0.0%	0	0.0%	0	0.0%	24	100%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
	6	1	4.0%	0	0.0%	0	0.0%	0	0.0%	24	96.0%	0	0.0%	0	0.0%	4	13.3%
	7	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	27	100%	0	0.0%	0	0.0%
	8	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	29	100%	0	0.0%
	9	0	0.0%	0	0.0%	0	0.0%	0	0.0%	1	4.0%	0	0.0%	0	0.0%	26	86.7%
	Other	1	4.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
% Correct, Free Response		0.0%		75.6%		36.6%		92.7%		61.0%		78.0%		80.5%		14.6%	
% Correct, First Presentation		87.5%		100%		95.7%		100%		92.0%		100%		96.6%		61.3%	
% Correct, Second Presentation		92.0%		100%		100%		100%		96.0%		100%		100%		86.7%	

Note: Each participant was only asked to recall the meaning of five randomly selected auditory icons, and the same set of auditory icons was used for both presentation sets. Shaded blocks indicate correct responses. Auditory Icon #3, Emergency Braking Warning, was omitted to prevent increased awareness of the emergency braking function.

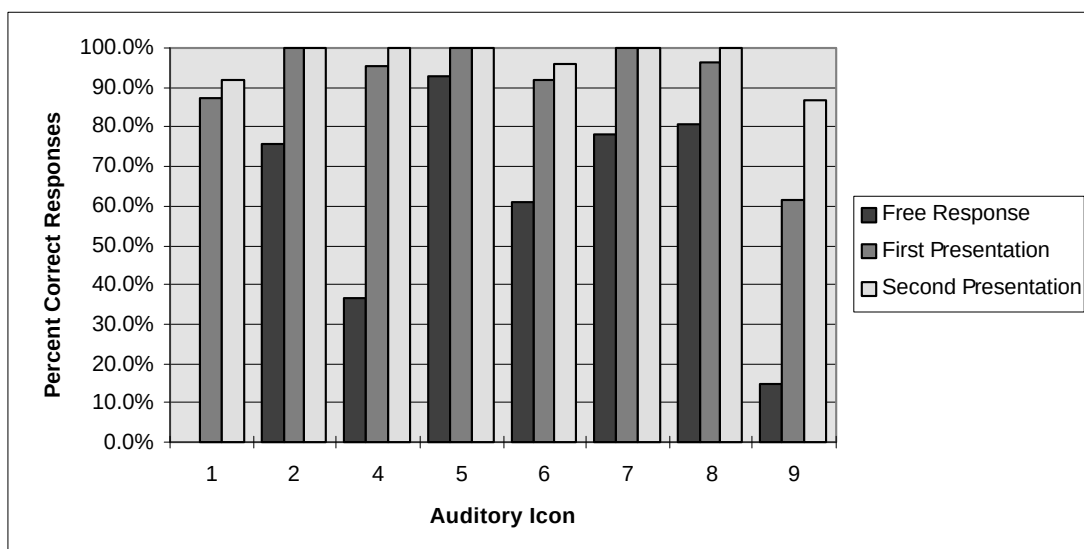


Figure 23. Percent correct identification of auditory icons in free response and recall trials. Auditory Icon #3, Emergency Braking Warning, was omitted to prevent increased awareness of the emergency braking function.

TABLE 21

Participant Reactions to Unexpected Obstacle

Subject Number	Warning Condition	ART [sec]	BPCT [sec]	TBRT [sec]	SRT [sec]	SDev [deg]	FRT [sec]	MBPA
4	NW	0.609	0.879	1.808	0.769	-16.52	0.609	0.7492
5	NW	1.383	2.750	2.801	1.383	40.78	1.383	0.1154
6	NW	0.598	1.540	1.700	0.879	-48.88	0.598	0.6506
7	NW	2.742	3.293	4.172	1.859	-20.71	1.859	0.3221
10	NW	0.550	*	*	*	*	0.550	*
11	NW	0.942	*	*	*	*	0.942	*
13	NW	0.929	1.429	1.539	0.773	17.10	0.773	0.5467
22	NW	0.930	1.258	1.430	*	*	0.930	0.8101
24	NW	0.993	1.262	1.372	1.102	14.12	0.993	0.7324
25	NW	0.492	0.883	1.371	0.492	46.82	0.492	0.9916
17	AW	0.770	1.371	1.430	0.930	-22.13	0.770	0.7041
18	AW	0.703	1.414	1.523	*	*	0.703	0.1448
19	AW	0.988	1.207	1.539	1.039	12.13	0.988	0.4533
27	AW	1.102	1.372	1.590	0.821	27.45	0.821	0.6558
29	AW	0.883	1.153	1.211	1.481	-19.22	0.883	0.9507
31	AW	0.383	*	*	0.551	16.67	0.383	*
32	AW	1.922	*	*	1.090	40.43	1.090	*
20	HW	0.723	1.102	1.160	1.051	11.63	0.723	0.6118
23	HW	1.098	1.598	1.649	2.039	-41.43	1.098	0.3347
28	HW	0.938	1.379	1.699	0.879	22.27	0.879	0.4680
30	HW	1.320	1.430	1.480	0.660	8.37	0.660	0.9203
34	HW	0.829	1.102	1.161	*	*	0.829	0.9979
35	HW	0.761	1.421	1.640	0.820	13.83	0.761	0.5666
36	HW	0.602	1.102	1.149	0.711	16.81	0.602	0.6653
37	HW	0.816	1.258	1.969	0.598	17.88	0.598	0.5929
Mean	NW	1.017	1.662	2.024	1.037	**	0.913	0.6148
Mean	AW	0.964	1.303	1.459	0.985	**	0.805	0.5817
Mean	HW	0.886	1.299	1.488	0.965	**	0.769	0.6447

Note: * signifies participant did not react; ** indicates no mean was calculated; ART = Accelerator Reaction Time; BPCT = Brake Pedal Contact Time; TBRT = Total Brake Reaction Time; SRT = Steering Reaction Time; SDev = Steering Deviation; FRT = First Response Time; MBPA = Maximum Brake Pedal Activation (normalized); NW = No Warning; AW = Auditory Warning; HW = Haptic Warning

of these participants have been included in Appendix J. Steering Deviation (SDev) is also listed in Table 21. This quantity indicates the severity of the driver's steering reaction. It is equal to the difference between the steering wheel angle at the start of the steering reaction and the maximum angle of the steering wheel during the reaction. Positive values signify turns away from the side on which the obstacle appeared. Negative values signify turns into the obstacle, most likely as an attempt to pass behind the barrels.

For each reaction time measure, the mean value was smaller for participants in each of the two warning conditions than when no warning was present. Due to the fact that not all participants braked or steered, some of the mean reaction times were calculated from fewer data points than others. The Accelerator Reaction Time of Participant #31 (0.383 seconds) appears to be too short, but was verified by examination of the videotape. While this value is very small, it is not unrealistic. Doi, Nagiri, and Takei (1994) reported that two of forty subjects had initial reaction times to an unexpected obstacle in the 0.2 to 0.4 second range in a simulator study, and Rice and Dell'Amico (1974) reported one reaction time as short as 0.35 seconds in a closed-track test.

Accelerator Reaction Time. The mean Accelerator Reaction Times (ARTs) for the No Warning, Auditory Warning, and Haptic Warning conditions were 1.017, 0.964, and 0.886 seconds respectively. An analysis of variance (ANOVA) performed on the data, Table 22, failed to show a significant main effect for warning condition.

Bartlett's test of homogeneity of variance was performed on the ART data as well for post-hoc analysis. This analysis revealed a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 6.75, p = 0.034$). Individual Hartley tests for homogeneity of variance were carried out to determine the source of the significant difference. In order to adjust for inflated α -error, the α -level for each of the three individual comparisons was reduced to 0.0170. The variance of the Haptic Warning condition was found to be less than that of the No Warning condition at the $p = 0.0052$

level. The variance of the Haptic Warning condition was also found to be less than the Auditory warning condition at the $p = 0.0364$ level, but this was not significant due to the α -error correction. The differences in variances are shown in Figure 24.

Brake Pedal Contact Time. The mean Brake Pedal Contact Times (BPCTs) for the No Warning, Auditory Warning, and Haptic Warning conditions were 1.662, 1.303, and 1.299 seconds respectively. Again, results of the ANOVA, Table 23, showed no significant main effect for warning condition.

Bartlett's test of homogeneity of variance was also performed on the BPCT data. This analysis revealed a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 20.30, p < 0.0001$). Individual Hartley tests for homogeneity of variance were carried out to determine the source of the significant difference. The variance of the No Warning condition was found to be greater than that of the Auditory Warning condition at the $p < 0.0001$ level and less than the Haptic warning condition at the $p = 0.0002$ level. The differences in variances are illustrated in Figure 25.

Total Brake Response Time. The mean Total Brake Response Times (TBRTs) for the No Warning, Auditory Warning, and Haptic Warning conditions were 2.024, 1.459, and 1.488 seconds respectively. The results of the ANOVA performed on the data, Table 24, showed no significant main effect for warning condition.

Bartlett's test of homogeneity of variance was performed on the TBRT data as well. This analysis revealed a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 15.12, p = 0.001$). Individual Hartley tests for homogeneity of variance were carried out to determine the source of the significant difference. The variance of the No Warning condition was found to be greater than that of the Auditory Warning condition at the $p = 0.001$ level and less than the Haptic warning condition at the $p = 0.0027$ level. The differences in variances are displayed in Figure 26.

TABLE 22

ANOVA Summary Table for Accelerator Reaction Time

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	0.0764	0.0382	0.15	0.864
Subjects (S/WT)	22	5.7211	0.2600		
<i>Total</i>	24	5.7975			

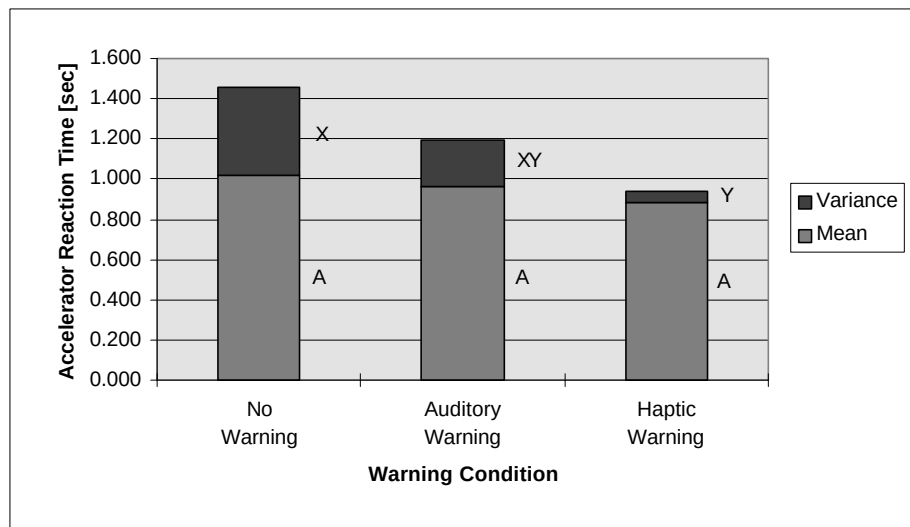


Figure 24. Effect of warning condition on variance of Accelerator Reaction Time. Means with the same letter are not significantly different at $\alpha = 0.05$ according to ANOVA; Variances with the same letter are not significantly different at $\alpha = 0.017$ according to Bartlett.

TABLE 23

ANOVA Summary Table for Brake Pedal Contact Time

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	0.6457	0.3228	1.01	0.384
Subjects (S/WT)	22	5.7556	0.3198		
<i>Total</i>	24	6.4013			

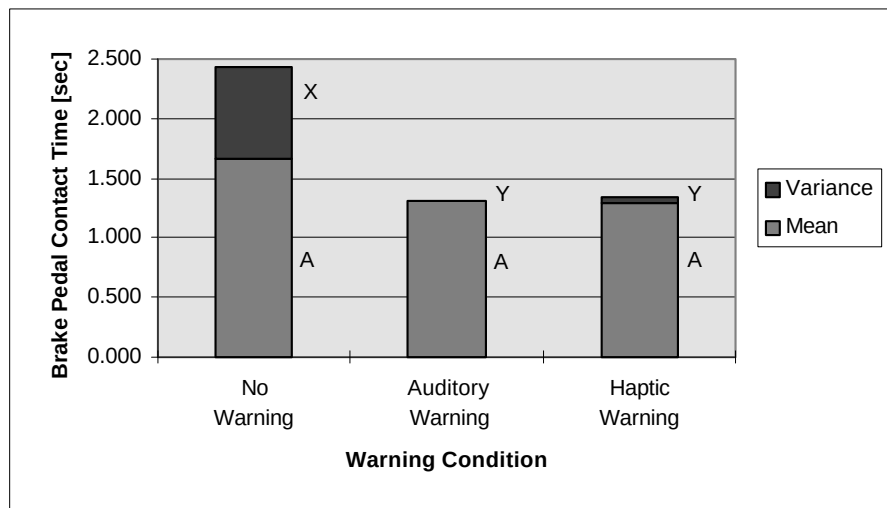


Figure 25. Effect of warning condition on variance of Brake Pedal Contact Time. Means with the same letter are not significantly different at $\alpha = 0.05$ according to ANOVA; Variances with the same letter are not significantly different at $\alpha = 0.017$ according to Bartlett.

TABLE 24

ANOVA Summary Table for Total Brake Response Time

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	1.4856	0.7428	1.77	0.199
Subjects (S/WT)	22	7.5532	0.4196		
<i>Total</i>	24	9.0389			

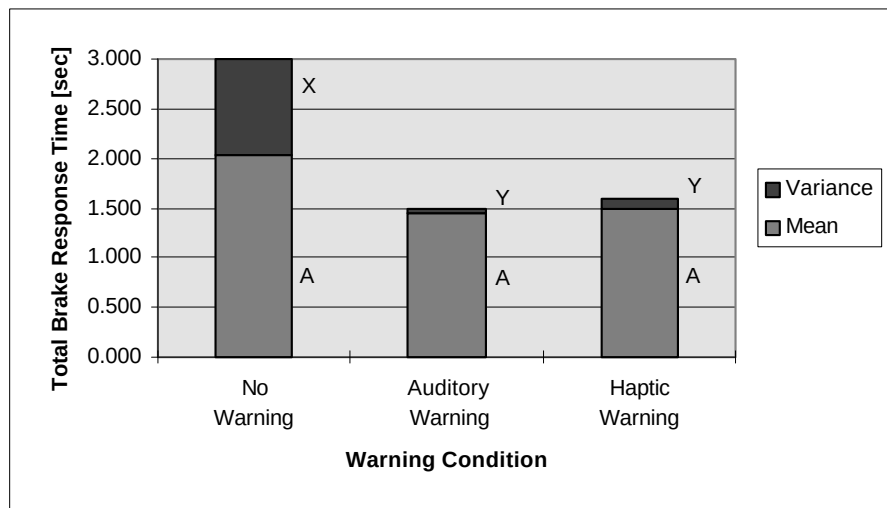


Figure 26. Effect of warning condition on variance of Total Brake Response Time. Means with the same letter are not significantly different at $\alpha = 0.05$ according to ANOVA; Variances with the same letter are not significantly different at $\alpha = 0.017$ according to Bartlett.

Steering Reaction Time. The mean Steering Reaction Times for the No Warning, Auditory Warning, and Haptic Warning conditions were 1.037, 0.985, and 0.965 seconds respectively. The results of the ANOVA performed on the data, Table 25, again showed no significant main effect for warning condition.

Bartlett's test of homogeneity of variance was performed on the Steering Reaction Time data as well. This analysis failed to reveal a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 1.118$, $p = 0.572$).

First Reaction Time. The mean First Reaction Times (FRTs) for the No Warning, Auditory Warning, and Haptic Warning conditions were 0.913, 0.805, and 0.769 seconds respectively. The results of the ANOVA performed on the data, Table 26, showed no significant main effect for warning condition.

Bartlett's test of homogeneity of variance was also performed on the FRT data. This analysis revealed a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 6.549$, $p = 0.038$). Individual Hartley tests for homogeneity of variance were carried out to determine the source of the significant difference. The variance of the Haptic Warning condition was found to be less than that of the No Warning condition at the $p = 0.0108$ level. No other significant differences were found. The differences in variances are shown in Figure 27.

TABLE 25

ANOVA Summary Table for Steering Reaction Time

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	0.0188	0.0094	0.05	0.952
Subjects (S/WT)	22	3.2229	0.1896		
<i>Total</i>	24	3.2417			

TABLE 26

ANOVA Summary Table for First Reaction Time

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	0.1019	0.0509	0.52	0.601
Subjects (S/WT)	22	2.1495	0.0977		
<i>Total</i>	24	2.2513			

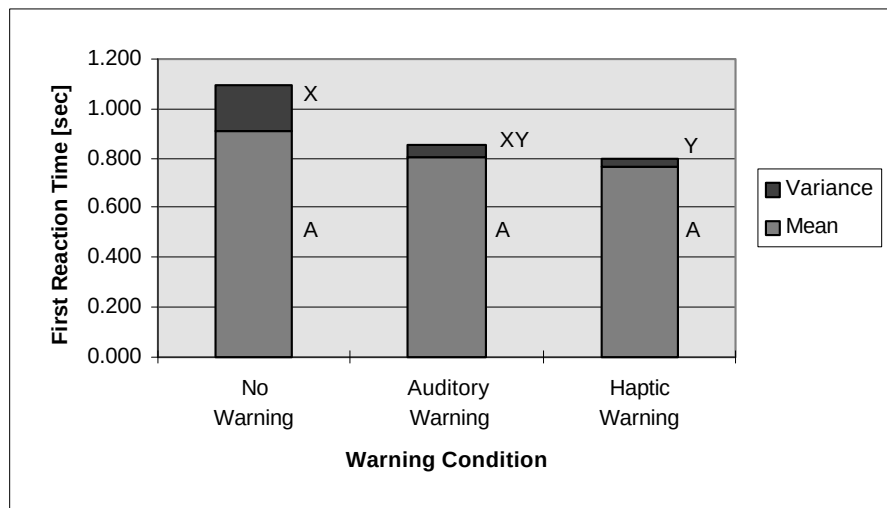


Figure 27. Effect of warning condition on variance of First Reaction Time. Means with the same letter are not significantly different at $\alpha = 0.05$ according to ANOVA; Variances with the same letter are not significantly different at $\alpha = 0.017$ according to Bartlett.

Maximum Brake Pedal Activation. The mean Maximum Brake Pedal Activation (MBPA) values for the No Warning, Auditory Warning, and Haptic Warning conditions were 0.6148, 0.5817, and 0.6447 respectively. The results of the ANOVA performed on the data, Table 27, showed no significant main effect for warning condition.

Bartlett's test of homogeneity of variance was performed on the MBPA data as well. This analysis failed to reveal a significant difference in variance between warning conditions at the $\alpha = 0.05$ level ($\chi^2 = 0.583$, $p = 0.747$).

Contingency data. Driver reactions to the unexpected obstacle were categorized as to whether or not the driver steered, swerved, braked, and stopped. The numbers and percentages of drivers in each condition that performed the listed actions appear in Table 28. The chi-square test of independence was used to determine whether or not there were statistically significant differences in reactions between conditions. The analysis determined that there was a significant difference ($\chi^2 = 6.43$, $p = 0.040$) between warning conditions for the Stop / No Stop measure.

A commonly accepted requirement of the chi-square test of independence is that each expected frequency is five or greater, with exceptions allowed for those distributions in which only a small percentage of the expected frequencies are less than five. Roscoe and Byars (1971) tested this requirement through study of previous research

TABLE 27

ANOVA Summary Table for Maximum Brake Pedal Activation

Source	df	SS	MS	<i>F</i>	<i>p</i>
<i>Between</i>					
Warning Type (WT)	2	0.0124	0.0062	0.09	0.916
Subjects (S/WT)	22	1.2553	0.0697		
<i>Total</i>	24	1.2677			

TABLE 28

Contingency-Level Participant Reactions to Unexpected Obstacle

Reaction	No Warning		Auditory Warning		Haptic Warning	
	Number	Frequency	Number	Frequency	Number	Frequency
Steer	7	70%	6	86%	7	88%
Swerve	4	40%	3	43%	2	25%
Brake	8	80%	5	71%	8	100%
Stop	3	30%	1	14%	6	75%

Note: Boldface denotes reactions with significant differences between conditions at the $\alpha=0.05$ level

and their own simulations. They found that this requirement is based more on tradition than any sound mathematical or statistical principles. They state that a more important factor is the overall or average expected frequency, which is equal to the total number of observations divided by the number of categories. According to their studies, the average expected frequency should be four or more for the chi-square test of independence with moderate departures from a uniform distribution at the $\alpha = 0.05$ level. For the chi-square tests carried out on this data, the average expected value was 4.17.

Primary response strategy comparison. Following the contingency analysis, it was recognized that the simple categorization of driver responses would not adequately address driver response strategies. A scheme that equated small amounts of pressure on the brake pedal long after a large steering wheel input with large and rapid brake reactions did not have very high validity when it came to describing drivers' primary response strategies. To remedy this, an attempt was made to determine each driver's initial and dominant response strategy. Classifications were made based on graphs of pedal and steering wheel positions (Appendix J) and videotapes of the drivers. In order to be classified as employing a braking strategy, a driver had to have more than a brief, momentary depression of the brake pedal before a significant steering reaction. In order to be classified as a steering strategy, the driver's steering reaction had to be a significant (greater than 20 degrees) turn of the steering wheel away from the obstacles in reaction to their appearance and before a significant pedal reaction. Of the 25 drivers, one had

simultaneous and significant steering and braking reactions. The results are shown in Table 29. The rationales for the classifications are included in Appendix K.

As per Roscoe and Byars (1971), the average expected frequency of all cells had to be 4 or greater to enable a valid chi-square test of independence for the primary response strategies. Since the No Warning and Auditory Warning condition data distributions were highly similar, these data were collapsed to permit their comparison with the data from the Haptic Warning condition data. To further reduce the number of cells, the data were collapsed again to compare braking and steering strategies separately. The number of drivers in the steering reaction and no reaction classifications were combined for comparison of the braking strategy data and the number of drivers in the braking and no reaction classifications were combined for comparison of the steering strategy data. The resultant chi-square tables, with both observed and expected frequencies, are shown in Tables 30 and 31. For the braking strategy comparison, the soft braking warning differed from the other two conditions at the $\alpha = 0.05$ level ($\chi^2 = 6.62, p = 0.0101$). There was no difference, however, in the steering strategies at the same level ($\chi^2 = 2.94, p = 0.086$).

TABLE 29

Driver Primary Response Strategies

Warning Condition	Primary Response Strategies		
	Braking	Steering	None
No Warning	5	3	3
Auditory Warning	3	2	2
Haptic Warning	8	0	0

Note: One driver in the No Warning Condition was classified as having a combination braking and steering reaction.

TABLE 30

Chi-Square Table for Braking Strategy Comparison

	No Warning & Auditory Warning	Haptic Warning	Row Total
Braking Strategy	8 (10.88)	8 (5.12)	16
Non-Braking Strategy	9 (6.12)	0 (2.88)	9
Column Total	17	8	25

Note: Numbers in parentheses are expected values.

TABLE 31

Chi-Square Table for Steering Strategy Comparison

	No Warning & Auditory Warning	Haptic Warning	Row Total
Steering Strategy	5 (3.4)	0 (1.6)	5
Non-Steering Strategy	12 (13.6)	8 (6.4)	20
Column Total	17	8	25

Note: Numbers in parentheses are expected values.

DISCUSSION AND CONCLUSIONS

The first of the two objectives of this research project was to evaluate the utility of auditory icons to present information in a truck-cab environment. The auditory icon data were compared to data collected using similar methods in the pilot study for the purpose of determining the optimal methods of creating and testing sets of auditory icons. The second objective was to compare auditory and haptic emergency braking warnings to a no warning condition, each measured in response to the appearance of an unexpected obstacle. Both driver reaction times and strategies were measured and analyzed.

Auditory Icons

Observation and statistical analyses revealed differences in the participant evaluations of the auditory icons between the pilot and in-truck studies. The methods used to collect the data in the two studies were identical, with the exception of the addition of the recall task to the on-road study. There are three major differences between the two data sets that may account for the differences in the results. Some of the variance between the studies may be due to differences in the participants' experiences. The majority of the participants from the pilot study possessed Class B CDLs, while all of the in-truck participants had Class A CDLs. The pilot study participants primarily had experience with commercial buses, but those tested during the in-truck study had significant experience driving combination (tractor-trailer) vehicles. It is conceivable that these differences in experience could produce some of the observed differences.

Additionally, the differences in the results could be due to situational and environmental differences. The act of driving an actual truck over the road while rating the auditory icons could have caused the participants to think differently of the sounds that they heard with respect to both urgency and association. Also, the presence of the background truck noise could cause the auditory icons to be perceived differently due to masking effects. If the auditory icons were to sound different physically, differences in perception and ratings between conditions would be almost inevitable.

Free responses. Most of the auditory icons showed similar distributions of perceived meaning in the two studies. The differences that appeared, however, are worthy of discussion. Auditory Icon #4 (High Engine Temperature) was interpreted as something similar to its intended meaning by 57% of the pilot study participants, but this value fell to under 37% in the in-truck study. This difference may be explained by further grouping of the responses. If the categories relating to water, fluids, or steam ("Engine Overheating" and "Teapot") and air ("General Air Leak or Release," "Windows Open," and "Brake Problem") are combined, a drastic difference in the responses in the two studies becomes apparent. In the pilot study, 71.4% of the responses related to water

and 7.1% related to air; in the in-truck study, those percentages changed to 41.5% and 34.1% respectively. It is possible that the masking provided by the truck noise caused this particular auditory icon to sound less like steam and more like rushing air.

Alternatively, the difference could be due to the testing environment or driver experience. Inside a truck cab, listening to air whistling through a partially opened window is a much more common than activity than is boiling water in a tea kettle. The sound of boiling water would be less in context in a truck cab, while rushing air would be more in context. With respect to driver experience, the drivers tested on-road typically had much more commercial driving experience than did the in-lab participants. Along with that greater amount of experience would come a greater exposure to one of the few auditory warnings currently in truck cabs, the High Engine Temperature warning. If these drivers already had a personal association formed between an overheating engine and whatever sound their own trucks used, it would not be unexpected for them to be less likely to associate an entirely different sound with that particular message.

Other differences occurred for Auditory Icons #6 (Road Construction Ahead) and #9 (Roadside Mowing Ahead). The Road Construction Ahead auditory icon was interpreted as expected 85.7% of the time in the pilot study but only 61.0% of the time in the in-truck study. The percent of responses matching the intended meaning of the Roadside Mowing Ahead auditory icon dropped even more drastically, from 78.6% to 14.6%. An examination of the spectral patterns of these two auditory icons (shown in Appendix B) reveals that they are broadband in nature and therefore easily masked by the background noise present in the truck. This similarity may be due in part to the low signal-to-noise ratio of the original lawnmower and jackhammer samples converted for use as auditory icons in this study. In amplifying the signal to a level of loudness equivalent to that of the other auditory icons, the noise of the sample may have also been amplified.

Perceived urgency. The perceived urgency scores were higher in the in-truck study for two of the auditory icons, #2 (Children Playing Ahead) and #5 (Railroad

Crossing Ahead). Arguably, these would be among the most urgent messages a truck driver could receive. The spectral patterns of these two sounds, especially the train crossing bell, do not lend themselves to masking. For this reason it is suspected that the reason for the difference between the two studies is the environment, with the background of the participants also possibly having an effect. Having children in the path of traffic or having a train approach a nearby railroad crossing would be of little urgency to someone sitting in a chair in a laboratory, but would be highly urgent to the driver of a vehicle traveling down the road at a speed of 55 mph. Although the participants were instructed to rate the urgency of the sound itself and not the urgency of the information they felt the sound may represent, achieving this separation may have been difficult or even impossible for some participants. The population differences may also influence this measure as the typical pilot study participant, experienced in driving a bus at low speeds around groups of pedestrians, would be accustomed to driving at slower speeds and feel more able to stop the vehicle and avoid any accident.

Perceived association. Of the nine tested auditory icons, only two showed a difference in their ratings of association between the two studies. Auditory Icons #5 (Railroad Crossing Ahead) and #7 (Emergency Vehicle Approaching) were rated as having a greater association with their intended meaning by the in-truck participants. It is improbable that these differences would be due to the masking effects of the in-truck background noise since, as shown by the free response data, these two auditory icons were interpreted in approximately the same way by the two populations. The difference could potentially be caused by differences in the populations themselves, but it is more plausible that it is due to situational differences. An approaching police car, ambulance, or train typically requires some sort of reaction by an individual driving a vehicle, but no reaction is required from an individual sitting in a laboratory. These sounds are therefore likely to be much more important when driving on the highway, and this importance could have increased the salience of these individual auditory icons, thereby affecting their scores of association.

Recall of intended meaning. The high recognition scores measured during the recall task indicate that with a minimal amount of exposure, associations can be temporarily strengthened or formed. In the first recall task, the participants were able to remember the intended meaning of the auditory icons with greater than 90% accuracy overall. This was achieved after the auditory icon had been paired with its intended meaning only twice. In the second recall task, the overall percentage of correct responses was almost 97%. Patterson (1982) states that remembering the meanings of more than seven sounds requires significant amounts of training. Yet with only minimal training, the participants were able to remember the intended meanings of nine auditory icons, although recall was only tested over an interval of less than fifteen minutes.

The recall results also demonstrate that even when the initial, stereotyped level of association of an auditory icon with its intended meaning is low or almost nonexistent, a minimal amount of training can significantly increase the level of association. In the free response trials, the percent of participants providing responses similar to the intended meaning of Auditory Icons #1 (Automatic Toll Payment Completed) and #9 (Roadside Mowing Ahead) were 0% and 14.6%, respectively. Yet after two pairings with the intended meaning, the percent of correct responses rose to 87.5% and 61.3%. Due to the short time intervals (two to fifteen minutes) used in this study, however, it is impossible to determine whether or not this increase in association would last over longer time periods or if it would be subject to extinction.

As high as the recognition scores in the recall task were, they could have been higher if not for the detrimental effects of masking and low signal-to-noise ratio in the original sound samples. Only seven of the 207 recorded second recall responses were incorrect; five of these errors resulted from confusion between Auditory Icons #6 (Road Construction Ahead) and #9 (Roadside Mowing Ahead). Perhaps the confusion is due to the similarity of the messages themselves, but inspection of the auditory icon frequency spectra shows the great similarity of the sounds themselves. Additionally, the in-truck background noise was highly effective in masking the distinctive, cyclic sound of the

jackhammer striking its target, causing the sounds to seem even more similar than when presented in quiet.

Summary. The analysis of the auditory icon data from the pilot and in-truck studies shows that differences in situation and background noise can affect participant perception and evaluation of auditory icons. The differences in populations may also cause differences, but these two effects are made apparent by the free response, perceived urgency, association, and recall data. Additionally, the potential problem of background noise is likely to be underestimated by the results of this study. The truck used, a 1997 Volvo VN, is quieter than the majority of the trucks on the road today. The interior noise levels measured in this truck were lower than the measured levels in other trucks on the road today (Robinson et al., 1997). It is a high-end model with very low mileage (less than 5,000 miles), and was used without a trailer, the use of which would only add to the in-cab noise level. Future research concerning in-vehicle auditory icon displays must account for this through testing the proposed auditory icons in appropriate levels of background noise.

