A SIMULATOR-BASED INVESTIGATION OF VISUAL, AUDITORY, AND MIXED-MODALITY DISPLAY OF VEHICLE DYNAMIC STATE INFORMATION TO COMMERCIAL MOTOR VEHICLE OPERATORS

by

Steven Mark Belz

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Dr. John G. Casali, Chair
Dr. Brian M. Kleiner
Dr. Gary S. Robinson

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Chairman: Dr. John Casali
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(ABSTRACT)

This simulator-based study examined the use of *conventional auditory warnings* (tonal, non-verbal sounds) and *auditory icons* (representational non-verbal sounds), alone and in combination with a *dash-mounted visual display*, to present information about impending collision situations to commercial motor vehicle operators. Brake response times were measured for impending front-to-rear collision scenarios under six display configurations, two vehicle speeds, and two levels of headway. Accident occurrence was measured for impending side collision scenarios under two vehicle speeds, two levels of visual workload, two auditory displays, absence/presence of mirrors, and absence/presence of dash-mounted iconic display. Subjective preference data was also obtained from participants.

For both front-to-rear and side collision scenarios, auditory icons elicited significantly improved driver performance over conventional auditory warnings. Driver performance improved when collision warning information was presented through multiple modalities. Brake response times were significantly faster for impending front-to-rear collision scenarios using the longer headway criterion. The presence of mirrors significantly reduced the number of accidents for impending side collision scenarios. Subjective preference data indicated that participants preferred multi-modal displays over single-modality displays.

A technique for systematically identifying, selecting, and evaluating candidate auditory icons was also developed. The potential exists to expand upon these

developments, toward the goals of identifying appropriate auditory icons, improving operator performance, and developing information display techniques to effectively managing workload across multiple modalities.

"Concern about the human being and his/her destiny must always be the main interest in every technical development effort...never forget that, amongst your diagrams and equations."

Albert Einstein

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TABLE OF CONTENTS

Page

Page

Page

LIST OF FIGURES

Figure		Page

LIST OF TABLES

INTRODUCTION

The costs incurred as a result of traffic congestion and accidents on the nation's roadway system are staggering. In excess of $100 billion annually is attributed to lost productivity due to traffic congestion. Costs associated with traffic accidents - many of which occur as a result of excessive traffic congestion, total an additional $70 billion annually (IVHS America, 1992b). Dollars alone cannot measure the costs associated with traffic accidents; in 1994, over 40,000 individuals lost their lives in motor vehicle accidents, an average of one person every thirteen minutes (NHTSA, 1996).

An increased number of vehicles on the nation's roadways and an increased quantity of goods carried by commercial trucks has resulted in a substantial traffic problem which shows no signs of improving in the near future. If the number of vehicles on the roadways continue to increase at their current rates, the Federal Highway Administration forecasts that by the year 2005 the number of vehicles on the road will increase 50% over levels seen in 1988 (FHWA, 1988). According to Ervin and Chen (1989), a 50% increase in the number of automobiles will result in a corresponding five-fold increase in congestion, stretching today's ten minute delay to an hour or more. Historically, when thoroughfares became heavily traveled and congested, new roads were built which were capable of handling the increased volume. In many parts of the country however, building new roads is no longer economically nor environmentally feasible and new solutions must be explored to improve the current state of our roadways (Committee on Public Works and Transportation, U.S. House of Representatives, 1989; IVHS America, 1992b).

ITS Initiative and Technologies

The Intelligent Transportation System (hereafter referred to as ITS) Initiative addresses the issues of traffic safety and congestion through the application of technology-based systems designed to improve the quality of travel while simultaneously increasing the volume of travel on the nation's roadways. Research related to the ITS initiative has been conducted for several decades; however, much of this research has been directed towards non-commercial, or passenger vehicles. Only recently have researchers begun to realize the potential benefits of applying ITS principles and technologies to Commercial Vehicle Operations (Bowers-Carnahan, 1991; Chen and Ervin, 1989). ITS America (previously IVHS America) is a non-profit organization charged with planning promoting, and coordinating the development and deployment of the intelligent transportation system within the United States.

Three major participants comprise the infrastructure of the ITS initiative: private sector, public sector, and academia. The combined efforts of each of these participants are required to meet the goals of the ITS initiative. Two of the principle goals of ITS research include accommodating the ever increasing driver population and reducing traffic congestion. Additional goals include increased and higher quality mobility, a reduced environmental impact, improved energy efficiency, improved economic productivity, and a viable U.S. ITS Industry (IVHS America, 1992b). Within the ITS Initiative, six system areas have been identified, three areas focus on technology development and three focus on application development. Areas focusing on technology development include Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), and Advanced Vehicle Control Systems (AVCS). Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS), and Advanced Rural Transportation Systems (ARTS) focus primarily on application development (Transportation Research Board, 1993; IVHS America, 1992b).

One of the tremendous challenges facing the ITS initiative is America's general reluctance to embrace mass transit systems. Much of this reluctance stems from an aversion to forfeit the image of freedom a personal automobile has traditionally provided. The price for this privilege is costly and can be measured in hours spent in rush hour traffic, exasperated drivers, and the environmental detriment incurred as a result of the increased emissions; yet Americans stand firm, unwilling to relinquish this freedom (Ervin and Chen, 1989; Texas Transportation Institute, 1990). The real burden of increased delays and congestion is not likely to be felt by the general commuting population. However, to the trucking industry, conveyor of approximately 80 percent of all goods transported within the United States, these delays and congestion correlate directly to increased operating costs and decreased competitiveness (Freund, 1993). Feeling the burden of inefficient travel, the trucking industry is looking for practical, cost effective solutions. This makes the trucking industry an ideal environment for ITS development.

Lost time and money are not the only driving forces behind ITS development. Americans logged two trillion vehicle miles in 1989 and this figure is expected to increase four percent annually. If this trend continues, experts expect a corresponding increase in the number of accidents, injuries, and fatalities (Banks, 1991; Texas Transportation Institute, 1990). When compared to noncommercial vehicles, commercial vehicles, especially tractor-trailers, are more prone to accidents as a result of their increased size and weight, decreased maneuverability and visual field (in front of and along the sides of the vehicle). Trucking industry surveys reveal a genuine need and desire among commercial vehicle operators to incorporate collision avoidance technologies into the commercial motor vehicle (Stone and Ervin, 1990).

Currently, progress is being made to assist the commercial vehicle driver with problems arising from increased traffic congestion, varying interstate regulations, tight delivery schedules, and presentation of complex information within the cab environment (IVHS America, 1992a). ITS initiatives addressing these issues include: automatic vehicle identification, weigh-in-motion, automatic vehicle classification, automatic vehicle monitoring, automatic vehicle clearance sensing, two-way real-time communications, digital real-time traffic broadcasts, dynamic network routing and scheduling, electronic log books, warning and control systems, fleet tracking, anti-theft devices, automated toll collection, electronic noise cancellation, maintenance schedule displays, and automatic vehicle guidance (Castle Rock Consultants, 1989; Chen and Ervin, 1989; IVHS America, 1992b; Stone and Ervin, 1990). By their very nature, ITS systems represent a new and unfamiliar source of information to the commercial motor vehicle (CMV) operator, much of which is in addition to information already presented through conventional sources. Increasing the quantity of information will likewise increase the workload of an already heavily-burdened driver. Workload issues need to be addressed. If not, overburdened drivers may fail to support the new technologies, or worse, overworked drivers may cause more accidents. If increased operator workload results in a lack of widespread support for emerging technologies, there is sufficient evidence to question the value of such systems (Morlok, Bedrosian, Zarki, and Hallowell, 1989).

Commercial Vehicle Operations

Commercial vehicles and commercial vehicle operators present unique challenges to the ITS researcher. The Virginia Department of Motor Vehicles (1995) defines commercial vehicles as:

- vehicles which have a manufacturer's gross vehicle weight rating (GVWR) or gross combination weight rating (GCWR) of 26,001 pounds or more, or
- vehicles made to carry 16 or more passengers, including the driver, or
- vehicles that transport hazardous materials that have to be placarded by federal law.

Generally speaking, these vehicles have an operating capacity beyond that of a passenger automobile and generally require a greater commitment to safety and reliability. Researchers must also consider the fundamental differences between commercial and noncommercial drivers, including time spent on the road, vehicle dimensions, handling characteristics, individual motivations, commitment to safety, and driver vigilance (IVHS America, 1992b).

Commercial motor vehicles make up approximately 24 percent of the total number of vehicles on the road while accounting for only eleven percent of the fatalities reported in 1994 (NHTSA, 1996; U.S. Department of Transportation, 1992). In 1994 only 1.4 percent of the fatal accidents involved an intoxicated driver of a medium or heavy truck as compared to 22.9 percent for light trucks, 19.4 percent for passenger cars, and 28.9 percent for motorcycles (NHTSA, 1996). The majority of commercial drivers are driving for business rather than pleasure; therefore, unnecessary delays become more than a mere nuisance, they are costly. As a result, commercial drivers exhibit a commitment to roadway safety beyond that of the average noncommercial driver and are eager to test ITS technologies designed to reduce unnecessary delays and improve the quality of travel (Texas Transportation Institute, 1990).

The goals for the CVO portion of the ITS Initiative encompass three complementary areas: productivity, regulation, and safety (Boehm-Davis and Mast, 1992; Texas Transportation Institute, 1990).

Productivity. Much of the concern within the trucking industry revolves around the central issue of productivity. Global competition is forcing many U.S. companies to change the way they do business and, as a result, commercial carriers are being asked to provide faster and more reliable service while simultaneously reducing costs. Truck and other highway vehicle fleets can increase their efficiency by implementing vehicle identification, advanced communications, and safety advisory systems (Manuta, 1992). ITS technologies may provide a cost-effective solution; automatic vehicle location, tracking, routing algorithms, two-way real-time communication, and in-vehicle digital navigation systems have already been implemented on a limited basis. ITS technologies improve the efficiency of the freight carrier, enabling U.S. businesses and industries to remain competitive in an ever changing global economy (Baker, Klimek, and McKelvey, 1990; IVHS America, 1992b; Texas Transportation Institute, 1990).

Regulation. Commercial Vehicle Operations are regulated at almost every level of government in the United States "to ensure public safety, protect roads and bridges, maintain economic competition, promote fair business practices, and generate funds for highway construction and maintenance" (Texas Transportation Institute, 1990, p. CVO.1). Enforcing CVO regulations results in substantial costs which much be shared by the government and trucking industry alike; over $100 million is spent annually enforcing truck weight restrictions alone (Texas Transportation Institute, 1990). Experts estimate a 90% reduction in time delays when ITS technologies, including weigh-in-motion scales, automated vehicle identification transponders, and automated vehicle classification devices are fully implemented (Baker, Klimek, and McKelvey, 1990; Boehm-Davis and Mast, 1992; Texas Transportation Institute, 1990).

Safety. Since the highway system was first developed in the United States, trends in automobile and truck size have diverged; trucks have increased in size seeking greater productivity while automobile size has decreased to improve fuel economy. Both trucks and automobiles must operate together on a congested highway system originally designed for fewer automobiles and smaller trucks. ITS technologies, including those which track hazardous materials, detect problems internal to the vehicle, and warn of impending collisions have the ability to reduce risk and improve safety on the nation's thoroughfares (Baker, Klimek, and McKelvey, 1990; Boehm-Davis and Mast, 1992; IVHS America, 1992b; Texas Transportation Institute, 1990).

Summary

In excess of $100 billion annually is attributed to productivity lost as a result of traffic congestion and accidents. Much of this loss in productivity is experienced by those employing commercial vehicles and their operators. Given the business nature of their driving, commercial vehicle operators appear eager to test those technologies designed to reduce unnecessary delays, improve their quality of travel, and ultimately in crease their productivity. These technologies, however, must be designed to demonstrate real utility and benefits while not contributing to an operator's already heavy workload.

DRIVER WORKLOAD

Much of a human factors engineer's involvement in ITS research is tied to safety and the evaluation of driver workload. Each emerging ITS technology is accompanied by its own set of displays and controls. As the number of displays and controls introduced into the vehicle increases, resolving issues of safety and operator workload becomes more pressing (Wierwille, 1995). Quantifying driver workload is necessary to assess the level of risk incurred while driving; likewise, it may also be useful in evaluating emerging ITS technologies and their role in the truck cab (Kantowitz and Sorkin, 1983; Kantowitz, 1992). Many of the concepts defining workload are grounded in the study of human-information-processing, therefore, it is prudent to review some of the prominent literature describing current research in this area prior to discussing workload as it relates to the commercial vehicle operator.

Human Information Processing

Wickens (1992) provides a general model of the fundamental constructs of human information processing. In the context of ITS research, this model serves as a useful framework in which to assess both the quantity of workload experienced by the driver and the modality to which the workload can be attributed. The model's components, including sensory processing, allocation of attentional resources, decision response and selection, and response execution, are illustrated in Figure 1.

The area of sensory perception and processing is comprised of three major areas of interest, including the characteristics surrounding the retention of visual and auditory stimuli and the short term memory store (STMS). One characteristic of STMS is the rapid rate at which the information decays (300 ms for iconic and 1-2 seconds for echoic memory); however, it does allow information to be retained temporarily for later use and without attention (Stene, 1991; Wickens, 1992). The nervous system recognizes and categorizes stimuli based upon information contained within the long-term and working memories. Information, once categorized, will elicit a decision, be retained in working memory, or be committed to long-term memory. If a decision is elicited the response is initiated, executed, and consequences monitored (Wickens, 1992).

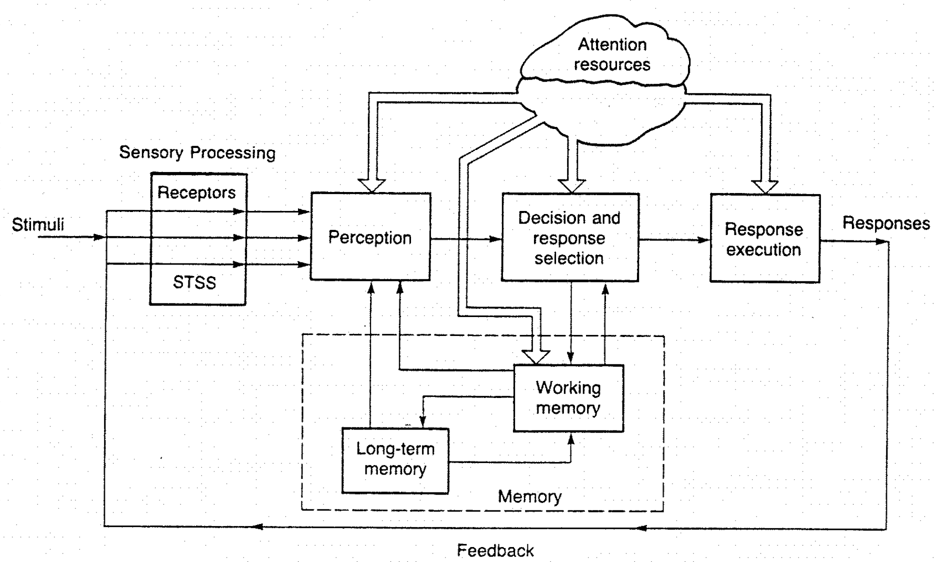

Figure 1. A model of human information processing (adapted from Wickens, 1992).

Attentional resources. Human information processing is limited by finite attentional resources. These resources are distributed and shared among the various processing units as required; but if a task demands excessive use of these limited attentional resources, task performance will deteriorate. Learning and practice, however, can dramatically reduce the demand placed on attentional resources. For example, a relatively inexperienced driver experiencing heavy rush hour traffic for the first time will be forced to commit more resources to navigation and collision avoidance than would be expected of a regular commuter (Stene, 1991; Wickens, 1992). Unfortunately, ITS system development frequently fails to adequately address the driver's needs and limitations in the design process. Poorly designed systems may deplete the driver's pool of attentional resources to the extent that the driver is unable to devote sufficient resources to the driving task and thus may be more likely to become involved in an accident. Conveying information through multiple channels or modalities (e.g. visual and auditory) enables a driver, heavily loaded in one modality, to assimilate information through an alternative modality. While such systems exhibit redundancy, they are generally more effective than those using a single modality (Kohler, 1971; Wickens, 1992).

Perception. Depending on the stimulus and task confronting an individual, perception may occur on any of three levels: detection, identification, and recognition. Detection deals with the fundamental question of whether or not a stimulus is present. Identification and recognition occur as the individual determines to which of several different classes the stimulus belongs (Sanders and McCormick, 1993; Wickens, 1992). Perception of auditory and visual information differs somewhat as a result of their intrinsic characteristics. The eye must be narrowly fixated upon visual stimuli in order accurately perceive the conveyed information; any information displayed outside of an individual's cone of vision is filtered and goes unnoticed. The ear, however, is omni-directional in nature and not capable of filtering information in the same manner as the eye, making the auditory domain the preferred modality for displaying warning messages.

Competition for resources. Wickens (1992) has suggested the possibility of multiple processing resources. The multiple resources model of the human processing system characterizes attention as a resource allocated to different levels of processing depending on the system demands. The more difficult the task, the larger portion of the available resources it requires, limiting the resources able to be accessed by other simultaneous tasks. Not all tasks, however, compete for the same pool of resources. As a result, effective timesharing occurs when two tasks use different groups of resources, whereas tasks using common or similar resources are more likely to interfere with one another. This concept is formalized in Figure 2 where the resources are identified as processing codes, processing modalities, and processing stages (Schlegal, 1993; Wickens, 1987). Processing codes contrast verbal and spatial tasks. Driving is essentially a complex manual tracking (spatial) task and can be accomplished quite effortlessly by the majority of drivers as they simultaneously converse (verbal task) with another individual in the vehicle. The concept of processing modalities may provide an explanation as to why it is easier to time-share mixed modality tasks than it is to concurrently undertake two tasks of the same modality. This is a reasonable conclusion as most drivers find it much easier listen to the radio while driving (one auditory and one visual task) than it is to read a newspaper while driving (two visual tasks). Processing stages are comprised of perceptual/cognitive activities and response activities. Two tasks involving response activities are less easily time shared than a task utilizing response in combination with another utilizing perception (Schlegal, 1993). The multiple resources model is of considerable importance to ITS/human factors engineers as it provides a framework for understanding drivers' information processing limitations. While the model does not predict perfect time-sharing of separate resources, it does provide the framework to greatly improve time-sharing efficiency (Wickens, 1992).

Decisions. Decision making is the means by which an individual evaluates alternatives and selects a course of action. Once the stimulus has been perceptually encoded an operator may opt to take action. Many decisions made while driving serve to minimize the risk of damage to self, passengers, or other individuals on the road. In order for drivers to minimize risk, they must estimate the probability of a dangerous or undesired event occurring. Unfortunately, humans are generally poor estimators of probability and many of their decisions are skewed as a result of personal bias; they place considerable reliance upon their perception of the world at the time the decision is made.

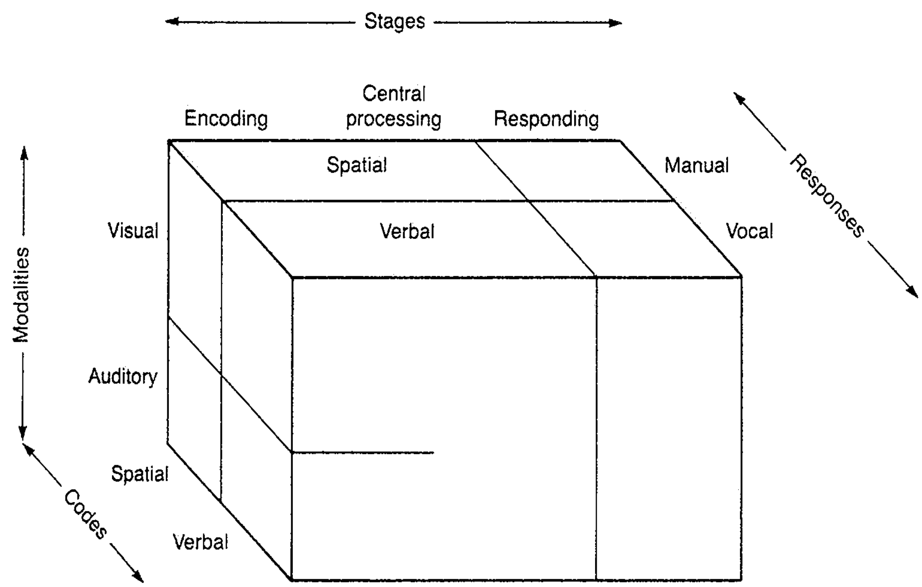

Figure 2. A model of multiple resources within the human processing system (adapted from Wickens, 1992).