The data collected in this study, particularly the recall measures, demonstrate the tremendous potential of auditory icons for auditory in-vehicle displays. If the associations between the auditory icons and their intended meanings that were created or strengthened in this testing can be maintained, in-vehicle display designers will be able to use auditory icons to provide additional information to drivers without resorting to more visual displays. But the effect of background noise demands that future sets of auditory icons be pretested with the appropriate levels of background noise present. Design decisions should also be made on a worst-case basis, accounting for the loudest vehicles in which the displays would be used.

Due to the temporal and pervasive nature of auditory messages, they are a worthy choice for warnings. For common or routine messages, especially in the case of the driver, they have the potential to become an annoyance. If the set of auditory icons as tested in this study were to be installed on an actual vehicle, some of the auditory icons

could become bothersome. If a driver happens to pass by a road construction site every day as he leaves from and returns to his residence, the vehicle would present the Road Construction Ahead auditory icon each time he approached that site. The repeated presentation of that auditory icon in a situation in which the driver already has that information could lead to a tendency to ignore that individual auditory icon or to even disable the entire system. To prevent such situations, one of three courses of action must be taken. First, the system could be designed to present such situational auditory icons only the first few times they are triggered. This could cause problems if the given vehicle were driven by a variety of individuals. Second, the actual set of auditory icons could be selected such that none of the messages that would be repeated in such situations would be included. This tactic, however, would limit the amount of information the auditory icon display could present. The third and probably best solution would be to simply design the system with separate levels of operation. Some messages, such as Low Fuel, High Engine Temperature, or Emergency Braking Warning could be operable at all times, while less critical messages like Roadside Mowing Ahead or Road Construction Ahead would only be functional at the discretion of the driver. The drawback of this solution is that the driver could cancel potentially important safety messages.

Additionally, an effort should be made to match the perceived urgency of the auditory icons with the urgency of the information they provide. The messages could be rated through the use of subject matter experts. The perceived urgency of the auditory icons, however, would have to be tested over time with repeated exposures until the ratings are stabilized.

Obstacle Response Data

Reaction time data. The measured differences in the various reaction time variables were in the correct direction to show the potential utility of auditory icons and the soft braking stimulus as emergency braking warnings. The size of the variance, particularly in the No Warning condition, combined with the small sample sizes,

prevented the mean differences from being statistically significant. The variances of the different measures, however, were dissimilar enough to be statistically significant.

The differences in Total Brake Response Time between the No Warning and other conditions were larger than 0.5 seconds. At a speed of 65 mph, a vehicle would travel more than 45 feet in that length of time. The differences in First Reaction Time were greater than one tenth of a second, in which time a vehicle moving at 65 mph will travel nearly ten feet. Differences in reaction times of these magnitudes demonstrate a dramatic advantage for drivers with warnings such as those tested in this study.

If greater numbers of drivers were to be tested, it is likely that the differences in the means would be statistically significant. But if more subjects were to be tested, how many is enough? Stein's Double Sampling Plan was applied to the data collected in this study to answer that question. The number of participants required per condition for significance at the $\alpha = 0.05$ level was calculated using the following formula:

$$n_o = \frac{4 \times t_{\alpha/2}^2 \times s^2}{l^2}$$

in which n_o is the required sample size, $t_{\alpha/2}$ is the t -value at $n-1$ (where n is the current sample size), s^2 is the current sample variance, and l is the desired confidence interval, defined here as twice the difference in the compared means. The results of that analysis are presented in Table 32.

The numbers listed in the table represent the minimum number of participants required in the listed limiting condition to show at least one significant difference in means between the three conditions. (The limiting condition is the condition requiring the most data points for the results to be statistically significant.) These numbers, however, are likely to be overestimations since they were calculated on the assumption that the variances will remain constant despite the larger sample size. It is likely, however, that the variance will decrease as the number of data points increases.

The fact that the No Warning condition is the limiting condition for four of the six measures illustrates the fact that the variance of the reaction time measures in that

TABLE 32

Results of Application of Stein's Double Sampling Plan to Collected Data

Measure	Number Required for Significance at $\alpha = 0.05$	Limiting Condition
Accelerator Reaction Time	132	No Warning
Brake Pedal Contact Time	31	No Warning
Total Brake Response Time	16	No Warning
Steering Reaction Time	271	Haptic Warning
First Reaction Time	45	No Warning
Brake Pedal Maximum Activation	138	Auditory Warning

condition is greater than that of the two conditions in which warnings are provided. For this reason, it is unlikely that increasing the TTC used in this study would improve the results. Given a longer period of time in which to react, individual responses are likely to be dispersed over a larger interval of time, increasing the variance. Additionally, the previous discussion demonstrated that although the selected TTC may be small in comparison to other studies, this is more than offset by the relatively low vehicle speed.

In each occasion that a difference in variance was shown, the variance of the No Warning condition was larger than that of the other condition(s). For the Brake Pedal Contact Time and Total Brake Reaction Time measures, the variance was smaller for both warning conditions. For the ART and FRT measures, the variance of the soft braking warning is significantly less than that of the No Warning condition, implying that the soft braking warning could be more effective than the auditory icon warning.

The implication of these results is that even if the inclusion of an auditory icon or soft braking warning would not decrease mean driver reaction time, it could still prevent or lessen the severity of accidents. If the variance of driver reaction time is decreased while the mean is held constant, then a greater percentage of drivers will have individual reaction times less than any given value greater than the mean. Of course, if the

distribution of reaction times is symmetric, then a greater number of drivers will also have reaction times longer than any given value that is less than the mean. Due to the fact that reaction times have a minimum value of zero and no maximum value, they are likely to be skewed such that a greater number of outliers are above the mean.

The advantages of the soft braking stimulus may be underestimated by the results of this study. Both the auditory and haptic warnings were triggered approximately 300 ms after the obstacles appeared. The auditory icon, however, became noticeable to the driver earlier than the soft braking warning. This discrepancy is due to the nature of the warnings. The emergency braking auditory icon was played and therefore noticeable almost immediately after the trigger signal was sent. In order for the driver to notice the soft braking warning, additional air pressure had to be applied to the front brake lines and the truck had to be slowed before the driver could sense the warning. The soft braking warning was therefore operating at a disadvantage in comparison to the auditory icon warning since its effective delay between appearance of the obstacle and noticeable onset of the stimulus was longer. It is possible that this delay could be reduced through redesign of the soft braking apparatus. If a shorter delay is attained, it is likely that the response times in the soft braking warning condition would be even smaller.

Despite the failure to measure statistically significant differences in reaction time means, this study demonstrated the validity of the scenario developed to safely measure driver responses to an unexpected obstacle. Of the 39 participants that drove through the obstacle presentation course, none of them appeared to anticipate the appearance of the barrels. Additionally, in the after-obstacle questionnaire (see Appendix I), none of the drivers stated that they felt they were endangered at any point of the testing. As for the validity of their responses to the obstacle, 73% of the participants claimed that they reacted to the appearance of the barrels as they would have in an on-road situation. Some of those participants, however, stated that their reactions would have been different for a more compelling obstacle, such as a car or a person.

The unexpected obstacle scenario may be further improved by selecting an obstacle of more uniform persuasiveness. Some of the participants, particularly those accustomed to driving around construction sites, stated that a set of plastic construction barrels was not an obstacle worthy of avoidance. The fact that none of the drivers felt endangered by the current scenario suggests that an obstacle of greater persuasiveness could be used without fear of mentally traumatizing the participants. While alternate obstacles suggested by participants included mannequins and a baby carriage, the use of a simulated vehicle would be likely to produce just as serious a situation without as great a potential for emotional side-effects.

In comparison to the brake pulse warning developed for the Delco Electronics FOREWARN system (Landau, 1995), the soft braking stimulus selected for this study is longer and probably provides a greater level of deceleration. Participant responses in the after-obstacle questionnaire, however, imply that the soft braking stimulus could be made even stronger, at least in the case of imminent collisions. Of the 14 participants exposed to the soft braking warning (in both valid and invalid trials), three suggested an increase in magnitude or length, five suggested no change, and five claimed not to feel the stimulus. The fact that none of the participants felt that the warning was too strong suggests that it could be made stronger. While five of the participants did not feel the warning, this is partially due to late or otherwise mis-timed warnings. Only two of the eight participants receiving a properly timed soft braking warning made such a claim. The failure of the soft braking stimulus to provide an adequate amount of perceptible deceleration could be due to vehicle factors. The size of the vehicle used in this study is much larger than that for which the Delco Electronics system was developed, and the vehicle speed during testing was relatively slow.

Contingency data. The contingency data analysis showed that participants provided with the soft braking warning were more likely to bring the truck to a complete stop. This difference could be due to an increase in the perceived seriousness of the situation caused by the soft braking warning. Unsolicited information given by some of

the participants indicates that it could also be due to the thought that there was something mechanically wrong with the truck that caused the deceleration. The soft braking warning could have elicited this response not because of an observed coincident obstruction but because of a perception on the part of the driver that there was something mechanically wrong with the truck. It remains to be seen whether or not the stopping reaction would disappear with greater exposure to the soft braking warning in the form of longer familiarization, training, and use.

The difference in the soft braking warning condition could also be due to a fundamental stimulus-response predisposition. Given a set of potential stimuli for one response, the stimulus that most closely resembles the desired response is most likely to have the strongest and most effective pairing with the response. In the case of this comparison of warning modalities, the desired response of depressing the brake pedal is conceptually closer to a haptic warning than to an auditory warning.

Independent of the cause, this difference demonstrates a potential advantage of a soft braking emergency braking warning over other warning types, if it is properly implemented. If the tendency to stop the vehicle is not diminished over time, then the soft braking warning should not be used as a preliminary level warning in multi-level collision avoidance warning systems or as the only warning provided. The annoyance and potential danger caused by false alarms in such a system would extend beyond the simple disturbance of unwanted auditory or visual messages. This type of alarm should instead be used in the second or even third stage of a multi-level collision avoidance warning system, where false alarms are highly unlikely.

Response strategy data. The response strategy data showed that the soft braking warning increased the likelihood that the driver will brake. As with the contingency data, this difference could be due to a greater stimulus-response compatibility or the belief on the part of the driver that something was mechanically wrong with the truck. Assuming that the increased tendency to brake does not disappear over time, this demonstrates a distinct advantage for the soft braking warning in comparison to the auditory icon

warning. Whether or not a driver applies the brakes is an intuitive measure of the effectiveness of an emergency braking warning, and the soft braking warning produced a significantly greater probability that the driver would apply the brakes.

The steering reaction data do not show a significant difference at the $\alpha = 0.05$ level, but this may be partially due to the small overall sample size of 25 drivers. Given an increase of approximately 9 in the number of drivers tested (assuming the same proportions of steering response strategies), the soft braking warning would have produced a significantly lower number of steering reactions at the $\alpha = 0.05$ level.

These differences, however, bring forth a second reason to measure the longevity of the response elicited by the soft braking warning – the natural tendency of drivers to brake. Given an obstruction in the road ahead, there is a critical distance inside which braking alone cannot prevent a collision and the driver must steer to avoid the obstacle. This critical distance is a function of factors such as the width of the obstacle, road conditions, and the speeds of the vehicle and obstacle. Drivers still tend to brake instead of steer after they are within this critical distance, and a simple increase in driver tendency to brake and decrease in tendency to steer could therefore increase the frequency of front-to-rear-end collisions (Limpert and Gamero, 1975). But if the mean time required for drivers to brake is decreased by the soft braking warning, the drivers would be more likely to brake before the critical distance to the obstacle is reached.

Suggestions for Future Research

Future research should seek to determine the maximum number of auditory icons that can be easily learned without training. It appears that this value is greater than that of nonrepresentational sounds, but the degree of difference has not yet been established and may very well depend on the particular auditory icons selected and their initial, stereotyped perceived meanings. The ability of the driver to recall the intended meanings of the individual auditory icons over a longer period of time must also be addressed to determine the full extent of the advantage of auditory icons. The time over which the association between the auditory icon and its intended meaning will last is important

since if implemented, individual drivers may go weeks without hearing a particular auditory icon.

Another relevant avenue of future research is the potential of the perceived urgency of the auditory icons to change over time. It must be determined whether or not the perceived urgency of the auditory icons would change with increased association with an intended meaning other than an individual's initial, stereotypical meaning. In this study, all of the perceived urgency ratings were recorded before the participants had heard the auditory icons paired with their intended meanings. It is possible that the creation or strengthening of the association of the auditory icon with a meaning other than the initial one could change the perceived urgency.

The next steps in evaluating the use of a soft braking stimulus as an emergency braking warning involve the speed of the vehicle and acclimation of drivers to the stimulus. The level of the soft braking stimulus tested may be too small for a speed of 15 mph, but it may be too great if the truck were to be traveling at highway speeds. The magnitude of the soft braking stimulus should be large enough to ensure reliable detection by drivers. Additionally, the psychophysical magnitude of the stimulus should be constant. The amount of additional braking must be controlled so as to provide identical driver sensations independent of vehicle speed. This requires that the air pressure applied to the brakes vary depending on the vehicle's speed.

The effects of the soft braking stimulus on driver behavior and reaction times must also be evaluated over time. Since this was the participants' first exposure to the soft braking stimulus, their responses may not be identical to the responses of those with greater training or experience with a soft braking warning. Driver reaction times may increase or acceptable following distances may decrease due to confidence in and dependence upon the ability of the soft braking warning to slow or stop the vehicle faster than the driver could alone. Such effects of a soft braking warning can only be realistically evaluated over continued use of the system.

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APPENDIX A.
SUMMARY OF RESULTS OF PILOT STUDY

TABLE A-1

Descriptions of Auditory Icons

Icon	Description of Sound	Message Number	Intended Meaning
1	Gurgling	1	Low fuel
2	Drain clearing	1	
3	Bottle rocket	2	Loss of air pressure
4	Leak	2	
5	Spurt	2	
6	Teapot whistling	3	High engine temperature
7	Boiling water	3	
8	Wildfire	3	
9	Gears grinding	4	Low oil
10	Grinding & squeaking	4	
11	Grinding & whirring	4	
12	Metal crushing	4	
13	Rattle	4	
14	Chain rumble	4	
15	Squeaking trailer	5	Problem with Trailer
16	Analog ringer	6	Incoming voice message
17	Digital ringer	6	
18	Dialing (touchtone)	7	Place call to someone
19	Fax	8	Incoming fax message
20	Typewriter (w/ carriage return)	9	Incoming text message
21	Teletype	9	
22	Rainfall	10	Poor weather (rain)
23	Thunder	10	
24	Rain with thunder roll	10	
25	Rain with thunder clap	10	
26	Foghorn (single tone)	11	Fog warning
27	Foghorn (2-tone)	11	
28	Coin dropped on table	12	Automated toll payment
29	Coin in slot	12	
30	Siren (wail)	13	Emergency vehicle approaching
31	Siren (fade)	13	
32	Siren (hi-lo)	13	
33	Jackhammer	14	Roadwork ahead
34	Bulldozer	14	
35	Mower (high pitch)	15	Roadside mowing ahead
36	Mower (low pitch)	15	
37	Train horn	16	Train crossing ahead
38	Train crossing bell	16	
39	Train (Doppler effect)	16	
40	Giggling	17	Children / playground ahead
41	Screaming	17	
42	Short honk	18	Collision avoidance warning
43	Long honk	18	
44	Double honk	18	
45	Short and long honk	18	
46	Tire skid	18	
47	Tire screech	18	
48	Tire skid and crash	18	
49	Tire screech and crash	18	
50	Truck back-up alarm	19	Vehicle / object behind
51	Congestion (coughing)	20	Congested traffic ahead

TABLE A-2

Summarized Results of Pilot Study

Icon number	Message number	Description of Sound	Non-CVO Percentage	CVO Percentage	Total Percentage	Association rating	Association rank	Message Rank	Urgency rating	Urgency rank	Message Rank
1	1	Gurgling	5.0%	0.0%	2.9%	10.078	40	-	7.145	40	-
2	1	Drain clearing	10.0%	7.1%	8.8%	10.226	39	-	6.971	42	-
3	2	Bottle rocket	15.0%	21.4%	17.6%	13.995	25	A	9.841	21	A
4	2	Leak	15.0%	21.4%	17.6%	14.449	22	A	9.889	20	A
5	2	Spurt	15.0%	14.3%	14.7%	8.507	46	B	7.289	38	B
6	3	Teapot whistling	35.0%	50.0%	41.2%	14.705	20	A	12.769	6	A
7	3	Boiling water	10.0%	0.0%	5.9%	10.658	38	B	8.302	29	B
8	3	Wildfire	0.0%	0.0%	0.0%	11.862	34	B	11.585	11	A
9	4	Gears grinding	5.0%	7.1%	5.9%	8.430	47	-	8.486	27	A
10	4	Grinding & squeaking	0.0%	0.0%	0.0%	9.515	41	-	8.893	24	A,B
11	4	Grinding & whirring	0.0%	7.1%	2.9%	9.442	42	-	8.705	26	A,B
12	4	Metal crushing	0.0%	0.0%	0.0%	7.383	50	-	9.929	19	A
13	4	Rattle	0.0%	7.1%	2.9%	9.059	43	-	8.709	25	A,B
14	4	Chain rumble	0.0%	0.0%	0.0%	7.984	48	-	6.811	43	B
15	5	Squeaking trailer	5.0%	7.1%	5.9%	8.538	44	-	8.251	30	-
16	6	Analog ringer	60.0%	64.3%	61.8%	14.199	23	-	9.362	22	A
17	6	Digital ringer	85.0%	92.9%	88.2%	15.515	17	-	7.763	35	B
18	7	Dialing (touchtone)	25.0%	21.4%	23.5%	16.009	13	-	5.578	48	-
19	8	Fax	25.0%	7.1%	17.6%	12.800	30	-	6.396	46	-
20	9	Typewriter (w/ carriage return)	45.0%	42.9%	44.1%	12.866	29	-	6.545	45	-
21	9	Teletype	10.0%	28.6%	17.6%	11.828	35	-	6.252	47	-
22	10	Rainfall	55.0%	64.3%	58.8%	13.818	27	B	9.089	23	A
23	10	Thunder	50.0%	64.3%	55.9%	15.594	16	B	7.420	37	B
24	10	Rain with thunder roll	90.0%	85.7%	88.2%	16.728	9	A	7.169	39	B
25	10	Rain with thunder clap	90.0%	92.9%	91.2%	18.015	6	A	10.263	16	A
26	11	Foghorn (single tone)	20.0%	50.0%	32.4%	13.535	28	-	6.772	44	A
27	11	Foghorn (2-tone)	35.0%	64.3%	47.1%	15.484	18	-	4.693	51	B
28	12	Coin dropped on table	0.0%	0.0%	0.0%	12.226	32	B	4.764	50	-
29	12	Coin in slot	5.0%	14.3%	9.4%	14.874	19	A	5.430	49	-
30	13	Siren (wail)	95.0%	92.9%	94.1%	18.724	3	A	15.938	4	A
31	13	Siren (fade)	85.0%	85.7%	85.3%	19.020	1	A	15.993	3	A
32	13	Siren (hi-lo)	65.0%	50.0%	58.8%	13.848	26	B	12.100	9	B
33	14	Jackhammer	90.0%	85.7%	88.2%	16.454	11	-	10.113	18	A
34	14	Bulldozer	40.0%	28.6%	35.3%	14.031	24	-	8.475	28	B
35	15	Mower (high pitch)	20.0%	21.4%	20.6%	16.342	12	-	7.942	33	-
36	15	Mower (low pitch)	40.0%	78.6%	55.9%	17.147	8	-	7.518	36	-
37	16	Train horn	70.0%	92.9%	79.4%	14.667	21	C	10.354	15	B
38	16	Train crossing bell	100.0%	92.9%	97.1%	18.768	2	A	12.600	7	A
39	16	Train (Doppler effect)	55.0%	100.0%	73.5%	16.478	10	B	11.362	12	A,B
40	17	Giggling	85.0%	100.0%	91.2%	18.235	4	A	8.006	32	B
41	17	Screaming	70.0%	64.3%	67.6%	15.946	14	B	12.065	10	A
42	18	Short honk	35.0%	14.3%	26.5%	7.870	49	D	7.054	41	D
43	18	Long honk	35.0%	35.7%	35.3%	10.797	37	B,C	10.251	17	C
44	18	Double honk	20.0%	35.7%	26.5%	8.528	45	B,C,D	8.030	31	D
45	18	Short and long honk	25.0%	14.3%	20.6%	11.565	36	B,C	10.758	14	C
46	18	Tire skid	55.0%	35.7%	47.1%	15.723	15	A	14.662	5	B
47	18	Tire screech	25.0%	35.7%	29.4%	12.228	31	B	11.048	13	C
48	18	Tire skid and crash	30.0%	14.3%	23.5%	18.213	5	A	16.800	2	A
49	18	Tire screech and crash	35.0%	28.6%	32.4%	17.928	7	A	17.192	1	A
50	19	Truck back-up alarm	30.0%	28.6%	29.4%	12.225	33	-	12.519	8	-
51	20	Congestion (coughing)	0.0%	0.0%	0.0%	6.363	51	-	7.824	34	-

Note: Percentages refer to the portion of subjects providing a free response comparable to the intended meaning; Ratings are the mean transformed free-modulus magnitude ratings; Identical letters in the Message Rank column indicate no statistically significant difference in ratings.

APPENDIX B.
AUDITORY ICON SPECTRAL PATTERNS

One-third octave bands marked with an * are the 1/3 octave bands that result in ISO 7731 being satisfied (maximum signal SPL is 13 dB greater than the masked threshold, 315 Hz to 3150 Hz 1/3 octave bands).

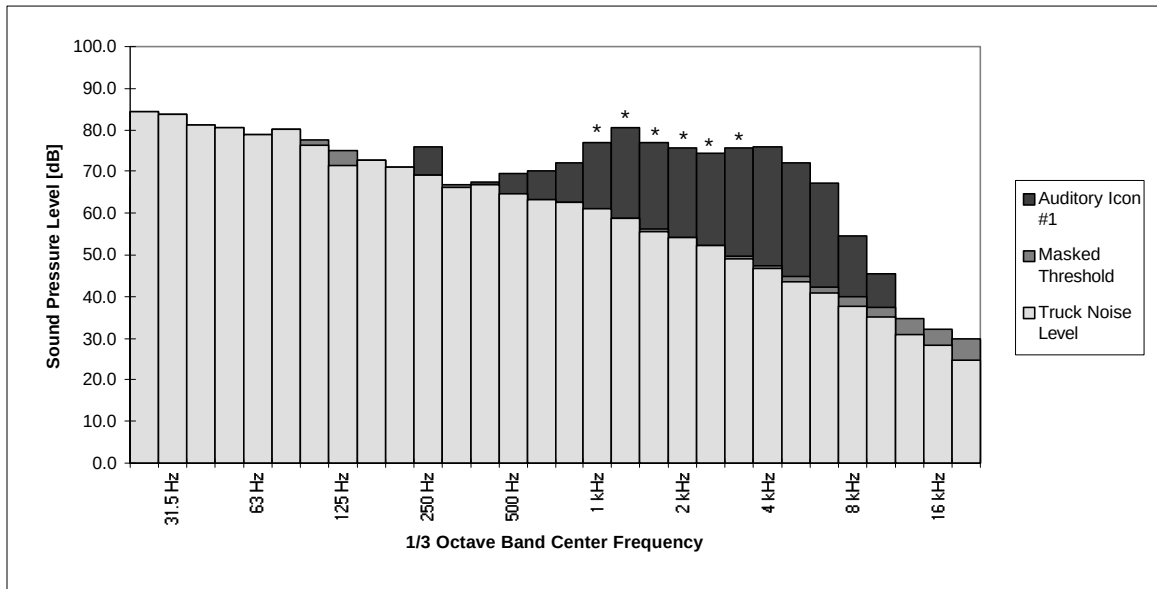
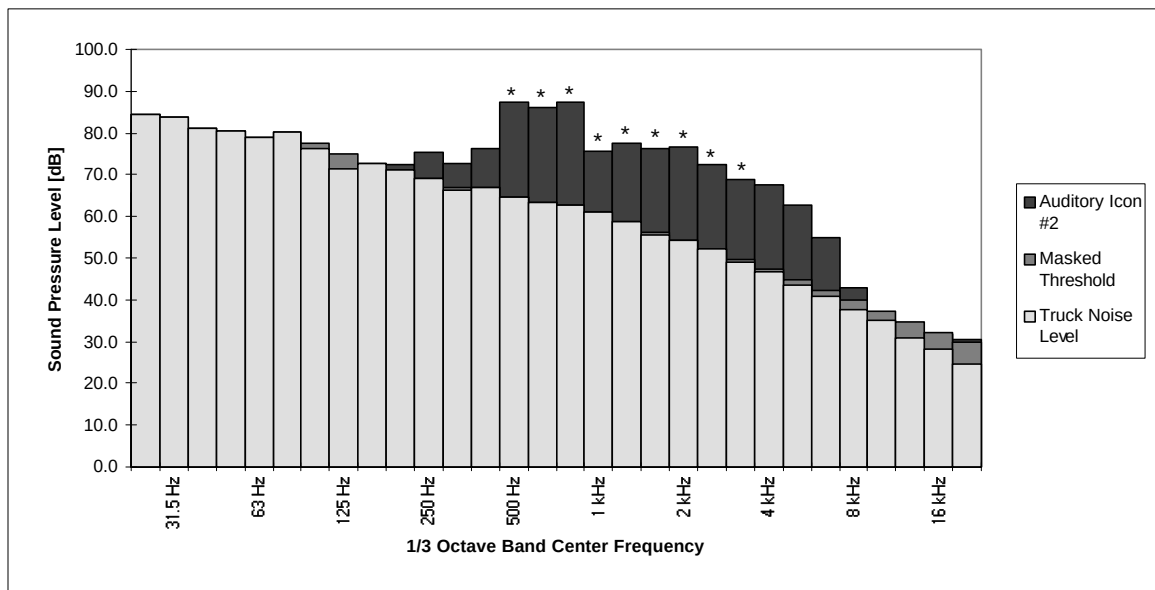


Figure B-1. Truck noise masked threshold versus maximum SPL of auditory icon #1, Automated Toll Payment Completed.



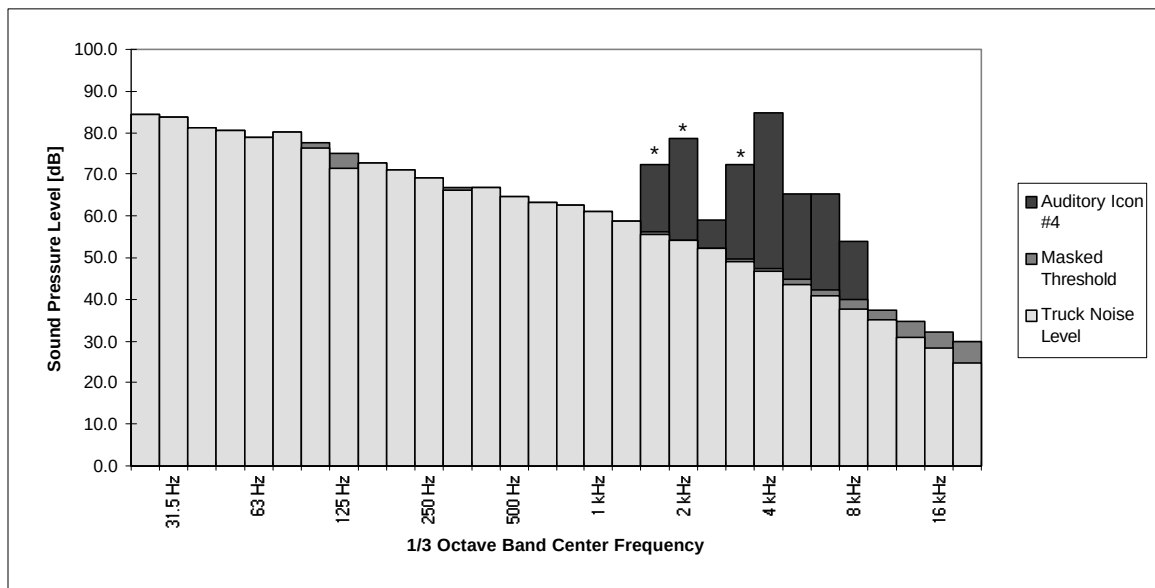


Figure B-4. Truck noise masked threshold versus maximum SPL of auditory icon #4, High Engine Temperature.

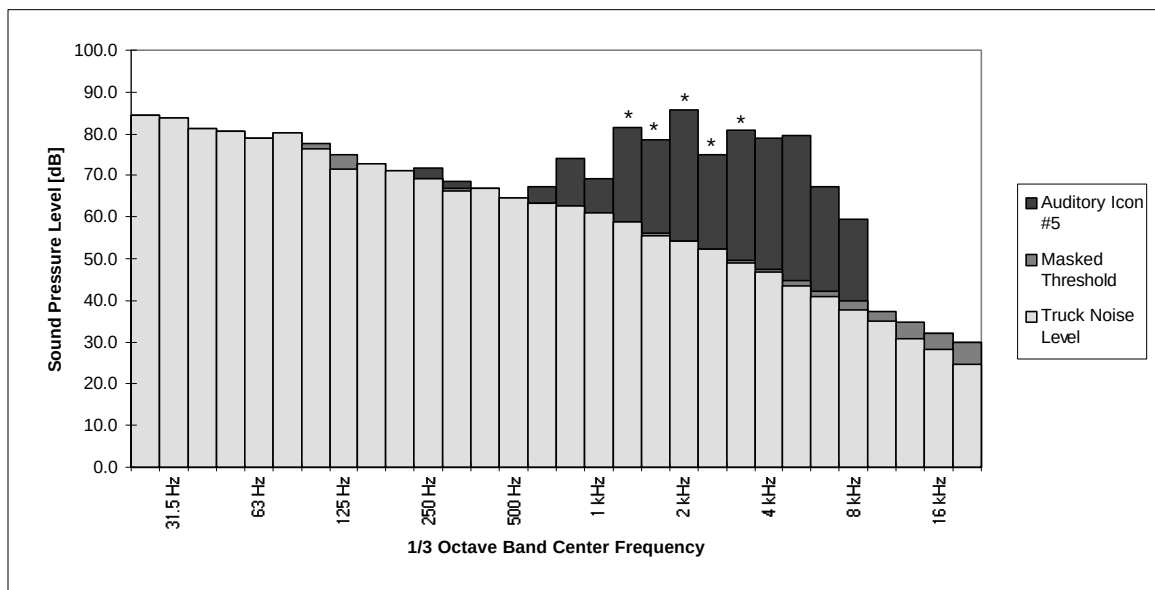


Figure B-5. Truck noise masked threshold versus maximum SPL of auditory icon #5, Railroad Crossing Ahead.

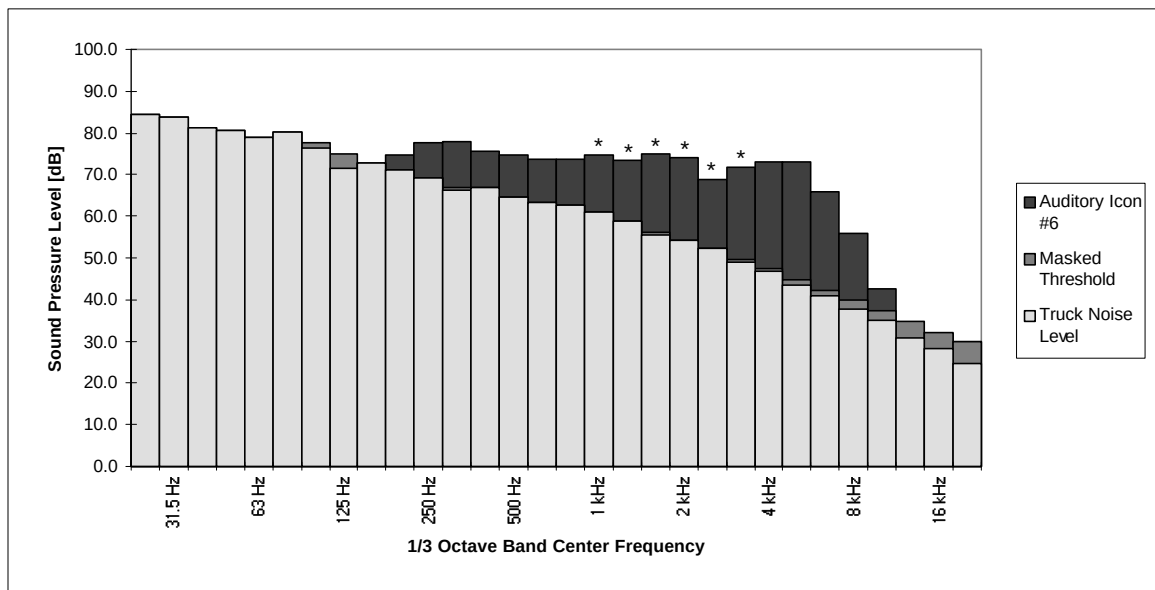


Figure B-6. Truck noise masked threshold versus maximum SPL of auditory icon #6, Roadside Construction Ahead.

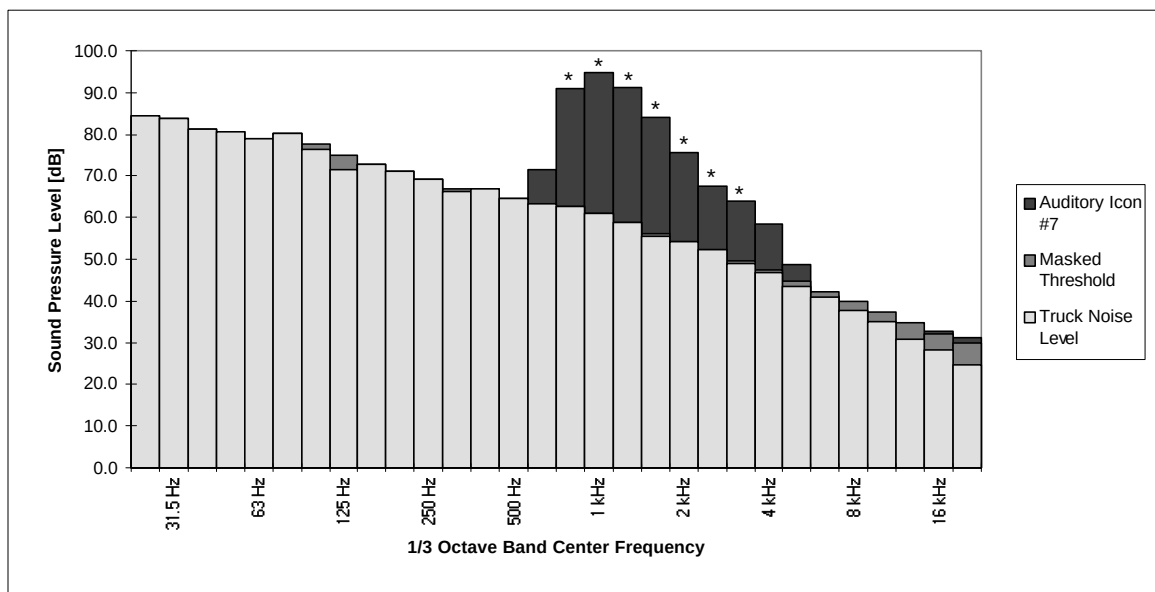


Figure B-7. Truck noise masked threshold versus maximum SPL of auditory icon #7, Emergency Vehicle Approaching.

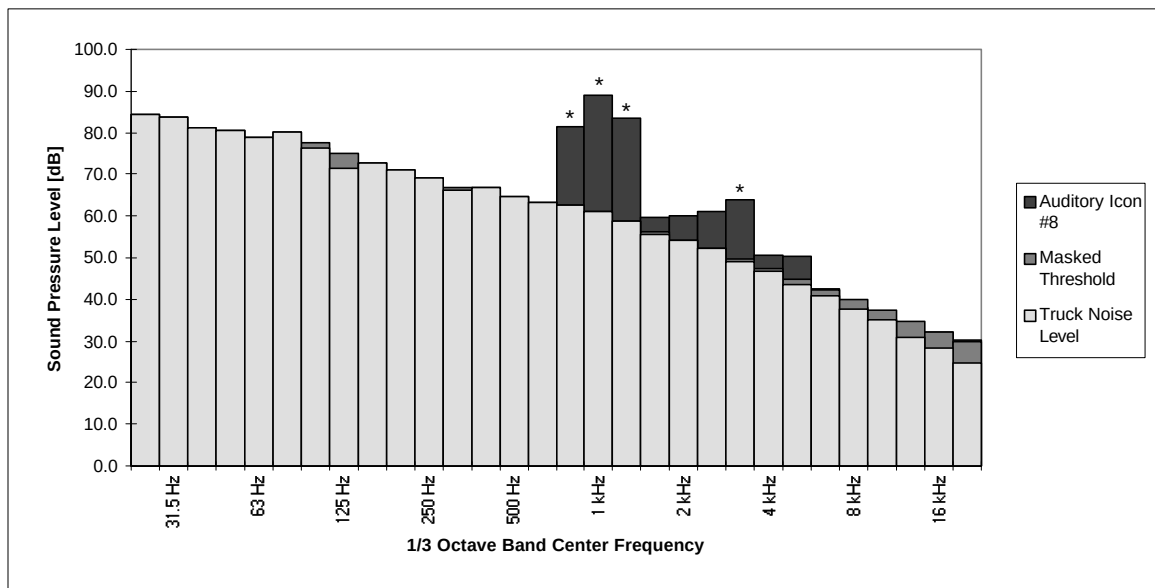


Figure B-8. Truck noise masked threshold versus maximum SPL of auditory icon #8, Incoming Voice Message.

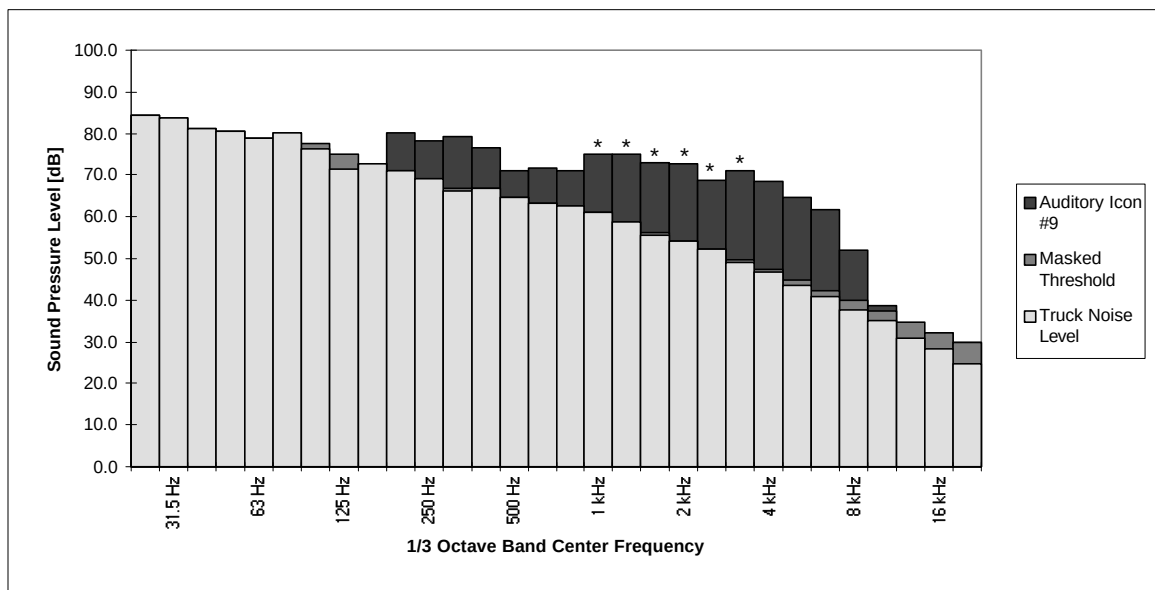


Figure B-9. Truck noise masked threshold versus maximum SPL of auditory icon #9, Roadside Mowing Ahead.

APPENDIX C.
PARTICIPANT BACKGROUND INFORMATION

TABLE C-1

Participant Background Information

Subject Number	Age	Overall Driving Experience	CVO Driving Experience	Class A miles (thousands)	Employed by	Type of Vehicle Driven	Typical Miles per Week	Maximum Miles per Week	Endorsements
1	27	11	6	700	pvt. car.	Comb	2500	3000	
2	53	37	15	600	own-op	Comb	125		
3	24	8	2	15	pvt. car.	Comb	30	3000	
4	31	13	13	700	pvt. car.	Comb	2200	3800	H N T
5	29	15	10	1,000	pvt. car.	Comb	2000		
6	37	21	17	2,000	pvt. car.	Comb	1500	5000	
7	30	14	7	750	pvt. car.	Comb	1600		H
8	32	18	8	25	pvt. car.	Comb	150		
9	48	32	10	500	pvt. car.	Comb	3000		H N T
10	29	13	4	75	pvt. car.	Comb	2500		H N
11	36	22	16	750	pvt. car.	Dmp Trk	2000		H N
12	43	27	27	1,500	pvt. car.	Comb	1550		H
13	22	7	1.5	300	pvt. car.	Comb	5000		H
14	29	15	4.5	200	pvt. car.	Comb	2250		H
15	27	10	4	500	pvt. car.	Comb	0	3500	H T
16	22	5	2.5	60	pvt. car.	Cmt Trk	300		H N T
17	39	23	5	60	pvt. car.	Comb	?		
18	37	15	0.5	40	pvt. car.	Comb	2200		H N T
19	36	22	2.5	100	none	Comb	0	4000	H N
20	35	18	15	900	pvt. car.	Comb	3100		H N
21	52	37	29	1,000	pvt. car.	Comb	580		H N T
22	33	17	2	100	pvt. car.	Comb	1000		H
23	38	22	10	1,000	pvt. car.	Comb	2500		H N
24	40	24	21	2,000	pvt. car.	Comb	2400		H N P T
25	46	30	29	1,000	none	Comb	0	2500	H N S P T
26	32	20	8	450	pvt. car.	Comb	800	5500	H T
27	22	6.5	2.5	250	pvt. car.	Comb	2000		N T
28	48	33	23	1,500	pvt. car.	Comb	1000		H P
29	36	21	9	700	none	Comb	0	3250	H N S P T
30	63	45	30	300	retired	Comb	0	200	H N P T
31	60	35	35	2,000	pvt. car.	Comb	1000		
32	48	30	22	2,500	pvt. car.	Comb	2600		H T
33	41	25	1	60	pvt. car.	Comb	6000		H N T
34	69	55	42	2,250	retired	Comb	0	1500	H N
35	32	17	15	500	pvt. car.	Comb	5750		H
36	36	21	13	1,250	pvt. car.	Comb, Dmp Trk	3000		H T
37	52	34	20	100	pvt. car.	Comb	500		H
38	31	15	3	300	pvt. car.	Comb	2500		H N T
39	26	11	5	375	pvt. car.	Comb	1500		H N
40	46	31	25	800	pvt. car.	Comb, Dmp Trk	400		T
41	42	17	3.5	250	none	Comb, Dmp Trk	2500		H N T

H - Hazardous materials; N - Tanker trailer; S - School bus; P - Passenger vehicle; T - Doubles or Triples

TABLE C-2

Participant Pure-Tone Audiogram Results

Subject Number	Age	HTL in dB, Right Ear				HTL in dB, Left Ear			
		500 Hz	1000 Hz	2000 Hz	4000 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	27	0	-5	5	5	5	-10	0	5
2	53	5	5	0	55	5	5	0	40
3	24	5	0	-5	0	5	0	-5	-10
4	31	0	5	5	5	5	5	5	40
5	29	5	0	-5	5	5	0	0	0
6	37	5	5	-5	-5	5	0	5	5
7	30	10	0	10	20	10	10	10	35
8	32	5	10	25	45	5	15	35	60
9	48	5	15	15	25	10	15	20	40
10	29	5	0	-5	5	0	-5	-5	5
11	36	10	5	0	10	10	5	-5	10
12	43	5	5	25	20	10	5	15	40
13	22	10	10	0	25	15	15	-5	5
14	29	0	-10	-5	0	0	0	0	15
15	27	10	0	0	5	10	5	0	-5
16	22	10	0	0	30	30	20	0	0
17	39	0	0	15	25	5	5	5	25
18	37	0	5	-5	20	10	5	0	15
19	36	10	10	5	5	15	10	5	15
20	35	5	0	0	15	5	5	-10	5
21	52	15	20	15	20	15	20	15	45
22	33	5	-10	-5	-5	5	0	-5	0
23	38	5	0	10	15	10	5	15	10
24	40	5	10	15	40	15	10	20	40
25	46	10	10	5	25	10	5	10	20
26	32	5	0	5	15	5	5	10	5
27	22	10	5	-5	0	10	5	-5	15
28	48	10	-5	-5	-5	5	0	-5	5
29	36	5	5	0	30	5	0	0	20
30	63	5	10	-5	40	10	10	5	55
31	60	10	5	10	25	10	5	5	55
32	48	10	15	10	45	10	25	15	50
33	41	15	15	20	85	15	15	20	35
34	69	5	-5	-10	15	10	0	-5	25
35	32	5	5	5	25	5	5	5	35
36	36	15	10	5	5	10	5	10	20
37	52	10	5	50	75	5	10	65	70
38	31	15	15	15	25	15	15	10	40
39	26	5	-5	5	-5	5	-5	5	5
40	46	5	10	10	70	10	5	40	40
41	42	5	5	10	5	5	0	15	-5

APPENDIX D.
PARTICIPANT'S INFORMED CONSENT DOCUMENT

**VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)**

Informed Consent for Participants of Investigative Projects

Title of Project: An Investigation of Auditory Icons in a Commercial Truck Cab Environment

Principal Investigators: Dr. J. G. Casali, Professor and Head, Department of ISE
Dr. T. A. Dingus, Professor, ISE; Director of University Center for Transportation Research
Dr. Gary S. Robinson, Senior Research Associate, ISE
John J. Winters, Graduate Research Assistant, ISE

Faculty Advisor: Dr. J. G. Casali, Professor and Department Head, ISE

I. The Purpose of this Research

You are invited to participate in a study designed to evaluate a set of representational, non-speech sounds being considered as information displays in commercial trucks. The information to be conveyed by these messages includes information available in current commercial vehicles as well as information from potential Intelligent Transportation System (ITS) functions. To participate, you must possess a valid commercial driver's license and have recent, regular experience driving a tractor-trailer combination vehicle. If you choose to participate, you will be one of approximately 30 participants in this study.

II. Procedures

The procedures to be used in this research are as follows. If you wish to become a participant after reading and signing this form, you will be screened to determine if you qualify for the experiment.

Screening will consist of a hearing test to determine if your hearing today meets the guidelines established by the Federal Highway Administration (FHWA) for commercial motor vehicle operators. If you do not qualify for participation because of this test, it does not mean that you no longer meet the FHWA hearing requirements. **This test is used for screening purposes only.**

Your right and left ear hearing will be tested with very quiet tones played through a set of headphones. You will have to be very attentive and listen carefully for these tones. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed-tones and release it when you do not hear the tones.** The tones will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented over the headphones. The hearing test may be conducted in a sound-proof booth with the experimenter sitting outside or in a quiet conference room with the experimenter sitting behind you. If the test is administered in such a booth, the door to the booth will be shut but not locked; either you may open it from the inside or

the experimenter may open it from the outside. There is also an intercom system through which you may communicate with the experimenter by simply talking (there are no buttons to push).

If you meet the hearing criteria, you will receive instructions in the magnitude estimation procedure that will be used later in the experiment. You will be asked to complete a short line-length estimation task to practice the method.

Following the line-length estimation task, you will be escorted to the truck to be used in this study. You will be given as much time as necessary to familiarize yourself with the truck and its controls. You will also have the opportunity to drive the truck around the parking area so that you can familiarize yourself with the truck's handling and braking characteristics. The truck you will drive is a 1997 Volvo VN, and you will be driving it without a trailer attached. As soon as you are comfortable with the truck and confident that you can operate it in a safe manner, the on-the-road portion of the experiment will begin. The experimenter will accompany you during the drive to direct you along the prescribed route, to present the test sounds to you while you are driving, and to record your responses to sounds.

As you drive along the route specified by the experimenter, the test sounds will be presented to you through a pair of small loudspeakers located behind you. For each sound, you will be asked to give the perceived meaning of the sound or the function it relates to the context of the driving task and the truck-cab environment. Ten to 15 different sounds will be presented in this manner.

After each of the sounds is evaluated in this manner, and a short break, the entire set of sounds will be presented a second time in a different order. During this second test segment, you will be asked to use the magnitude estimation method to rate the perceived urgency of the sounds by assigning a number to each sound as it is presented. By speaking aloud, you will rate each sound twice during non-consecutive presentations.

After rating each sound's perceived urgency, you will be asked to turn the truck around at the next suitable location and return to the staging area. During the return trip, the sounds will be presented a third time. You will be asked to use the free-modulus magnitude estimation method to rate the level of association of the sound with the meaning specified by the experimenter. Again, you will rate each sound twice during non-consecutive presentations.

During the remainder of the trip back to the staging area, you will receive training in a selected subset (three to five) of the sounds presented earlier. First, you will be presented with the sounds individually and informed of their intended meaning. The sounds will be presented again, and you will be asked to repeat their intended meaning. This process will continue until you exit the four-lane highway.

After returning the truck to the staging area, you will be directed to the start area of a short handling course outlined by a set of traffic cones. There will be no other vehicles or pedestrians on or near this closed course. At this time, a set of in-truck cameras will be activated. One camera will be directed in front of the truck, one at your feet, and one at your eyes. The videotapes recorded during this portion of the testing will be analyzed to assess your and the truck's responses to the handling course. In order to

permit the collection of eye position data during the course, you will not be allowed to wear sunglasses. (All tapes will be stored in a locked cabinet and erased after data has been collected from them.) You will be asked to complete the course at a speed of 15 miles per hour. Completion of the course may require some abrupt driving maneuvers, but please maintain a speed as close to 15 mph as possible and stay within the cones. Remember, your truck will be the only vehicle on this course.

Following the handling course, you will be asked to return to the room in which the screening and training sessions were held. There, you will be asked questions concerning the experiment, the handling characteristics of the truck, and your opinion of the test sounds. You will then be paid for your participation. The entire session is expected to last between two and a half and four hours.

III. Risks

The tests described herein are believed to pose not more than minimal risk to your health or well-being. The auditory icon presentation equipment will be checked prior to each session to ensure that its volume has been set at a safe but audible level, and all auditory icons will be presented at approximately equal loudness levels. The only known risks associated with your participation in this project are those encountered in the truck driving task. In order to minimize these risks, you will be driving the truck without a trailer. If at any point during the tests the experimenter believes that continuing the session will endanger you or the equipment, he will stop the testing.

IV. Benefits of this Project

Your participation in this study will provide useful information about the meanings and urgencies of non-speech auditory messages.

No guarantee of benefits has been made to encourage you to participate. You may receive a summary of the results of this research when completed. Please leave or send a self-addressed envelope if you are interested in the summary. To avoid biasing other potential participants, you are requested not to discuss the study with anyone until **six months** from now.

V. Extent of Anonymity and Confidentiality

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than the individuals working on the project without your written permission. The information you provide will have your name removed and only a participant number will identify you during subsequent analyses and any written reports resulting from the research.

As stated earlier, cameras will be used to collect information as you complete the handling course. The recorded videotapes will be stored in a locked cabinet until they are analyzed. Once all necessary data has been collected from the tapes, they will be erased.

VI. Compensation

At the end of your participation in this session, you will receive \$50.00 as compensation for your participation. You will also be able to request a copy of the results of this study. If you so desire, these results will be mailed to you once the study has been completed.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time you have spent in the study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or equipment.

VIII. Approval of Research

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering.

IX. Participant's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

- To notify the experimenter at any time about a desire to discontinue my participation.
- To complete the hearing tests to the best of my ability.
- To operate the truck used in this experiment in a safe and responsible manner.
- To answer all questions as to the perceived meanings and urgencies of the presented auditory messages fully and truthfully.

Signature of Participant

X. Participant's Permission

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you decide to participate, please sign your name on this page and the following pages.

I have read and understand the Informed Consent and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid only for the portion of the time that I spend in the study.

Signature _____
Printed Name _____
Date _____

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory, Dr. Thomas A. Dingus, Director of the Center for Transportation Research, Dr. Gary S. Robinson, Senior Research Associate, and John J. Winters, Graduate Research Assistant. Mr. Winters will serve as the primary experimenter. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory
538 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061-0118
Dr. John G. Casali: (540) 231-9081
Dr. Thomas A. Dingus: (540) 231-8831
Dr. Gary S. Robinson: (540) 231-2680
John J. Winters: (540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Tom Hurd
Director of Sponsored Programs
301 Burruss Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-9359

APPENDIX E.
PARTICIPANT'S INFORMED CONSENT DOCUMENT
(POST IN-TRUCK STUDY)

**VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)**

Debriefing Form for Participants of Investigative Projects

Title of Project: An Investigation of Auditory Icons and Brake Response Times in a Commercial Truck Cab Environment

Principal Investigators: Dr. J. G. Casali, Professor and Department Head, ISE
Dr. T. A. Dingus, Professor, ISE; Director of University Center for Transportation Research
Dr. Gary S. Robinson, Senior Research Associate, ISE
John J. Winters, Graduate Research Assistant, ISE

Faculty Advisor: Dr. J. G. Casali, Professor and Department Head, ISE

I. The Purpose of this Research

This research project has two purposes, the first of which is to investigate the use of everyday sounds (auditory icons) to convey information in the heavy truck cab environment. This was accomplished during the first portion of the experiment in which you answered questions concerning the meaning and urgency of different sounds. Your answers to these questions and the answers of other participants in this project will be used to determine the stereotypical meanings of the presented sounds.

The second goal of the project is to determine brake response time (BRT) to an unexpected event. To achieve this goal, your response to the appearance of the traffic barrel has been recorded. Your brake response time will be calculated from measurements of brake and accelerator pedal position taken during a period of time surrounding the appearance of the barrel. Brake response time data will be compared for four different conditions: (1) no warning, (2) auditory warning, (3) haptic warning (automatic partial braking), and (4) a combination of auditory and haptic warnings. You were randomly placed in the **(list group name)** warning category.

II. Procedures

As explained in the initial informed consent form, the first portion of the in-truck testing involved the use of auditory icons to convey information. While driving the truck, you were asked questions about the meaning and urgency of the set of auditory icons. You were then trained in the use of a subset of the auditory icons.

The second portion of the in-truck testing concerned brake response times. You were not informed about the appearance of the barrel due to the fact that expectancy has been shown to reduce brake response times. For the results of this study to be applicable to real-life situations, it was necessary to present the barrel in an unexpected manner.

The location for the brake response time measurement was selected to prevent outside interference. The presentation area was monitored by a second experimenter

who had the ability to prevent the presentation of the barrel if he had reason to doubt your safety, his safety, or the safety of the equipment. Soon after you began the handling course, the truck activated a sensor controlling the presentation of the barrel. The presentation mechanisms were designed to prevent the appearance of the barrel if the speed of the truck was greater than 20 miles per hour.

III. Risks

Your participation in this project exposed you to some limited risks. In order for the barrel's appearance in the path of your vehicle to be unexpected, the first informed consent form only listed those risks that you would encounter in the auditory icon and handling portions of this experiment. The risks involved in the brake response time measurement portion of this experiment were:

1. The risk of collision with the presented object (deformable traffic barrel). (This risk has minimal implications for injury or vehicle damage.)
2. The risk of vehicle rollover or collision with another object due to your response to the appearance of the traffic barrel. (This risk is minimized due to the low speeds involved.)
3. The risk of driver stress due to a high-stress event, such as the unexpected presentation of the traffic barrel.

The following precautions were taken to minimize your risk for participating in this project:

1. The first informed consent form stated that abrupt maneuvers may be necessary during the handling portion of the testing.
2. All data collection equipment for this portion of the experiment was installed in such a way as to prevent interference with the driving task.
3. The presented object was selected to not damage the truck and to be of low psychological and emotional value.
4. The BRT measurement area was monitored by a second experimenter to ensure the safety of the equipment and to prevent anyone not associated with the experiment from interfering.
5. The truck was operated without a trailer to reduce the stopping distance required.
6. The barrel presentation equipment was designed not to eject the barrel if your speed was less than 10 mph or greater than 20 mph.
7. Both the in-truck experimenter and ground-based experimenter had the ability to prevent the presentation of the barrel if there was any reason to doubt your safety, their safety, or the safety of the equipment.
8. A medical prescreening interview concerning heart condition history was required for all participants.

IV. Benefits of this Project

Your participation in this study will provide useful information about the perceived meanings and urgencies of auditory messages. It will also help to determine the best method of presenting collision avoidance warnings to drivers. No guarantee of benefits was made to encourage you to participate. You may receive a summary of the results of this research when completed. Please leave or send a self-addressed envelope if you are interested in the summary. **To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.**

V. Extent of Anonymity and Confidentiality

You will remain anonymous, and all data and information provided by you will remain strictly confidential. Your name will be removed from any materials that could associate your identity with the responses you provided. Only the experimenter will have the knowledge of which data are yours, and your identity will not be included or reported in any presented or published results of this project. As stated previously, the videotapes from this study will be stored in a locked cabinet and will be erased after the data they provide have been fully analyzed.

VI. Compensation

At the end of this session, you will receive \$50.00 as compensation for your participation as indicated in the pre-experiment informed consent. As previously mentioned, you will also be able to request a copy of the results of this study.

VII. Freedom to Withdraw

You were free to withdraw from this study at any time without penalty. If you had chosen to withdraw, you would have been compensated for the portion of time you spent in the study. Had there been circumstances under which the experimenter determined that you should not continue as a participant of this project, he would have canceled the remainder of the experiment. These circumstances included, but were not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the a participant, experimenter, and/or equipment.

VIII. Approval of Research

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering.

IX. Participant's Responsibilities

I voluntarily accept the following responsibilities:

- Not to tell anyone about the emergency brake response time portion of the testing for the next **six months**.
- To inform the experimenter **now** if I have any concerns or questions about this study.

Signature of Participant

X. Participant's Permission

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. Then if you understand the nature and reasons for the brake reaction time portion of this experiment, please sign your name on this page and the following pages.

I have read and understand the Informed Consent and understand the nature of the research and my rights as a participant.

Signature _____
Printed Name _____
Date _____

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory, Dr. Thomas A. Dingus, Director of the Center for Transportation Research, Dr. Gary S. Robinson, Senior Research Associate, and John J. Winters, Graduate Research Assistant. Mr. Winters served as the primary experimenter. They may be contacted at the following address and phone numbers:

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Dr. Gary S. Robinson: (540) 231-2680
John J. Winters: (540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Tom Hurd
Director of Sponsored Programs
301 Burruss Hall
VPI & SU
Blacksburg, VA 24061
(540) 231-5281

APPENDIX F.

SUBJECT INSTRUCTIONS

Free-Modulus Magnitude Estimation Method Familiarization

I am going to present to you, in random order, a series of lines. Your task will be to estimate how long the lines are by using positive, non-zero numbers. When you are shown the first line, give its length a number – any number greater than zero that you would like. Write this number on your scoresheet. I will then show another line to which you will also give a number, then a third, and so on. Use high numbers for long lines and low numbers for short lines. Try to make the ratios between the numbers that you assign to the different lines match the ratios between the lengths of the lines. In other words, if the second line is twice as long as the first line, give it a rating twice as large as the rating you gave the first line. Remember that you can use any numbers greater than zero. There is no upper limit to the numbers that you can use, and there are no right or wrong answers. I want to know how you judge the length of lines. Do you have any questions?

In-Lab Auditory Icon Familiarization

Auditory icons are sounds that are defined not by their pitch or other such qualities, but by the object or the action that caused the sound. They can be described as representational sounds since the sound represents some object or action. We will be testing the use of auditory icons to present information to truck drivers. It is hoped that using sound instead of vision to present this information will reduce the visual workload of the driver and therefore increase the safety of the driving task.

During the driving task, a set of nine auditory icons will be played for you. You will be asked to say what you would expect the sounds to mean when presented to a truck driver during the driving task. In order to allow you to practice this, you will now hear a different set of auditory icons. But instead of treating the sounds as being heard in a truck cab, assume that they have been designed to provide information in a person's home. Listen to the sounds and let me know what you would expect them to mean. I do not want to know the object or action that caused the sound, but the information or instructions that you would expect the sound to represent. Remember that there are no right or wrong answers - I am only interested in your opinion of what the sounds could mean. Do you have any questions?

Free response to perceived meaning

I am going to play for you, in random order, a set of sounds. Your job is to tell me what you think the sounds mean. Remember that these are sounds designed to give information to a vehicle driver. The sounds may give information that you would normally see on the truck's instrument panel, on a sign on the side of the

road, or they may give you other information that you as a driver would want to know. When you hear each sound, please tell me what instructions you think the sound may be giving or what information you think the sound is intended to present. There are no right or wrong answers. I want to know how you interpret the meanings of the sounds and what you believe them to mean. You do not need to be overly specific in your answers. If a response is too vague, I will ask you to clarify your answer. Do you have any questions?

Rating of perceived urgency

I am going to play for you, in random order, a set of sounds. Your job is to tell me how urgent these sounds are by assigning numbers to them. When you have heard the first sound, give its urgency a number – any number greater than zero that you want. I will then play another sound to which you will also give a number, then a third sound, and so on. Please make your best effort to rate the urgency of the sound itself and not the urgency of the information you feel the sound represents. Use high numbers for sounds with high urgency and low numbers for sounds with low urgency. Try to make the numbers proportional to the urgency of the sound as you hear it. In other words, if the second sound is twice as urgent as the first sound, give it a number twice as large as the number you gave the first sound. Remember that you can use any numbers greater than zero. There are no right or wrong answers. All I want to know is how you judge the urgency of the sounds. Do you have any questions?

Rating of association

I am going to play for you, in random order, a set of sounds. Before the presentation of each sound, I will name a function or task. Your job is to rate how well the sound matches or associates with its corresponding function by assigning a number to it. When you have heard the first sound and its intended function, give a number to the association – any number greater than zero that you want. I will then present another function and sound pair to which you will also give a number, then a third, and so on. Use high numbers for sounds that match well and low numbers for sounds that do not match well. Try to make the numbers proportional to the degree to which you associate the sound as you hear it with the named function. In other words, if the second sound and function pair matches twice as well as the first pair, give it a number twice as large as the number you gave the first pair. Remember that you can use any numbers greater than zero. Do not be concerned if the functions I list do not match the functions you named when you first heard these sounds. There are no right or wrong answers. All I want to know is how you rate the associations of the sound and function pairs. Do you have any questions?