Incorporating additional displays designed to provide the driver with more accurate information, thereby resulting in improved decision making, may not eliminate an operator's bias when faced with time constraints. Instead, the operator will tend to make a decision based solely on the information presented by the salient display, even if that display has no relevance whatsoever to the decision (Wickens, 1992).

Reaction time. The elapsed time between an operator's perception of a stimulus and the initiation of an action is defined as reaction time. Simple reaction time elicits a specific response from a known stimulus; it is rarely seen outside of the laboratory setting and requires absolute certainty in a subject's ability to identify the appropriate stimulus, and desired response, and the experimenter's ability to capture the response. Choice response time, however, involves uncertainty regarding the stimulus onset and required action. Choice response time is more applicable to the real-world task of driving where there is a considerable level of uncertainty in both the stimulus and the appropriate response. Because of the uncertainty regarding the stimulus onset and required action, choice reaction time will always be longer than simple reaction time (Wickens, 1992).

Defining Workload

The scientific community has yet to reach a universally agreed upon definition of workload (McCloy, Derrick, and Wickens, 1983), though many definitions have been offered: "...the integration effects on the human operator of task-related, situation-related, and operator-related factors that occur during the performance of a task" (Hart, 1986, p.1116); "… the integrated mental effort required to perform the primary task. It includes such factors as level of attention, depth of thinking, and level of concentration required by the primary task" (Casali, 1982, p.174); "… an intervening variable, similar to attention, that modulates or indexes the tuning between the demands of the environment and the capacity of the organism" (Kantowitz, 1988). Wickens (1989) offers a more systematic approach, suggesting that workload involves the load on the perceptual, central, and output processing resources, while Gopher and Donchin (1986) offer yet another opinion suggesting that workload is comprised of the interactions between the demands of the tasks and work environment and the ability of the operator to meet those demands.

Although the precise definition of workload remains an enigma, common denominators within the above definitions recognize that workload includes the effect incurred on an individual's capabilities as a result of internal or external stressors, in the course of performing a task. While it is difficult to provide a precise, universally agreed upon definition of mental workload, the importance of mental workload as a measure of an operator's information processing demands is undisputed. Gaillard (1993, p. 997) offers several reasons highlighting the importance of mental workload evaluation:

(a) the probability that errors will occur is much larger when the operator has to work at the margins of his capacity;
(b) stress reactions may occur when the operator has to work for longer periods under conditions of high workload;
(c) the task configuration and the work environment may be improved when the factors that produce the high workload can be identified;
(d) new tasks or task assignments can be better designed when the workload to be expected is known; this also applies for the introduction of new material;
(e) the evaluation of workload is important for reasons of management and salary policy, and for the selection and training of personnel.

Mental workload and operator or driver workload are not synonymous and should not be confused. Mental workload measurements concentrate on measuring the demands placed on an individual's information processing resources, driver workload adopts a more holistic approach including the driver's physical interaction with their environment. As a result, Verwey (1993, p. 238) has elaborated upon Wicken's (1989) definition of workload: "...the load on perceptual (visual, auditory, and tactile), central (cognitive) and output (hand, foot, and vocal) resources." Schlegal (1993, pp. 360-361) uses the analogy of stress and strain to describe driver workload: "...Task demands and the operating environment determine the level of *stress*. The impact on the particular individual represents the *strain* and is reflected in task performance and other measures. Thus, the same level of stress does not result in the same level of strain for all drivers."

Workload Conditions Within CVO

The fundamental driving task is representative of both ends of the workload spectrum; but commercial drivers, more so than their non-commercial counterparts, are prone to experience excessive workload. While workload for both groups increases in high traffic areas, poor weather, and unfamiliar terrain, commercial drivers must also contend with increased vehicle size, reduced maneuverability, and additional instrumentation not found in non-commercial vehicles. Much of the driving encountered by commercial drivers, however, is quite monotonous; consisting of 8 to 10 hours traveling alone over interstate highways. An overloaded operator is likely to experience degraded performance, fail to attend to some aspect of the task, or attempt to shift workload management, whereas an under loaded operator may fail to attend to critical monitoring tasks and suffer from boredom (Weimer, 1995). The resulting situation is analogous to a delicate scale in that workload must be carefully balanced so the driver is neither overloaded nor under loaded; allowing the scale to fall to either extreme will adversely affect commercial drivers' performance (Schlegal, 1993).

Verwey (1991) distinguished between cognitive and visual loads as he described an experiment in which the major aim was to find the determinants of driver workload. Each of twenty-four subjects, balanced by gender and experience, drove an instrumented vehicle approximately 5km through six different roadway situations while performing one of four different secondary tasks (including a control condition). Experienced drivers possessed valid drivers licenses for more than five years and had driven in excess of 10,000 km annually, whereas inexperienced drivers possessed their license for less than one year and had driven less than 10,000 km during that time. The six tasks, ordered from highest to lowest visual loading were merging/exiting, a two lane roundabout, a complex left turn, a simple left turn, a straight rural road, and finally a straight stretch of highway. Although this study indicated that visual loading was relatively equivalent between the two experience groups, cognitive load differed significantly with the less experienced driver reporting higher workload. While this experiment did not involve commercial vehicles or their operators, the following two general conclusions can be made: visual load accounts for a larger portion of the operator workload than cognitive workload, and experienced drivers demonstrate lower cognitive loading than do less experienced drivers.

As much as 90 percent of the information required to operate a motor vehicle is delivered to the driver through the visual channel. Almost all of the major driving tasks, including route selection, lane position, monitoring of mirrors and instruments, and collision avoidance rely almost exclusively on vision (Olson, 1993). Other modalities are generally underutilized and play a supplementary role in the overall driving task. Auditory, kinesthetic, and to a lesser extent somosthetic senses provide information about vehicle operation (e.g., is the engine running smoothly) and some information about the surrounding environment (e.g., road quality and presence of sirens). While these modalities provide useful information to the driver, they play a relatively minor role in the overall driving task (Olson, 1993; Wierwille, 1993).

" With other components relatively invariant over time, most of the burden of adaptation to the fast changing conditions in road traffic falls on the flexible human being," (Rothengatter, Alm, Kuiken, Michon, and Verwey, 1993, p. 33). Much of the human factors engineer's involvement in ITS has been devoted to developing useful systems which do not disturb or result in excessive burdening of the operator. Driving is essentially a manual control tracking task overburdened by visual cues, therefore supplementary displays should be designed to minimize the additional loads assigned to the visual channel (Alm, Sviden, and Waern, 1994; Verwey, 1991). Failure to relieve the heavily-burdened visual channel is of particular concern to the human factors engineer because additional visual workload will more than likely draw the operator's attention away from the driving task, increasing the likelihood of an accident (Wierwille, 1995). Because the primary driving task is intensely visual, other tasks requiring vision must be regarded as secondary (Wierwille, 1993). With the advent of ITS technologies, more and more information is available to operator, much of it visual, making it necessary to limit the visual workload to preserve the quality of the driving task. Distributing operator workload across multiple modalities, including auditory, kinesthetic and tactile, is a viable method of avoiding excessive visual workload (Hancock and Caird, 1992; Pachiaudi and Blanchet, 1990).

COLLISION WARNINGS

Background

Pioneering efforts within Automated Vehicle Control Systems (AVCS) research surrounds the development of effective collision warnings. Ultimately, AVCS will use designated, instrumented highways and vehicles to relieve the driver of most driving related tasks. AVCS technology promises to greatly increase vehicle speed, throughput, and safety without requiring the construction of new thoroughfares. Collision warning systems are necessary first steps towards meeting this end (Alicandri and Moyer, 1992; IVHS America, 1992b).

Collision warning systems are vehicle-based technologies designed to enhance a driver's awareness of the environment surrounding the vehicle, thereby reducing motor vehicle accidents. Early systems will serve as warning devices, an 'unbiased evaluator' of a driver's performance designed to increase a driver's awareness to potentially dangerous situations. More mature collision warning systems will incorporate vehicle control technologies, such as intelligent cruise control and soft-braking, designed to compensate for driver performance (Najm, 1994; Transportation Research Board, 1993).

Motor vehicle accidents can be divided into five categories representing major collision configurations: front-to-rear, lane change/merge, backing, intersection/crossing path, and single vehicle roadway departure. Collision kinematics serve as the limiting factor to the feasibility of an effective collision warning system. Two of these collision configurations, front-to-rear and lane change/merge, have been identified by researchers as being especially good candidates for collision warning system development (Allen, 1994).

Front-to-rear collisions comprised approximately 25 percent of all motor-vehicle crashes in 1993 (Knipling, 1995). Driver inattention, or failure to pay adequate attention to the driving task, is the single most common cause of front-to-rear crashes. Following too closely has been identified as the second most common cause in front-to-rear collisions (U.S. Department of Transportation, 1993a). Accidents occurring as the result of lane changes or merges account for 4 percent of collisions annually and generally result from a driver's failure to see the other vehicle (Knipling, 1995). With respect to combination-unit trucks, this type of collision occurs most frequently for left-to-right lane change/merges or when the impending vehicle is in the driver's blind spot, adjacent and slightly behind the driver. (Allen, 1994; U.S. Department of Transportation, 1994).

Collision Activation Criteria

Two questions of paramount importance must be addressed before an effective collision avoidance system can be implemented. What criterion activates the system? And, what action (if any) should the system take once it has been activated? (Janssen, 1989). The overwhelming majority of collision avoidance research has centered around front-to-rear collisions; thus, while the following discussion is relevant to collision warnings in general, it is especially pertinent to those involving front-to-rear collisions.

Three alternative criterion, according to Janssen (1989), may be identified a priori for collision warning system activation. They are identified as fixed, momentary, or conditional in nature. Collision warnings employing a fixed activation criterion are activated by any vehicle appearing within a pre-identified time or distance range (Janssen, 1989; Michon, 1993). Since the fixed criterion does not take into account the motion of an object within the vehicle path, every object detected will result in an alarm, even in situations where the motion of the object precludes collision. The fixed criterion is the most conservative of the three activation criteria.

A 'time-to-collision' (TTC) criterion can be defined in terms of a momentary collision configuration (Janssen, 1989; Michon, 1993). A momentary collision configuration does take relative velocities, positions, and bearing angles into account. The system then evaluates the position of the vehicle and object at some time in the future, and if a collision is imminent, activates the collision warning system.

The third criterion is a hybrid of the first two criteria. The conditional, or 'worst case' criterion evaluates the current situation; if a momentary collision configuration would result should one of the parameters (e.g. velocity) suddenly change (e.g. if the vehicle preceding a vehicle equipped with a collision warning system equipped were to suddenly apply its brake) the collision warning system would be activated. The conditional criterion, while more conservative than the dynamic (momentary) criterion, is less conservative than the static (fixed) criterion.

Fixed criterion. The fixed criterion has not been seriously considered by designers for use in collision warnings because a single fixed distance or time range for all vehicle speeds would result in excessive false alarms that most drivers would find unacceptable (Janssen, 1989; U.S. Department of Transportation, 1993a). At the very least, a collision warning system based on the fixed criterion would have to use several different detection distances or time ranges to reduce false alarms and achieve consumer acceptability. The discussions in the literature surrounding the application of the fixed criterion are thoughtfully academic, lacking experimental substantiation.

TTC criterion. The TTC criterion has been used by several researchers to evaluate the effectiveness of collision warnings (Hirst and Graham, 1994; Janssen and Nilsson, 1990). Although the TTC criterion is frequently used by researchers because it represents an easily understood quantity, several researchers have identified shortcomings of this criterion.

Janssen (1989) discusses findings by van der Horst (1984) which indicate that a TTC criterion of 1.5 seconds or less distinguishes configurations which have become critical. Janssen argues that while the TTC criterion may reduce the number of false alarms, there are at least two associated, albeit hypothetical, disadvantages. First, while drivers will avoid TTCs below 1.5 s, they may become reliant on the collision warning system to notify them when the situation becomes critical and reduce their following distances accordingly. Secondly, as a result of the collision warning system using TTC criterion, drivers could become less attentive, resulting in increased reaction times and potentially more accidents.

Hirst and Graham (1994) evaluated the TTC criterion and its possible relationship to driver braking behavior. The study consisted of video and auditory warning displays overlaid on video-taped sequences of an approach to a target vehicle. Participants, seated in a stationary vehicle, were required to brake at the last point they felt a collision could be avoided. The results indicated that braking did not tend to follow a constant Time-To-Collision measure but rather a linear distance/speed curve.

Looking forward to vehicle implementation of the TTC criterion, the weaknesses of the TTC criterion become more pronounced. The study conducted by Graham and Hirst depicted an ideal TTC environment, one in which the exact time-to-collision could be identified and controlled for through the video presentation of driving footage in a simulated environment where the 'driver' lacked even the most basic vehicle controls. Incorporating the TTC criterion into a real driving task, however, would introduce several additional unknowns. Vehicle speed, environmental conditions (e.g. warm, cold, humid, dry), vehicle type and dynamics, roadway surface conditions (e.g. wet, dry, oil), vehicle condition, and driver reaction time are a few of the factors which can affect vehicle braking and would therefore affect the time to collision. A real driving task would be a severe test of the TTC criterion; incorporating the TTC criterion into the collision warning system could involve a potentially high (and undesirable) level of uncertainty.

Conditional criterion. The conditional or 'worst case' criterion has the potential to serve as the activation criterion of choice for the collision warning system. The effectiveness of such a system is dependent upon its ability to reliably predict the future actions of the object to be avoided. Panik (1984) describes a 'worst case' scenario for front-to-rear collisions occurring when the following vehicle is close enough to the leading vehicle that a velocity difference of at least 10 km/h would result if the lead vehicle were to suddenly brake with full deceleration. Janssen and Nilsson (1990) used this criterion to evaluate the differences between TTC and 'worst case' criteria.

Janssen and Nilsson (1990) used a simulator study, to compare the differences between TTC and conditional 'worst case' criteria while evaluating the effects of various collision warning systems (auditory warning, visual warning, 'smart' gas pedal) on driver performance. Instead of warning the driver aurally or visually, the 'smart' gas pedal would exert an additional 5N force upon the driver when signaling an impending collision. An additional collision warning system, or braking distance indicator, continuously displayed a perpendicular bar over the roadway marking the distance it would take for the simulated vehicle to stop assuming maximum braking; human reaction time was accounted for in the placement of the braking indicator. Results (Table 1) indicated an overall degradation of driver performance when collision warnings were

TABLE 1

Effects of Various Collision Warnings and Activation Criterion (adapted from Janssen and Nilsson, 1990).

System	Headways <1s	Effect On:		
		Average Speed	Level of accel./decel.	Driving in left lane
TTC and Light	Increased	Increased	Increased	Greatly Inc.
TTC and Buzzer	Reduced	Increased	Increased	Increased
TTC and Pedal	Reduced	Less	Same	Same
Worst Case and Light	Reduced	Same	Increased	Same
Worst Case and Buzzer	Reduced	Increased	Increased	Increased
Worst Case and Pedal	Reduced	Increased	Increased	Increased
Brake Distance Indicator	Greatly Red.	Increased	Increased	Same

used. The only collision warning system which did not suffer from adverse side-effects was the TTC + ‘Smart’ gas pedal combination.

The results of the Janssen and Nilsson (1990) study contradict the results presented by Hirst and Graham (1994) which suggest that driver braking behavior does not follow the TTC criterion. The reasons for this disparity are unknown. One possibility is the ‘worst case’ criterion described by Panik (1984) is not an effective prediction of object movement. Another explanation for the differing results may be the different experimental methodologies employed by the two researchers. Graham and Hirst used a stationary vehicle combined with a projection facility to evaluate braking behavior. Video sequences of approaches to a target vehicle accompanied by visual and auditory warnings were shown to subjects who were required to depress a brake pedal at the last point they felt a collision could be avoided. No provision was made to replicate the actual driving task. Janssen and Nilsson, on the other hand, used a higher fidelity setup including a simulated driving task and fixed-base simulator. A perspective view of 50 degrees, outlining the road, was electronically generated by the simulator and projected in front of the automobile mock-up. The simplicity of the environment presented by Hirst and Graham may have unintentionally biased the participants’ true breaking behavior.

Headway criterion. A discussion of various collision warning system activation criterion would not be complete without considering the concept of headway and a related likelihood display proposed by McGehee, Dingus and Horowitz (1994). Headway differs from TTC in that it does not take into account the plethora of parameters needed to accurately model the dynamic vehicle relationship; rather, it is a measure of how much ‘free space’ proceeds the vehicle. Free space is a measure of distance or time. For example, a headway of 100 feet is independent of velocity and delineates that no obstructions are present for at least the 100 feet in front of the vehicle. On the other hand, a headway of 2 seconds is velocity dependent. At 25 mph (37 ft/s), two seconds of headway would correspond to 74 feet, whereas at a velocity of 65 mph (96 ft/s), would correspond to 192 feet of headway.

The display proposed by McGehee, Dingus, and Horowitz (1994) consists of a series of nine multi-colored bars, simulating a three-dimensional perspective of the roadway (Figure 3). The number of bars change from one to nine depending on the impending headway. Li-Fen, Hofmeyer, Yenamandra, Bartelme, and Loventinsky (1993) used this display to test the effects of varied information reliability on collision warning systems. Four levels of information reliability were tested; 0, 25, 50, and 75 percent false alarm rates. In their research, the green bars were displayed for safe headways 1.6 seconds or greater; yellow bars for headways necessitating caution and ranged from 1.1 to 1.6 seconds, and red bars for 0.9 to 1.1 second headways. Headways less than 0.9 seconds were considered to be critical and the three red segments flashed at 4 Hz. Results of the study indicate that collision warning system displays with lower false alarm rates tend to be more helpful and result in fewer distractions.

Several comparisons can be made between headway and the various criteria proposed by Janssen (1989) as the impetus for collision warning system activation First, headway is similar to the fixed criteria in that it maintains a constant envelope, defined by time or distance, around the vehicle. Secondly, while initially less intuitive than the TTC criterion, combining the concept of headway with a likelihood display similar to that proposed by McGehee, Dingus, and Horowitz (1994) is likely to increase the driver's perception and understanding of the display. Additionally, headway is a simple measured quantity (distance or time) and can be obtained with a high level of accuracy, whereas TTC is derived through several quantities some of which can be measured (e.g. distance and relative velocity) and some of which must be estimated (e.g. effects of roadway, weather, and vehicle dynamics).

The field of collision warning system activation criterion is still in its infancy and several voids currently exist in the literature; specifically the trade-off between effective collision prediction and maintaining a low level of nuisance or false alarms. None of the proposed collision warning system activation criteria have demonstrated an ability to address both issues. Janssen (1989) argues that a fixed criterion, while effective in detecting potential obstacles, will result in an unacceptable level of nuisance alarms. Unfortunately, there is a lack of published research supporting that assertion. Although, Li-Fen, Hofmeyer, Yenamandra, Bartelme, and Lovetinsky (1993) were able to determine that there was a difference between 0% and 75% false alarm rate levels,

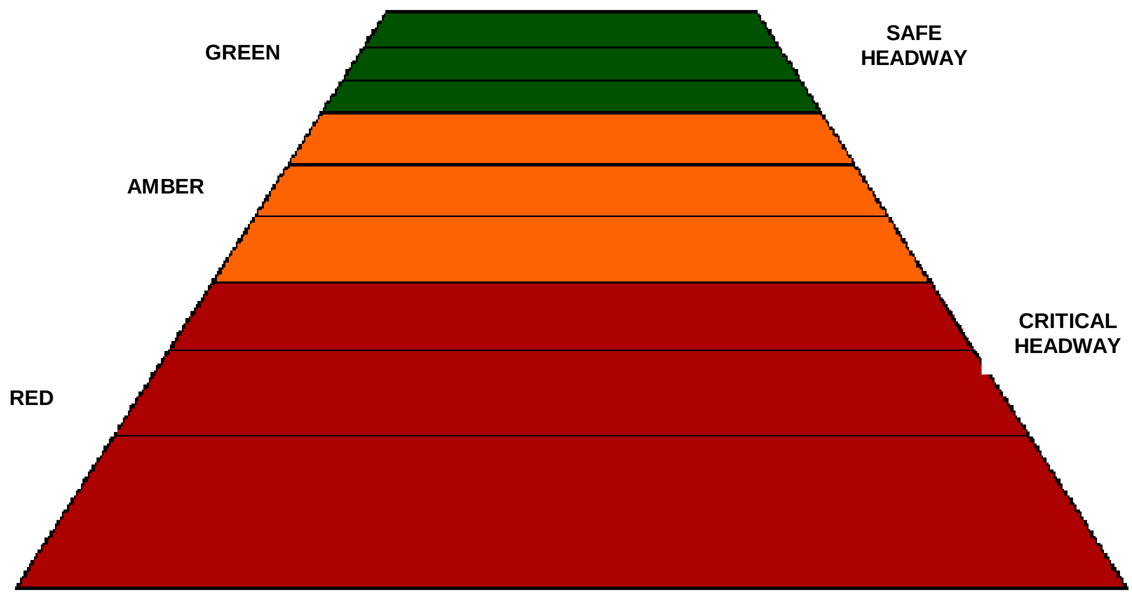

Figure 3. Headway display (adapted from McGehee, Dingus, and Horowitz, 1994).

further research is needed to determine the highest false alarm rate compatible with a good driver response.