APPENDIX G.
IN-TRUCK FAMILIARIZATION INSTRUCTIONS AND PARTICIPANT
RESPONSES

Subject: _____

Date / Time: _____

Auditory Icon familiarization

Describe the concept of auditory icons. Inform the participant that he will be asked to say what he thinks the auditory icon would mean if heard in a truck cab. Play the auditory icon twice.

Ask the participant: "Remember that the sound is simply the playback of a sound by equipment within the truck itself. It is designed to convey specific information to the driver. What would you think the intended meaning of the auditory icon would be if you heard it while driving?"

Inform the participant: "I will play the auditory icon you just heard another time. Please rate the effectiveness of this auditory icon as a low fuel warning as completely ineffective, somewhat ineffective, somewhat effective, or completely effective."

- _____ Completely ineffective
- _____ Somewhat ineffective
- _____ Somewhat effective
- _____ Completely effective
- _____ No opinion

Inform the participant: "The auditory icon will be presented two more times, and you are to determine whether or not the effectiveness of the auditory icon as a low fuel warning could be improved by increasing or decreasing the volume of the sound or by selecting a different sound."

Play the auditory icon twice.

- _____ Increase volume
- _____ Decrease volume
- _____ Keep volume the same
- _____ No opinion

- _____ Same sound
- _____ Different sound: _____

Problem with current sound:

- _____ Too long
- _____ Too short to identify
- _____ Poor quality
- _____ Other: _____

TABLE G-1

Participants' Perceived Meanings of Low Fuel Warning Auditory Icon

Subject	Response
12	**No Answer
13	**No Answer
14	Wet road
15	Overheating engine
16	**No Answer
18	Engine problem (grinding sound)
20	**No Answer
21	Coolant problem (water gurgling)
23	Something wrong with the gears
25	Liquid leak
28	Fluid level warning
30	Somebody drinking a beverage
33	Radiator boiling over or overflowing
34	Low coolant in radiator
35	Low on water
36	Out of water
37	Hot - overheating
39	Low on fuel
40	**No Answer

TABLE G-2

Effectiveness Ratings of Low Fuel Warning Auditory Icon

Response	Number	Percent
Completely ineffective	4	21%
Somewhat ineffective	4	21%
Somewhat effective	6	32%
Completely effective	5	26%
No opinion	0	0%

TABLE G-3

Auditory Icon Low Fuel Warning Improvement

Response	Number	Percent
Increase volume	1	5%
Decrease volume	0	0%
Keep volume the same	18	95%
Same sound	7	37%
Different sound	12	63%

TABLE G-4

Problems with Auditory Icon Low Fuel Warning

Response	Number	Percent
Too long	0	0%
Too short to identify	1	8%
Poor quality	0	0%
Sound doesn't fit message	7	54%
Sound fits other fluid better	3	23%
Other reason	2	15%

Subject: _____

Date / Time: _____

Soft Braking familiarization

Describe the concept of soft braking. Inform the participant that he will be asked to say what he thinks the soft braking stimulus would mean if he felt it while driving. Present the stimulus twice.

Ask the participant: "Remember that the deceleration is intentionally caused by equipment within the truck itself. It is designed to convey specific information to the driver. What would you think the intended meaning of the this stimulus would be if you felt it while driving?"

Inform the participant: "I will present the soft braking stimulus you just felt another time. Please rate the effectiveness of this stimulus as an emergency braking warning as completely ineffective, somewhat ineffective, somewhat effective, or completely effective."

- ☐ Completely ineffective
- ☐ Somewhat ineffective
- ☐ Somewhat effective
- ☐ Completely effective
- ☐ No opinion

Inform the participant: "The soft braking stimulus will be presented two more times, and you are to determine whether or not its effectiveness as an emergency braking warning could be improved by increasing or decreasing either the amount or length of the deceleration."

Present the soft braking stimulus twice.

- ☐ Increase magnitude of stimulus
- ☐ Decrease magnitude of stimulus
- ☐ Increase length of stimulus
- ☐ Decrease length of stimulus
- ☐ Keep stimulus the same
- ☐ No opinion

TABLE G-5

Participants' Perceived Meanings of Soft Braking Stimulus

Subject	Response
12	Low air pressure
13	Brakes are grabbing
14	I need to stop
15	Stop the truck
16	Something's wrong with the brakes
18	You have a problem with the brakes
20	Something's dragging, like the brake; may be a motor problem
21	Air problem and the brakes are locking up
23	I got a brake problem; brakes are sticking, something under my wheels
25	Brakes are being applied
28	Some sort of problem with road ahead - accident, road conditions
30	You have a brake problem, like the trailer brakes just locked up
33	Trailer brakes are locking up - air brake
34	Brakes - low air
35	I've got a brake sticking or dragging, possibly trailer brake
36	There's something wrong with the brakes
37	Air pressure is down
39	Stopped traffic ahead
40	Panic stop - something major is wrong with the engine

TABLE G-6

Effectiveness Ratings of Soft Braking Stimulus as an Emergency Braking Warning

Response	Number	Percent
Completely ineffective	0	0%
Somewhat ineffective	2	11%
Somewhat effective	4	21%
Completely effective	13	68%
No opinion	0	0%

TABLE G-7

Soft Braking Stimulus Emergency Braking Warning Improvement

Response	Number	Percent
Increase magnitude	0	0%
Decrease magnitude	7	37%
Increase length	2	11%
Decrease length	4	21%
Keep stimulus the same	8	42%
Concept is a bad one	1	5%
No opinion	0	0%

Note: Participants were permitted to select more than one response

APPENDIX H.
PARTICIPANTS' PERCEIVED MEANINGS OF AUDITORY ICONS

TABLE H-1

Participants' Perceived Meanings of Auditory Icon #1 - Automatic Toll Payment Completed

Subject	Response
1	**No Answer
2	Toll Booth
3	**No Answer (dropping metal)
4	Toll booth ahead
5	Something's broken
6	**No Answer (change falling)
7	**No Answer (money)
8	You dropped something inside the truck
9	Something has fallen off of the truck; a part is loose
10	Tools falling off the truck
11	Stop for toll booth
12	Slow down for toll booth
13	**No Answer
14	Pay a toll
15	Toll booth ahead
16	**No Answer (something fell from a shelf)
17	I want a Coke (change falling)
18	Engine knock
19	Something's wrong with the truck; it's broken
20	Something's fallen off the truck
21	**No Answer
22	Load is loose
23	Toll booth ahead
24	Secure whatever is loose in the cab
25	Exact change toll booth ahead
26	Toll booth ahead
27	Something fell in the truck
28	**No Answer
29	Refreshments ahead, roadside rest area (drink machine)
30	You just ran over someone's car with the trailer
31	**No Answer
32	Something falling inside the truck
33	Something's falling from underneath your truck
34	**No Answer
35	Something on the truck is breaking or about to break
36	Toll booth ahead
37	Something falling off the truck
38	**No Answer
39	Toll booth ahead
40	Railroad crossing ahead of you
41	Something may be loose

TABLE H-2

Participants' Perceived Meanings of Auditory Icon #2 - Children Ahead

Subject	Response
1	**No Answer (laughing)
2	Children playing ahead
3	Residential area / kids at play
4	Kids playing in the street
5	Kids are playing - slow down
6	Kids playing / play area
7	Children playing
8	Kids playing
9	Children crossing road / school zone
10	Kids on the side of the road playing
11	Children / playground / school
12	Coming into a school zone
13	Children playing
14	Children / school
15	Children playing ahead
16	Children playing, slow down
17	Kids goofing off
18	Somebody's playing by the side of the road
19	Children playing
20	Kids near truck
21	Pedestrians
22	Kids playing
23	Kids playing / residential area
24	Be careful; residential neighborhood, children
25	Child close by
26	Children - avoid them
27	Kids playing
28	Children at play / school zone
29	Children ahead
30	People talking outside the vehicle
31	Radio playing
32	CB radio on
33	Children on the side of the road
34	Children playing with CB radio
35	Children playing
36	**No Answer
37	Vehicle sliding
38	**No Answer
39	Children playing - danger
40	**No Answer (kid laughing)
41	Kids playing

TABLE H-3

Participants' Perceived Meanings of Auditory Icon #3 - Emergency Braking Warning

Subject	Response
1	Need to brake
2	You need to brake
3	Back off / slick road
4	Stop - hit the brakes
5	Stop
6	Accident ahead; be alert to out-of-control vehicle
7	Apply brakes
8	Car skidding nearby
9	Car in front is stopping - watch for it
10	About to be an accident ahead
11	Somebody's about to hit you
12	A car is sliding out of control near you
13	Dead battery
14	Somebody's skidding; look out
15	**No answer (car skidding)
16	Watch, look ahead of you (someone's stopping)
17	**No answer
18	Somebody's slamming on the brakes near you
19	Skidding (somebody else); find out where they are
20	Car squealing on the brakes; watch for it, avoid collision
21	**No Answer
22	Accident ahead of you, somebody coming up behind you
23	Slick roads ahead
24	**No Answer
25	Someone close by is skidding
26	Somebody's skidding, avoid them
27	Somebody nearby hit the brakes; watch for them
28	Be prepared to stop
29	Crash ahead, about to happen
30	Somebody nearby applying their brakes
31	Your wheels are sliding
32	**No Answer
33	Car stopping quickly in front of you
34	**No Answer
35	Car skidding somewhere around you
36	Accident ahead, about to happen
37	Somebody's sliding out of control
38	Somebody's skidding near you
39	Trailer brakes are locked
40	Wreck ahead of you, already happened
41	Accident about to happen

TABLE H-4

Participants' Perceived Meanings of Auditory Icon #4 - High Engine Temperature

Subject	Response
1	Air leak
2	Fan belt slipping
3	Overheating
4	Leak in tire
5	Shut the windows or vent
6	Overheating
7	Check air brakes or air gauge
8	Air pressure too low
9	Overheating
10	Window is not shut
11	Busted radiator hose
12	Engine is overheating
13	Window is open
14	Air leak
15	Overheating
16	**No answer (teapot)
17	**No answer (teapot)
18	Warning that your brakes are really low
19	There's a malfunction; brakes, possibly
20	Electronic interference
21	Overheated engine
22	Radiator overheating
23	Truck is overheating
24	**No Answer
25	Air leak
26	Motor overheating
27	Radiator boiling over
28	**No Answer
29	**No Answer
30	Bearing noise; metal rubbing against metal on the truck
31	Siren
32	Overheating (metal rubbing)
33	Radiator problem
34	Loose fan belts
35	Blown radiator hose
36	Air leak, in line or tire
37	Alarm going off, like for brakes
38	Radiator boiling
39	Heavy braking by somebody ahead
40	Brake locked up on trailer
41	Metal scraping; dragging on the ground

TABLE H-5

Participants' Perceived Meanings of Auditory Icon #5 - Railroad Crossing Ahead

Subject	Response
1	Railroad crossing ahead
2	Railroad tracks ahead
3	Railroad crossing
4	Train coming
5	Railroad crossing
6	Stop - Railroad crossing ahead
7	Railroad crossing / train
8	At a railroad crossing; train is coming
9	Railroad crossing coming up
10	Railroad crossing; train coming
11	Railroad crossing; stop for the train
12	Coming to a railroad crossing
13	Train's coming
14	Train coming / Railroad crossing
15	Railroad crossing
16	Coming up on a railroad crossing
17	Dinnertime
18	Stop for railroad tracks, train going by
19	Railroad crossing
20	Railroad crossing; train is about to come across
21	Railroad crossing
22	Train ahead
23	Railroad crossing
24	Stop - Railroad crossing
25	Railroad crossing; a train's coming
26	Train - stop
27	Railroad crossing
28	Train crossing
29	Railroad crossing ahead
30	Railroad crossing
31	Railroad crossing
32	Train crossing ahead
33	Train
34	Low air warning
35	Train - stop for railroad crossing
36	Railroad crossing ahead
37	Railroad crossing
38	**No Answer (Church bells)
39	Railroad crossing
40	Railroad crossing; get ready to stop, train is coming
41	Railroad crossing

TABLE H-6

Participants' Perceived Meanings of Auditory Icon #6 - Roadside Construction Ahead

Subject	Response
1	You have a flat tire
2	Train ahead
3	Men at work
4	Change tires (sound of air wrench)
5	**No Answer
6	Construction ahead
7	Construction ahead
8	Construction zone (jackhammer)
9	Train
10	Railroad crossing
11	Road construction (jackhammer)
12	Coming into a construction area
13	Construction ahead (jackhammer)
14	Construction (jackhammer)
15	Construction zone
16	Approaching a construction area; slow down
17	There's construction ahead (jackhammer)
18	Muffler leak or engine problem
19	Road construction; you need to slow down
20	Working on highway (jackhammer)
21	Construction
22	Construction zone
23	Construction ahead
24	Slow down, prepare to stop; road construction
25	Jackhammer on the side of the highway
26	Construction - slow down (jackhammer)
27	Construction ahead or close by
28	Train ahead
29	Construction up ahead
30	**No Answer
31	Train coming
32	**No Answer
33	Something dragging
34	Engine going bad; rod going bad or low oil pressure
35	Entering construction zone
36	Something mechanical is tearing up
37	Something's dragging off the back of the truck
38	Road construction
39	Road construction
40	Put your jake brake on; steep hill ahead
41	Construction

TABLE H-7

Participants' Perceived Meanings of Auditory Icon #7 - Emergency Vehicle Approaching

Subject	Response
1	Pull over / Slow down
2	Pull over
3	Pull over (cop)
4	Move over; police or ambulance nearby
5	Police - pull over
6	Ambulance - need to get out of the way / slow down
7	Emergency vehicle - danger
8	Rescue Squad coming
9	Ambulance / police coming up close to you
10	Rescue squad or police
11	You're going too fast
12	State troopers
13	I'm in trouble! Police, emergency vehicle coming
14	Emergency vehicle
15	Ambulance coming up behind you
16	Police - look to see if they are pulling you over or trying to get around you
17	I was speeding
18	Ambulance nearby / Cop pulling you over or trying to pass
19	Fire department, police - pull over, get out of the way
20	Ambulance or police car need you to get out of the way
21	Emergency vehicle
22	Police pulling you over / ambulance waiting to come by
23	Emergency vehicle nearby
24	Pull over to the right as far as possible
25	Emergency vehicle
26	Cops behind you - pull over
27	Police / Rescue / Fire truck nearby
28	Emergency vehicle somewhere in area
29	Police or emergency vehicle
30	Some sort of emergency vehicle, police or fire truck
31	Emergency siren
32	Emergency vehicle
33	Ambulance
34	Pull over & stop - blue light behind you
35	Police department or fire and rescue
36	Police car asking you to pull over - violation
37	Rescue or police
38	I'm in trouble; emergency vehicle around
39	Police
40	Emergency vehicle, coming in from behind you
41	Ambulance coming

TABLE H-8

Participants' Perceived Meanings of Auditory Icon #8 - Incoming Voice Message

Subject	Response
1	Low air
2	Answer the phone
3	Check your messages (on-board computer)
4	Answer the phone
5	Answer the telephone / on-board computer
6	Answer the telephone
7	You have a telephone call
8	Answer the phone
9	Dispatcher wants you to call him
10	Cellular telephone is ringing
11	Pick up the phone
12	Telephone is ringing
13	Somebody's phone is ringing
14	Telephone / Cellular phone
15	Answer the phone
16	Cell phone - answer it
17	Someone wants to talk to me on the phone
18	Telephone / Somebody is trying to contact you by computer
19	Answer the phone
20	Somebody's trying to call you
21	Cell phone call
22	Cell telephone
23	Telephone
24	Answer the phone
25	Cell phone's ringing
26	Cell telephone - answer the phone
27	Telephone ringing
28	Phone is ringing
29	Telephone ringing
30	Cellular phone
31	Telephone ringing
32	Someone's calling
33	Phone - somebody with your computer is trying to get a hold of you
34	Low coolant or air
35	Telephone (cellular)
36	Phone - dispatcher trying to contact you
37	Somebody's calling
38	Somebody's paging you or calling you
39	Cell phone ringing
40	Emergency vehicle, coming through an intersection at you
41	Telephone ringing

TABLE H-9

Participants' Perceived Meanings of Auditory Icon #9 - Roadside Mowing Ahead

Subject	Response
1	**No answer (Air wrench)
2	Need engine repair (Impact wrench)
3	Men at work
4	**No answer (Jake brake)
5	Construction
6	Construction area (lawnmower)
7	Construction
8	Construction zone
9	Coming into construction area
10	Road construction
11	Lawnmowers ahead
12	Coming into a construction area
13	Jake Brake is on
14	Construction
15	Construction zone ahead
16	Truck is slowing itself down (Jake Brake)
17	Somebody's mowing the grass
18	Exhaust leak
19	Engine brake is on
20	Construction work
21	Construction zone
22	Close to airport (airplane)
23	Mowing ahead
24	Road construction
25	Jackhammer work on the side of the road
26	Construction - slow down (jackhammer)
27	Lawnmower nearby
28	Train ahead
29	Residential area
30	Road work
31	**No Answer
32	Truck is slowing down (Jake Brake)
33	Rain
34	Broken exhaust line, blown muffler
35	Mowing ahead
36	Loose wheel, mechanical problem (air hammer)
37	Something's wrong with the motor
38	Lawnmower nearby
39	Road construction
40	Coming up on road construction
41	Construction ahead

APPENDIX I.
PARTICIPANT RESPONSES TO AFTER-OBSTACLE QUESTIONNAIRE

Subject: _____

Date / Time: _____

Auditory Icon / Brake Response Time post-drive questionnaire

I. For all participants:

At any time did during the obstacle presentation, did you feel as if your safety were endangered?

Y N

If so, do you think that the design of this experiment should be changed?

Y N

If so, what changes would you suggest?

When you first saw the obstacle(s), describe your reaction in as much detail as possible. (When did you decide to react? What did you do to try to avoid a collision?)

When you tried to avoid hitting the barrels, do you feel that you reacted as you would have reacted in an actual on-road situation?

Y N

If not, what would you have done differently? (Reacted earlier or later, Swerved instead of braked or braked instead of swerved)

II. For participants exposed to soft braking warning:

Do you think that the use of soft braking (temporary automatic deceleration) is useful as a warning in an emergency braking situation?

Y N

Do you think that the effectiveness of the soft braking warning could be improved by changing the degree of deceleration? (select the appropriate response)

- ☐ Increase magnitude of deceleration
- ☐ Decrease magnitude of deceleration
- ☐ Increase length of deceleration
- ☐ Decrease length of deceleration
- ☐ No change - it's fine as currently set
- ☐ Changing the rate of deceleration won't help - the concept is a bad one

Do you have any other comments concerning the use of the soft braking warning?

III. For participants exposed to auditory icon warning:

Do you think that the use of an auditory icon (representational sound) is useful as a warning in an emergency braking situation?

Y N

Do you think that the effectiveness of the auditory icon warning could be improved by changing it in some way? (select all applicable responses)

- ☐ No change - it's fine as currently set
- ☐ Increase volume
- ☐ Decrease volume
- ☐ Increase length or duration of sound
- ☐ Decrease length or duration volume
- ☐ Use of a different auditory icon would be better
- ☐ Use of a nonrepresentational sound (beep, tone, chime) would be better
- ☐ Changing it won't help - the concept is a bad one

Do you have any other comments concerning the use of the auditory icon warning?

I. Questions for all participants

Question: At any time did during the obstacle presentation, did you feel as if your safety were endangered?

Response	Number	Percent
Yes	0	0%
No	35	100%

Question: When you first saw the obstacle(s), describe your reaction in as much detail as possible. (When did you decide to react? What did you do to try to avoid a collision?)

Subject Number	Warning Type	Response
1		(No Barrels)
2		(No Barrels)
3		(No Barrels)
4	None	Stop! Right away.
5	None	I thought the wind blew over the barrels; I didn't think I'd have time to stop.
6	None	It did catch me by surprise; I jerked to the left and hit the brakes.
7	None	I thought about stopping but realized they were only plastic barrels. I run over those on a daily basis. I slowed slightly.
8	Failed	I didn't see the barrels. I was looking ahead at the road.
10	None	When I saw them, I was already on them. I think I touched the brakes a little bit.
11	None	"Ooooooh!! A barrel!!" (<i>Intense sarcasm</i>). I run over cones and barrels all day.
13	None	I wanted to slam on the brakes, but was afraid to. I wasn't sure if I was supposed to stop or not.
14	Failed	I felt the truck brake at the same time I saw the barrels. I was looking at the mirrors when the barrels rolled out.
15	Failed	I went to hit the brakes, but the truck brakes kicked in before I got hold of them.
16	Failed	(<i>Barrels came out later than usual</i>) I kept going, I didn't want them under the truck.
17	Auditory	Shock, because I wasn't expecting it. I decided to react when I knew I was going to run over them.
18	Auditory	Either slam on the brakes or turn to the left.
19	Auditory	Confused - I could not figure out what they were doing there. I didn't know what to do, so I didn't stop.
20	Haptic	Hit the brakes and drop the clutch; get out of it as soon as possible.
21	Failed	I saw the barrels as I passed them, then the truck braked itself.
22	None	I had to stop, and hoped nobody was behind me.
23	Haptic	I thought one of the barrels kicked over; wasn't sure what to think. I went to brake, but didn't want to get out of the lane.
24	None	I need to stop and avoid them.
25	None	I need to stop as quickly as possible.
26	Failed	(No Barrels)
27	Auditory	Oh, no - I decided to brake.
28	Haptic	I thought it was part of the course, thought twice, thought I wasn't supposed to run over these and hit the brakes.
29	Auditory	Surprise, and then I realized I needed to stop.
30	Haptic	I said "oops." Go ahead and stop.

31	Auditory	I should have hit the brakes.
32	Auditory	I felt a rush. My first instinct was to turn away from it to the left.
33	Failed	Stop!
34	Haptic	There's something getting in my path and I didn't want to hit it. It could have been a child, a vehicle, or an animal.
35	Haptic	I didn't want to swerve, so I decided to stop as quickly as I could without endangering anybody else.
36	Haptic	Stop!
37	Haptic	It was just like something coming out in the road in front of you. I decided I better stop.
38	Failed	I tried hit them (the brakes) as best I could, but it was a little sudden. I heard the braking device, too. It (the barrels) was very surprising.
39	Failed	Until I identified what it was, my reaction was "stop."
40	Failed	I tried to cut the wheel, but I didn't feel like I cut it quick enough.
41	Failed	I was going through the gears and I didn't want to hit the barrels, but I didn't think it was a part of the course.

Question: When you tried to avoid hitting the barrels, do you feel that you reacted as you would have reacted in an actual on-road situation?

Response	Number	Percent
Yes	24	73%
No	9	27%

Question: If not, what would you have done differently? (Reacted earlier or later, Swerved instead of braked or braked instead of swerved)

Subject Number	Y/N	Comments:
1		(No Barrels)
2		(No Barrels)
3		(No Barrels)
4	Yes	
5	Yes	
6	Yes	(Car or person -) I would have hit the brakes quicker or turned more if the obstacle had been a car or kids.
7	Yes	My reaction was because of the obstacle type.
8		(Didn't see the barrels)
10	No	Probably would have nailed the brakes.
11	Yes	I wouldn't bother not trying to hit barrels.
13	No	I would have probably slammed on the brakes and messed my britches.
14	Yes	
15	No	I would have been looking more to the side and would have braked harder for a different object.
16		
17	No	I would have reacted with a greater sense of urgency. I saw that they were plastic barrels and knew that no one was in danger.
18	Yes	(Car or person -) About the same.
19	Yes	Perhaps I would have mashed the brakes, at this speed.
20	Yes	I just braked; I might have swerved with a different obstacle.

21	No	I don't think I reacted. I would have probably gotten off the accelerator and braked, if there was no automatic truck deceleration, and swerved to the left if it was clear.
22	Yes	I would have reacted the same with other obstacles.
23	No	Even if the obstacle was barrels, I would have hit the brakes quicker and swerved if there was no traffic on the left.
24	No	I thought I was supposed to keep going; I didn't know I was supposed to stop.
25	Yes	I would have reacted quicker if the obstacle were a vehicle or person.
26		(No Barrels)
27	Yes	For a different obstacle, I might have reacted differently - swerved and hit the brakes harder. I wasn't as aware as in a parking lot situation, when you're expecting people to do something stupid.
28	Yes	I would have reacted differently depending on the weather and traffic. I would have reacted the same if it was a car or a person - right away.
29	Yes	(Car or person -) I probably would have swerved more.
30	Yes	(Car or person -) Same reaction.
31	No	I would have reacted more on the road; braked quicker and harder.
32	Yes	(Car or person -) I would have jerked the wheel harder, because slamming brakes does no good.
33	No	Depending on the road conditions, weather, construction, pedestrians ... Having barrels in the road is not an uncommon thing.
34	Yes	(Car or person -) Same reaction.
35	Yes	(Car or person -) I would have stopped a whole lot faster. I probably would have locked it up.
36	Yes	I would have really put you through the windshield if it had been a child. You're taking into consideration you're going 15 mph and can stop without panicking.
37	Yes	I might have applied the brakes quicker. I would have swerved to the left to miss a child.
38	Yes	(Car or person -) Prayed a whole lot more.
39	Yes	(Car or person -) I would have stomped the brakes and stopped.
40	Yes	(Car or person -) Nothing different.
41	Yes	(Car or person -) Reacted the same.

II. Questions for participants exposed to soft braking warning

Question: Do you think that the use of soft braking (temporary automatic deceleration) is useful as a warning in an emergency braking situation?

Response	Number	Percent
Yes	8	62%
No	2	15%
No Opinion	3	23%

Question: Do you think that the effectiveness of the soft braking warning could be improved by changing the degree of deceleration?

Response	All Haptic Warning Recipients		Valid Haptic Warning Recipients	
	Number	Percent	Number	Percent
Increase magnitude of deceleration	2	14%	2	25%
Decrease magnitude of deceleration	0	0%	0	0%
Increase length of deceleration	1	7%	1	13%
Decrease length of deceleration	0	0%	0	0%
No change - it's fine as currently set	5	36%	2	25%
Changing it won't help - the concept is a bad one	1	7%	1	13%
Didn't feel it	5	36%	2	25%

Question: Do you have any other comments concerning the use of the soft braking warning?

Subject Number	Valid Warning?	Comments:
14	N	Depending on the situation in the tractor, you don't want something too abrupt.
15	N	Not just a warning, but also an aid. Wouldn't mind greater deceleration if in the truck by myself. Should also be sure that seat belts are hooked. Should brake the trailer as well, but not front steering tires. Brakes shouldn't lock up on trailer.
16	N	Didn't feel it.
20	Y	Definitely increase the time. It's a good idea.
21	N	(No comments)
23	Y	(No comments)
28	Y	I think that other warnings would be better due to the things that could go wrong with the system.
30	Y	It would have helped more with a more distant situation. With an instant accident, your reflexes control it.
33	N	Too many other factors are involved. You have to maintain control. I think they need to scrap it.
34	Y	(Didn't feel it.) Increase the magnitude in a situation like this. It could be a little stronger & faster acting since it has ABS. I think it's very effective.
35	Y	(No comments)
36	Y	Maybe like a little soft bell or "ping" could go off when it first activates.
37	Y	(No comments)
39	N	(No comments)
40	N	I could have cut the wheel for the turn to the left if the truck hadn't braked.

III. Questions for participants exposed to auditory icon warning

Question: Do you think that the use of an auditory icon (representational sound) is useful as a warning in an emergency braking situation?

Response	Number	Percent
Yes	7	88%
No	1	13%
No Opinion	0	0%

Question: Do you think that the effectiveness of the auditory icon warning could be improved by changing it in some way?

Response	All Auditory Warning Recipients		Valid Auditory Warning Recipients	
	Number	Percent	Number	Percent
Increase volume	3	33%	3	43%
Decrease volume	0	0%	0	0%
Increase length or duration of sound	0	0%	0	0%
Decrease length or duration of sound	0	0%	0	0%
Use of a different auditory icon would be better	0	0%	0	0%
Use of a nonrepresentational sound would be better	1	11%	1	14%
No change - it's fine as currently set	5	56%	3	43%
Changing it won't help - the concept is a bad one	0	0%	0	0%

Question: Do you have any other comments concerning the use of the auditory icon warning?

Subject Number	Valid Warning?	Comments:
17	Y	I don't think I would have noticed it in real life. Use of a bell would be better.
18	Y	I didn't really hear it too good. I couldn't really tell what it was.
19	Y	I didn't notice it. It's better than strobe lights or other visual warnings.
27	Y	The warning may be a distraction, too. The sound caused me to look up when I heard it to see what it was.
29	Y	I didn't hear it until I was into my emergency braking. It seems like a pretty good idea, all in all.
31	Y	(No comments)
32	Y	You'd have to get used to the sound, or it wouldn't mean much to you. You need a short, quick burst of sound like it is.
38	N	If you put it any louder, it'd scare the hell out of the driver.
41	N	It makes you put the panic button on. It made it seem more serious than it really was. It'd be more appropriate if it (the obstacle) were a car.

APPENDIX J.
DRIVER RESPONSES TO UNEXPECTED OBSTACLE

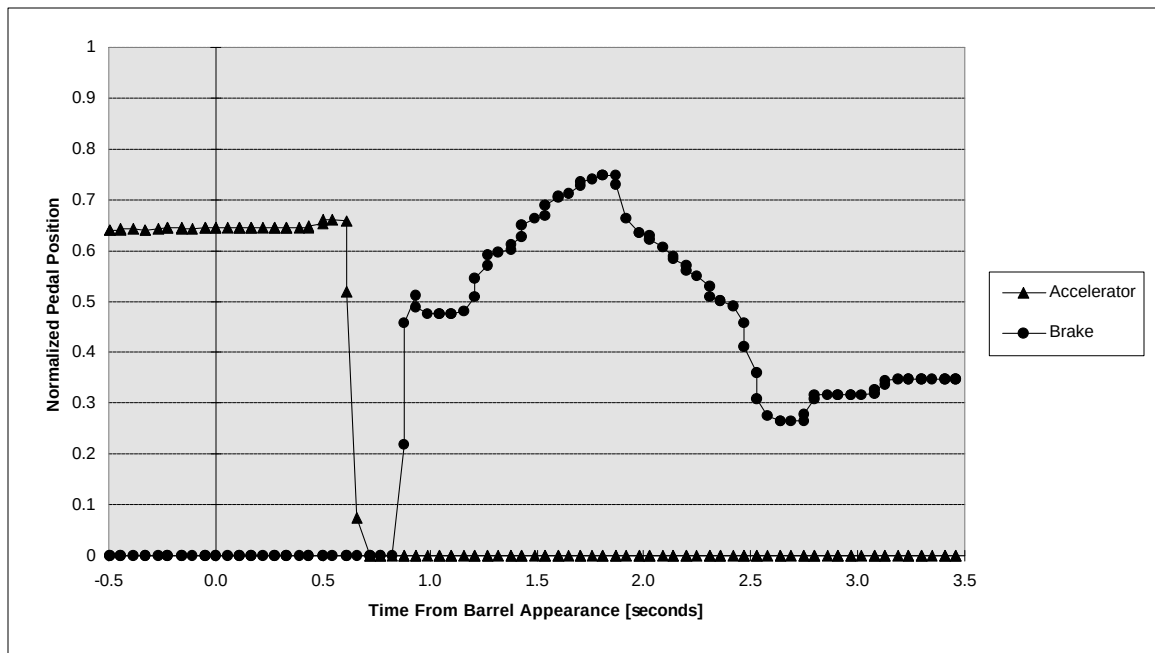


Figure J-1. Accelerator and brake pedal reaction: Subject #4, No Warning condition.

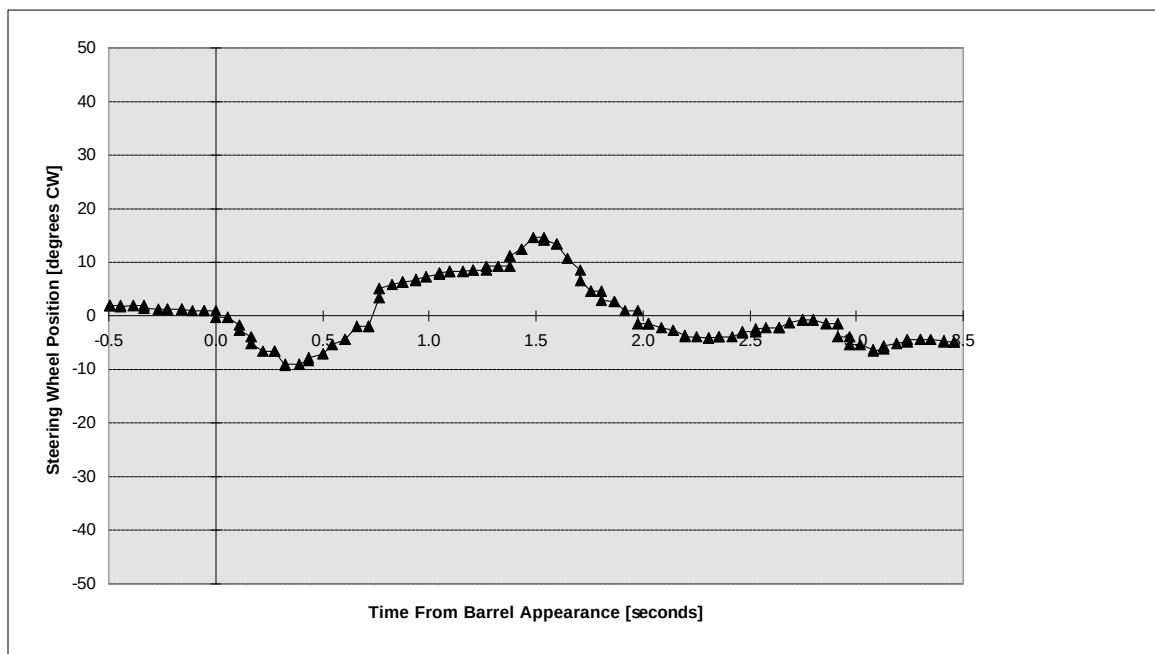


Figure J-2. Steering wheel reaction: Subject #4, No Warning condition.

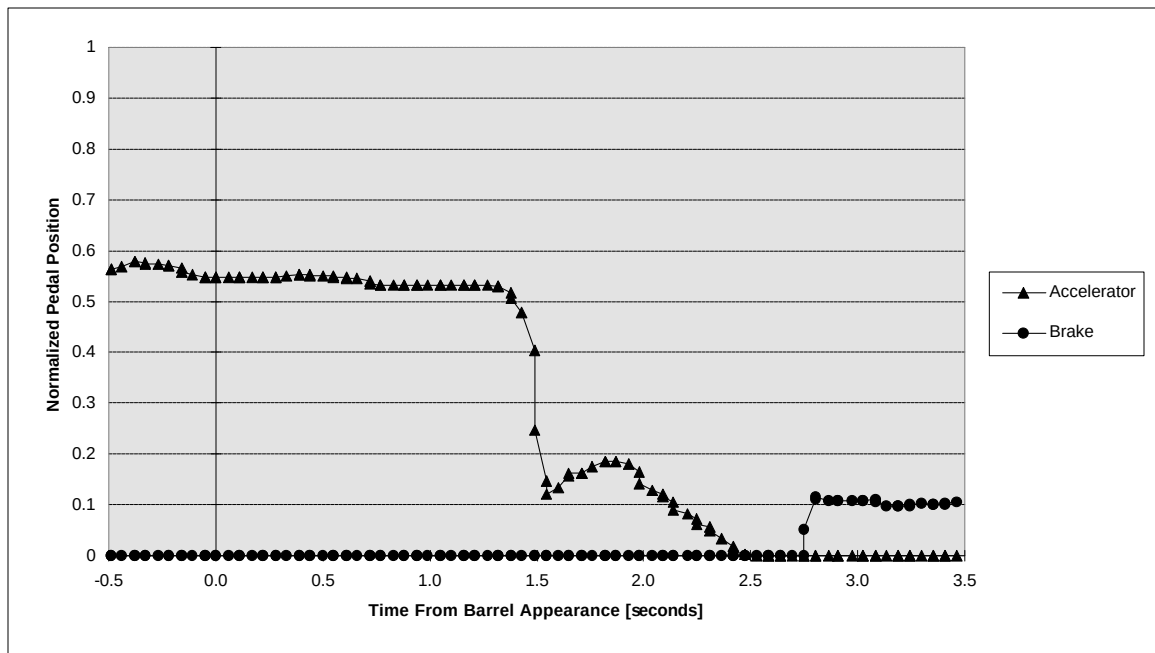


Figure J-3. Accelerator and brake pedal reaction: Subject #5, No Warning condition.

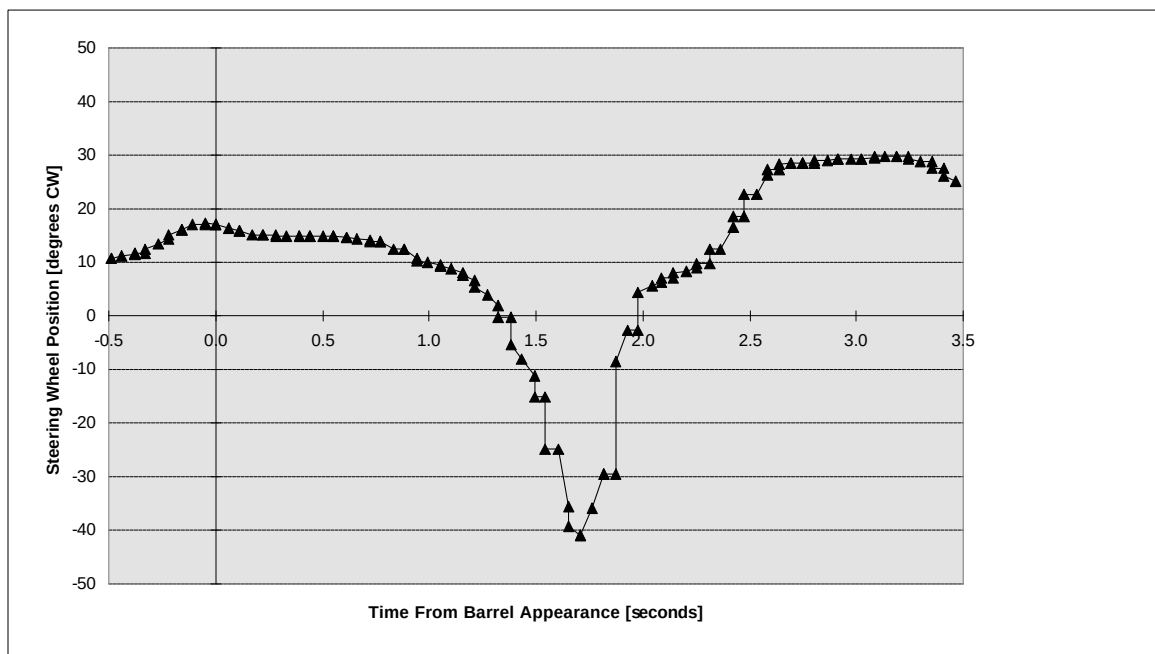


Figure J-4. Steering wheel reaction: Subject #5, No Warning condition.

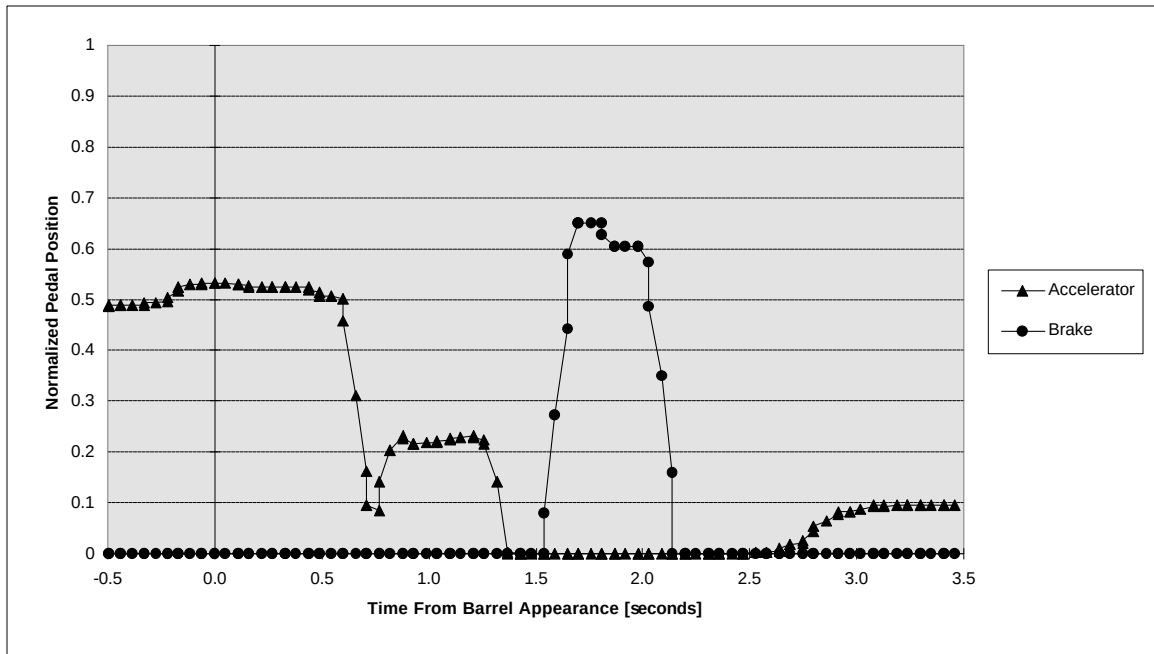


Figure J-5. Accelerator and brake pedal reaction: Subject #6, No Warning condition.

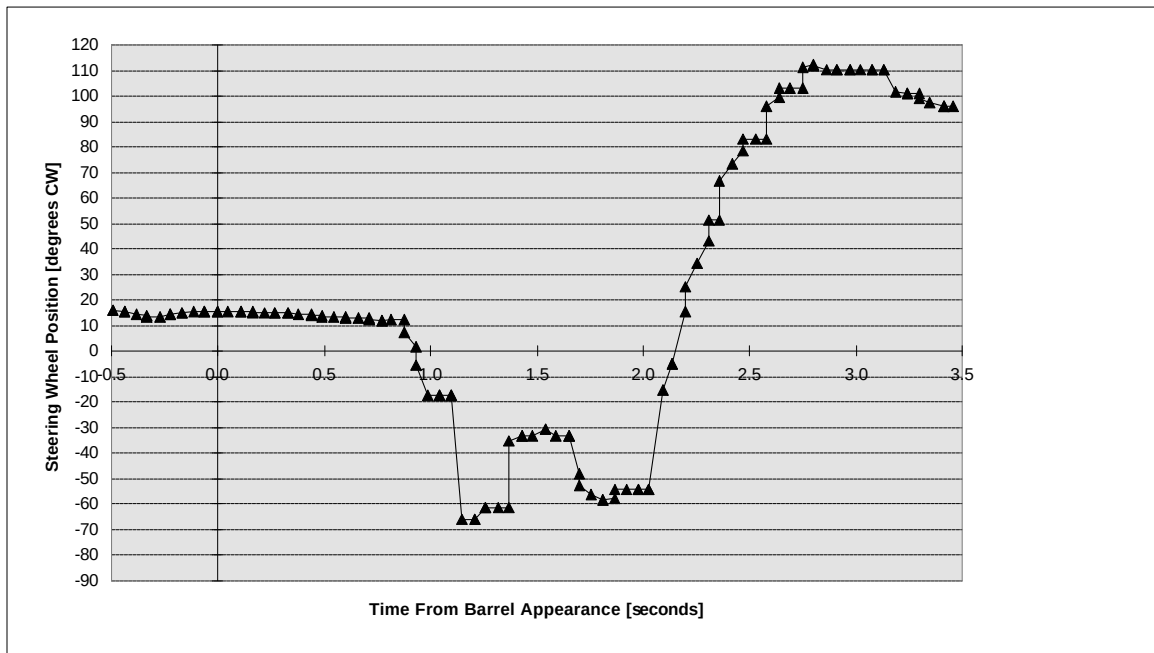


Figure J-6. Steering wheel reaction: Subject #6, No Warning condition.

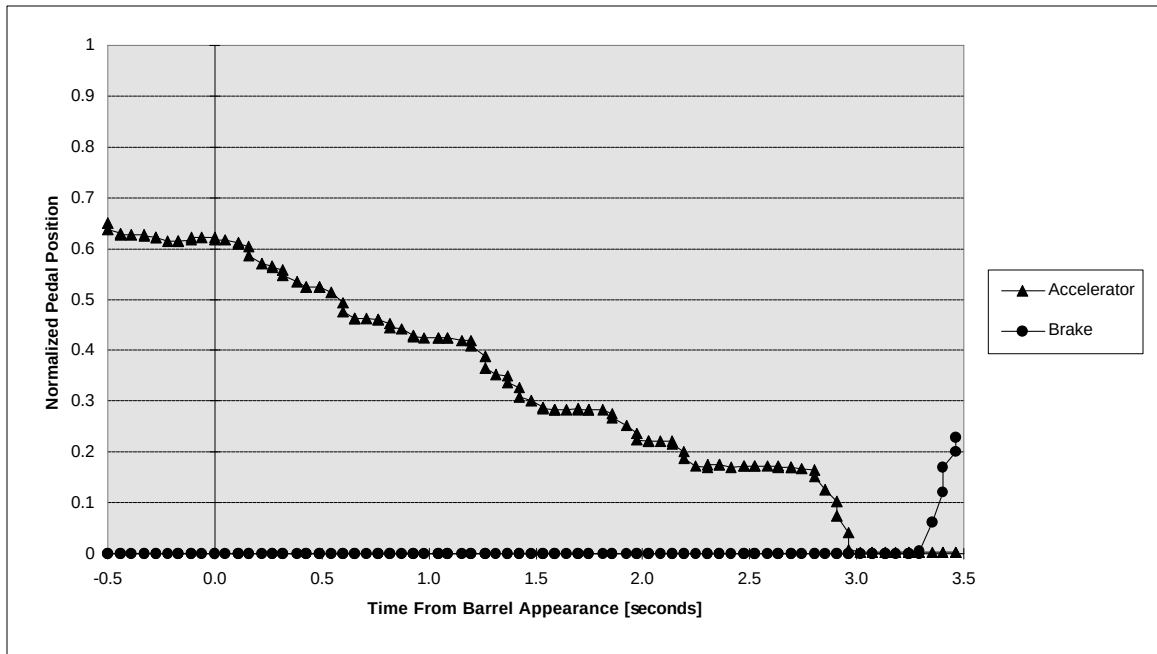


Figure J-7. Accelerator and brake pedal reaction: Subject #7, No Warning condition.

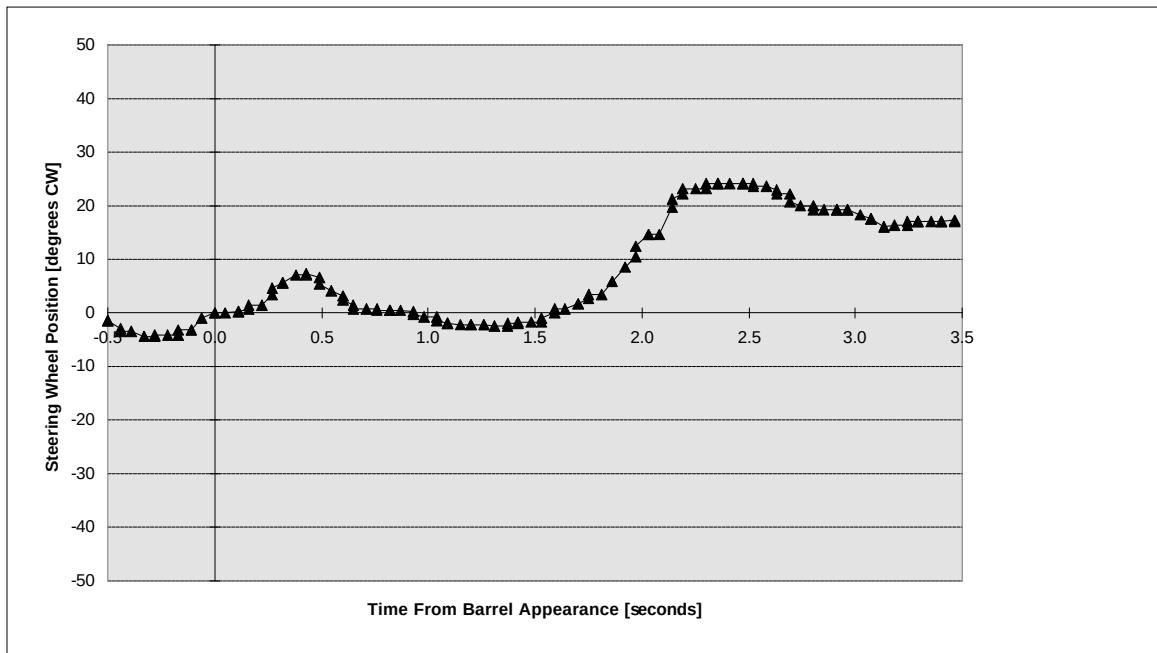


Figure J-8. Steering wheel reaction: Subject #7, No Warning condition.

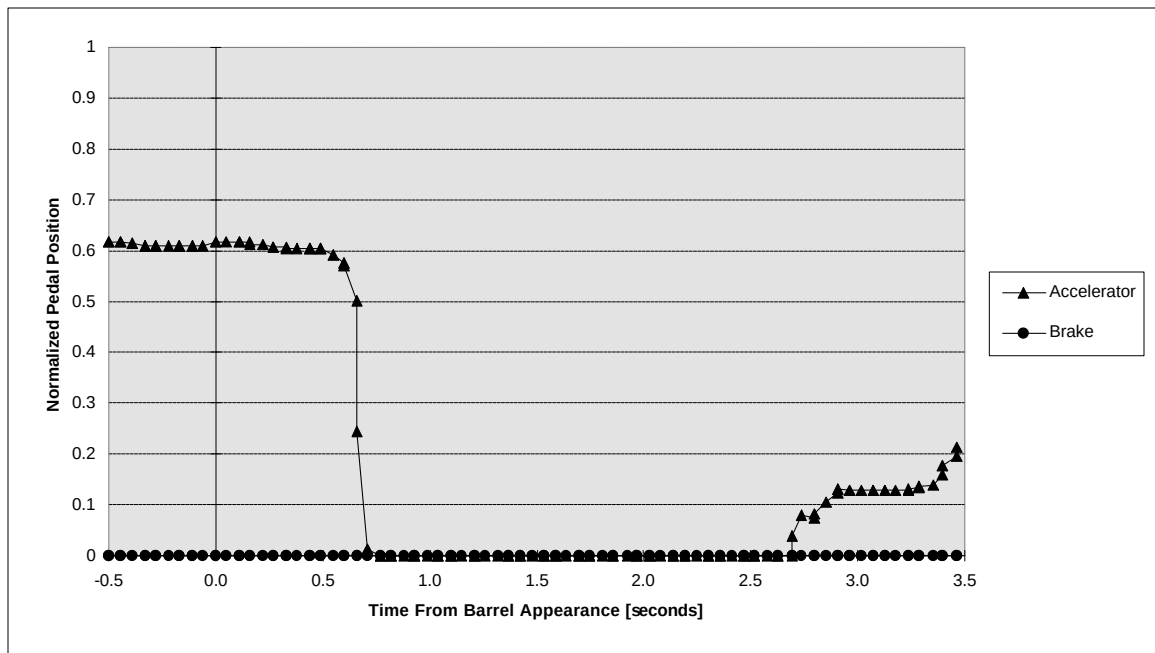


Figure J-9. Accelerator and brake pedal reaction: Subject #10, No Warning condition.

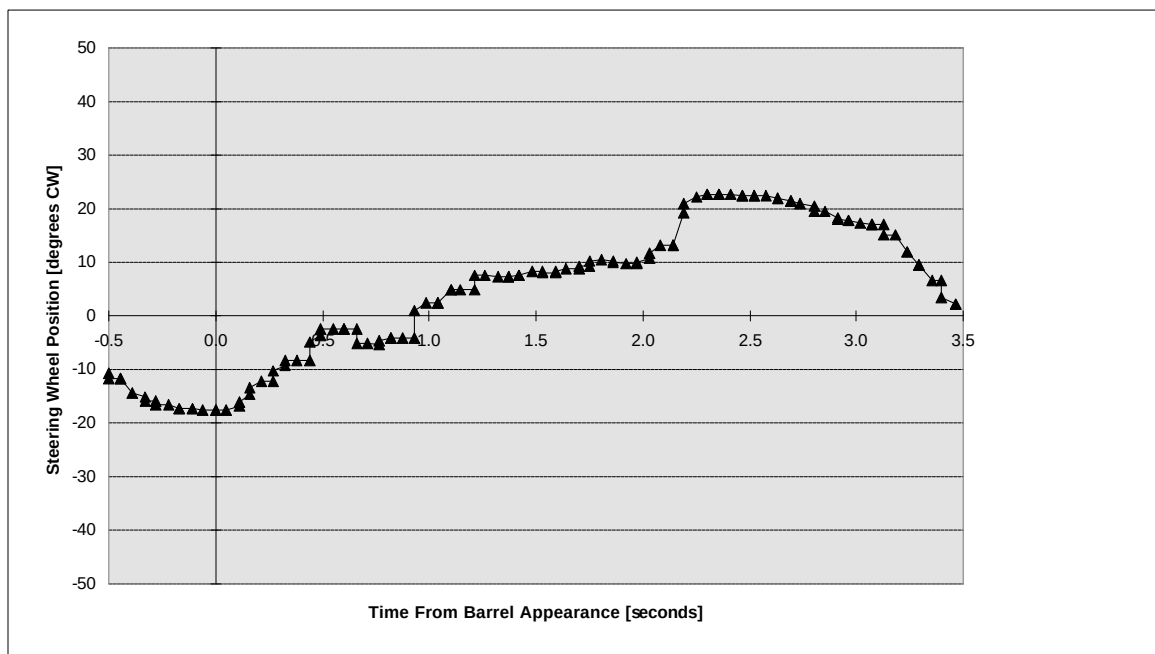


Figure J-10. Steering wheel reaction: Subject #10, No Warning condition.

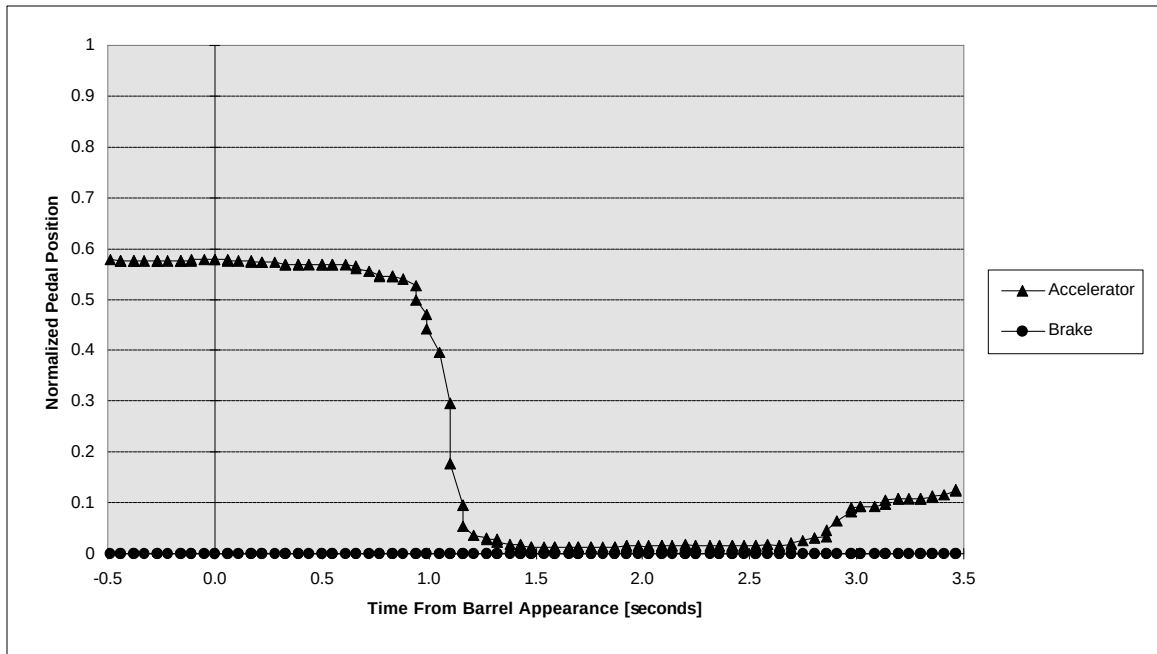


Figure J-11. Accelerator and brake pedal reaction: Subject #11, No Warning condition.

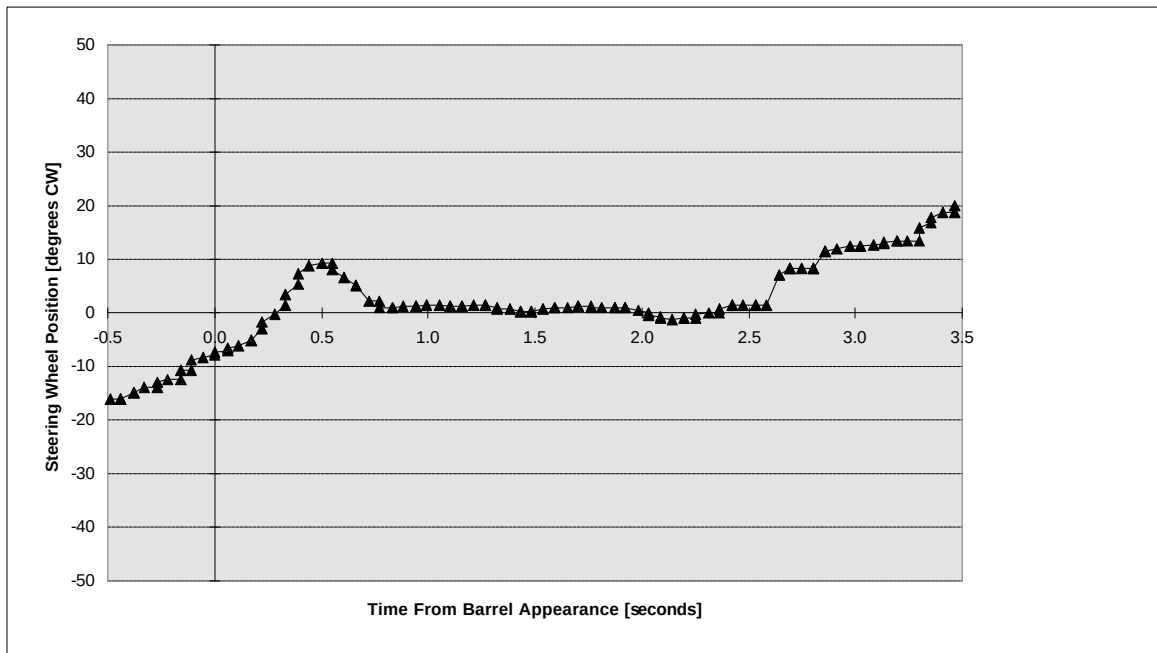


Figure J-12. Steering wheel reaction: Subject #11, No Warning condition.

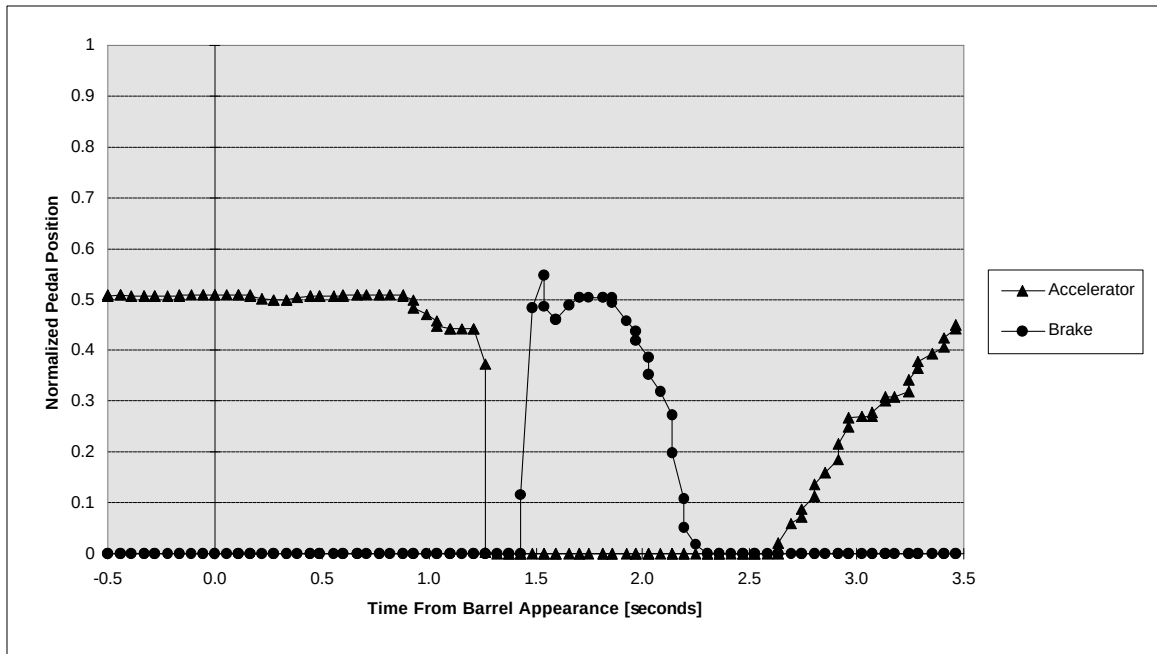


Figure J-13. Accelerator and brake pedal reaction: Subject #13, No Warning condition.