MODALITIES CONVEYING INFORMATION

The design of warning systems has long presented a challenge to human factors engineers. The challenge is to adequately warn the operator of an impending situation or hazard without distracting or increasing the workload on the operator (Roland and Moriarty, 1990). ITS technologies have achieved a level of sophistication and usefulness where their integration into the commercial truck cab is now certain. With the introduction of each new technology or device comes the additional need to inform, warn, or notify the driver. Failure to adequately address the mode and format used to convey information to the driver may result in a situation similar to that described by Patterson (1990) in discussing the shortcomings of aircraft auditory warnings: too many sounds, too loud, and too confusing. Fortunately, no research indicates that commercial vehicle operators currently experience the same difficulties encountered by aircraft pilots, but rapid development and implementation of ITS technologies could produce a similar situation if warning system design is not formally addressed.

Warning signals may be conveyed through any of the body's senses, though sight and hearing are the most commonly used (Helander, 1987; Sorkin, 1987). Both modalities have their strengths and limitations; Table 2 lists guidelines for the appropriate use of auditory and visual displays (Deatherage, 1972). As a result of their omni-directional nature, auditory displays are preferred for the presentation of warning messages. However, excessive use of auditory displays in warning systems yield increased operator workload resulting in confusion, and frustration (Patterson, 1990).

Verwey (1991) advocates the development of an algorithm capable of predicting driver workload and only delivering ITS information when the driver is capable of handling the increased demand of workload. While this approach may be useful for auxiliary information such as route guidance and communications technologies, the desirability of such a system in situations involving emergency warnings is questionable given the immediacy of demands placed upon the driver.

Multi-modal displays are displays utilizing multiple information processing channels, presenting the same information to each channel. Multi-modal information is

TABLE 2

Guidelines for Appropriate Visual or Auditory Presentation of Information (adapted from Deatherage, 1972).

Use auditory presentation if:

1. The message is simple.
2. The message is short.
3. The message will not be referred to later.
4. The message calls for immediate action.
5. The visual system of the operator is overburdened
6. The receiving location is too bright, or dark adaptation integrity is necessary
7. The operator's job requires continuous movement.

Use visual presentation if:

1. The message is complex.
2. The message is long.
3. The message will be referred to later.
4. The message does not call for immediate action.
5. The auditory system of the operator is overburdened.
6. The receiving location is too noisy.
7. The job requires the operator to remain stationary.

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likely to increase the salience of a warning. According to multiple resources theory (Wickens, 1992), as workload in one modality increases, delivering additional stimuli through that modality may result in an undesired increase in driver workload. By presenting redundant information to the operator through multiple modalities, it is reasonable to assume the operator will ignore the channel experiencing heavy loading yet detect and use the warning being presented through the alternative channel. The advantages of combined audio and visual (AV) displays are summarized in Table 3 (Kramer, 1994).

Selcon, Taylor, and Shadrake (1992) presented visual-only, auditory-only, or multi-model (both stimuli) warning icons to indicate 'Warning' (high priority) and 'Caution' (low priority) situations in aircraft. Conditions using multi-modal stimuli elicited a significantly faster response time than either auditory or visual stimuli alone. No significant differences were found when comparing the error rates of the three conditions. Subjects also rated the visual-only warnings as being more demanding of their attention than either the auditory-only or mixed-modality displays. The mixed modality display was ranked as being less demanding than the auditory-only conditions, although the difference was not significant. This study demonstrates the ability of multi-modal displays to decrease pilot response times to warning signals; however, no such study has been conducted within the purview of motor vehicles and the results may not be generalizable to the driver population as a whole, let alone to the sub-population of commercial motor vehicle operators.

Visual Channel

Research has shown that an operator's attentiveness to a monitoring task decreases over time. Operator performance is especially poor in situations involving infrequent or low probability signals. Warning signals, by their very nature, occur infrequently. As a result, effective warning systems must be able to attract the operator's attention and identify the problem or the action required to remedy the problem. The warning itself should not be likely to fail; likewise, when activated, the warning should not impair the operator's ability to attend to other duties (Grether and Baker, 1972).

TABLE 3

Benefits of Multiple Modality Displays (adapted from Kramer, 1994).

Quality	Advantage
Non-intrusive enhancement	Augments visual displays without interfering with existing tools and skills.
Superior temporal resolution	Time series data. Shorter duration events can be detected with auditory displays.
High dimensionality	Adds to (and exceeds) dimensionality of visual displays.
Engagement	Decrease learning times, reduce fatigue, and increase operator enthusiasm.
Inter-modal correlation	Reinforcement of sensed experiences.
Synesthesia	Reallocation of inappropriate cues from other sensory channels.

Attracting the operator's attention requires signals that have a high attention value. Visual attention value increases with size, brightness, and motion. Additionally, pulsating displays are more noticeable than static displays.

While there are numerous examples of visual warning displays within commercial vehicles, specifically the gas gauge, high-beam indicator, air pressure status, and multiple temperature gauges (e.g., pyrometer, front and rear axle, transmission), few of these indicators indicate an immediate hazard (Alliance, 1981). Center high-mounted stop lamps (CHMSLs), however, are more demonstrative of a visual warning display occurring within the driver's forward field of view and indicating an impending hazard. Several studies have attempted to demonstrate the effects of center mounted stop lamps (CMSLs) on driver performance (McKnight and Shinar, 1992; Sivak, Post, Olson, and Donohue, 1981; Theeuwes and Alferdinck, 1995).

Theeuwes and Alferdinck (1995) examined the effects of lamp and brake light configuration on reaction time. The simulated driving environment used a full-size plywood automobile rig capable of displaying various brake light configurations. CMSL height was found to be significant with high CMSLs being more effective (lower response times) than low CMSLs. One explanation for the improved performance is that high CMSLs is that higher CMSLs are centered in the driver's field of vision, whereas vehicles lacking CHMSLs or equipped with low-mounted CMSLs located out of a driver's cone of vision require increased scanning of the driving scene, thus resulting in longer reaction times.

Another study evaluated driver response to various vehicle brake lamp configurations, including vehicles with and without supplemental high-mounted brake lamps (Sivak, Post, Olson, and Donohue, 1981). Responses were obtained on-the-road from unsuspecting drivers. Utilizing two test conditions, single and dual high-mounted brake lamps, and a control condition, no high-mounted brake lamps, Sivak and his colleagues found driver response rates significantly greater in both conditions involving high-mounted braking devices. This suggests that drivers are more likely to discern visual warnings which occur within their immediate field of view, i.e., including a visual warning device within the driver's field of view resulted in increased driver response rates. While an increased number of drivers responded to high-mounted brake lights, brake reaction time across the three systems did not differ statistically. Previous and subsequent studies evaluating brake light configuration have yielded statistically significant differences in brake reaction times (Allen Corporation, 1978; McKnight and Shinar, 1992). The reasons for this discrepancy are unclear although it may be explained in part by the presence of many uncontrolled variables influencing the results. These variables are most obvious in the studies involving on-road evaluation where it was impossible for the experimenter to know anything about what was occurring in the subject vehicle during the experiment. For example, when the lead vehicle activated its brake lights, the subject may have had his foot hovering over the brake pedal, the driver's foot may have been resting on the floorboards with the cruise control engaged, or the driver may have already begun lifting his/her foot off the accelerator pedal in order to increase the headway between the two vehicles.

McKnight and Shinar (1992) performed an experiment similar to the aforementioned study performed by Sivek, et al. (1981). McKnight and Shinar attempted to determine the benefit of extending CHMSLs to heavier vehicles, including pick-ups, mini vans, full-sized vans, and straight trucks. Their results indicated a significant difference in following vehicle brake response times for vehicles with CHMSLs compared to vehicles without CHMSLs. Again, driver performance improved when the visual warning stimulus was presented within the driver's cone of vision or immediate forward view.

Assuming high-mounted stop lamps are accurate representations of a visual warning display, results from the preceding studies infer that visual warning displays can be effectively integrated into the motor vehicle. While CHMSLs are located near the center of the forward scene, it may be possible to achieve similar results by implementing dash mounted iconic displays capable of delivering ITS information to the driver, just outside the driver's cone of vision. This may be acceptable in situations not requiring excessive visual workload demands; such situations may necessitate the incorporation of alternative modalities to successfully manage driver workload levels.

Auditory Channel

Auditory warnings can be categorized as either intentional or incidental (Wilkins and Martin, 1987). Intentional warnings are engineered sounds specifically designed to warn. Sirens, horns, simple and complex tones, and speech warnings are all examples of intentional warnings. Incidental warnings, by contrast, are intrinsic sounds sometimes caused by changes in the operating state of a system which warn of an impending or dangerous situation. Examples of incidental warnings include the hissing noise generated by air escaping a punctured tire, the screeching of worn brakes, and the cacophony of a malfunctioning engine or drivetrain. While incidental warnings are of considerable value to a vehicle operator, because they are caused by an event having just occurred, or one that is about to occur they are not especially useful in situations necessitating advanced warning such as collision avoidance situations, and thus they will not be addressed here. Although incidental warnings are limited in their ability to warn the CVO in advance of a critical situation, auditory icons, or non-verbal representational sounds can be used to depict incidental warnings well in advance of an impending critical situation. Auditory icons are charicatures of naturally occurring sounds and differ from traditional non-speech displays in which various sound attributes are defined or manipulated. Auditory icons are defined by the distal stimulus or source of the noise whereas the traditional non-speech displays are defined by psychoacoustic properties. Both types of warning signals will be covered in more detail in a later section.

Auditory displays conveying intentional warnings include both speech and non-speech signals. Table 4 distinguishes between situations appropriate for the use of speech and non-speech signals (Deatherage, 1972).

Speech. Speech displays are often considered a viable alternative to visual displays as a means to reduce visual workload (Sorkin, 1987). In addition to being highly redundant, a major attribute of speech is its tremendous transmission rate, up to 250 words per minute (wpm) in environments where a high signal to noise ratio (S/N) prevails (Deatherage, 1972). Research indicates an operator preference for auditory warning systems which making use of speech signals (Kemmerling, Geiselhart, Thornburn, and Cronburg, 1969). Speech-based warning signals have been found to be

TABLE 4

Guidelines for Appropriate Use of Speech or Non-Speech Auditory Presentation (adapted from Deatherage, 1972).

Use of speech is preferred over non-speech or noise signals in the following conditions:
1. For flexibility.
2. To identify a message source.
3. When listeners are without special training in coded signals.
4. There is a necessity for rapid two-way exchanges of information.
5. The message deals with a future time requiring some preparation.
6. Situations of stress might cause the listener to "forget" the meaning of a code.
Use of non-speech signals is preferred over speech in the following conditions:
1. For simplicity.
2. When listeners are trained to understand coded signals.
3. For designating a point in time that has no absolute value.
4. When immediate action is desired.
5. In conditions unfavorable for receiving speech messages.
6. When security of the message is desired.
7. If speech communications channels are overloaded.
8. If speech will mask other speech signals or annoy listeners for whom the message is not intended.

especially favorable under high workload conditions because they afford the operator flexibility to evaluate the situation prior to responding. Furthermore, speech-based warnings are easily learned and remembered.

Speech displays, while very effective in some situations, are not suitable in all environments or situations. For example, if a warning system uses multiple speech signals, individual warnings may be confused with one another. Speech signals also take a relatively long time to present a simple message or warning. As a result, Patterson (1982) recommends speech signals be used to augment non-speech signals, especially in urgent or imminent situations.

Morrison and Casali (1994) investigated the effect of background truck noise on intelligibility of synthesized speech. Recordings of background noise in new (1993) commercial truck cabs were used to develop a sound field similar to that found in a typical commercial motor vehicle. Using the modified rhyme test (MRT) as the experimental paradigm, an intelligibility score of only 72% was attained at a speech-to-noise ratio of 15 dB. When background speech noise (such as that from the radio or CB) was added, intelligibility dropped to less than 60%. Likewise, hearing-impaired individuals demonstrated decreased intelligibility when compared to normal-hearing individuals. Until intelligibility of synthesized speech improves, results from this research suggest the use of synthesized speech to be less than ideal in the truck cab environment.

Non-speech. Auditory displays are particularly well suited to represent infrequently occurring information where it is necessary to gain the operator's attention. An emergency-vehicle siren is one of the most common auditory warning devices and uses non-speech audio and the conventional "brute force" or "better safe than sorry" approach to warnings (Edworthy, Loxley, and Dennis, 1991; Patterson, 1990). According to Patterson (1990), this sort of warning occurs in environments where sounds are used to identify dangerous or potentially dangerous situations. While signals of this nature are certain to attract attention, Patterson argues the consequences of such alarms, if used excessively, include startled operators and hampered communications at crucial times. These factors lead to high operator annoyance levels causing many operators to disable or turn off alarms (Edworthy, Loxley, and Dennis, 1991; King and Corso, 1993).

Much of the recent research into auditory signals suggests the "brute force" or "better safe than sorry" approach is often unsatisfactory, especially in environments employing multiple auditory warnings (Ballas, 1994). When multiple alarms are necessary, operator confusion can be reduced by using warning signals with distinctive spectral and temporal patterns. Incorporating several different spectral components from throughout the auditory spectrum creates a distinctive sound less prone to operator confusion (Patterson, 1982). A well designed set of auditory displays should be both discernible and discriminable, enabling the use of multiple simultaneous alarms (Patterson, 1982; Sorkin, 1987). While operators have the ability to learn large sets of warning signals, it is often impractical to do so because of the time spent acquiring and maintaining knowledge of the system; current guidelines suggest that a maximum of five or six signals be used (Patterson and Milroy, 1980).

Patterson (1982) proposed several design principles to improve the design of auditory warnings. These design principles are shown in Table 5. The sound pulse, or core, of the warning alarm is interspersed with periods of silence and comprises a sound burst. These guidelines, offered by Patterson (1982) provide an overall structure for the development of warning signals; however, specific design issues remain unresolved. Additionally, when these guidelines were first reported by Patterson (1982), he offered no discussion of experimental results backing his assertions, but subsequent research by Edworthy, Loxley, and Dennis (1991) provided support for these guidelines.

Edworthy, Loxley, and Dennis (1991) used Patterson's design guidelines to investigate the concept of perceived urgency where the most urgent conditions are represented by the most urgent warning signals, and the least urgent signals would represent the least urgent situations. They further refine the definition of bursts and pulses. The sound pulse, generally lasts from 100-300 ms, serves as the core of the warning alarm, has a short onset and offset time, and its harmonic content consists of a fundamental frequency plus several other harmonics. This core, or pulse, is then repeated at several different pitches, at different amplitudes, and with different time intervals separating the core pulse. A series of eight experiments were conducted to determine the effects of varying spectral and temporal aspects on the perceived urgency

TABLE 5

Guidelines for Improving the Design of Auditory Warnings (adapted from Patterson, 1982).

1. Determine the necessary signal sound pressure (SPL) level for the pulse.
2. Develop a pulse lasting from 100 - 300 milliseconds.
3. Include the fundamental frequency and several harmonics in the pulse.
4. In order to reduce operator startle, the sound pulse should be contained within an amplitude envelope making use of a relatively short onset and offset times.
5. Develop a pulse by repeating the pulse several times, each time at a different pitch, amplitude, and with varying time periods between each pulse.

of warning signals. The eight experiments were divided into three major segments; the first and second segments concentrated on the development of the warning pulse respectively while the third segment tested the findings of the two previous segments. Factors manipulated during the first two experiments, development of the warning pulse, included: amplitude envelope, fundamental frequency, and harmonic series.

The amplitude envelope of a pulse directly affects perceived; a quicker onset and offset ramp is perceived to be more urgent than slower onset and offset ramps with a slow onset determined to be more urgent than a slow offset. The fundamental frequency of a warning was also found to have some effect on perceived urgency. Pitch range (large ranges are perceived as being more urgent than shorter ones) appears to be less influential than direction (low pitch rising to a high pitch is perceived as being more urgent than a high pitch falling to a low pitch); the more salient feature of pitch. Unpredictable harmonic series (not equally weighted in amplitude) were rated as more urgent then predictable series (equally weighted in amplitude). Pulse development or the temporal and melodic characteristics of sound, including speed, rhythm, number of pulses, acceleration, pitch range and contour, and musical structure, were evaluated in the following four experiments. Of all the parameters evaluated, speed was found to have the greatest effect on perceived urgency with faster signals being perceived as more urgent than slower ones. Speed was manipulated by increasing or decreasing the time between pulses, or changing the period of the burst without affecting the pulse period. Perception of speed is affected by operator arousal levels and may be of limited use in an applied situation lacking a static metric for comparison. Acceleration (systematically reducing the interpulse time from the beginning until the end of the burst) and deceleration (systematically increasing the interpulse time from the beginning to the end of the burst) of a sound burst also affects perceived urgency and is capable of providing a relative assessment of speed. A regular rhythm is perceived to be slightly more urgent than an irregular rhythm; however, the differences among types of irregularities are not fully understood. Increasing the number of pulses also increases the perceived urgency of a warning, though excessive use results in increasingly long alarms and overly insistent alarms potentially resulting in a high level of operator annoyance.

A large pitch range has been shown to increase a warning's perceived urgency over that of a medium or small pitch range, although a smaller pitch range was determined to be more urgent than a medium pitch range (attributed to atonality). Pitch contour contributed relatively little to perceived urgency making it more useful in signal discriminability than assessment of signal urgency. Finally, when evaluating the musical structure of warning signals, atonal melodic structures were determined to increase a signal's perceived urgency more so than complete or incomplete sounding warning.

The final experiment consisted of ranking 13 auditory warning pulses according to their perceived urgency. Results indicated a high level of agreement among subjects when evaluating the perceived urgency of warnings. Overall, the perceived urgency of a warning appears to increase with unpredictability, or in other words, the less predictable a warning signal appears, the greater its perceived urgency.

Haas (1993) further investigated the assertions made by Patterson (1982) and elaborates on the study conducted by Edworthy, Loxley, and Dennis (1991) by investigating the effects of pulse format, time between pulses, and pulse level on perceived urgency. Pulse format was evaluated at three levels including simultaneous, sequential, and frequency-modulated (saw-tooth) signals, and all signals incorporated frequencies ranging from 500 to 3000 Hz. The time between pulses variable contained three levels ranging from 0 to 300 ms (0, 150, 300 ms). Pulse level was evaluated at rms sound pressure levels of 65 and 79 dBC. Eighteen auditory signals, consisting of eight pulses each, were developed. Each pulse had equal onset and offset times of 25 ms and a duration of 350 ms. Pulse format was found to have a relatively strong effect. Sequential pure tones were perceived as being significantly less urgent than frequency-modulated or simultaneous tones; however, no significant differences were found between simultaneous and frequency modulated tones. Signals with shorter inter-pulse intervals were rated as being more urgent than signals with longer intervals with no time between pulses (0 ms) being the most urgent. Finally, the effect of pulse signal level and perceived urgency yielded a strong positive relationship.

While the studies conducted by Edworthy, Loxley, and Dennis (1991) and Haas (1993) are by no means exhaustive, they provide the fundamental framework for designing non-speech auditory alarms. A summary of the parameters found to have an

TABLE 6

Parameters Affecting Perceived Urgency of Auditory Warning Signals (adapted from Edworthy, Loxley, and Dennis, 1991; Haas,1993)

Parameter	Effect on Perceived Urgency
Fundamental frequency	The change in fundamental frequency is the significant factor since the salient feature of a pitch change is the direction of change rather than the magnitude of change. Higher frequencies elicit a higher perceived urgency.
Amplitude envelope	Shorter onset and offset times are perceived as being more urgent than longer ones.
Harmonic series	Irregularity and unpredictability contribute to urgency in the resulting pulse.
Speed	Faster warning signals increase perceived urgency.
Rhythm	A regular rhythm is perceived to be more urgent than an irregular, syncopated rhythm.
Number of times a pulse is played	Increasing the number of times a pulse is played results increases the perceived urgency of an auditory signal.
Pitch range	A large pitch range is perceived to be more urgent than a small pitch range.
Musical structure.	A pulse with an atonal melodic structure increases perceived urgency.
Pulse level.	The higher the pulse level, the greater the perceived urgency.
Time between pulses	The shorter the interval between pulses, the greater the perceived urgency.

effect on perceived urgency is shown in Table 6 (Edworthy, Loxley, and Dennis, 1991; Haas, 1993).