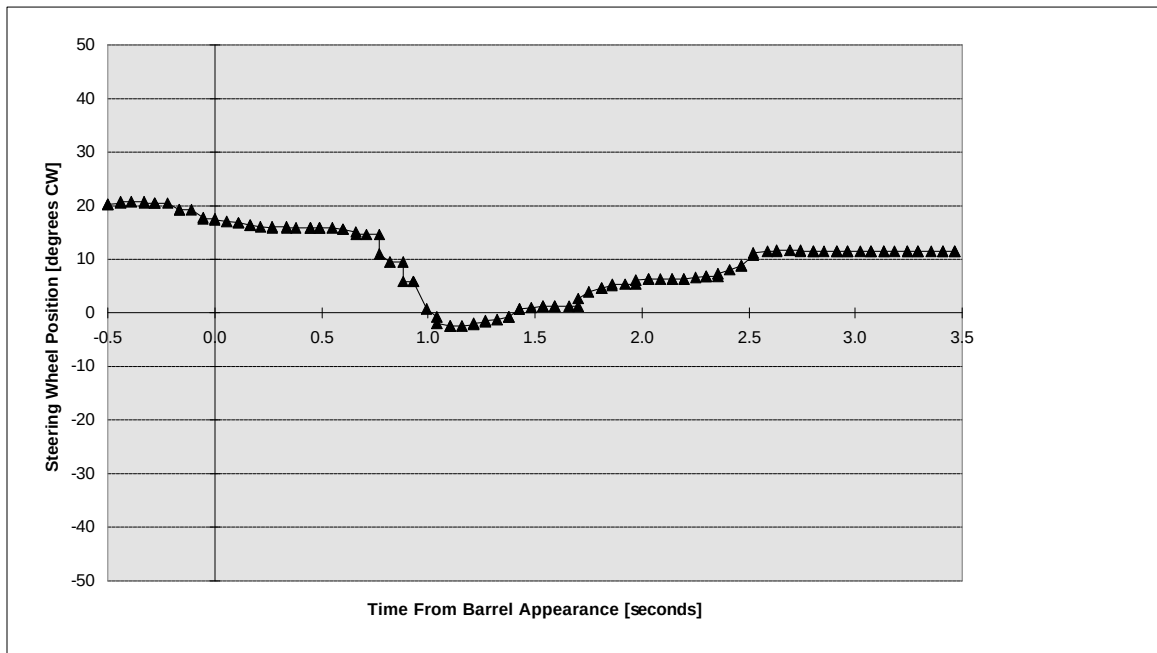


Figure J-14. Steering wheel reaction: Subject #13, No Warning condition.

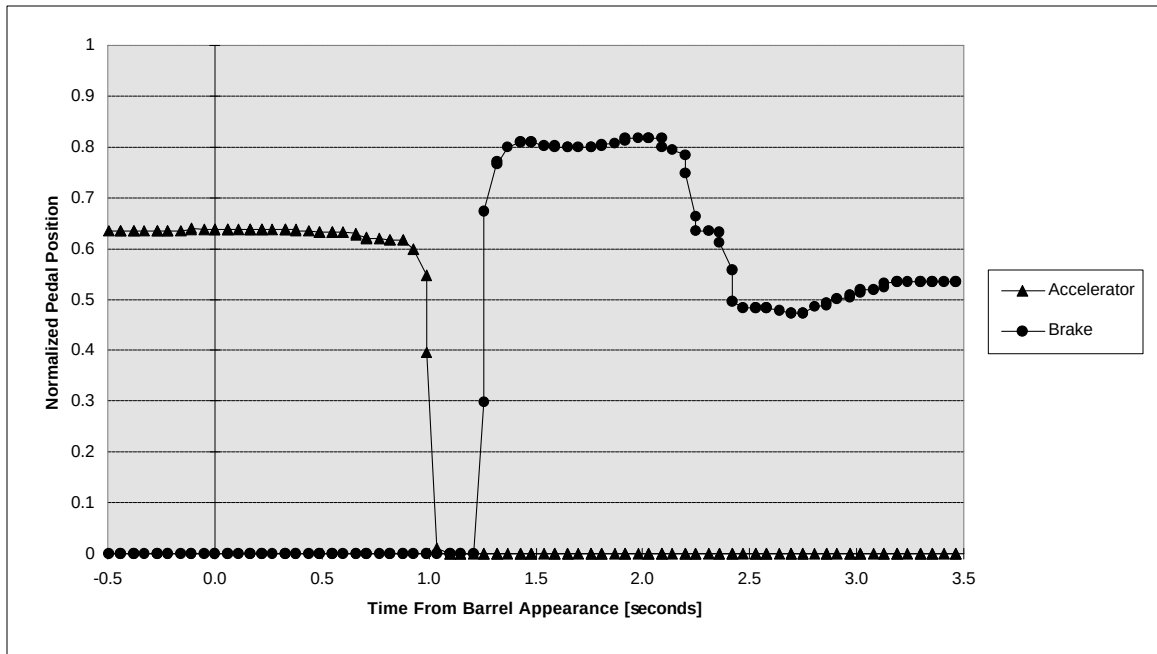


Figure J-15. Accelerator and brake pedal reaction: Subject #22, No Warning condition.

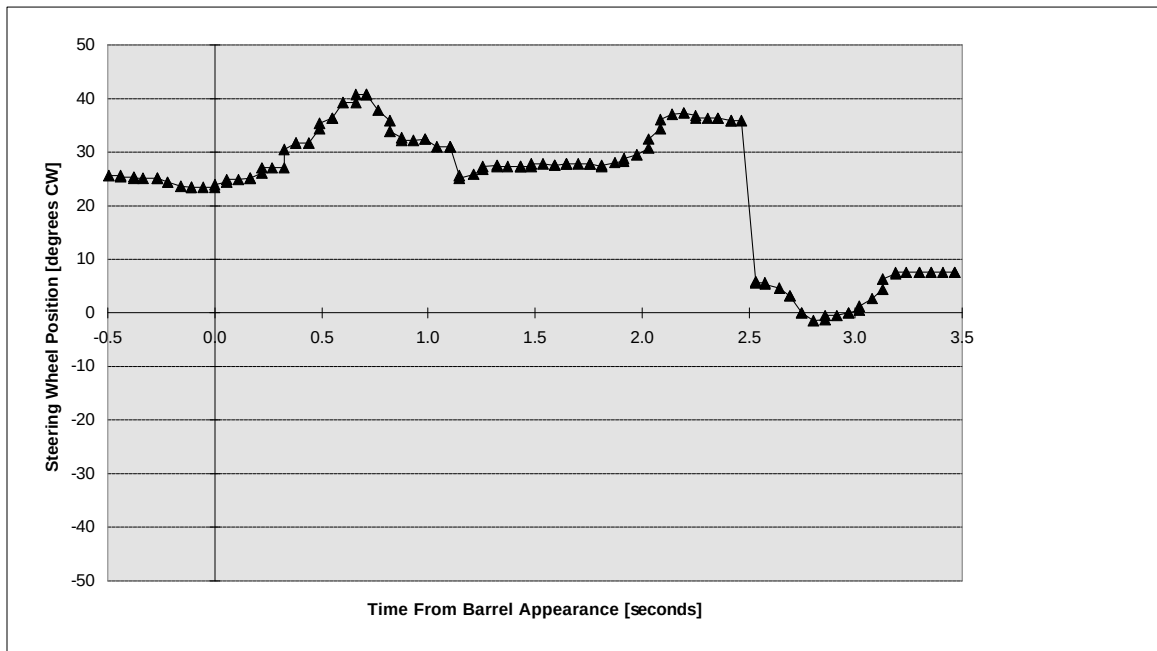


Figure J-16. Steering wheel reaction: Subject #22, No Warning condition.

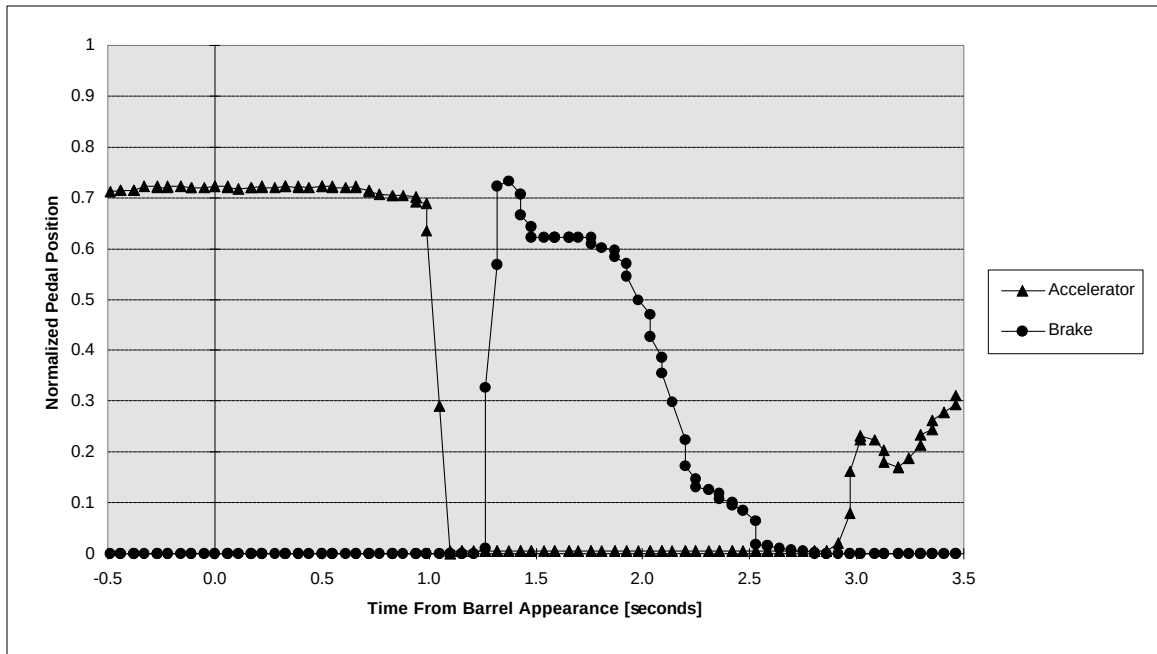


Figure J-17. Accelerator and brake pedal reaction: Subject #24, No Warning condition.

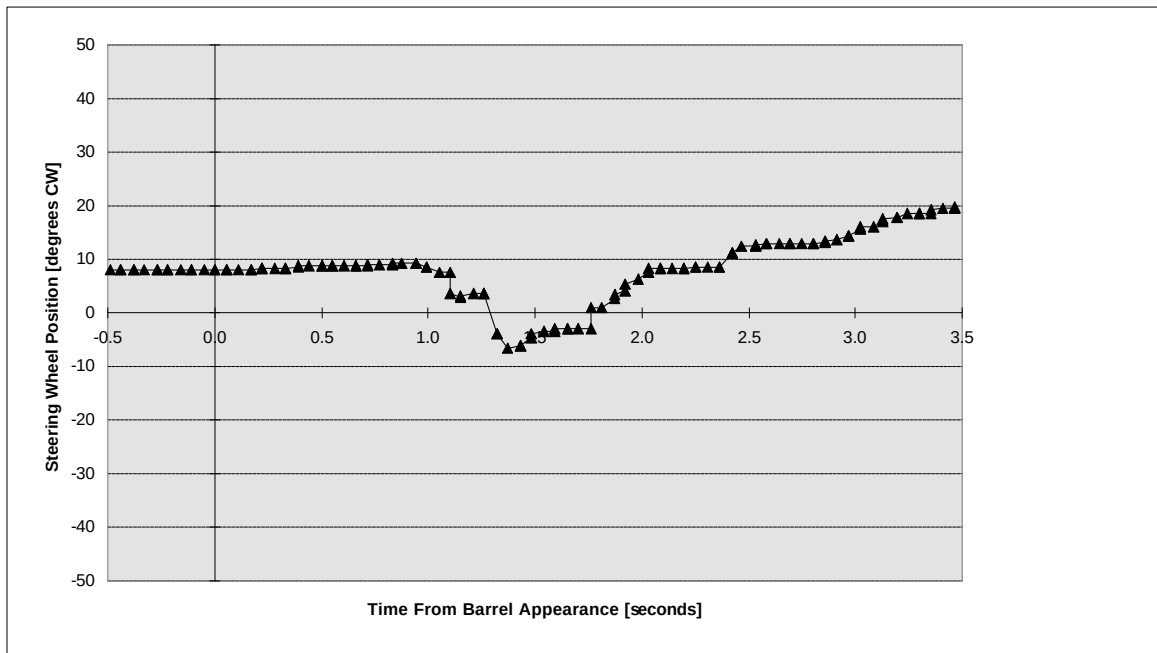


Figure J-18. Steering wheel reaction: Subject #24, No Warning condition.

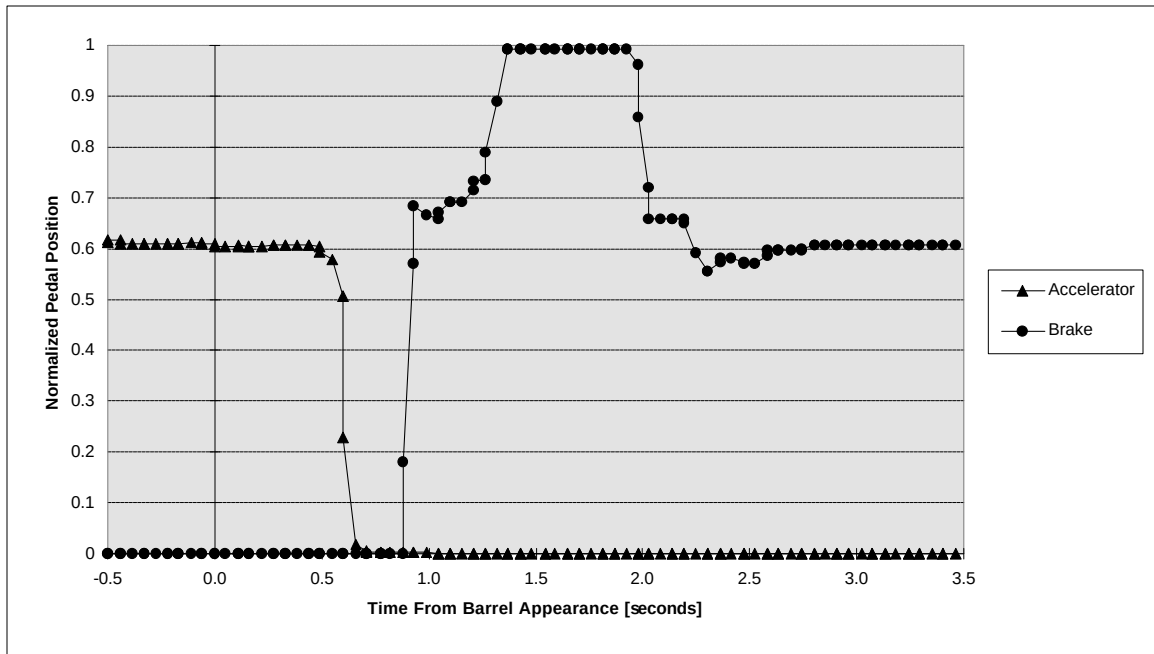


Figure J-19. Accelerator and brake pedal reaction: Subject #25, No Warning condition.

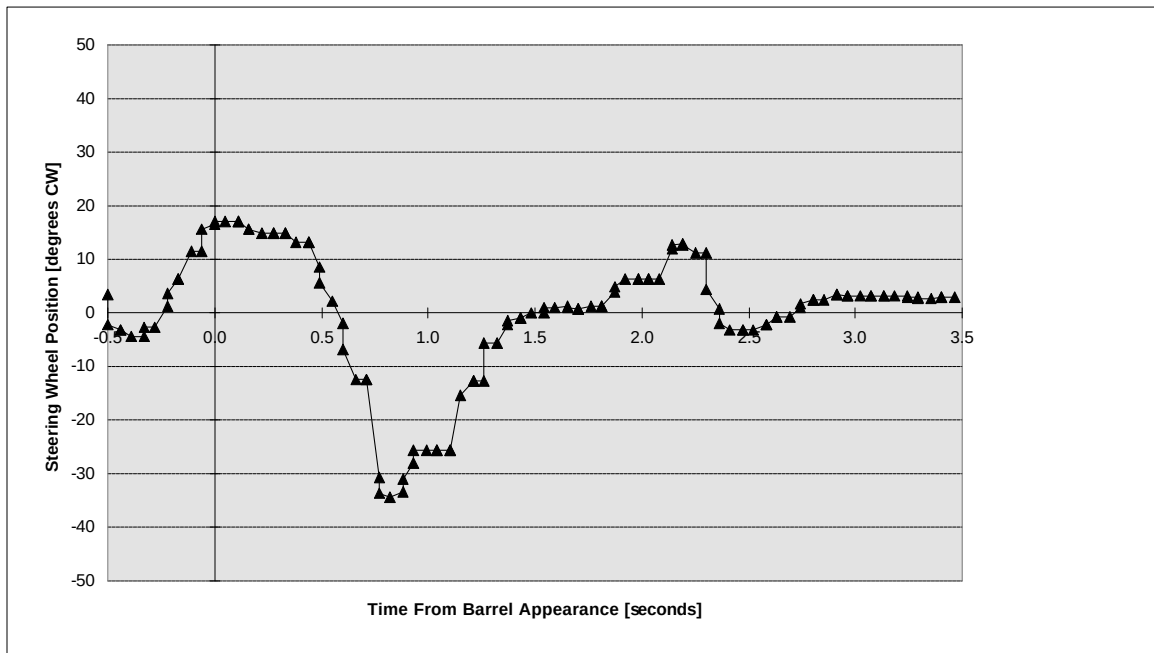


Figure J-20. Steering wheel reaction: Subject #25, No Warning condition.

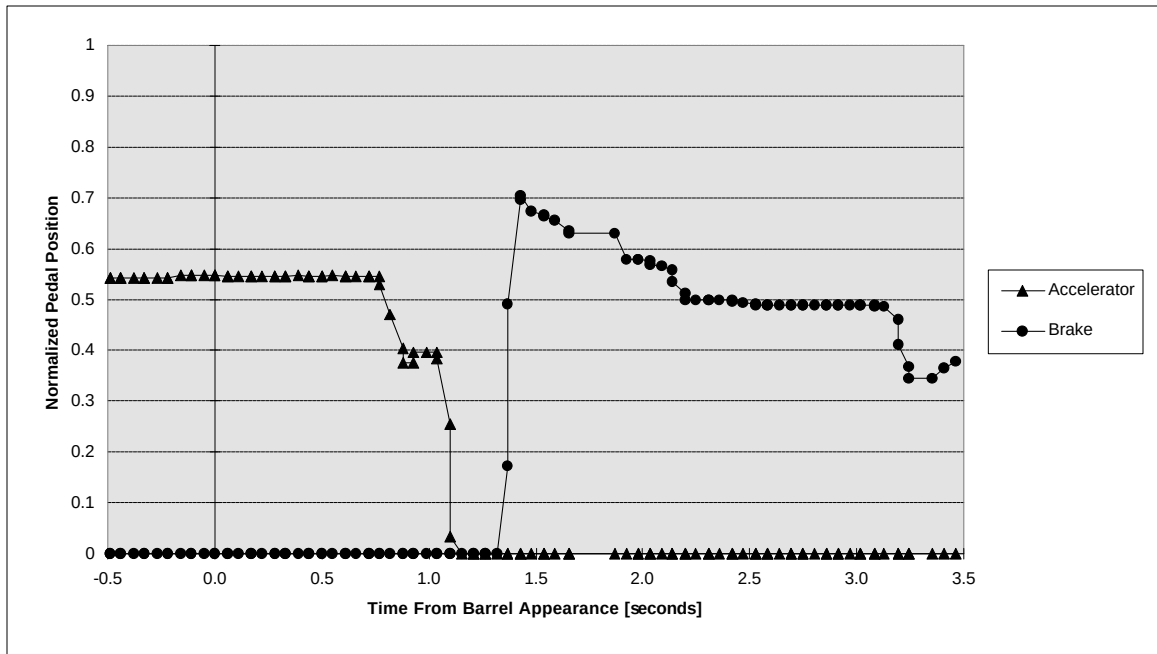


Figure J-21. Accelerator and brake pedal reaction: Subject #17, Auditory Warning condition.

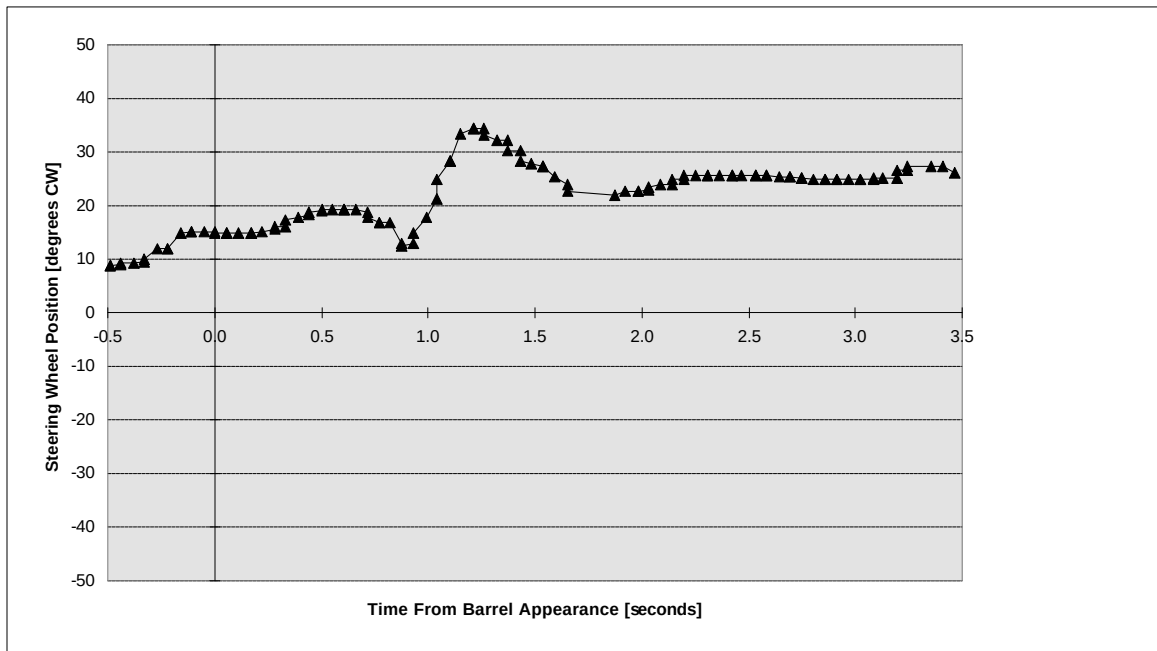


Figure J-22. Steering wheel reaction: Subject #17, Auditory Warning condition.

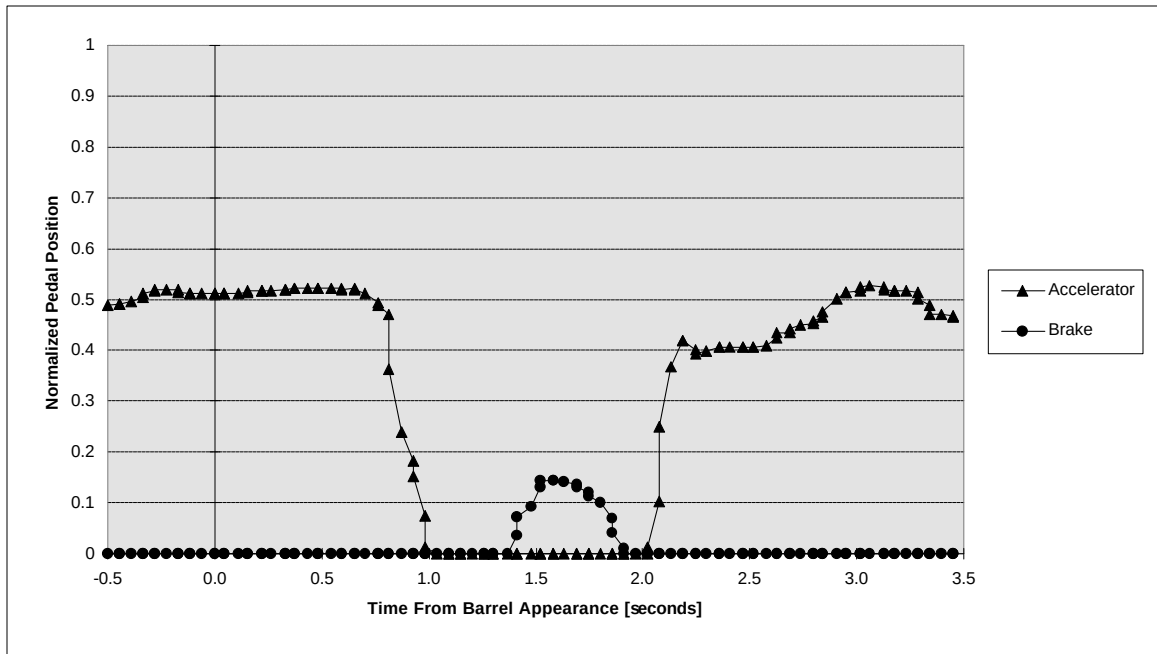


Figure J-23. Accelerator and brake pedal reaction: Subject #18, Auditory Warning condition.

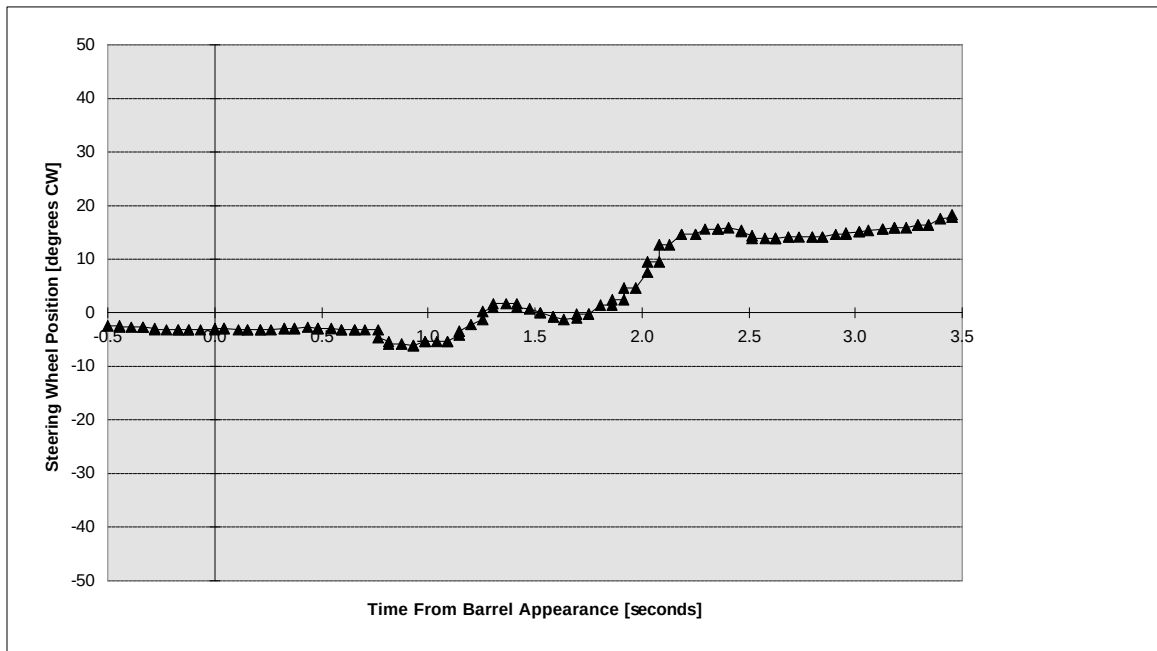


Figure J-24. Steering wheel reaction: Subject #18, Auditory Warning condition.

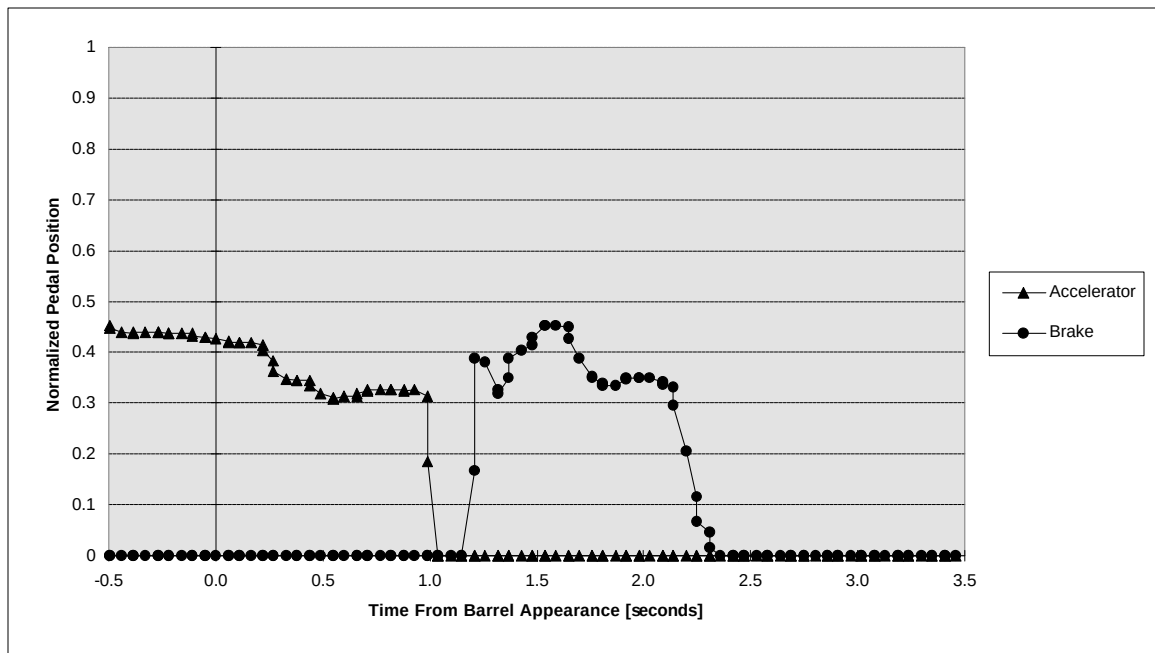


Figure J-25. Accelerator and brake pedal reaction: Subject #19, Auditory Warning condition.

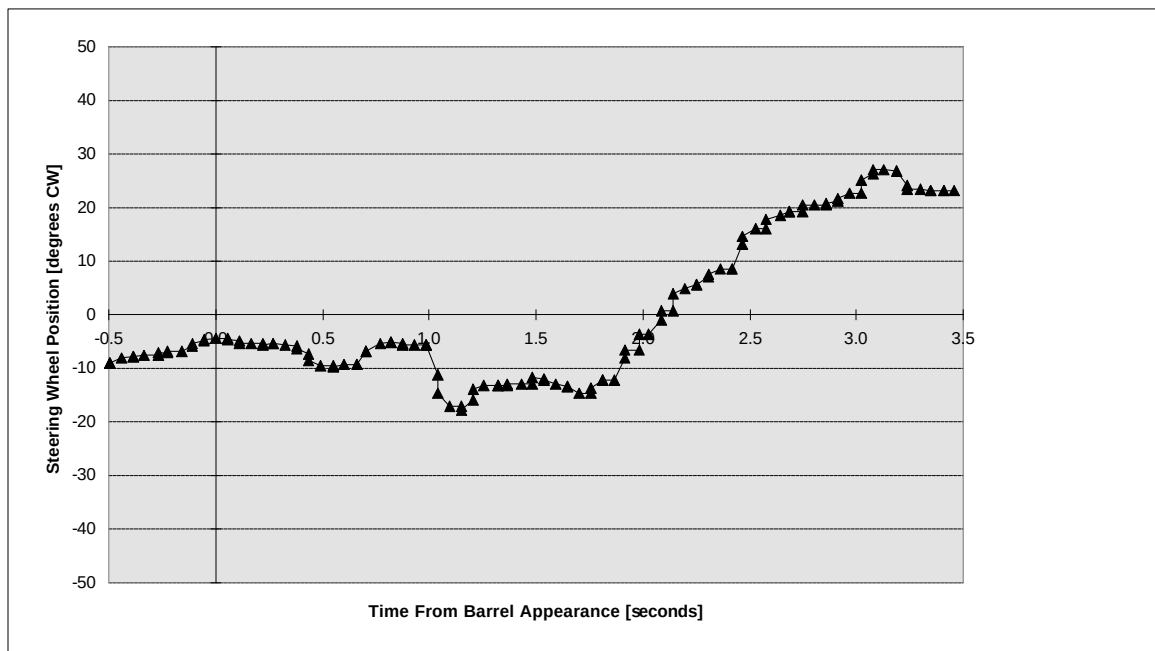


Figure J-26. Steering wheel reaction: Subject #19, Auditory Warning condition.