Both speech and non-speech auditory warnings have shortcomings. While speech is capable of conveying information about the nature of a problem in addition to alerting the user of its occurrence, speech warnings are generally longer in duration than non-speech warnings and have limited effectiveness in environments with a low S/N ratio. Non-speech displays, on the other hand, are capable of functioning in environments with low S/N ratios, are generally shorter in duration than speech displays. Non-speech displays are also capable of providing limited additional information to the operator through coding. Coding enables additional information to be embedded in non-speech audio signals. Perceived urgency is one such example, where in addition to the presence of the alarm, the alarm conveys the seriousness of the impending situation. Coding, however, relies heavily on specialized training to inform the operator of a signal's meaning and are frequently incomprehensible to untrained individuals.

Auditory icons. Auditory icons are caricatures of naturally occurring sounds and differ from traditional non-speech auditory displays in which various sound attributes are manipulated. Instead, Gaver (1986, 1989) proposed using non-speech sounds to map domain-specific events with familiar sounds. Auditory icons are representative audio images capitalizing on an operator's lifetime experiences in everyday listening. Such cues can be used to convey information about a system's status, and because auditory icons build upon everyday sounds, they will be more easily learned and less likely to be forgotten than traditional non-speech auditory displays (Buxton, 1989).

It has been suggested that auditory icons (Gaver, 1986, 1989) could reduce the learning effects of coding while significantly reducing an operator's reaction time. Auditory icons are based on a theory of sound resources. Conventional non-speech warning signals rely on an operator's interpretation of the psychophysical properties of the sound, whereas with auditory icons, what an operator believes produced the sound is of primary importance.

Matching system states with appropriate auditory icons, or similar auditory cues, requires careful design and testing if the auditory icons are to serve as effective warning signals (Buxton, 1989). A series of five experiments was conducted by Ballas (1993) to evaluate the acoustical, ecological, perceptual, and cognitive factors common in identifying 41 sounds. Of particular interest to this study were the acoustical and ecological factors of sound identification. Acoustic variables were determined to be influential when evaluating accuracy (correct response) and the identification time of sounds. Ballas found that combinations of acoustic variables, including spectral (1/3 octave band analysis) and temporal (number of pulses, duration of pulses, and ratio of pulse duration to total duration) measures, yielded the best results. High ecological frequency, or how often the sound appears in nature, was found to enhance identification of a sound; however, it did not reduce the speed of sound identification. Effective use of auditory icons, in their pure form, relies on accurate interpretation and identification of the source. Employing auditory icons as warning signals requires not only high accuracy but a short identification time. Table 7 shows selected information for some of the 41 sounds used by Ballas (1984).

Overall, there is a paucity of research in the areas of widespread everyday sound identification and implementation of auditory icons as warning devices. The research conducted by Ballas (1993) is the first to address the issue of widespread ‘everyday’ sound identification; previous research concentrated instead on specific types or groups of sounds. As a result, there is a lack of information on the identifiability of brief everyday sounds. Additionally, no research exists correlating these sounds to various system states in automobiles or commercial motor vehicles, a critical piece of information if auditory icons are to be used as warning systems in motor vehicles. Finally, only two studies have evaluated auditory icons as warning devices (Graham, Hirst, and Carter, 1995; Haas and Schmidt, 1995).

Haas and Schmidt (1995) compared auditory icons and pure tone signals as warning and advisory signals in the U.S. Army Battlefield Combat Identification System (BCIS). The BCIS is designed to reduce the number of ‘friendly-fire’ casualties, and provide target information to troops. The selection and identification of auditory icons was accomplished through ‘expert opinion’; none of the individuals serving on the selection committee were end-users of the BCIS system. Five different auditory icons, chosen during pre-testing because of their high level of functional association, were selected to represent five different signal functions. These include: a doorbell (target

TABLE 7

Sound, Description, Mean Identification Time (MIT, in Milliseconds), and Accuracy of Identification Responses of Selected Sounds (adapted from Ballas, 1994).

Sound	Description	MIT	Accuracy
Telephone ring	High-pitched ringing	1,253	0.90
Car horn	Single medium pitch horn	1,611	1.00
Doorbell	Two chimes, first higher pitched	1,642	0.96
Water drip	Single water drip	1,831	0.91
Church bell	Two high-pitched bells	2,614	0.82
Toilet flush	Toilet flushing water	2,779	0.65
Door opened	Metallic door latch opening	3,335	0.48
Car ignition	Three engine rotations	3,802	0.30
Cork popping	Single pop	4,296	0.22
Door closed	Two muffled impact noises	4,372	0.52
Car backfire	One explosive backfire	4,610	0.04
Gunshot outdoors	Single shot with echo	5,240	0.25
Light switch	Two clicks of chain switch	6,022	0.18
Stapler	Slightly muffled impacts of stapler	6,055	0.06
Electric lock	Buzz followed by lock opening	6,823	0.44

identified as friendly, don’t shoot); two rapidly oscillating dissonant sweeps (target identity unknown, you may have to shoot); submarine sonar (the BCIS user is being interrogated by another unit using BCIS); two sequential chords (sighted target identified as hostile; however, friendly forces are in the same sector); and a slow downward sweep (system non-functional). Ten auditory signals, five pure tone signals and five auditory icons were tested at an rms sound pressure level of 65 dB, approximately 30 dB above the ambient (quiet) level of the test booth. Twenty U.S. Army Infantrymen, all male, estimated the degree of association of the signal with its intended function.

Results indicated only one situation (friend in sector) where the auditory icon provided a significantly greater association to the intended function than the respective tonal signal. The remaining situations showed no significant differences in association between the auditory icons and conventional displays. However, participants also indicated that the ‘doorbell’ auditory icon used to indicate friendly forces was inappropriate for a military system. One additional factor noted by the experimenters which may partially explain the lack of subject approval for auditory icons was the complexity of the intended signal functions themselves. Conveying information that a BCIS user is being interrogated by another BCIS user or system represents one such instance where complex concepts were communicated by a single signal function. They suggest further research to explore the ability of auditory signals to represent conceptually complex functions.

The study conducted by Haas and Schmidt (1995) yielded mixed results, but proposes several questions regarding the use of auditory icons as warning signals. How were the auditory icons selected? Aside from identifying that the selection process was accomplished through ‘expert opinion’, no information is available regarding the procedures by which the auditory icons were selected. Additionally, would the same results prevail with increased workload? The testing environment was relatively sterile, lacking the workload expected in a battlefield situation. Clearly, further investigation is necessary.

Graham, Hirst, and Carter (1995) compared the use of auditory icons to conventional and speech signals for use in collision avoidance warnings. Video sequences of actual driving footage representing a vehicle traveling at 30 mph were presented to twenty-four subjects controlled for age and gender. The driving footage was presented to the subjects while they were seated in a stationary experimental vehicle and engaged in a simultaneous head-down tracking task. Auditory warnings (a 600 Hz tone, the single word "ahead," and two auditory icons: a car horn and the sound of skidding tires) were presented at random intervals. Upon hearing a warning signal, subjects were instructed to look up at the driving scene and to depress the brake pedal as soon as possible, if a collision was judged to be imminent. Three different potential collision scenarios were evaluated: left-hand pull-out, right-hand pull-out, and a stopped vehicle in the roadway. A fourth ‘dummy’ scenario presented a situation in which no collision was imminent. All of the auditory warnings were the same length (0.7 seconds) and were presented at comparable sound pressure levels (59 to 63 dB). Background engine noise was presented at approximately 50 dB.

Results indicated both auditory icons (tire skid, horn) resulted in a braking time approximately 100 ms faster than the conventional warnings (speech, horn). The auditory icons, however, also resulted in more false positives (depressing the brake pedal when no collision was imminent) than did the conventional warning signals. For right and left pull-out situations, subjective responses favored the horn, ranking it significantly higher than the tire skid, speech, or tonal signal. Subjective evaluation of the warning signals suggested that the tire skid was disliked not because of its nature but because of the quality of the sound recording. Speech was rated as the most appropriate warning for situations in which there was a stationary vehicle ahead. The authors suggested this may not have been wholly accurate, because while many subjects felt the speech warning to be appropriate to the situation presented in the experiment, they did not necessarily feel it was appropriate for all headway obstructions. Although their results generally supported the use of auditory icons in the driving environment, some subjects reported that the auditory icons were confusing and excessively urgent. The authors did not elaborate on the method used to select the auditory icons.

RESEARCH OBJECTIVES

The integration of ITS technologies into commercial motor vehicles is inevitable. These emerging technologies are designed with the well-placed intention of reducing driver workload and improving the overall quality of the driving task. Each technology is also replete with individual displays vying for the driver's attentional resources. *This multitude of displays could potentially result in driver overload if the issues of display design and modality allocation are not adequately addressed.*

The increasing traffic volume on America's roadways gives added importance to the development of effective collision avoidance systems. When effectively implemented, these systems will reduce the likelihood of a collision by maintaining constant surveillance of the area immediately surrounding the vehicle. Two types of collisions, front-to-rear and lane change, which comprise almost 30% of vehicle accidents annually (Knipling, 1995) and are particularly well suited for inclusion in collision avoidance technologies. While only a fraction of the accidents involve commercial motor vehicles, given their increased size and mass, collisions involving medium and heavy trucks are generally more severe than those involving passenger vehicles (NHTSA, 1996). Further, combination-unit commercial vehicles are likely to be involved in a larger number of expected collisions over their operating life than passenger vehicles (U.S. Department of Transportation, 1993b). These factors highlight the importance of incorporating collision avoidance technologies in commercial vehicles.

The preceding discussions make evident the dearth of research concerning the use of auditory icons and mixed modality displays as warning devices. Further, no published research exists which discusses the application of these warning methods to commercial motor vehicles. The use of auditory icons as warning signals has only recently been proposed. As a result, only two studies have addressed this issue (Haas and Schmidt, 1995; Graham, Hirst, and Carter, 1995). Additionally, while multi-modal displays have proven effective in the aircraft cockpit (Selcon, Taylor, and Shadrake, 1992), their usefulness within commercial motor vehicles has not been investigated. The voids in previous research suggest a particular need for study of auditory icon selection and warning display effectiveness for front-to-rear and lane change collisions in commercial motor vehicles.

Failure to accurately interpret or identify the source of an auditory icon greatly reduces its effectiveness. Therefore, identifying a process to select and identify auditory icons is necessary in order to increase the accuracy by which the auditory icon is identified. Neither of the experiments utilizing auditory icons as warning signals (Graham, Hirst, and Carter, 1995; Haas and Schmidt, 1995) elaborated on the method of auditory icon selection. Haas and Schmidt used ‘expert opinion’; however, none of the individuals serving on the selection committee were end-users of the BCIS system. Graham, Hirst, and Carter also did not explain how the auditory icons used in their study were selected.

The primary objective of the experiment described in the following sections was to examine the effectiveness of different displays, including auditory icon and mixed modality displays, as warning devices for a simulated commercial truck driving task. With the ever increasing workload demands placed on the driver, it is important to explore alternative modalities when presenting information, thereby enabling drivers to better manage their attentional resources. Secondary objectives of the study were to evaluate the effects of vehicle speed, headway (for front-to-rear collision scenarios), and driver workload (for lane change collision scenarios) on the presentation of collision avoidance warnings. The purpose of this evaluation was to provide a usable description of the variables affecting the driver’s reaction to the presentation of collision avoidance warnings.

The experiment described herein was preceded by a pilot study (Belz, Winters, Robinson, and Casali, 1997a; 1997b) designed to elicit drivers’ interpretations of various auditory icons. The primary goal of the pilot study was directed towards developing a meaningful set of auditory icons. Specific attention was given to determining an auditory icon’s perceived meaning and urgency as it applies to the driving environment. The secondary goal of the pilot study was to develop a methodology for determining an auditory icon’s perceived meaning and urgency. Several researchers (Gaver, 1989; Graham, Hirst, and Carter 1995; Haas and Schmidt, 1995) have reported the potential benefits of auditory icons; however, no one has developed a rigorous methodology for identifying an auditory icon's perceived meaning. Until now, researchers have primarily relied on one form or another of expert opinion to assign meaning to their auditory icons. The pilot study filled this void by developing an empirical research methodology for assigning meaning and urgency to auditory icons.

EXPERIMENTAL METHODOLOGY

The main experiment described herein was comprised of two smaller studies directed at evaluating the effects of different measures on front-to-rear and side collision avoidance. Each of these studies was comprised of multiple scenarios; each scenario corresponded to a singular combination of treatment conditions. Scenarios from both the front-to-rear and side collision avoidance were intermixed and presented randomly to the participants.

Front-to-Rear Collision Avoidance

The front-to-rear collision avoidance study utilized a three-way, within-subject design examining the following independent, fixed-effects variables; Display Presentation Mode (6 levels), Vehicle Speed (2 levels), and Vehicle Headway (2 levels). Subjects were treated as random-effects variables. A complete factorial design (24 treatment combinations) resolved all main effects and interactions in an analysis of variance (ANOVA). The 24 treatment combinations were each presented once. Figure 4 portrays the experimental design graphically.

Display presentation mode. The display presentation mode variable consisted of no display, dash-mounted visual display, conventional auditory warning signal, auditory icon warning signal, mixed modality 1 (dash-mounted visual display and conventional auditory warning signal), and mixed modality 2 (dash-mounted visual display and auditory icon). The presentation and timing of the display presentation mode variable levels were controlled through the use of digital output signals embedded within the simulation program to ensure uniform presentation to all participants.

The dash-mounted visual display consisted of an iconic display of a commercial vehicle with a red trapezoid warning indicator located forward of the vehicle. The light, disengaged during travel where adequate headway is maintained, flashed intermittently at a rate of 2-4 Hz when activated by critical headway. Figure 5 shows a graphical representation of the display; Figure 6 shows the placement of the visual display.

The conventional auditory warning chosen for use in this experiment followed the design recommendations proposed by Haas (1993). The conventional auditory warning

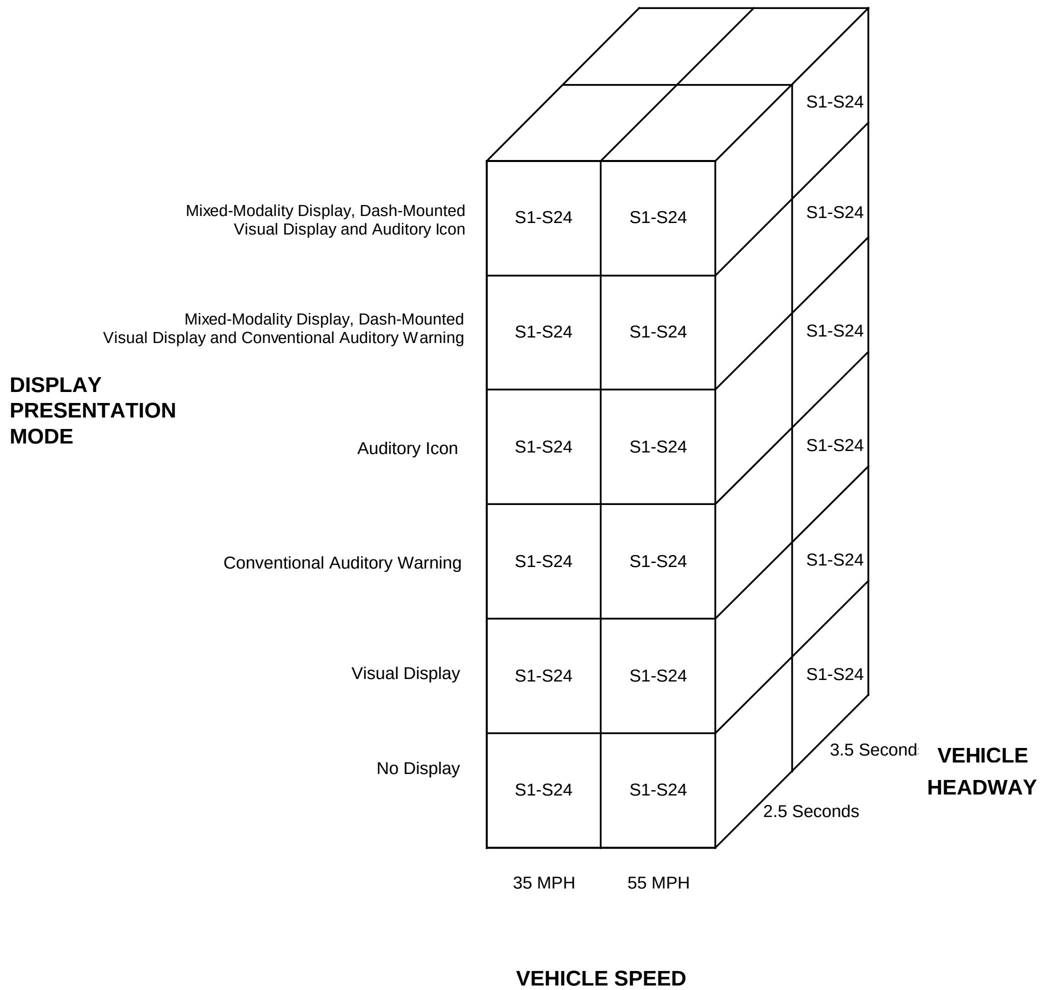


Figure 4. Front-to-rear collision experimental design matrix.

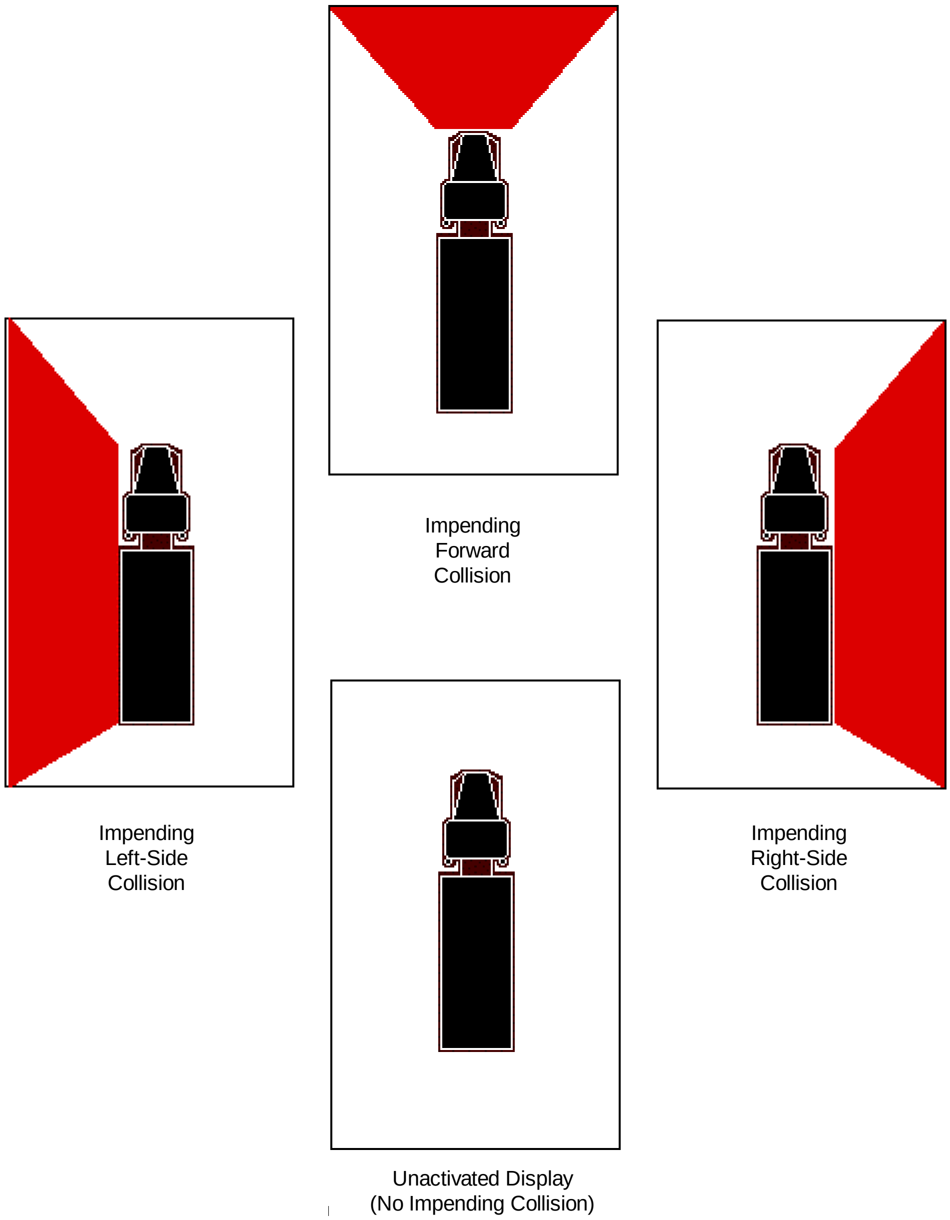


Figure 5. Dash mounted visual iconic display.

Figure 6. Placement of dash-mounted visual display.

was a multi-tone signal with four concurrent components; the signal consisted of four pure tones at 500, 1000, 2000, and 3000 Hz presented concurrently during one pulse duration (0.35 seconds). The warning signal was comprised of two pulses, separated by 0 seconds, for a total duration of 0.70 seconds. This signal was chosen for inclusion because previous research identified it as being relatively urgent (Edworthy, et al. 1991; Haas, 1993).

The auditory icon warning was selected on the basis of results from previously conducted research (Belz, Winters, Robinson, and Casali, 1997a; 1997b). The auditory icon chosen to represent an impending forward collision was that of a tire skid. The duration of the signal was 0.70 seconds. This signal was chosen because the aforementioned pilot study identified it as being relatively urgent while having a high level of association with inadequate headway or an impending forward collision.

Vehicle speed. Vehicle Speed was manipulated at two levels. The slower of these speeds was 35 miles-per-hour, corresponding to in-town driving. The higher speed, 55 mph, represented interstate driving.

Vehicle headway. Vehicle Headway was also manipulated temporally at two levels. Current guidelines for implementing collision warning systems into automobiles suggest that while traveling at normal, legally posted speed limits, a headway of 1.5 seconds is adequate to avoid collisions (NHTSA, 1993); Triggs and Harris (1982) support this guideline as their research found very few drivers reacted to a lead vehicle's brake lamps for headways exceeding 1.4 seconds. No similar research exists for commercial vehicles which, as a result of their dynamics, require greater headway than automobiles. Temporal, as opposed to the more conventional distance, manipulation of headway is preferred in this experiment as previous research has already established that a fixed-distance headway range would lead to excessive false alarms resulting in driver annoyance and dissatisfaction (U.S. Department of Transportation, 1993). As a vehicle's velocity increases, front-to-rear collision warnings must compensate by increasing their forward-scanning distance. A 2.5. second headway, for example, a vehicle traveling at 35 mph would have a forward-scanning distance of 128 feet while a vehicle traveling at 55 mph would require a forward-scanning distance of 202 feet. This established, there has been little research on the temporal timing of such warnings; just how far forward does the collision warning system need to scan to be effective? Manipulating vehicle headway temporally will begin to address this question. Taking into account the additional headway required for commercial vehicles, headway was manipulated at 2.5 and 3.5 seconds.

Dependent measures. Measuring the effectiveness of the collision avoidance system requires the measures of the likelihood of accurate driver response and latency of response. According to Tijerina (1995) the best measure of a collision avoidance system's effectiveness, assuming the vehicle operator fully and accurately complies with the warning, is that of brake response time. In order to gain a full understanding of how the various measures affect the dependent measure, braking response was further divided into four distinct and easily measured component intervals: initial response time, accelerator release time, accelerator-to-brake travel time, and brake depression time. Figure 7 shows a hypothetical graph of brake response time subdivided into its component intervals.

Lane Excursion Collision Avoidance

The lane-excursion collision avoidance portion of the experiment utilized a five factor fractional-factorial design with two levels of each factor. A one-half replicate of a 2^5 fractional-factorial design (16 treatment combinations) resolves all main effects and two-way interactions involving the auditory display independent measure in an analysis of variance (ANOVA). Resolving all main effects and two-way interactions would have resulted in a saturated design; therefore, it was decided to resolve only those two-way interactions involving the Auditory Display independent variable. Independent variables include; Dash Mounted Iconic Display, Mirrors, Auditory Display, Vehicle Speed, and Workload. Figure 8 shows the experimental design graphically.

Dash mounted iconic display. The dash mounted display chosen for this portion of the study was an extension of the display used in the front-to-rear collision avoidance study. The display was Boolean in nature and was either present or not present. The display consisted of an iconic display of a commercial vehicle with dual red trapezoids located on either side of the vehicle, corresponding to impending left and right collisions.

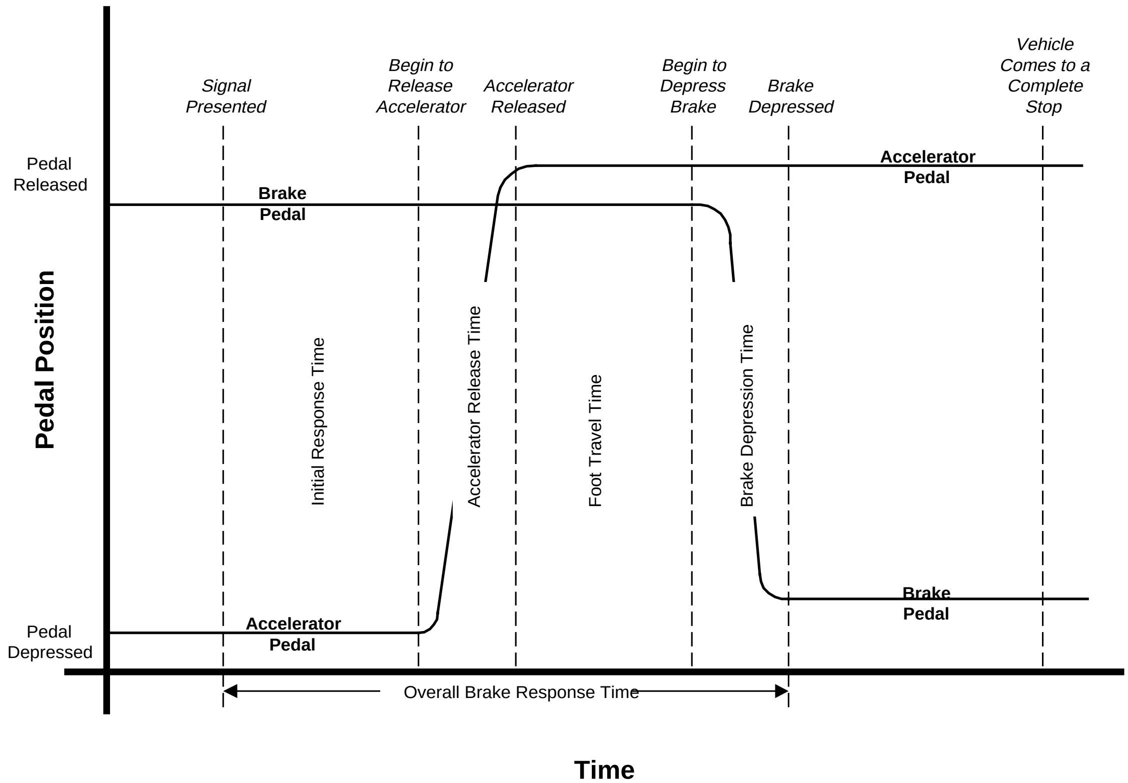


Figure 7. Hypothetical graph of overall brake response time subdivided into component intervals

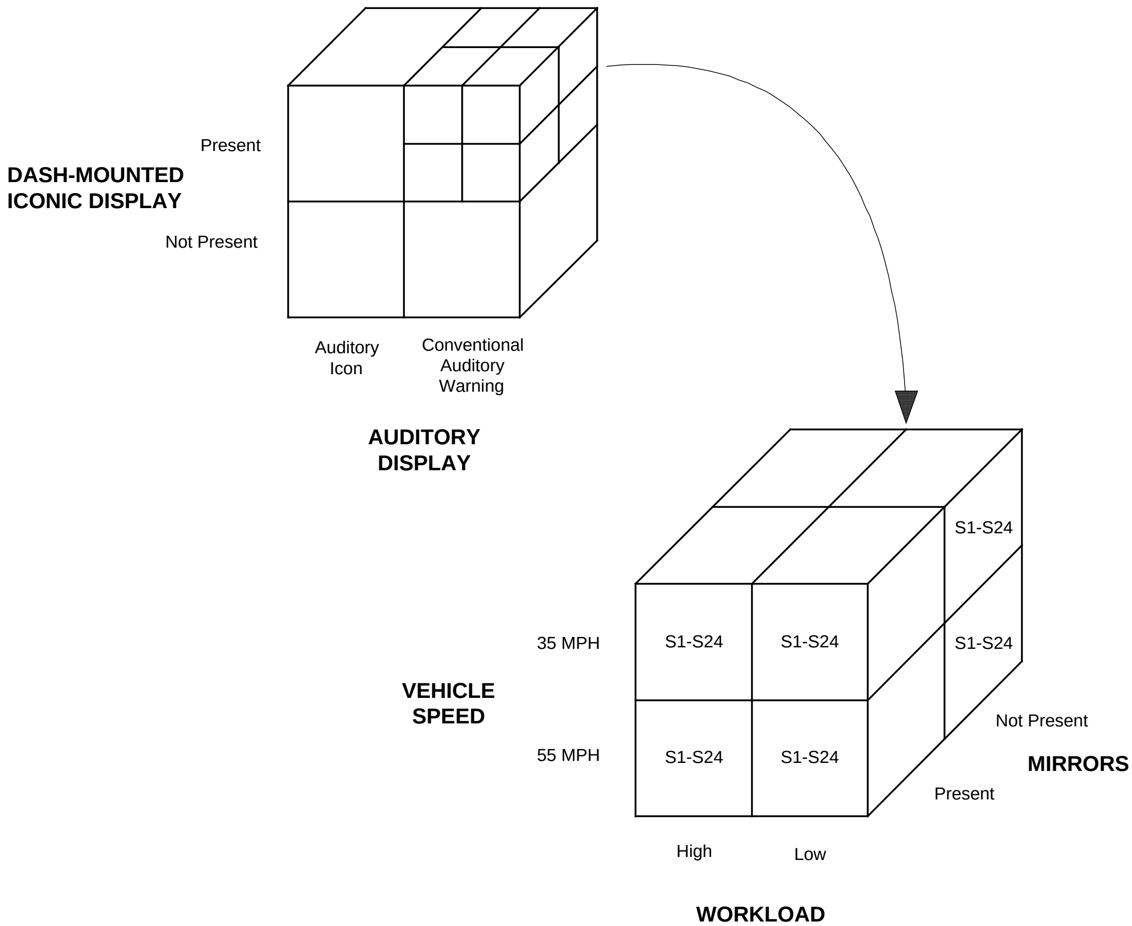


Figure 8. Lane excursion collision experimental design matrix.

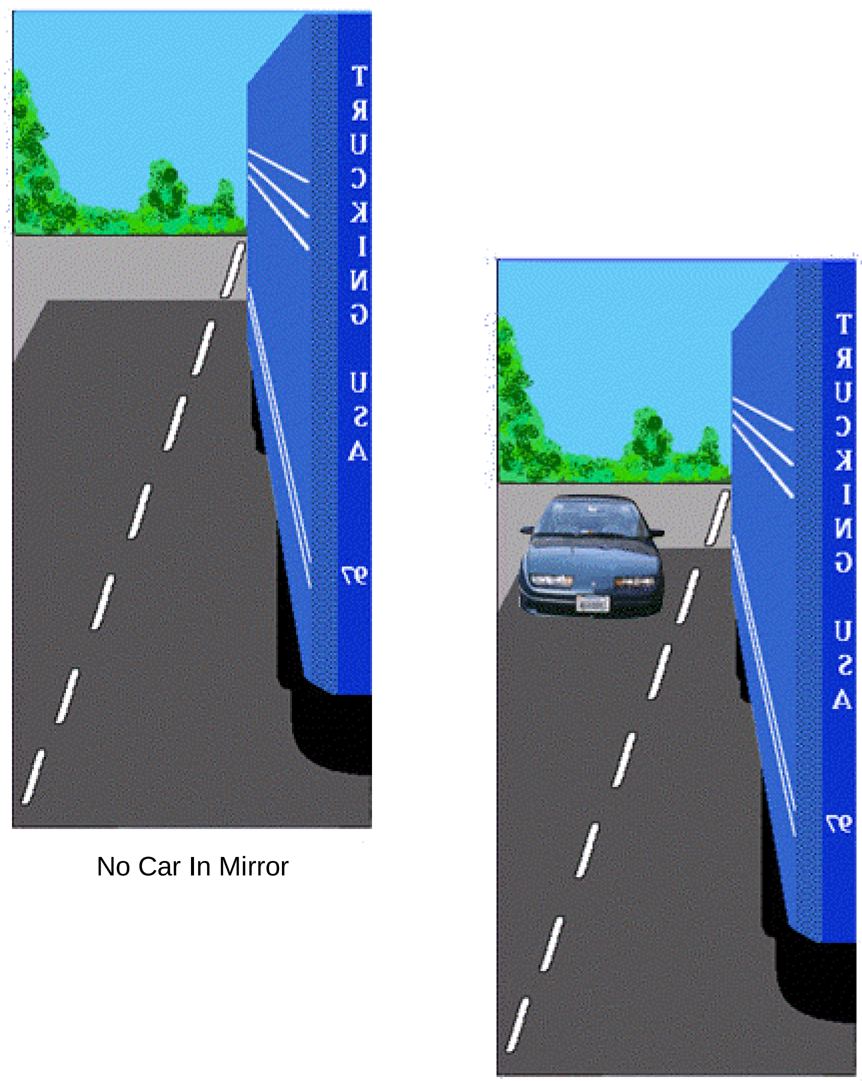
The iconic display was off unless the area on either side of the vehicle was occupied and the driver indicated an imminent lane change. Figure 5 shows a graphical representation of the display; Figure 6 shows the placement of the visual display.

Mirrors. The mirrors, like the dash-mounted iconic display independent variable, were Boolean in nature and were either present or not present. The simulator was equipped with side mirrors, similar to those found on commercial vehicles. These mirrors were adapted to allow the simulator to control the display of a vehicle alongside a truck. Figures 9 and 10 show the driver and passenger side rectangular mirrors, respectively. Figure 11 shows the smaller, convex mirrors.

Auditory display. Two types of auditory displays were used, an auditory icon and a conventional auditory warning signal. The conventional auditory warning used in this experiment followed design recommendations proposed by Haas (1993). Consisting of a ‘sawtooth’ waveform, the conventional auditory warning was a frequency modulated signal comprised of a 500-Hz pure tone carrier with a positive sawtooth function frequency-modulated over one pulse duration (0.35 seconds). The warning signal was comprised of two pulses; 0 seconds separated the pulses for a total duration of 0.70 seconds. The signal was chosen for inclusion because previous research identified it as being relatively urgent (Haas, 1993).

The auditory icon warning used in this experiment was selected on the basis of results from the previously conducted research (Belz, Winters, Robinson, and Casali, 1997a; 1997b) identifying it as having a high level of association to an impending collision. The auditory icon chosen was that of a long honk. The duration of the signal was 0.70 seconds. The signal was chosen for inclusion because the aforementioned study identified it as being relatively urgent while having a moderately high level of association with an impending collision and the need to pay more attention to the driving task.

Vehicle speed. Vehicle speed was manipulated at two levels in order to determine if vehicle speed had an effect on side collision avoidance. The slower of these speeds was 35 miles-per-hour, corresponding to in-town driving. The higher speed, 55 mph, represented interstate driving.



No Car In Mirror

Car In Mirror

Figure 9. Rectangular side-mounted mirrors-driver's side.

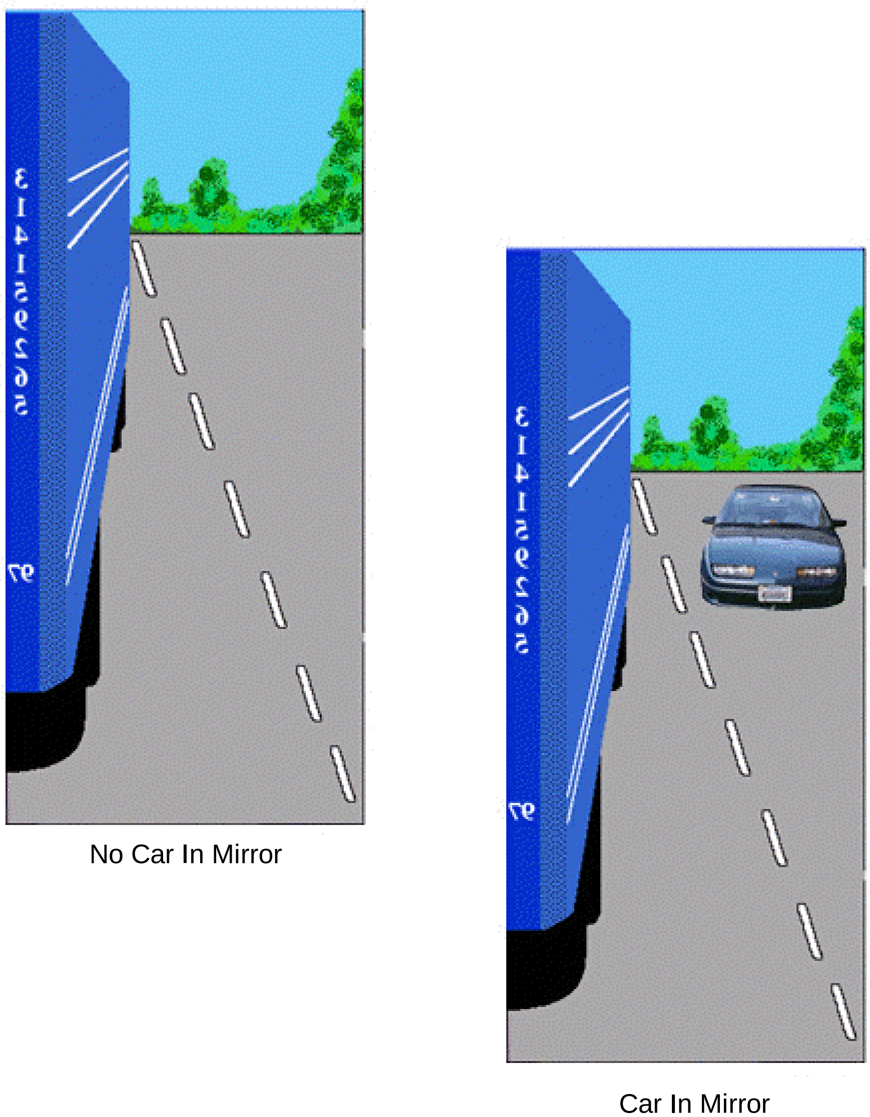


Figure 10. Rectangular side-mounted mirrors-passenger’s side.

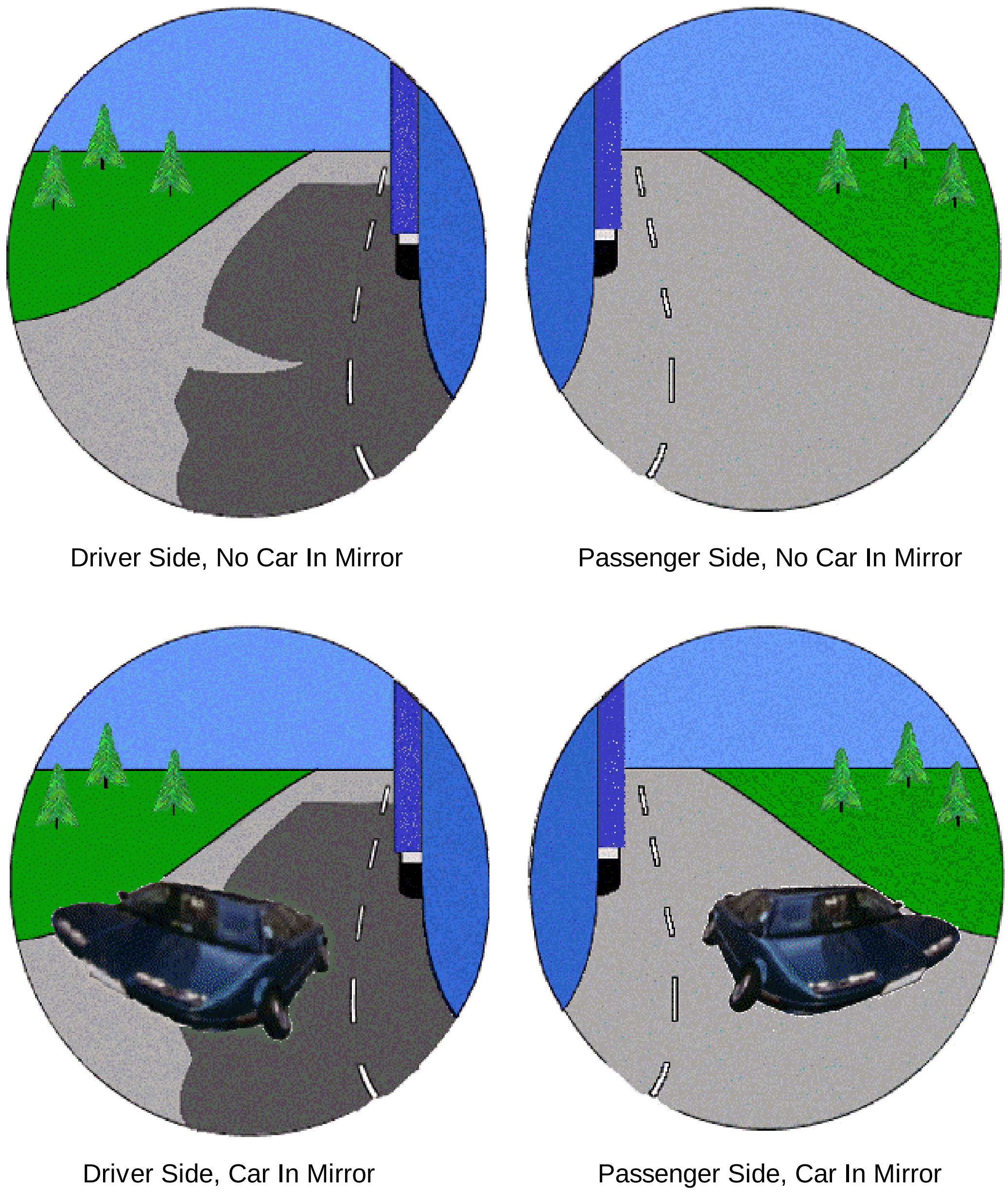


Figure 11. Convex side-mounted mirrors.