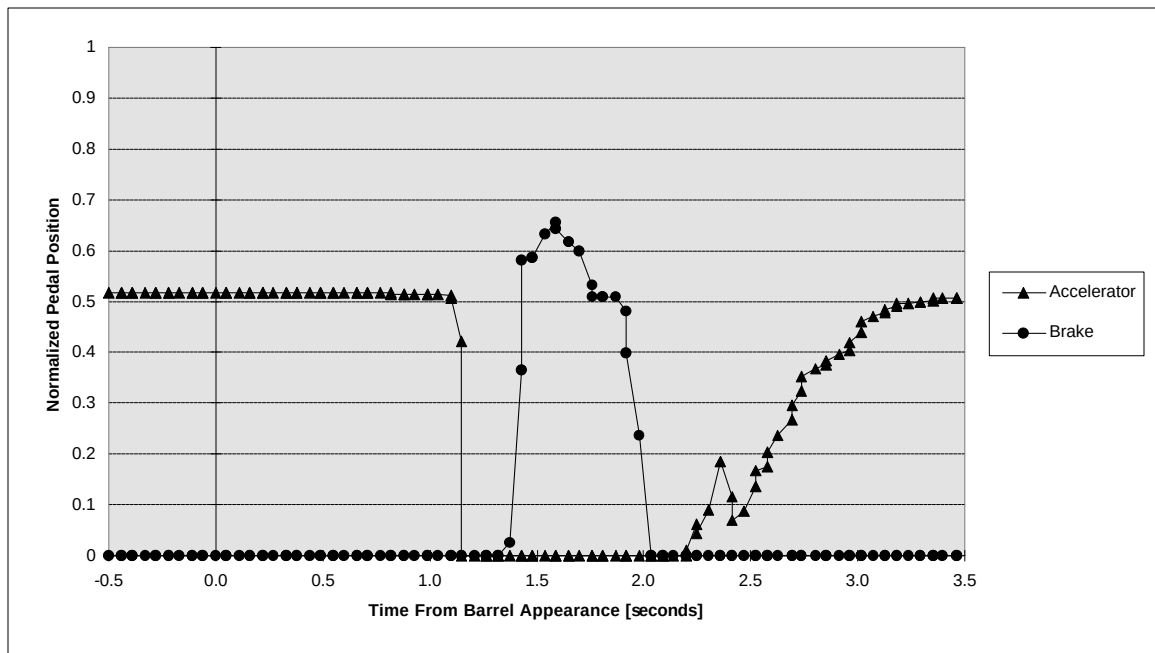


Figure J-27. Accelerator and brake pedal reaction: Subject #27, Auditory Warning condition.

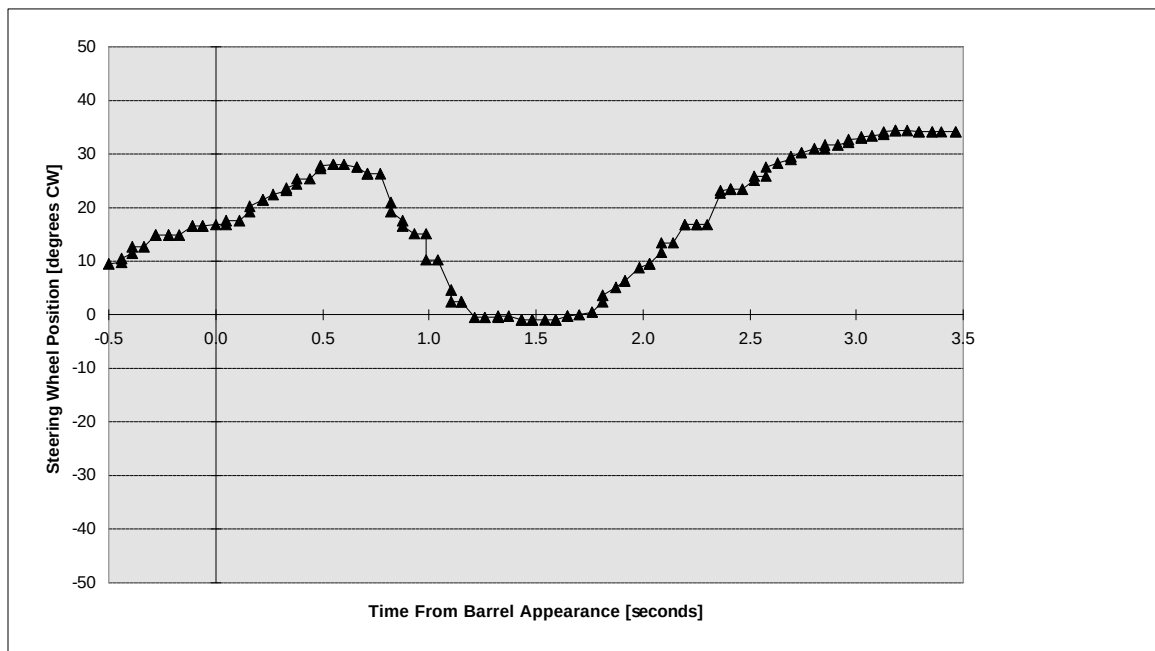


Figure J-28. Steering wheel reaction: Subject #27, Auditory Warning condition.

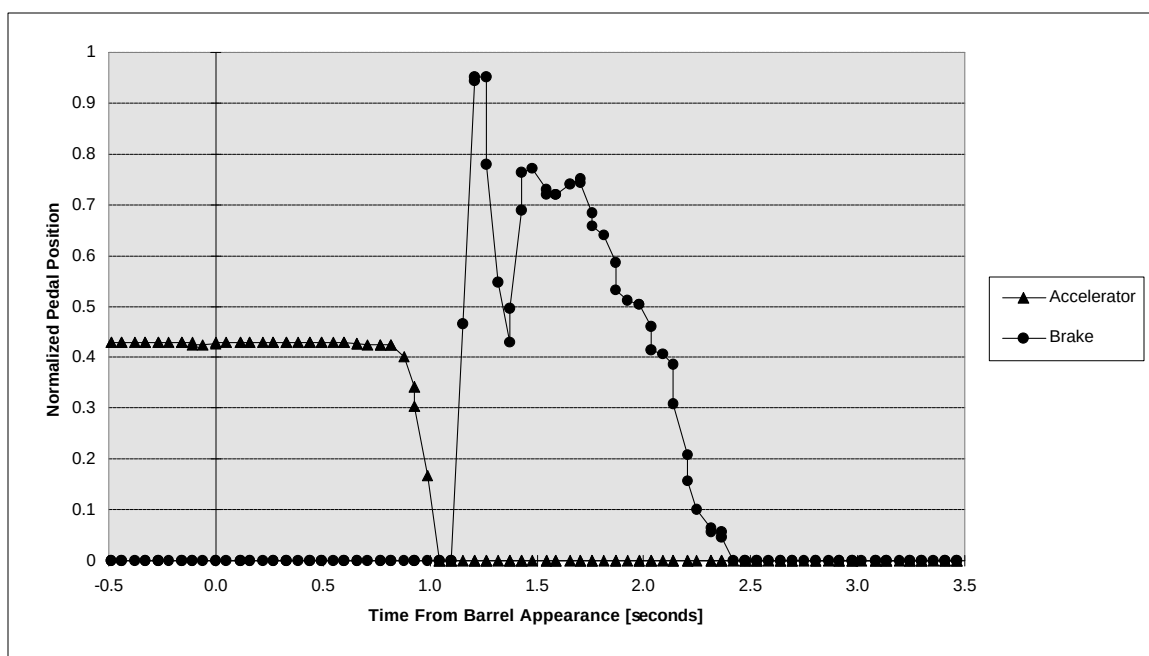


Figure J-29. Accelerator and brake pedal reaction: Subject #29, Auditory Warning condition.

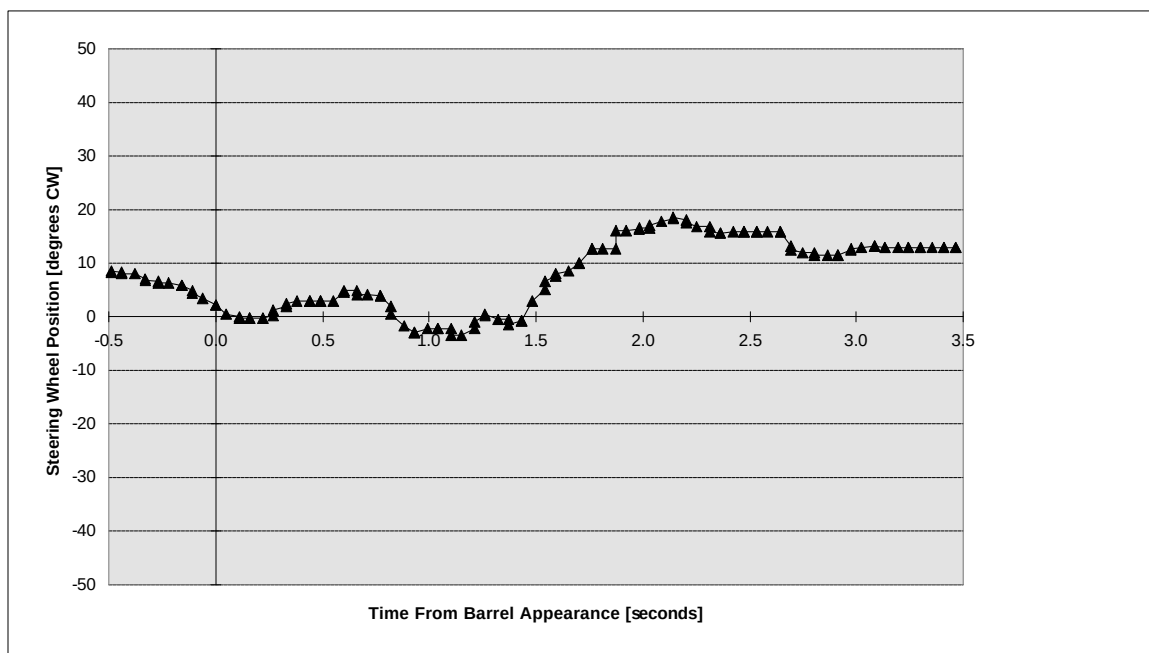


Figure J-30. Steering wheel reaction: Subject #29, Auditory Warning condition.

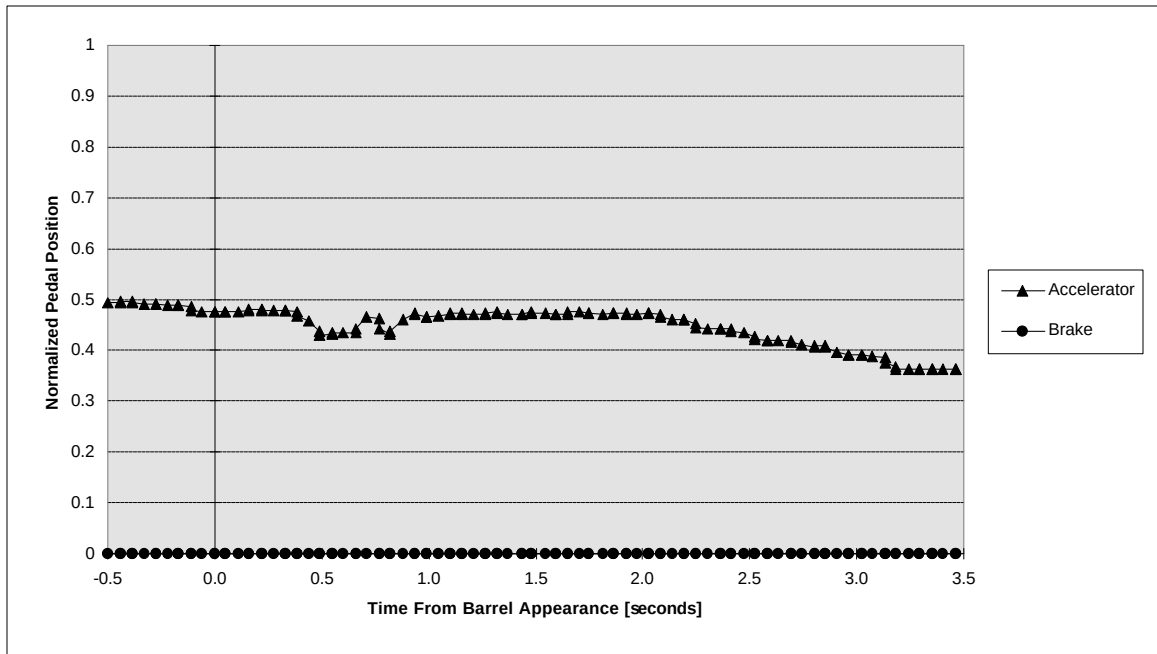


Figure J-31. Accelerator and brake pedal reaction: Subject #31, Auditory Warning condition.

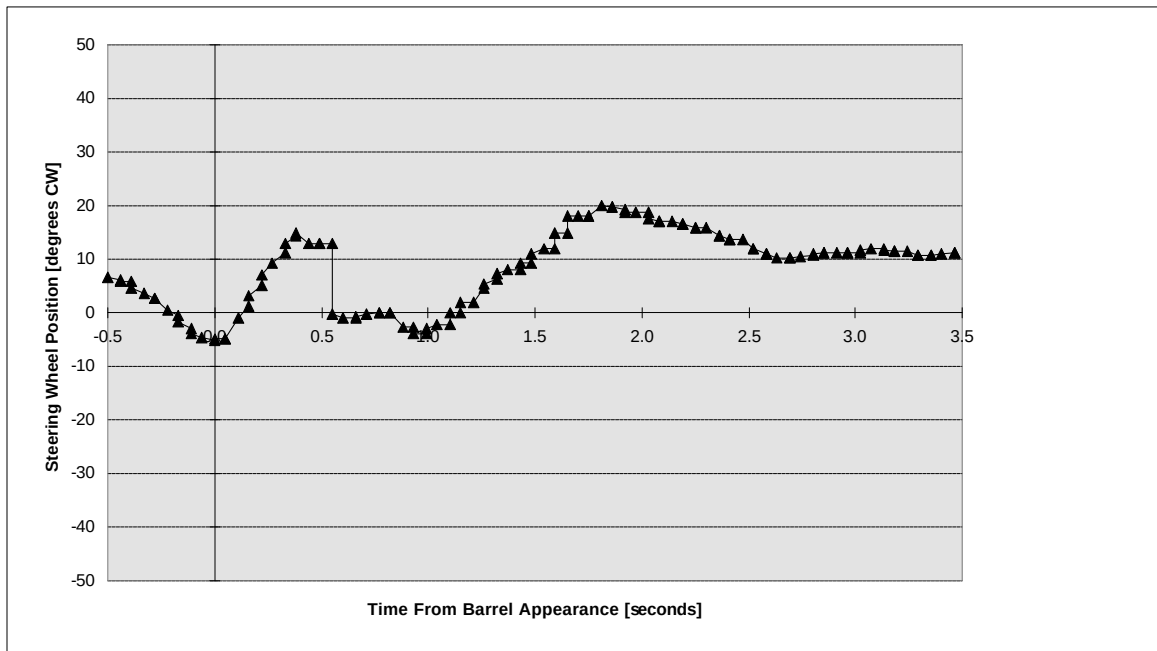


Figure J-32. Steering wheel reaction: Subject #31, Auditory Warning condition.

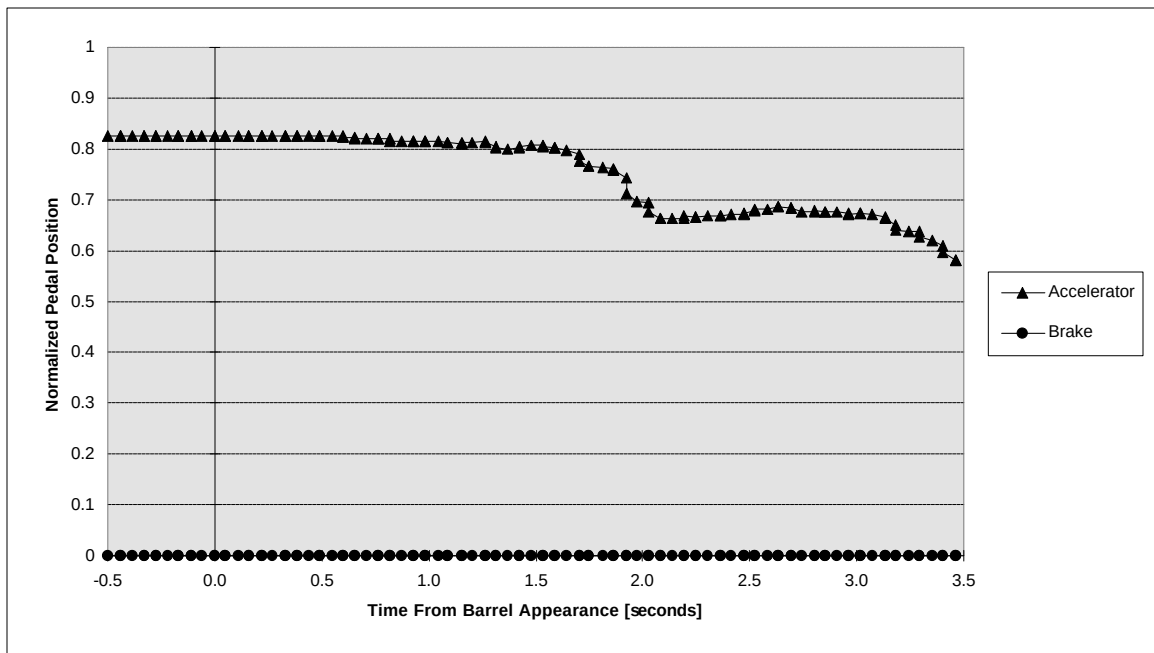


Figure J-33. Accelerator and brake pedal reaction: Subject #32, Auditory Warning condition.

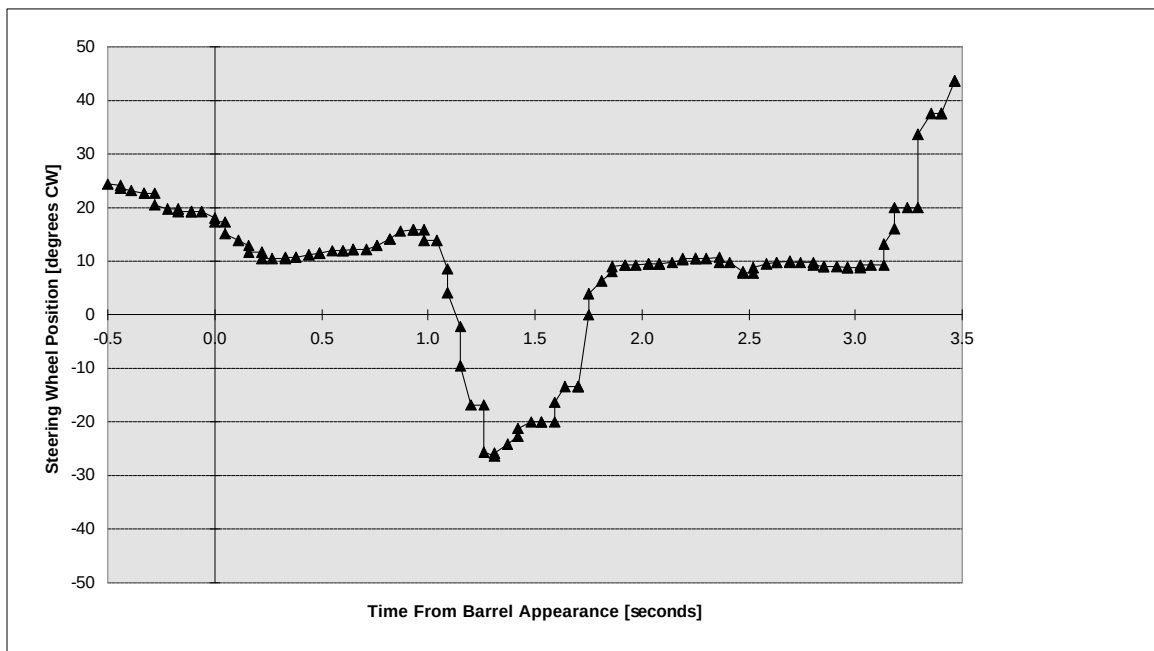


Figure J-34. Steering wheel reaction: Subject #32, Auditory Warning condition.

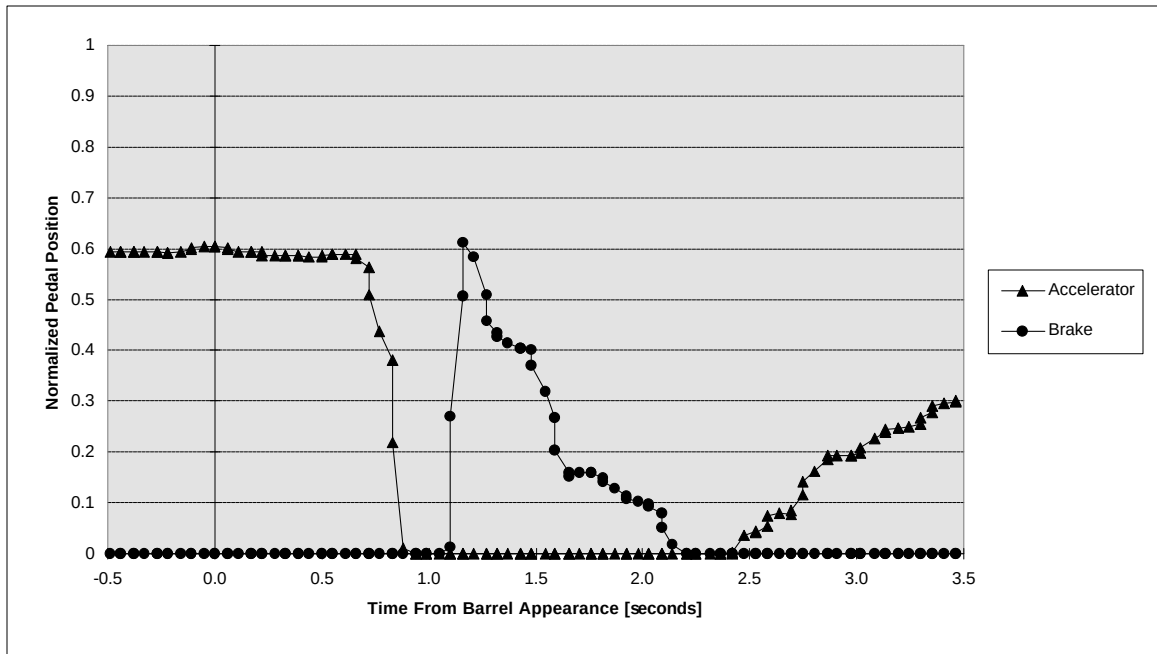


Figure J-35. Accelerator and brake pedal reaction: Subject #20, Haptic Warning condition.

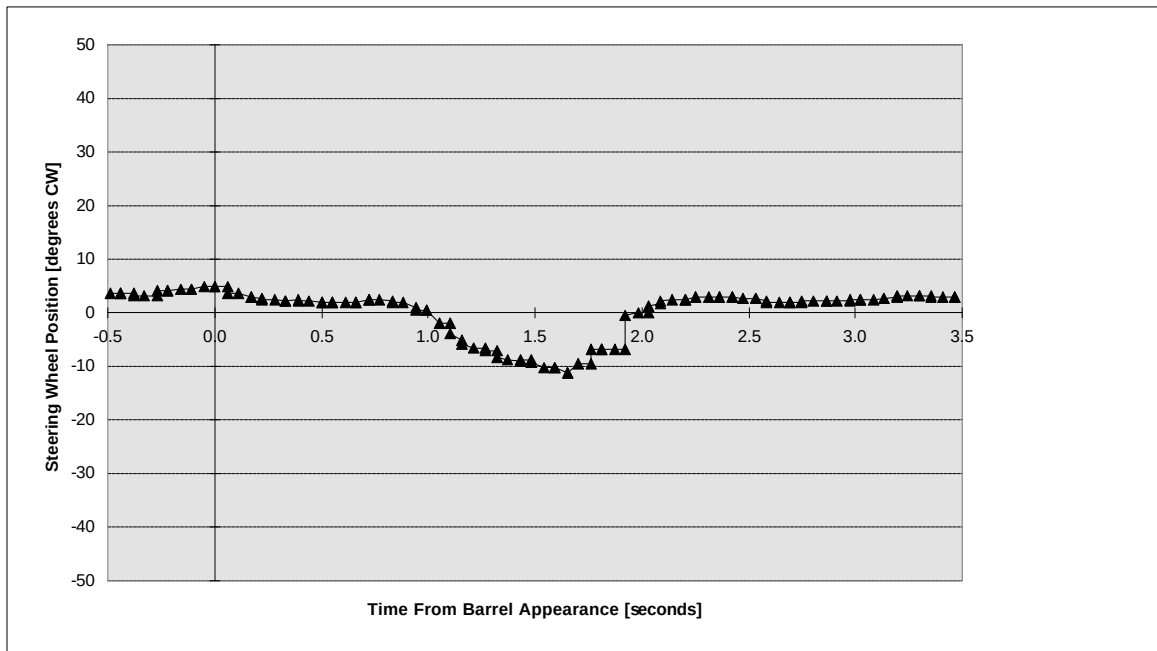


Figure J-36. Steering wheel reaction: Subject #20, Haptic Warning condition.

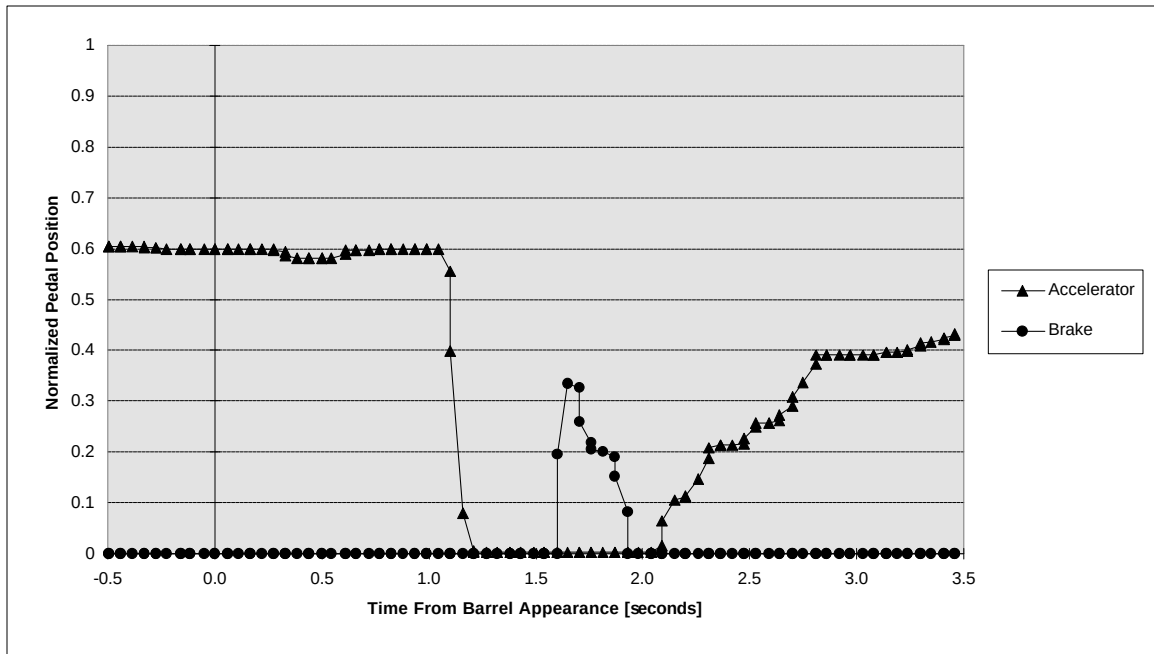


Figure J-37. Accelerator and brake pedal reaction: Subject #23, Haptic Warning condition.

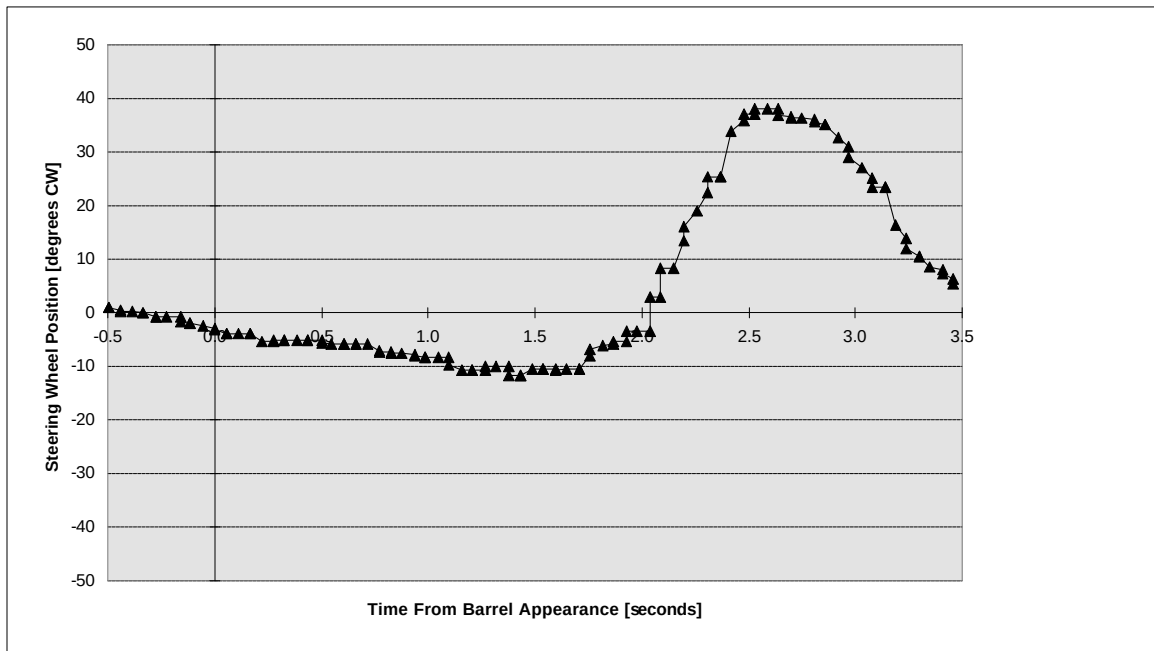


Figure J-38. Steering wheel reaction: Subject #23, Haptic Warning condition.