Driver visual workload. Two levels of driver visual workload were presented to determine if forward visual workload had an effect on side collision avoidance. High workload was portrayed by increasing the complexity of the forward visual scene (e.g. traffic density, curves, number of intersections, and buildings) while low workload had fewer objects in the forward visual scene (Liu, 1996).

Dependent measures. Lane excursion collision avoidance has been less thoroughly investigated than front-to-rear collision avoidance, and therefore, appropriate dependent measures are not well defined. Unfortunately, while brake response time is appropriate for forward-impending collisions, it is not as well suited as a side collision metric. As a result, one of the most widely accepted metrics of driver performance, the occurrence of accidents, was used. Accident occurrence was determined using data from the simulator.

Treatment Condition Presentation

As previously mentioned, the main experiment was comprised of two smaller studies designed to evaluate the effects of different measures on front-to-rear and side collision avoidance. Each of these smaller studies were comprised of multiple scenarios; each scenario corresponded to a singular combination of treatment conditions. The front-to-rear collision avoidance study was comprised of 24 scenarios (treatment conditions) while the side collision avoidance study was comprised of 16 scenarios (treatment conditions). Twenty scenarios lacking an imminent collision were developed to reduce the vehicle operator’s expectation of a collision situation. Scenarios varied in length from 30 seconds to two minutes. To reduce ordering effects, scenarios were intermixed and presented randomly.

Participants

Twenty-four licensed male commercial truck drivers participated in the study. The mean age of the participants was 31 (range: 19 to 51). Participants’ commercial truck driving experience ranged from six months to thirty years with a mean of seven years. Seventeen of the twenty-four participants possessed Class A licenses, while the remaining possessed Class B licenses. When driving, participants averaged in excess of 1700 miles per week on the job. Only male drivers participated in the study as an estimated 86.8% of all commercial motor vehicle operators are male (Kinghorn and Bittner, 1993).

Pilot Study

A pilot study preceded the main experiment (Belz, Winters, Robinson, Casali, 1997a; 1997b). The purpose of the pilot study was to overcome some of the difficulties encountered by previous researchers in identifying and selecting candidate auditory icons. This was accomplished through developing a rigorous process for selecting and evaluating auditory icons for use in commercial motor vehicles. The resulting process involved utilizing end-users, in this case commercial vehicle operators, to evaluate candidate auditory icons in three areas; perceived meaning, perceived urgency, and perceived association with an experimenter-chosen meaning. The informed consent forms for the auditory icon pilot study is included as Appendix A; results and relevant discussion are included as Appendix B.

Experimental Apparatus

The study was conducted using the Commercial Vehicle Driving Simulator Facility housed in a specially prepared room of the Auditory Systems Laboratory located in the Human Factors Engineering Center at Virginia Tech. The simulator facility is housed in two rooms; the experimenter's station (Figure 12) and simulator room (Figures 13 and 14) are located in adjacent rooms and the simulator is visible from the experimenter's station via one-way glass. Two-inch thick Sonex sound-absorbing foam was used to manipulate the acoustical parameters of the simulator room to match those found within a commercial truck cab (Morrison and Casali, 1993). Truck noise was presented through a pair of Infinity SM-155 speakers. Auditory warning signals were presented through a pair of Optimus XTS-3 speakers located on either side of the headrest; directional auditory presentation was used for the lane-excursion study (Micheal, 1995).

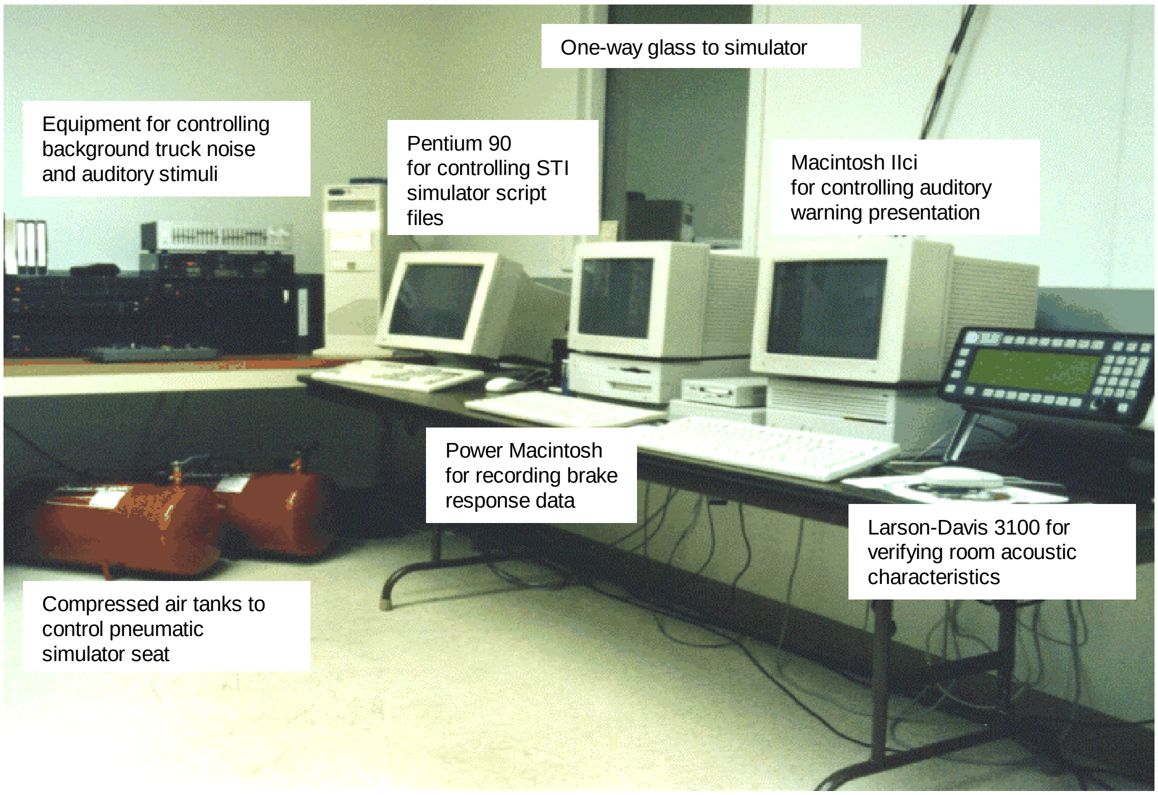


Figure 12. The commercial vehicle driving simulator facility -- experimenter's station.

Figure 13. Side View of the commercial vehicle driving simulator facility -- participant's station.

Figure 14. Overhead view of the commercial vehicle driving simulator facility -- participant's station.

The Commercial Vehicle Driving Simulator itself is a modified Systems Technology Incorporated (STI) low-fidelity, fixed-base driving simulator. The simulation software runs on a 90 MHz Pentium-based computer while the driving scene is presented on a 21-inch monitor. The physical configuration of the simulator buck (seat, steering wheel, monitor, and accelerator and brake pedals) have been adjusted to represent the physical arrangement of a typical commercial truck. The STI simulator software is also configured to represent the control/response characteristics typical of commercial tractor-trailer vehicles (Table 8). The simulator scenario definition language was used to program each of the treatment conditions. These events included pedestrians, stopped and oncoming traffic, construction barrels, and traffic signs. Digital input and output events were used to control the timing and presentation of auditory and visual warning signals. The definition language allowed a variety of dependent driving measures (e.g. vehicle heading angle error, lateral lane position, steering wheel angle input, turn signal indicator, collisions, velocity, and acceleration) to be recorded for later analysis.

The computer running the simulator software also controlled a Power Macintosh via digital I/O. The Power Macintosh, utilizing data acquisition software developed in-house, was used to collect brake response times. Output from the optical encoders attached to the brake and accelerator pedals were input to the Power Macintosh through a National Instruments NB-TIO-10 digital I/O computer board. Pedal position was taken at a rate of 250-333 Hz. Knowing the position of the pedals made it possible to accurately determine the driver’s brake response time as the data clearly delineated exactly when the driver began to release the gas pedal, when his foot left the gas pedal, how long it took his foot to travel to the brake, when he began depressing the brake pedal, and when the pedal was completely depressed.

Each of the warning signals were recorded digitally as Macintosh sound resource files. A third computer, a Macintosh IIci, received digital output from the computer running the simulation software and presented the warning signals via digital audio output. The signals were then passed through an AudioControl octave band equalizer and amplified using an Adcom GFP-55II pre-amplifier and an Adcom GFA-545A

TABLE 8

GAINS File Parameters Changed to Correspond with Commerical Motor Vehicle Handling Characteristics.

Gains File Parameter	Automobile (Default) Settings	Commercial Vehicle (Truck) Settings
1. Oversteer, Understeer Coefficient	0.0003	0.000015
2. Yaw Error Instability (Causes Vehicle Drift)	0	0.3
3. Speed Integration Instability (Causes Speed Fluctuation)	0	0.00025
4. Steering Sensitivity (Yaw Rate/Wheel Angle)	0.0005	0.000075
5. Steering Gain	0.0265	-0.06584
6. Drag Coefficient	0.0005	0.00005
7. Maximum Longitudinal Acceleration Limit	0.4	-0.6
8. Torque Feedback Parameters (Torque Motor Steering Wheel)	See a through i below	
8.a. Lateral Acceleration Torque Brake (ft-lbs)	175	0.50
8.b. Speed Torque Break (ft-lbs)	200	4
8.c. Initial Lateral Acceleration Torque (ft-lbs/ft/sec^2)	10	1
8.d. Assisted Lateral Acceleration Torque Gain (ft-lbs/ft/sec^2)	5	0.25
8.e. Stiction Torque Break (ft-lbs)	2	0.085
8.f. Maximum Continuous Motor Force (ft-lbs)	250	10
8.h. Torque Transition Speed (ft/sec)	20	5
8.i. Steer Damping Gain ((ft-lb-sec)/degree)	0.50	0.01
9. Driver Eye Height Above Road Surface (feet)	3.5	7.33

amplifier combination. Output from the amplifier was directed to two Optimus XTS-3 speakers located behind and to either side of the participant's head.

Experimental Procedures

Re-calibration. Prior to each experimental session, it was necessary to adjust the sound parameters of the room to represent those of a commercial truck cab. Two-inch thick Sonex™ sound-absorbing foam and speaker location were manipulated to modify reverberation time of the simulator facility to match that found within a typical commercial truck cab (Morrison and Casali, 1993). Table 9 shows the reverberation times found within the truck cab and the room containing the commercial vehicle simulator.

The truck cab noise used for the experimental background noise was recorded in a 1995 GM-Volvo extended sleeper tractor equipped with a Caterpillar 3406 engine while traveling 55 mph on a straight section of highway. The noise was recorded using a Sony Digital Audio Tape-recorder (DAT) TCD-D10 Pro II. In order to achieve the most consistent background noise, a 15-second segment of the original recording was digitally reproduced into a 45-minute sound file. The file was then recorded onto an analog tape for use in this experiment.

Truck noise was presented at the same level (74.9 +/- 0.5 dBA) as was measured in the on-road tests. Two Infinity Model SM 155 loudspeakers were used to present the recorded truck noise; they were positioned in the room to create a diffuse sound field around the head of the driver. Prior to each participant's arrival, the sound level in the simulator facility was set using a Larson Davis 3100D RTA in order to ensure that the noise presented was consistent across all experimental sessions. The presentation levels of the auditory warning signals were adjusted digitally to ensure that they were perceived to be equally loud. Volunteers (not commercial vehicle operators) performed an exhaustive paired comparison evaluation of the randomly presented warning signals. Signal levels were adjusted between participants until five consecutive participants concurred that the signals were perceived to be equally loud.

TABLE 9

Truck Cab and Experimental Room Reverberation Times

Octave Band (Hz)	Conventional Cab T60 (s)	Cab-over-engine T60 (s)	Experimental Room T60 (s)
63	0.29	0.39	0.34
125	0.26	0.23	0.29
250	0.16	0.16	0.36
500	0.16	0.16	0.17
1000	0.15	0.16	0.19
2000	0.16	0.16	0.18
4000	0.16	0.16	0.15
8000	0.15	0.16	0.14

Appropriate warning signal level was calculated pursuant to ISO 7731 (1986). Table 10 shows the resultant masked threshold values for the background truck noise. In accordance with ISO 7731 (1986), the sound level of the warning signal exceeded the masked threshold values by at least 13 dB in at least one 1/3 octave band ranging from 300 to 3000 Hz. Appendix C contains the graphs (one-third octave band spectral data) of the various warning signals plotted against the background truck noise. Since all of the signals had been adjusted to be perceived as being equally loud, the warning signal with the lowest sound level energy at 1000 Hz, Tire Screech, was used to set the signal presentation level for the remaining warning signals.

Telephone screening. Drivers were recruited through local companies, by flyers, and by word of mouth. Interested participants were interviewed by telephone to pre-qualify them as experimental participants. A modified version form of the telephone screening questionnaire used by Micheal (1995) was used and is included as Appendix D. Once the driver was initially qualified as a candidate for the experiment, an experimental session was scheduled.

Pre-experimental procedures. Once the participant arrived in the laboratory, the experimental session began by having the driver read a detailed description of the experiment (Appendix E). The experimenter then asked the participant if he had any questions concerning the experiment. Once any questions had been answered the participant was asked to read and sign the informed consent form (Appendix F).

Upon completing the informed consent form, the participant was screened for visual and auditory acuity according to the requirements of the Federal Highway Administration (1994). These requirements are specific with regards to minimum visual and auditory acuity. The form used for recording the results of the screening is contained in Appendix G.

A Beltone Model 114 clinical pure-tone audiometer was used in conjunction with a set of Telephonics TDH 50 earphones to determine each participant’s pure-tone hearing threshold at 500, 1000, and 2000 Hz. The Federal Highway Administration requires that individuals must have an average hearing loss in their better ear of no more than 40

TABLE 10

Masked Threshold Values Calculated Pursuant to ISO 7731 for the Background Truck Noise.

1/3 Octave Band Center Frequency (Hz)	Background Truck Noise (dBA)	ISO 7731 Calculated 1/3 Octave Band Criteria (dBA)
25	72.1	85.1
31.5	77.1	90.2
40	83.4	96.4
50	87.9	100.9
63	91.2	104.2
80	84.2	101.7
100	86.5	99.5
125	80.8	97.0
160	80.1	94.5
200	76.6	92.0
250	68.6	89.5
315	68.9	87.0
400	62.6	54.5
500	65.5	82.0
630	56.0	79.5
800	62.9	77.0
1000	65.3	78.3
1250	58.1	75.8
1600	55.0	73.3
2000	54.5	70.8
2500	48.9	68.3
3150	43.5	65.8
4000	41.1	63.3
5000	39.8	60.8
6300	37.9	58.3
8000	34.8	55.8
10000	29.8	53.3
12500	29.4	50.8
16000	32.0	48.3
20000	30.7	45.8

decibels at the above frequencies (Federal Highway Administration, 1994). Given that the signals were to be presented directionally, this requirement was extended to include both ears. None of the subjects failed to qualify for the experiment on the basis of hearing loss.

The participant was then screened for vision. A Stereo Optical OPTEC™ 2000 Vision Tester was used to present the Snellen Test to measure minimum-separable acuity. In accordance with the Code of Federal Regulations, participants were screened to ensure a minimum corrected visual acuity of 20/40 in each eye and a distant binocular acuity corrected to at least 20/40 in each eye (Federal Highway Administration, 1994). None of the subjects failed to qualify for the experiment on the basis of visual acuity.

The Federal Highway Administration regulations also requires that commercial vehicle operators must be able to identify the colors of traffic signals and devices, specifically red, green, and amber. Individuals were not screened on the basis of this criterion. This decision was made on the basis that the only traffic signal or device present in the experiment was a sign denoting the speed limit. None of the known color deficiencies conflicts with black lettering on a white background; therefore, the decision was made not to screen for this deficiency.

Simulator test drive. Prior to beginning the actual experiment, subjects participated in a practice driving scenario to familiarize themselves with the simulator prior to collecting data. The practice scenario demonstrated all of the different display types presented during actual experimental conditions. Participants were instructed to drive as they normally would, paying attention to all traffic regulations (stop signs, speed limit, etc.). During the test drive, the experimenter provided feedback to the participants. Likewise, participants were encouraged to ask questions of the experimenter. Participants were able to repeat the practice scenario until they were comfortable in doing so while demonstrating to the experimenter their ability to successfully drive the simulator, or until the experimenter concluded that the subject was incapable of operating the simulator successfully. One participant was incapable of operating the simulator. As a result, the participant was thanked, paid for his time, and dismissed on this basis.

Data collection. Once the participant had successfully completed the test drive, data collection began. The subject was reminded to pay attention to all traffic regulations and to drive as they normally would. Between scenarios, subjects were asked if they would like to take a break. The experimenter answered questions throughout the simulation as they arose.

After successfully completing the driving scenarios, each participant was asked to complete two subjective preference questionnaires. The first of the questionnaires (Appendix H) consisted of fifteen Likert-type scales, designed to solicit a response as to various attributes of the simulator and collision warnings. The last four Likert-type scales were unique in that they were used in conjunction with a free response. For each of these scales one of the collision avoidance sounds were presented. Participants were asked to respond using the Likert-type scale, indicating how appropriate they felt this warning signal was to what they perceived it to mean. They were then asked to write the meaning of that signal in the space provided below the respective Likert-type scale. The four warning signals were presented randomly to each subject. The second subjective preference questionnaire (Appendix I) queried the drivers as to which combination of collision avoidance displays they preferred. Upon completion of the subjective preference questionnaires, participants were paid for their time, thanked for their cooperation, and dismissed.

EMPIRICAL RESULTS

Data Reduction

The raw data, as they existed at the end of the experimental session, consisted of three data files for each treatment condition. The first data file was generated by the simulation software and contained a time stamp, vehicle acceleration and velocity, distance traveled, lane position, steering wheel angle, and whether or not a collision had occurred. The second data file was generated by the Power Macintosh and contained time stamped accelerator and brake pedal position data. The third and final data file contained the time, in milliseconds, measured from a fixed distance preceding the presentation of the impending collision. Each of these data files were imported into a Microsoft Excel Spreadsheet where the time stamped data from each of the first two files was synchronized and the point where the impending collision occurred identified. This was done for each subject's data for all treatment conditions within both the front-to-rear and side collision data sets. Once the data for a given treatment condition had been entered into the spreadsheet, it was necessary to resolve the appropriate dependent measures for each treatment condition.

Front-to-rear collision avoidance. For the front-to-rear collision avoidance scenarios, it was necessary to determine the brake response times and its components. This was accomplished by evaluating the changes in pedal position and recording the associated time stamp. Several criterion were used to determine if an observation was to be included in the statistical analyses.

First, the velocity, at the time the warning signal was presented, had to be within five miles-per-hour of the speed limit, plus or minus. This was to ensure that the participant was in fact traveling close to the posted limit and that the two headway conditions did not overlap. Figure 15 shows the actual range of acceptable headways, based upon including those velocities which deviated from the posted limits by five miles-per-hour or less.

Second, the vehicle had to be in the appropriate lane of the roadway at the time the signal was presented. While the scenarios were programmed to account for the

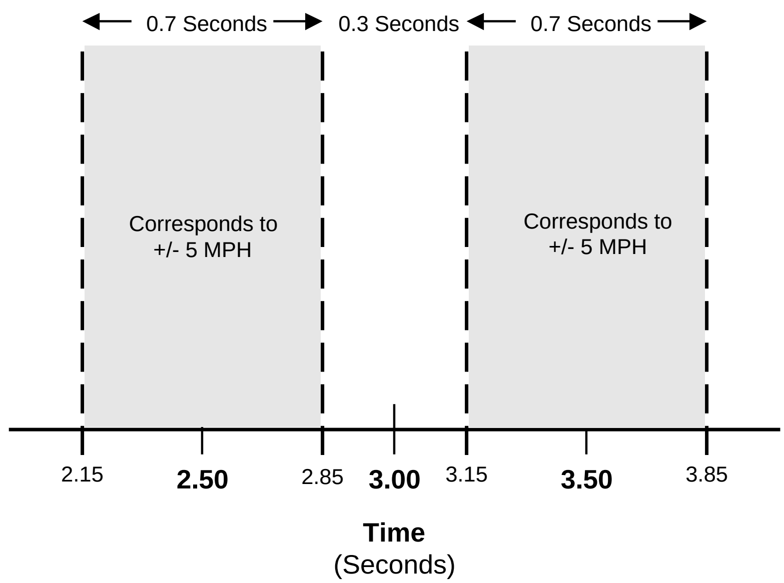


Figure 15. Range of acceptable deviation from the ‘true’ 2.5 and 3.5 headway criteria.

location of the vehicle, occasionally, the vehicle operator would be out of the appropriate lane (either off the road entirely, or in the oncoming lane of traffic) as the result of accidentally colliding with another object (not the intended stimulus) in the simulation.

Third, the driver had to begin responding to the impending collision prior to the time at which the collision occurred. Originally, the front-to-rear collision avoidance scenarios were to have included accidents as an additional dependent measure. The situation described above, where the driver did not react prior to the collision occurring, was the criterion by which an accident occurring would have been judged. Since none of the front-to-rear collision sequences resulted in an accident, this dependent measure was not used.

Side collision avoidance. For the side collision avoidance scenarios, it was necessary only to determine whether or not an accident had occurred. This was accomplished by evaluating the lane position of the simulator after the warning signal had been presented signifying that a vehicle was alongside the simulator. If the vehicle operator was able to change lanes without colliding with the passing vehicle, no accident was registered. However, if the vehicle operator changed lanes after the signal had been presented, but before the vehicle passed, a collision was registered.

Velocity and lane position were used to determine if an observation was to be included in the statistical analyses. The velocity at the time the warning signal was presented had to be within five miles-per-hour of the speed limit, plus or minus. Five miles per hour, over or under the posted speed limit was chosen in order to be consistent with the front-to-rear collision scenarios. The vehicle also had to be in the appropriate lane of the roadway at the time the signal was presented. While the scenarios were programmed to account for the location of the vehicle, occasionally, the vehicle operator would be out of the appropriate lane (either off the road entirely, or in the oncoming lane of traffic) as the result of accidentally colliding with another object (not the intended stimulus) in the simulation.

Statistical Analyses

Analysis of variance (ANOVA) was used to determine the significance of main effects and interactions for both the front-to-rear and side collision scenarios. Post-hoc

Newman-Keuls and simple-effect *F*-tests were conducted to determine the nature of significant effects and interactions. The Newman-Keuls test uses progressive critical values according to the number of compared means making the test more powerful than some other potential analyses (Winer, Brown, and Michels, 1991).

Corrections to the ANOVA. Because the experimental design was constructed entirely of within-subjects variables, the Geisser-Greenhouse correction factor for the heterogeneity of covariance was used when calculating the within-subject effects for Display Presentation Mode in the front-to-rear scenarios (Winer, Brown, and Michels, 1991). The Geisser-Greenhouse is a maximum correction for the heterogeneity of covariance. It was unnecessary to correct for the other independent measures as heterogeneity of covariance can only occur when more than two levels of a variable are present (Williges, 1995).

Front-to-rear collision avoidance. The dependent measures, overall brake response time (defined as the time from the presentation of the warning signal until the brake is depressed), and initial response time (defined as the time between initial presentation of the warning signal and the instant the participant begins to release the accelerator) were each subjected to a three-way, within-subjects ANOVA. Although the remaining components of the overall brake response time (accelerator release time, accelerator-to-brake travel time, and brake depression time) were collected, it was felt that these measures were subject to too many extraneous influences (initial pedal position, mass of driver's leg, muscle tone, foot size, etc.) outside the control of the experiment to warrant analysis. As a result, they were not included in the analysis. All main effects and interactions of display presentation mode, velocity, and headway were included as sources of variance for the impending front-to-rear collision condition.

Being defined by the distal stimulus, auditory icons are intended to evoke a representative image of an impending situation. Conventional warning signals, on the other hand, are defined by temporal and acoustic characteristics and must be translated before their meaning is understood. One hypothesis held by supporters of auditory icons is that they require less cognitive processing than a conventional auditory warning signal.

Initial response time is the metric which comes closest to representing a measure of cognitive processing. Since a reduction in cognitive processing is one hypothesis used in support of auditory icons, initial response time was the relvant dependent measure collected in the experiment. Initial response time, however, does not provide practitioners with all of the necessary information (e.g. time to complete the braking maneuver) on which future systems can be designed. Therefore, while not as 'pure' a measurement, overall brake response time was also included as a dependent measure.

Neither the initial response time data set nor the overall brake response time data set were full rank as both were missing a number of observations. Missing observations occurred if the participant's velocity was not within the previously described +/- 5 mph or because the simulator malfunctioned. As a result of the missing observations, the degrees-of-freedom normally available (575) were reduced to 433 for the initial response time and 427 for the overall response time. Traditional sum-of-squares calculations would have been unable to resolve all main effects and interactions (K. Kim, personal communications, May 27, 1997). Type IV sum-of-squares, a computer-based numerical estimation procedure made available by Statistical Analysis Software (SAS) to account for incomplete data sets, was used to resolve all main effects and interactions.

Significant ($p<0.05$) main effects of Display (D) {F (5, 112) = 4.77, p = 0.0311} and Headway (H) {F (1, 22) = 4.53, p = 0.0447} were observed for the initial response time. The complete ANOVA summary table for initial response time is provided in Table 11. Means and standard deviations for all possible treatment conditions are shown in Table 12.

Results of the Newman-Keuls analysis for Display Type (D) appear in Figure 16. Response times for both mixed modality displays (visual and auditory icon and visual and conventional auditory warnings) and the auditory icon were significantly shorter than the other three display conditions (conventional auditory warning, dash-mounted visual display, or no display). Response times associated with the dash-mounted visual display were significantly longer than any other display. While the conventional and auditory warnings and the no-display condition produced significantly faster response times than did the visual display, they were significantly longer than the mixed-modality or auditory icon conditions. Finally, the Headway criterion of 3.5 seconds resulted in significantly shorter initial response times (61ms) compared with a headway criterion of 2.5 seconds, Figure 17.

TABLE 11

Analysis of Variance Summary Table for Front-to-Rear Collision Avoidance, Initial Response Time Dependent Measure

Source	df	SS	MS	*F* [ι]	*p*	*G-G*
Between Subjects						
Subjects (S)	23	734330.2	31927.4			
Within Subjects						
Display (D)	5	1042859.9	208571.9	4.77	0.0005	0.0311*
D*S	112	4895181.3	43706.9			
Headway (H)	1	226555.3	226555.3	4.53	0.0447*	
H*S	22	1100011.2	50000.5			
Velocity (V)	1	5428.9	5428.9	0.13	0.7203	
V*S	23	950009.2	41304.7			
D*H	5	328384.8	65676.6	1.59	0.1720	
D*H*S	87	3599281.9	41371.1			
D*V	5	367106.6	73421.3	2.18	0.0637	
D*V*S	83	2791243.4	33629.4			
H*V	1	106682.8	106682.8	1.85	0.1896	
H*V*S	19	1095322.6	57648.6			
D*H*V	5	238268.0	47653.6	0.99	0.4356	
D*H*V*S	41	1966279.1	47958.0			
Total[◊]	433					

* Statistically-significant effect at $p \leq 0.05$.

[ι] For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F*-test above.

[◊] A full rank Factorial Design would yield 575 degrees-of-freedom. Missing observations reduced the available degrees-of-freedom to 433. Using Type IV SS to compensate for the missing observations, resolution of all main effects and interactions was still possible.

TABLE 12

Mean Values, Standard Deviation, and Number of Observations of Main Effects for the Initial Response Time Dependent Measure (Mean and std. deviation values are in ms.)

Display Condition				**Headway** 3.5 Seconds	2.5 Seconds
Mixed Modality: Dash-Mounted Visual Display and Auditory Icon					
	Velocity	35 MPH	Mean	347	428
			Std. Deviation	(61)	(83)
			Observations	23	22
		55 MPH	Mean	414	484
			Std. Deviation	(82)	(223)
			Observations	16	21
Mixed Modality: Dash-Mounted Visual Display and Conventional Auditory					
	Velocity	35 MPH	Mean	397	433
			Std. Deviation	(76)	(93)
			Observations	19	17
		55 MPH	Mean	368	506
			Std. Deviation	(86)	(224)
			Observations	16	13
Auditory Icon					
	Velocity	35 MPH	Mean	450	453
			Std. Deviation	(116)	(126)
			Observations	21	19
		55 MPH	Mean	382	377
			Std. Deviation	(113)	(114)
			Observations	18	15
Conventional Auditory					
	Velocity	35 MPH	Mean	423	789
			Std. Deviation	(103)	(346)
			Observations	20	17
		55 MPH	Mean	431	504
			Std. Deviation	(66)	(110)
			Observations	20	14
Visual Display					
	Velocity	35 MPH	Mean	512	678
			Std. Deviation	(244)	(376)
			Observations	21	18
		55 MPH	Mean	714	475
			Std. Deviation	(359)	(107)
			Observations	19	19
No Display					
	Velocity	35 MPH	Mean	454	469
			Std. Deviation	(131)	(119)
			Observations	21	21
		55 MPH	Mean	549	573
			Std. Deviation	(141)	(335)
			Observations	19	17

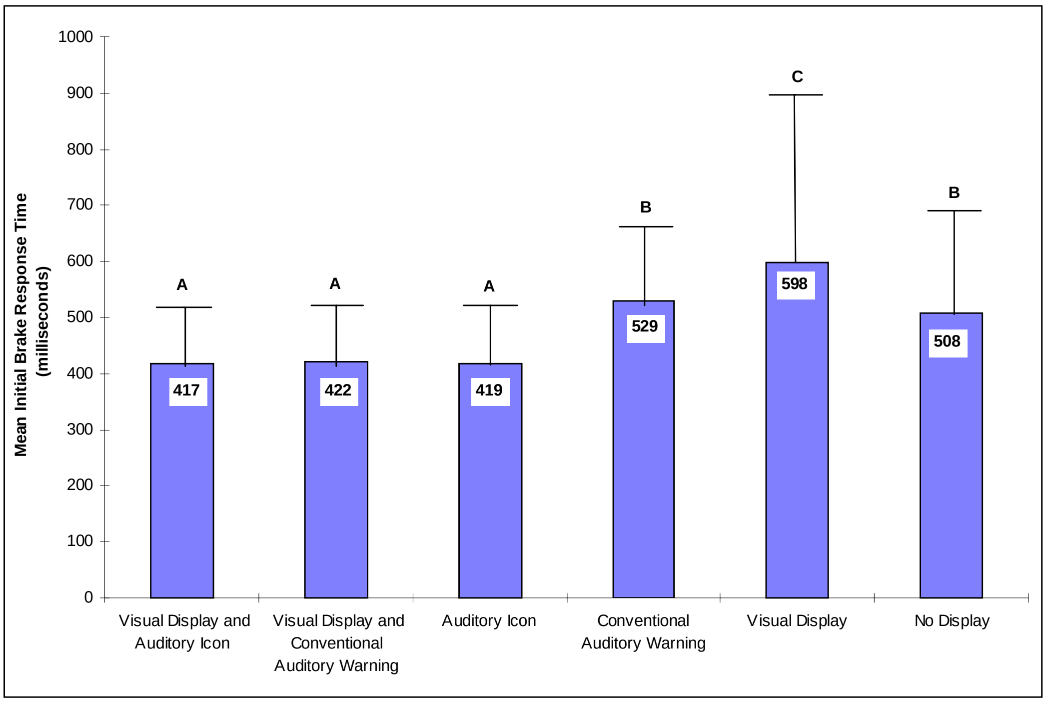


Figure 16. Display Type main effect for initial brake response time dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

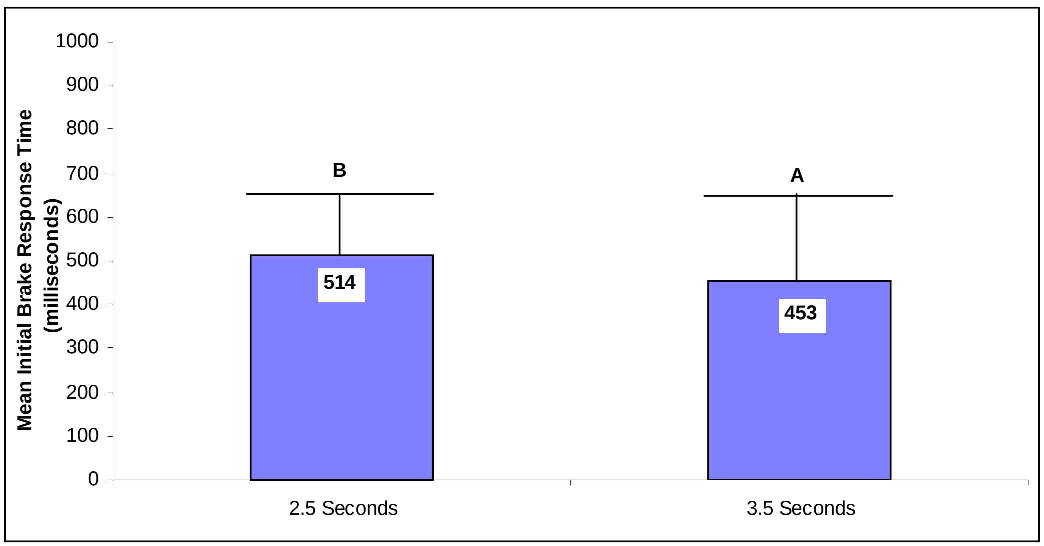


Figure 17. Headway main effect for initial brake response time dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

For the overall braking response time, a significant ($p<0.05$) main effect of Display Type (D) {F (5, 108) = 10.77, p < 0.0001} and Headway (H) {F (1, 22) = 13.63, p = 0.0013} was also observed. The complete ANOVA summary table for overall brake response time is provided in Table 13. Means and standard deviations for all possible treatment conditions are shown in Table 14.

The patterns of significance for these effects that were observed after performing the analyses were identical to those observed in the analysis of initial response time, see Figures 18 and 19.

Side collision avoidance. The dependent measure, accident occurrence, was subject to a five-way, within-subjects ANOVA. A full rank, one-half replicate 2^5 Fractional Factorial Design would yield 383 degrees-of-freedom. Missing observations reduced the available degrees-of-freedom to 300. The experimental design, coupled with the quantity of missing observations could not be fully resolved though the use of traditional or Type IV sum-of-squares calculations (K. Kim, personal communications, May 27, 1997). As a result, only those two way interactions involving the independent variable Auditory Display, yielding 229 degrees-of-freedom, were resolved in the analysis. Interactions with Auditory Display were chosen to determine the significance of adding an auditory display to each of the remaining display types (mirrors or dash-mounted visual display).

Statistically significant ($p<0.05$) main effects of Auditory Display (A) {F (1, 23) = 6.66, p = 0.0167}, Mirrors (M) {F (1, 21) = 9.55, p = 0.0055}, and the interaction of Auditory Display-by-Dash-Mounted Visual Display (AxVD) {F (1, 17) = 5.22, p = 0.0354} were observed. The complete ANOVA summary table for accident occurrence is provided in Table 15. Means and standard deviations for all possible treatment combinations for the dependent measure of accident occurrence are shown in Table 16. The mean accident occurrence for the auditory icon was significantly less than for the conventional auditory warning, Figure 20. Likewise, the presence of mirrors significantly reduced the number of accidents, Figure 21.

Simple-effects F-tests were conducted on the AxVD interaction for accident occurrence to determine how the main effects of auditory display differed at different

TABLE 13

Analysis of Variance Summary Table for Front-to-Rear Overall Brake Response Time Dependent Measure

Source	df	SS	MS	*F* [†]	*p*	*G-G*
<u>Between Subjects</u>						
Subjects (S)	23	8937065.9	388568.1			
<u>Within Subjects</u>						
Display (D)	5	5940795.2	1188159.0	10.77	0.0001	<0.0001*
D*S	108	11916666.1	110339.5			
Headway (H)	1	2732327.3	2732327.3	13.63	0.0013*	
H*S	22	4409502.3	200431.9			
Velocity (V)	1	83936.1	83936.1	0.50	0.4845	
V*S	23	3823315.6	166231.1			
D*H	5	657413.1	131482.6	1.30	0.2728	
D*H*S	85	8615576.9	101359.7			
D*V	5	690465.5	138093.1	1.08	0.3752	
D*V*S	83	10570570.4	127356.3			
H*V	1	724189.1	724189.1	4.19	0.0547	
H*V*S	19	3283458.2	172813.6			
D*H*V	5	1216266.9	243245.4	1.04	0.4073	
D*H*V*S	41	9526647.1	232357.2			
Total[◊]	427					

* Statistically-significant effect at $p \le 0.05$.

[†] For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F-test* above.

[◊] A full rank Factorial Design would yield 575 degrees-of-freedom. Missing observations reduced the available degrees-of-freedom to 445. Using Type IV SS to compensate for the missing observations, resolution of all main effects and interactions was still possible.

TABLE 14

Mean Values, Standard Deviation, and Number of Observations of Main Effects for the Overall Response Time Dependent Measure (Mean and std. deviation values are in ms.)