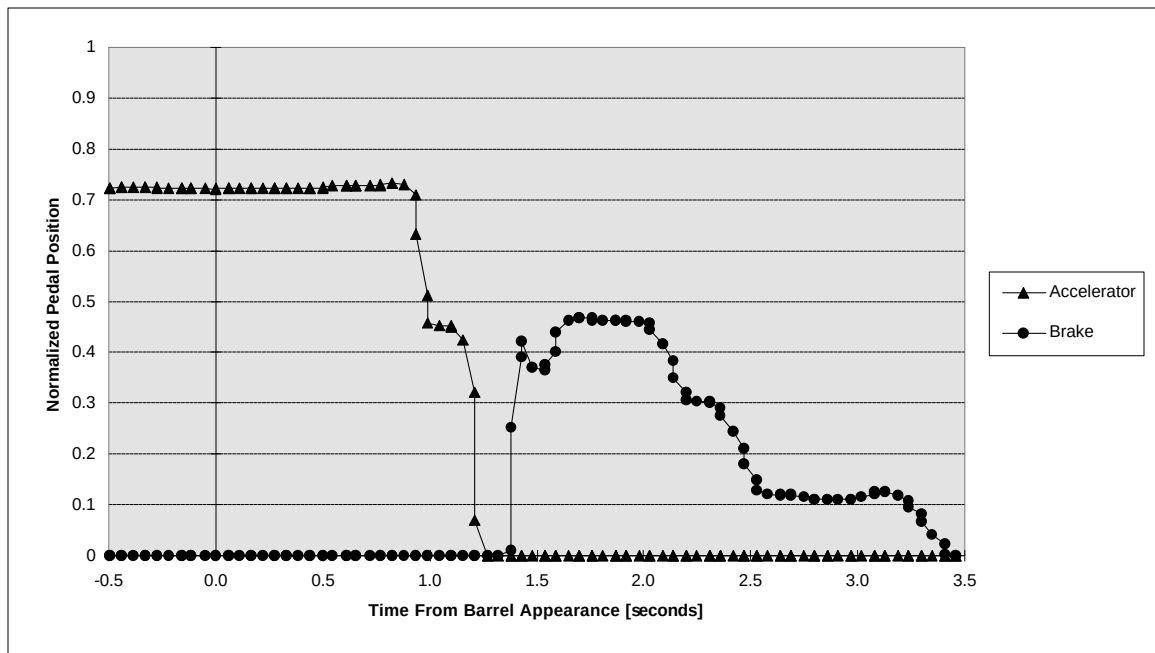


Figure J-39. Accelerator and brake pedal reaction: Subject #28, Haptic Warning condition.

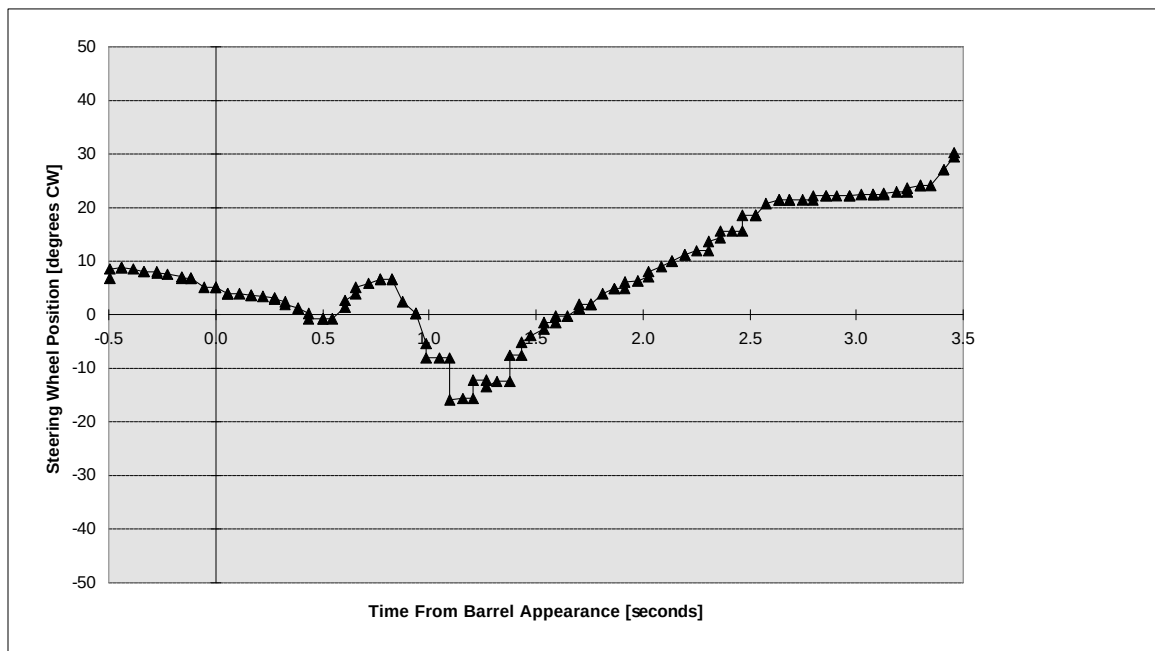


Figure J-40. Steering wheel reaction: Subject #28, Haptic Warning condition.

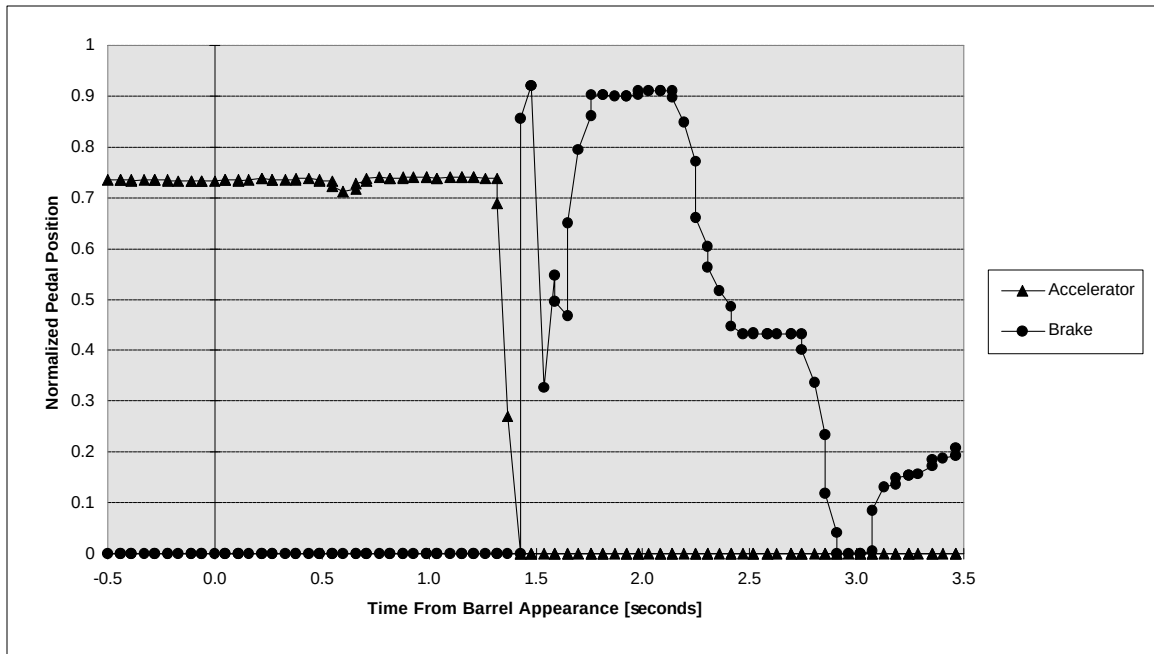


Figure J-41. Accelerator and brake pedal reaction: Subject #30, Haptic Warning condition.

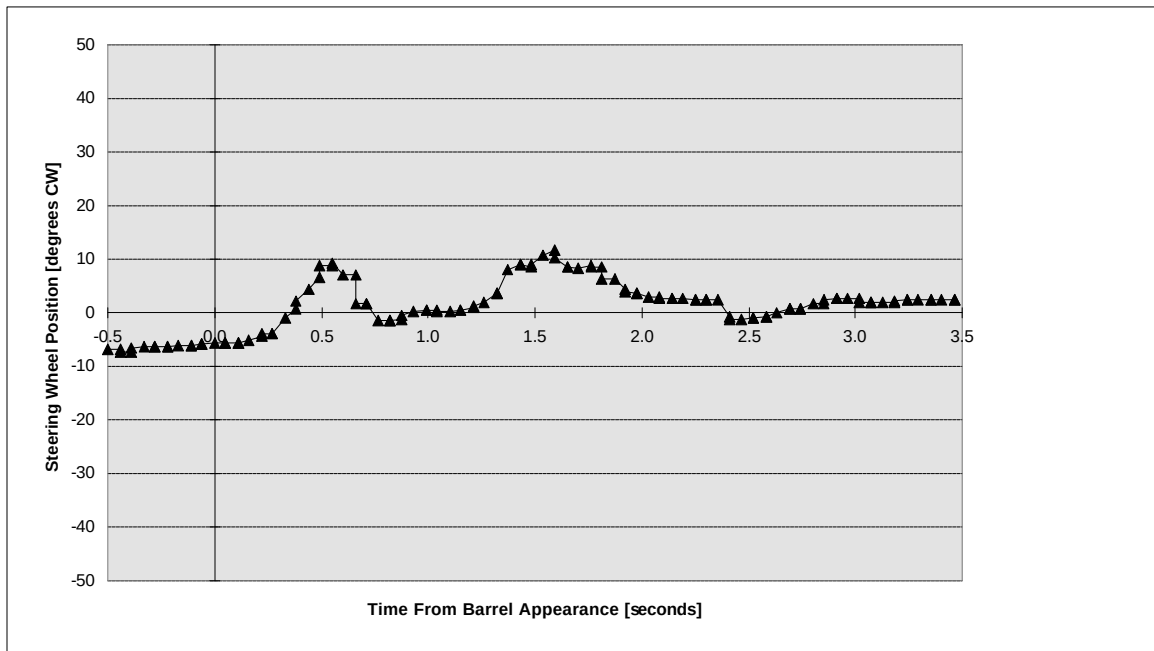


Figure J-42. Steering wheel reaction: Subject #30, Haptic Warning condition.

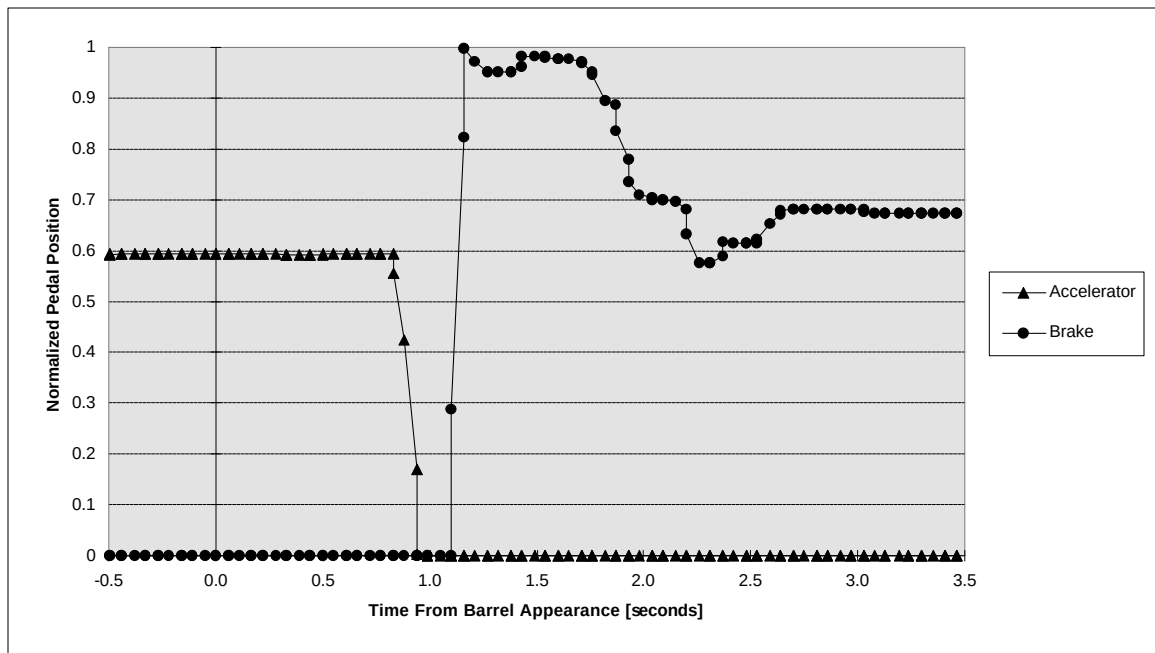


Figure J-43. Accelerator and brake pedal reaction: Subject #34, Haptic Warning condition.

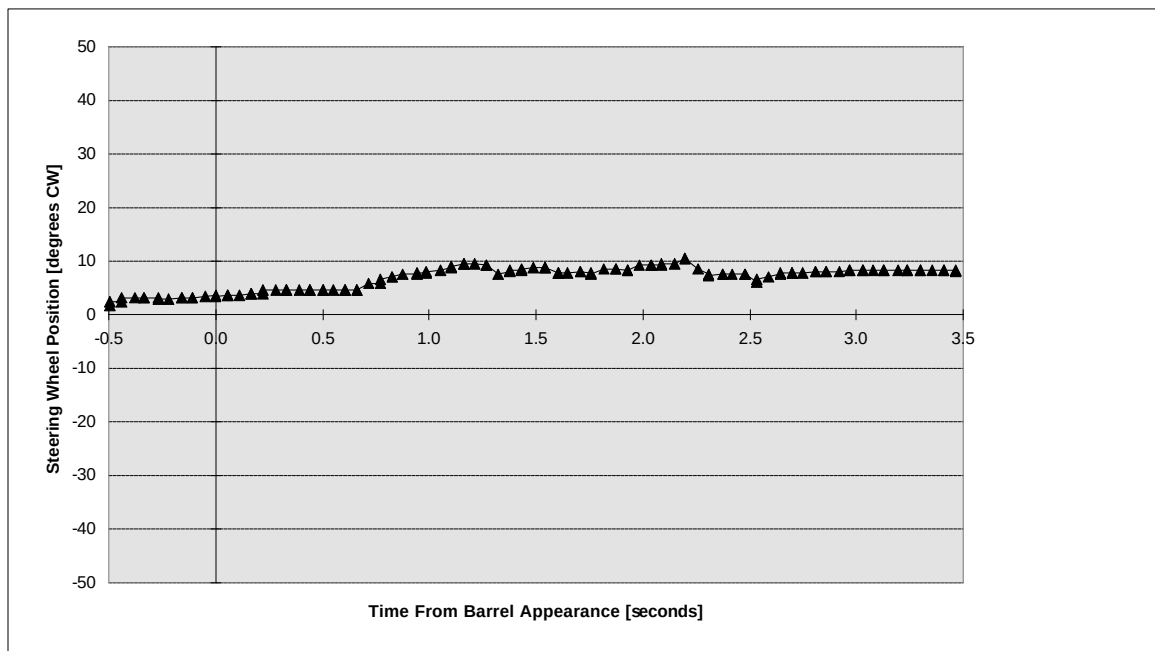


Figure J-44. Steering wheel reaction: Subject #34, Haptic Warning condition.

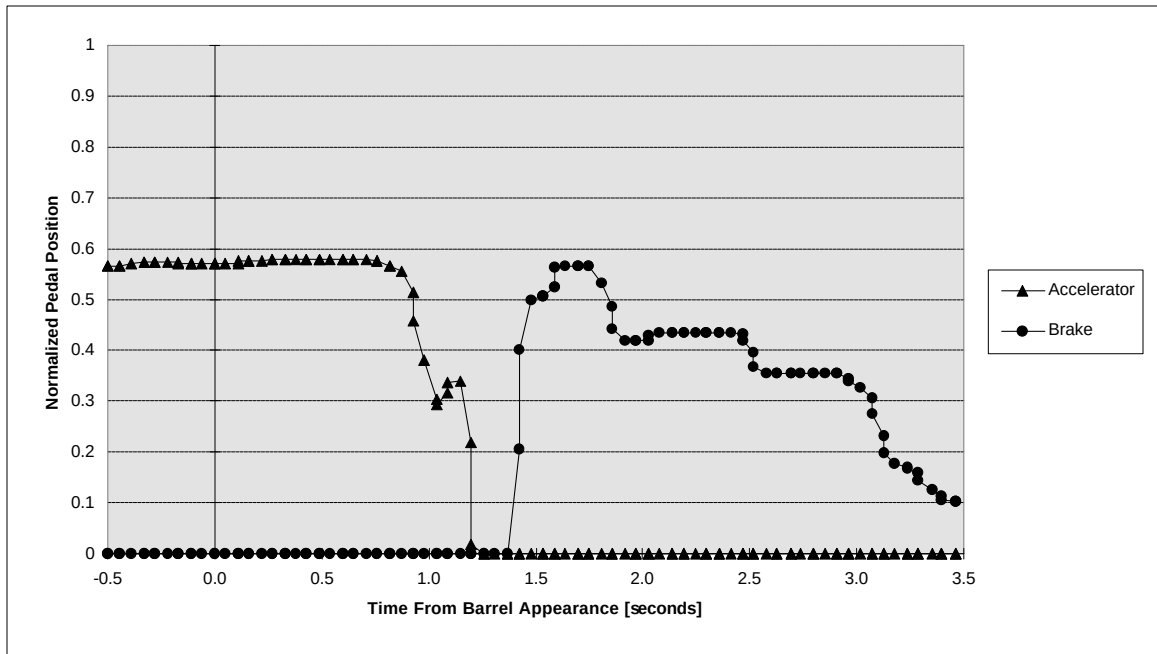


Figure J-45. Accelerator and brake pedal reaction: Subject #35, Haptic Warning condition.

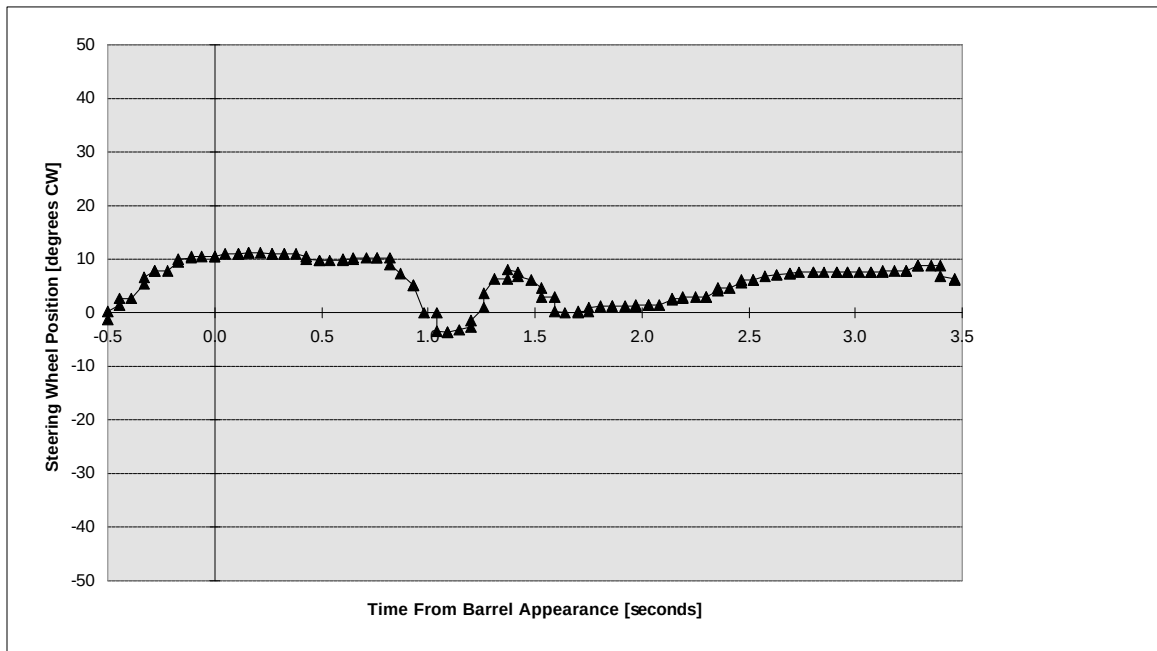


Figure J-46. Steering wheel reaction: Subject #35, Haptic Warning condition.

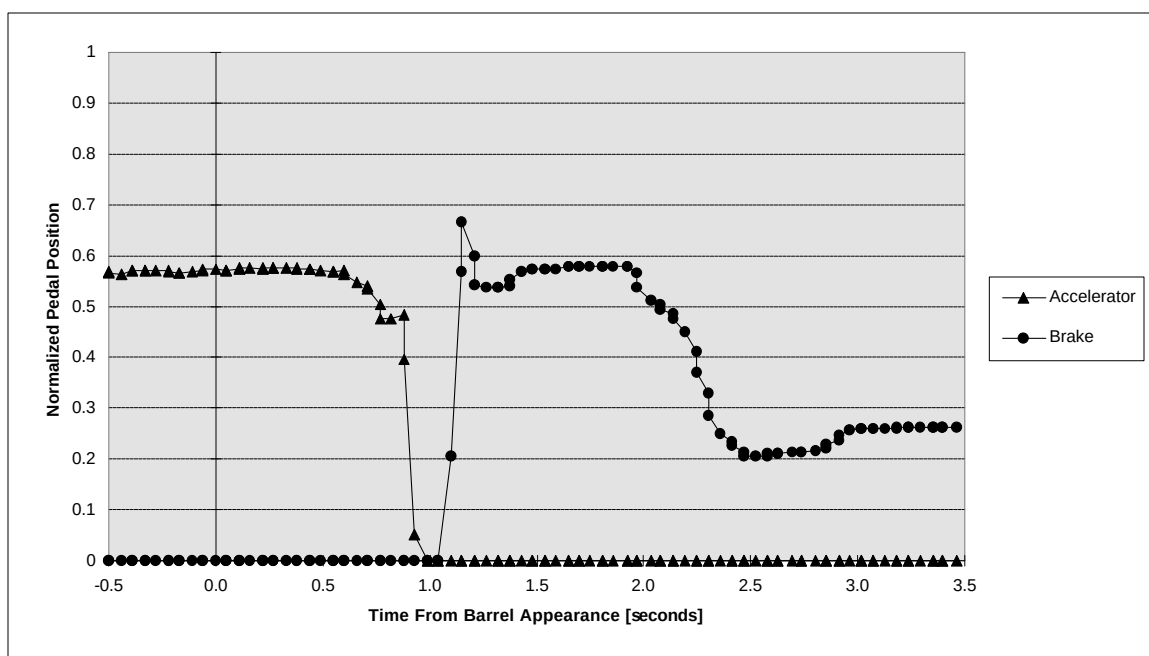


Figure J-47. Accelerator and brake pedal reaction: Subject #36, Haptic Warning condition.

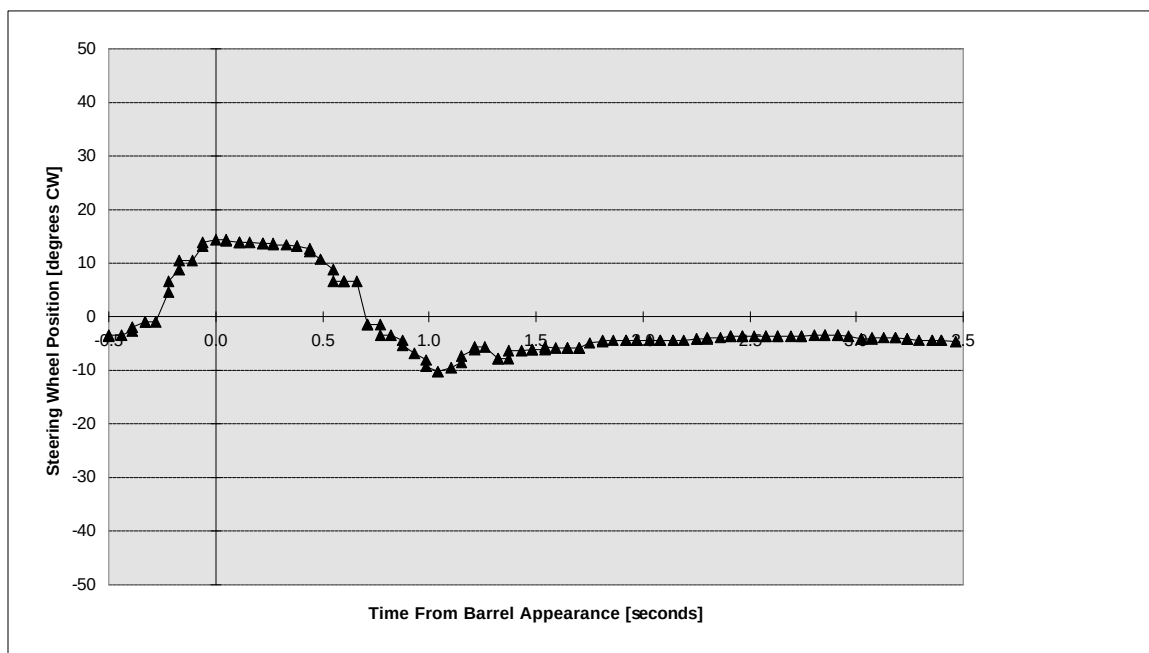


Figure J-48. Steering wheel reaction: Subject #36, Haptic Warning condition.

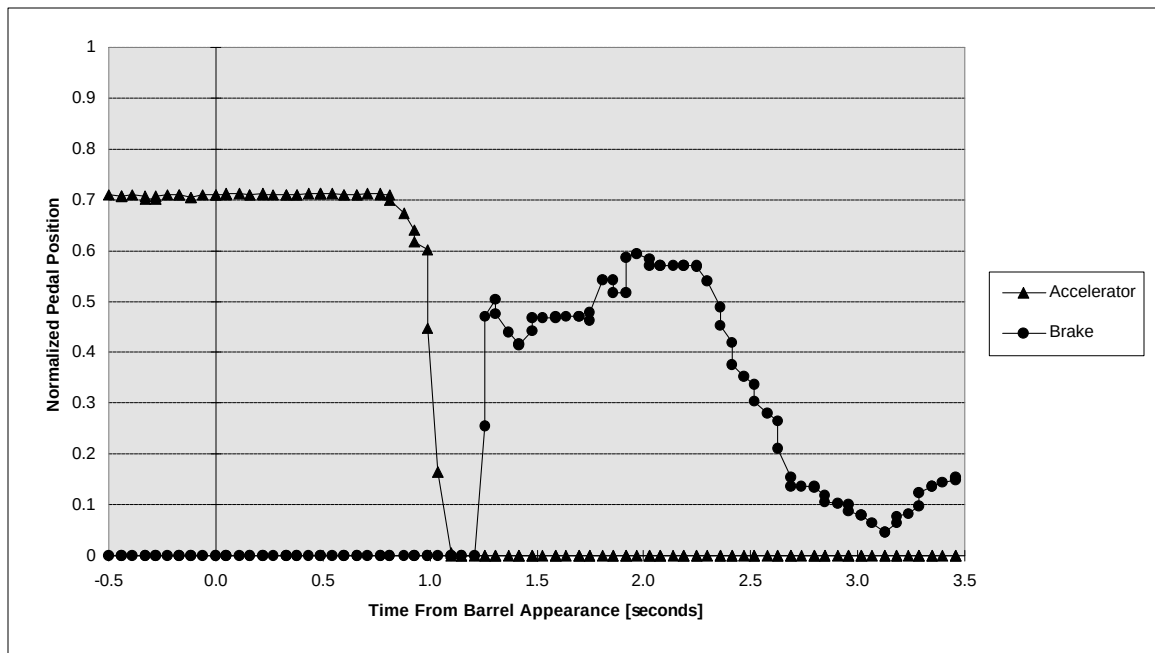


Figure J-49. Accelerator and brake pedal reaction: Subject #37, Haptic Warning condition.

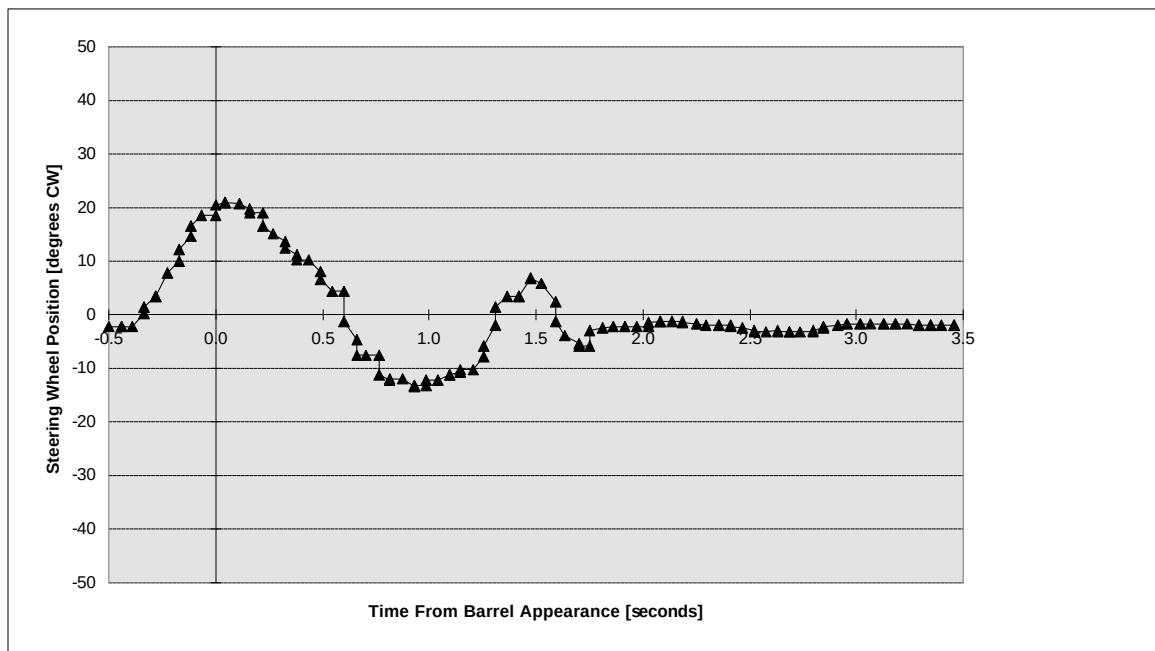


Figure J-50. Steering wheel reaction: Subject #37, Haptic Warning condition.

APPENDIX K.
DRIVER RESPONSE STRATEGY CLASSIFICATIONS

TABLE K-1

Driver Response Strategy Classifications and Rationale

Subject Number	Rationale for Classification	Classification		
		Brake	Steer	No Rxn
No Warning Condition				
4	Braked; Steering reaction was 16° towards barrels	X		
5	Brake response occurred about 1.5 seconds after steering response		X	
6	Very large steering reaction; driver only hit brakes well after he was into his turn		X	
7	No significant brake or steering reactions			X
10	Never hit brakes; steering was gradual and towards the barrels			X
11	No brakes; no steering, either			X
13	Small steering reaction; main response was to brake	X		
22	Driver braked; he also steered, but after the braking reaction	X		
24	Braked; driver only had slight steering reaction	X		
25	Large braking and steering reactions, initiated simultaneously	X	X	
Warning Condition Summary:		5	3	3
Auditory Icon Warning Condition				
17	Braked; small steering reaction, but smaller and later than pedal reaction	X		
18	Very tentative brake reaction, no steering			X
19	Braked; steered, but gradually and late	X		
27	Only braked after done with large (over 27°) steering reaction		X	
29	Braked; minimal steering change	X		
31	No braking; steering was almost a startle reaction			X
32	No braking; significant steering away from the barrels		X	
Warning Condition Summary:		3	2	2
Soft Braking Warning Condition				
20	Braked; minimal steering	X		
23	Steering reaction came after braking	X		
28	Steering reaction minimal compared to braking	X		
30	Braked; very small steering deviations	X		
34	Braked; no steering change	X		
35	Braked; steering reaction was smaller and later than pedal reaction	X		
36	Braked; driver made only slow and gradual steering changes	X		
37	Braked; some steering, but less than 20°; initial steering changes are not reactions to barrels	X		
Warning Condition Summary:		8	0	0

VITA

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