Display Condition				**Headway**	
				3.5 Seconds	2.5 Seconds
Mixed Modality: Dash-Mounted Visual Display and Auditory Icon					
	Velocity	35 MPH	Mean	678	866
			Std. Deviation	(62)	(151)
			Observations	23	22
		55 MPH	Mean	847	971
			Std. Deviation	(250)	(403)
			Observations	17	21
Mixed Modality: Dash-Mounted Visual Display and Conventional Auditory					
	Velocity	35 MPH	Mean	816	856
			Std. Deviation	(266)	(167)
			Observations	19	17
		55 MPH	Mean	756	934
			Std. Deviation	(209)	(317)
			Observations	16	13
Auditory Icon					
	Velocity	35 MPH	Mean	834	863
			Std. Deviation	(235)	(199)
			Observations	20	19
		55 MPH	Mean	758	804
			Std. Deviation	(175)	(148)
			Observations	18	15
Conventional Auditory					
	Velocity	35 MPH	Mean	824	1411
			Std. Deviation	(206)	(573)
			Observations	20	17
		55 MPH	Mean	867	957
			Std. Deviation	(229)	(230)
			Observations	18	14
Visual Display					
	Velocity	35 MPH	Mean	901	1539
			Std. Deviation	(288)	(492)
			Observations	20	18
		55 MPH	Mean	1302	1143
			Std. Deviation	(390)	(465)
			Observations	19	18
No Display					
	Velocity	35 MPH	Mean	842	1034
			Std. Deviation	(185)	(277)
			Observations	21	20
		55 MPH	Mean	1048	1113
			Std. Deviation	(185)	(386)
			Observations	19	18

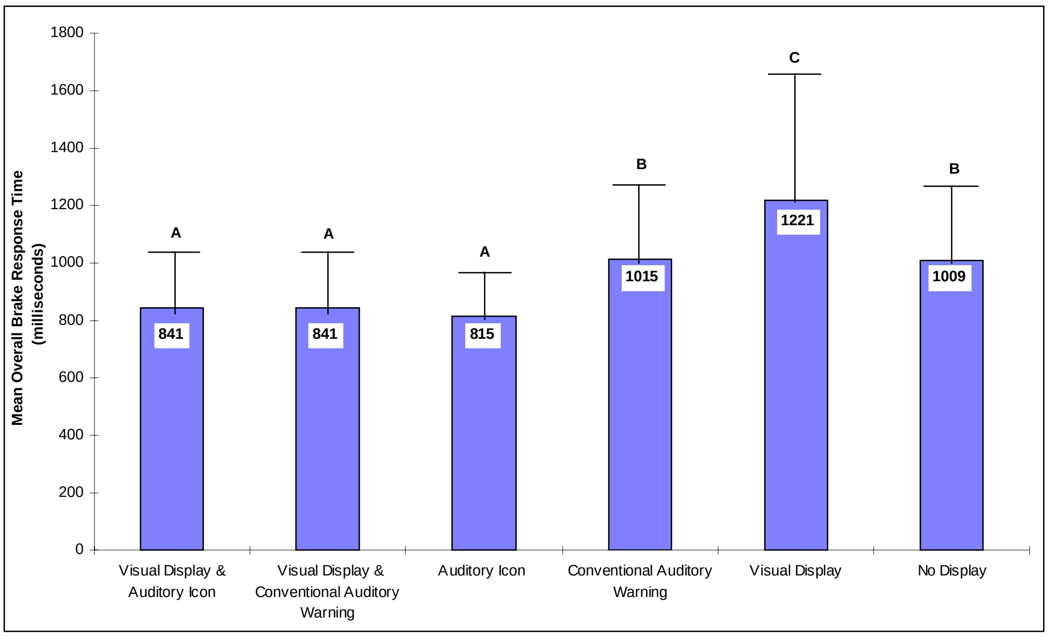


Figure 18. Display Type main effect for overall brake response time dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

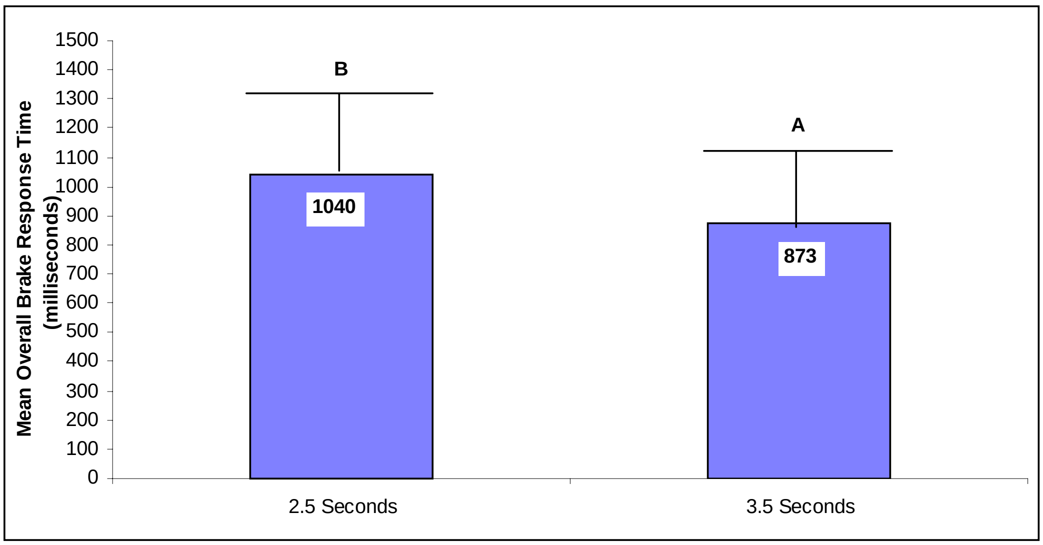


Figure 19. Headway main effect for overall brake response time dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

TABLE 15

Analysis of Variance Summary Table for Side Collision Accident Occurrence Dependent Measure

Source	df	SS	MS	*F* [ɩ]	*p*
Between Subjects					
Subjects (S)	23	7.77397516	0.33799892		
Within Subjects					
Dash-Mounted Visual Display (DVD)	1	0.74032106	0.74032106	3.60	0.0716
DVD*S	21	4.31883372	0.20565875		
Auditory Display (A)	1	0.44940952	0.44940952	6.66	0.0167*
A*S	23	1.55133820	0.06744949		
Velocity (V)	1	0.24023275	0.24023275	2.15	0.1575
V*S	21	2.34770888	0.11179566		
Workload (W)	1	0.33890374	0.33890374	4.31	0.0502
W*S	21	1.64941588	0.07854361		
Mirrors (M)	1	1.65986842	1.65986842	9.55	0.0055*
M*S	21	3.64929183	0.17377580		
A*W	1	0.05971338	0.05971338	0.50	0.4899
A*W*S	17	2.03831054	0.11990062		
A*M	1	0.01997041	0.01997041	0.17	0.6883
A*M*S	17	2.08066370	0.12239198		
A*V	1	0.13675969	0.13675969	0.94	0.3460
A*V*S	17	2.96334297	0.17431429		
A*DVD	1	0.52380952	0.52380952	5.22	0.0354*
A*DVD*S	17	1.70567923	0.10033407		
Total[◊]	229				

* Statistically-significant effect at $p \leq 0.05$.

[ɩ] For each source of variance, the interaction of subjects (S) with that source was used as the error term in the *F-test* above.

[◊] A full rank, ½ Replicate 2^5 Fractional Factorial Design would yield 383 degrees-of-freedom. Missing observations reduced the available degrees-of-freedom to 300. Type IV sum of squares was unable to fully resolve this model. A decision was made to resolve only those two way interactions involving the independent variable Auditory Display, yielding the 229 df used in this analysis.

TABLE 16

Mean Values, Standard Deviation, and Number of Observations of Main Effects for the Collision Occurrence Dependent Measure (Mean and std. deviation values dimensionless.)

Visual Display	Auditory Display	Velocity	Workload	Mirrors	Accident Occurrence	
No	Traditional Auditory Warning	35 MPH	Low	Yes	Mean Standard Deviation Observations	0.08 (0.29) 23
No	Traditional Auditory Warning	35 MPH	High	No	Mean Standard Deviation Observations	0.43 (0.50) 23
No	Traditional Auditory Warning	55 MPH	Low	No	Mean Standard Deviation Observations	0.50 0.51 22
No	Auditory Icon	35 MPH	Low	No	Mean Standard Deviation Observations	0.50 0.51 22
Yes	Traditional Auditory Warning	35 MPH	Low	No	Mean Standard Deviation Observations	0.21 (0.42) 23
No	Traditional Auditory Warning	55 MPH	High	Yes	Mean Standard Deviation Observations	0.13 (0.35) 15
No	Auditory Icon	35 MPH	High	Yes	Mean Standard Deviation Observations	0 (0) 12
Yes	Traditional Auditory Warning	35 MPH	High	Yes	Mean Standard Deviation Observations	0.10 (0.31) 20
No	Auditory Icon	55 MPH	Low	Yes	Mean Standard Deviation Observations	0.15 (0.37) 20
Yes	Traditional Auditory Warning	55 MPH	Low	Yes	Mean Standard Deviation Observations	0.41 (0.51) 17
Yes	Auditory Icon	35 MPH	Low	Yes	Mean Standard Deviation Observations	0.09 (0.29) 22
Yes	Auditory Icon	55 MPH	Low	No	Mean Standard Deviation Observations	0.17 (0.39) 17
Yes	Auditory Icon	35 MPH	High	No	Mean Standard Deviation Observations	0.04 (0.20) 23
Yes	Traditional Auditory Warning	55 MPH	High	No	Mean Standard Deviation Observations	0.40 (0.51) 15
No	Auditory Icon	55 MPH	High	No	Mean Standard Deviation Observations	0.33 (0.48) 18
Yes	Auditory Icon	55 MPH	High	No	Mean Standard Deviation Observations	0.11 (0.33) 9

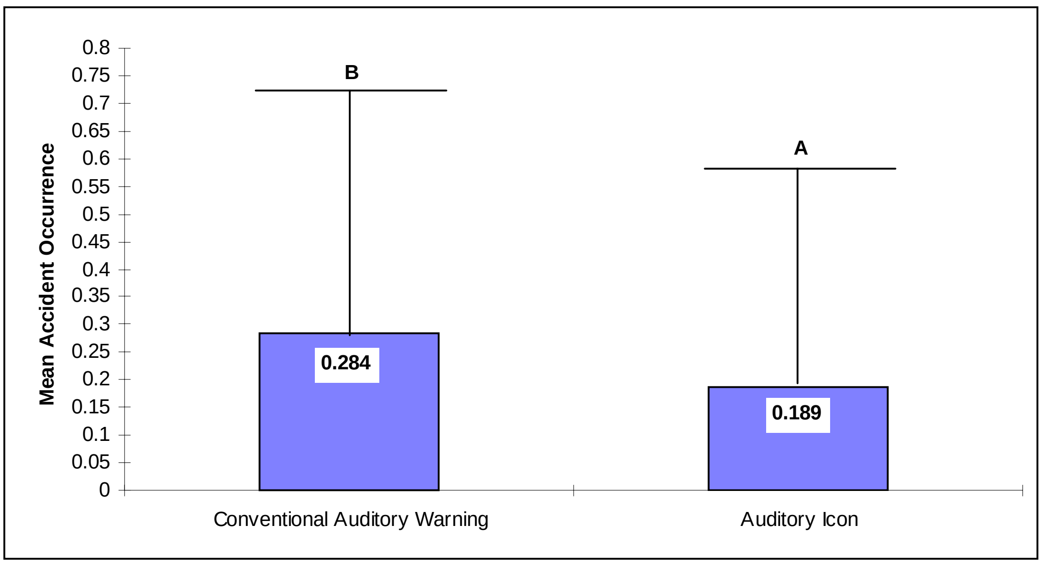


Figure 20. Auditory Display main effect for side collision occurrence dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

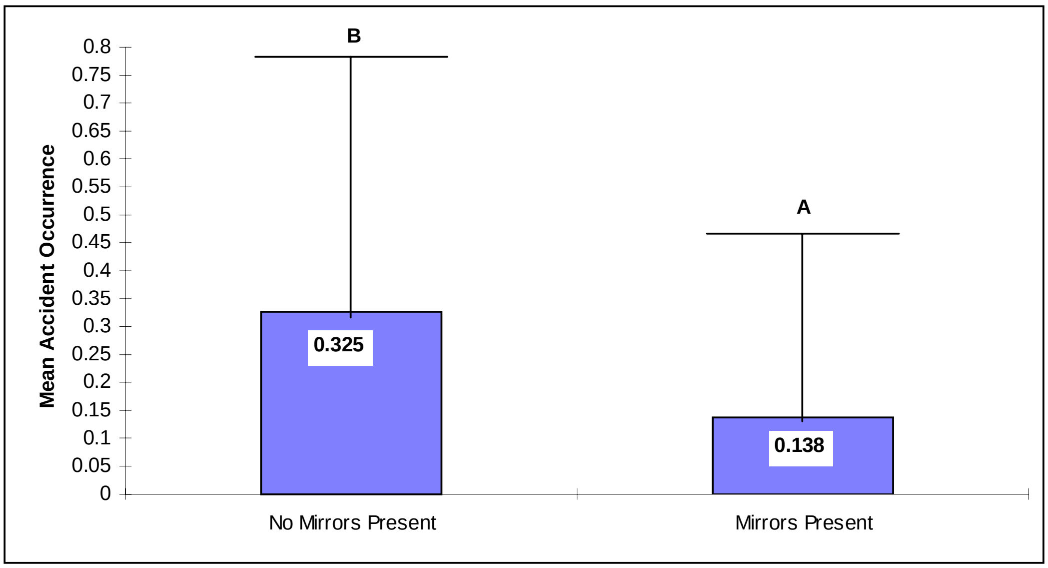


Figure 21. Mirrors main effect for side collision occurrence dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

levels of the visual display variable. Significant simple main effects of auditory display occurred at only one level of visual display. The presence of a visual display in combination with an auditory icon was found to significantly reduce accident occurrence {F (1, 23) = 8.07, p = 0.0081}. The AxDVD interaction is depicted graphically in Figure 22.

Subjective preference. Participants completed eleven Likert-type questions or scales with respect to the driving simulator and collision warnings. These scales were anchored at "1-Strongly Agree" and "5-Strongly Disagree." Descriptive statistics illustrating the subjects' responses to the first eleven Likert-type scale questions are presented in Table 17. Participants generally agreed that the collision warnings were easy to understand (subjective rating of 1.85), were useful (subjective rating of 1.90), helped them to drive more safely (subjective rating of 2.08), aided them in reacting more quickly to hazards (subjective rating of 2.10), and did not negatively affect their driving behavior (subjective rating of 2.29). Participants were undecided as to whether the simulator offered a realistic driving environment (subjective rating of 3.00). They were also undecided as to whether they would purchase a collision warning system on their next vehicle if it cost $500 (subjective rating of 3.35) or $1000 (subjective rating of 2.94). Participants generally disagreed with the statements that the simulator was annoying (subjective rating of 3.81) or distracted them from driving properly (subjective rating of 3.90) or presented unreliable information (3.94). Given the nature of these questions, no further analysis was conducted.

Upon completing the subjective preference scales, each of the warning signals was played and the participants asked to identify its meaning. Approximately one-half of the participants (43% side, 57% front-to-rear) were able to correctly identify the meaning of the conventional auditory warning signals, while 96% of the participants correctly identified the auditory icons, Table 18. Given the data were representative of a dichotomous population, a binomial test was used with the null hypothesis predicting no difference between the probability of correctly identifying the warning signal and the probability of incorrectly identifying the warning signal. Phrased colloquially, the null hypothesis suggested the participants were guessing at the meaning of the warning signal.

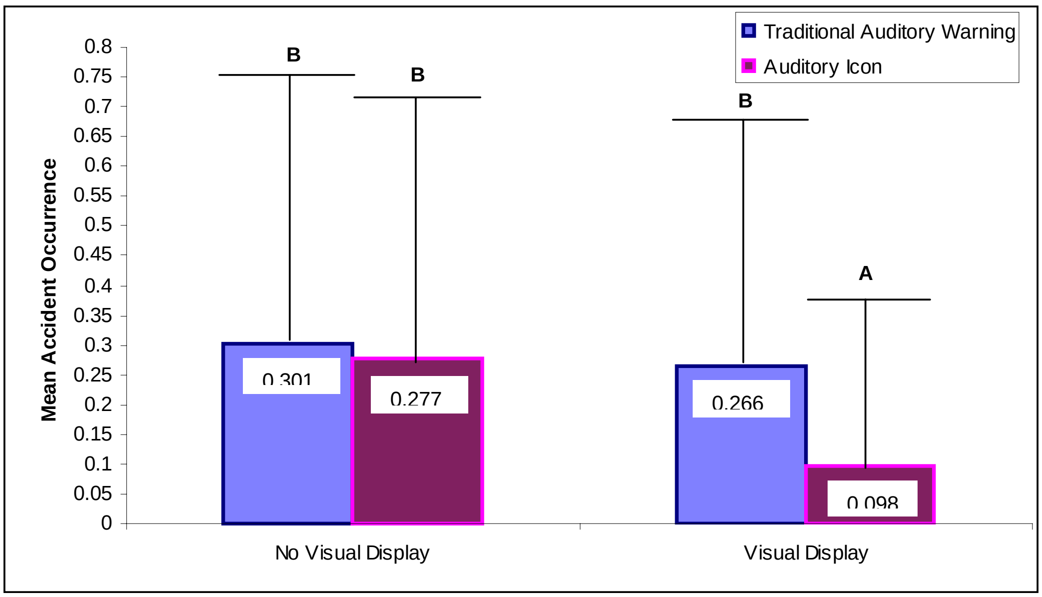


Figure 22. Simple-effects *F*-test results for Visual Display-by-Auditory Warning interaction effect for side collision occurrence dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

TABLE 17

Responses to Likert-type Scale Questions. The Likert-type Scales Used were Anchored at "1 - Strongly Agree" and "5 - Strongly Disagree."

	Question	Response	
1.	The information communicated by the collision avoidance warning system was useful.	Mean Standard Deviation	1.90 (0.78)
2.	The collision warning system did not negatively change my driving behavior.	Mean Standard Deviation	2.29 (1.00)
3.	The information presented by the collision warning system helped me to drive more safely.	Mean Standard Deviation	2.08 (0.78)
4.	The collision warning system seemed to give unreliable information; therefore I paid little attention to it	Mean Standard Deviation	3.94 (0.60)
5.	I was able to react more quickly to potential hazards because of the collision warning system.	Mean Standard Deviation	2.10 (0.91)
6.	The collision warning system distracted me from driving correctly.	Mean Standard Deviation	3.90 (1.00)
7.	The driving simulator seemed very realistic.	Mean Standard Deviation	3.00 (0.97)
8.	The collision avoidance system was annoying.	Mean Standard Deviation	3.81 (0.89)
9.	The collision avoidance system was easy to understand.	Mean Standard Deviation	1.85 (0.65)
10.	If a collision avoidance system was available as a $1000 option on my next vehicle, I would be likely to purchase it.	Mean Standard Deviation	2.94 (1.35)
11.	If a collision avoidance system was available as a $500 option on my next vehicle, I would be likely to purchase it.	Mean Standard Deviation	3.35 (1.18)

TABLE 18

Number of Front-to-Rear and Side Warning Signals Correctly and Incorrectly Identified.

		Warning Signals Identified		
		Correctly	Incorrectly	Total
Side	Traditional	10	13	23
	Auditory Icon	22	1	23
Front-to-rear	Traditional	13	10	23
	Auditory Icon	22	1	23

Participants were also asked which auditory warning signal they preferred for a given collision scenario (either an impending front-to-rear or side collision). Fifty-four percent of the participants preferred the conventional auditory warning for the impending front-to-rear collision while only 38% preferred the conventional auditory warning for the impending side collision. Of the participants indicating a preference for the conventional auditory warning, only about half (46% front-to-rear and 56% side) were able to correctly identify its meaning. Of the participants who indicated a preference for auditory icons, all were able to properly identify its meaning. These results are shown in Table 19.

Finally, for a given collision scenario (impending front-to-rear or side collision) participants were asked to identify which collision avoidance technology they preferred, Table 20. Few individuals indicated a preference for a single warning device. For the front-to-rear collision avoidance scenarios, two participants chose no display, three participants chose having only a dash-mounted visual display and four indicated that having only an auditory display was their preference. Fifteen of the twenty-four participants indicated their desire to have both an auditory and dash-mounted visual display for front-to-rear collision avoidance. For the side collision avoidance scenarios, two participants indicated their desire to remain with the status quo, or mirrors only. One individual preferred only dash-mounted visual display and another only and auditory display. Five participants indicated that they preferred a dash-mounted display in addition to the existing mirrors and three indicated they would prefer an auditory display in addition to the existing mirrors found on commercial vehicles. Two participants indicated their preference as having a dash-mounted visual display in addition to an auditory display without the use of mirrors. Ten of the twenty-four participants indicated their desire to have both a dash-mounted visual display and an auditory display in addition to the existing mirrors for impending side collision detection (Table 21).

Given the categorical nature of these data, the Chi-Squared Goodness-of-Fit test was employed. For both the front-to-rear ($\chi^2 = 18.15$, 6 df, $p \leq 0.0085$) and side collision scenarios ($\chi^2 = 18.3$, 3 df, $p \leq 0.0004$), the results indicate there is an observed preference for a certain display configuration. The expected value for each of the side collision categories was calculated to be 3.4. This violated one of the assumptions put forth by

TABLE 19

Individuals Preferring Conventional auditory warning Signal and Auditory Icon in a Given Collision Situation. Number in Parentheses Indicates the Number of Individuals Who Were Also Able to Correctly Identify Named Signal.

	Individuals Preferring	
	Conventional auditory warning	Auditory Icon
Impending Front-to-Rear Collision	13 (6)	11 (11)
Impending Side Collision	9 (5)	15 (15)

TABLE 20

Responses Identifying a Preferred Display Combination for the Front-to-Rear Collision Avoidance.

Display Type	Individuals Preferring
No Display	2
Dash-mounted Visual Display Only	3
Auditory Display Only	4
Auditory and Dash-Mounted Visual Display	15

TABLE 21

Responses Identifying a Preferred Display Combination for Side Collision Avoidance.

Display Type	Individuals Preferring
Mirrors Only	2
Dash-mounted Visual Display Only	1
Auditory Display Only	1
Mirrors and Dash-Mounted Display	5
Mirrors and Auditory Display	3
Dash-mounted Visual Display and Auditory Display	2
Mirrors, Dash-mounted Visual Display, and Auditory Display	10

Siegel and Castellan (1988) which suggests the expected value for each category be at least 5.

As a result, a computer-based simulation (K. Kim, personal communications, May 27, 1997) was developed to evaluate the robustness of the Chi-Squared Goodness-of-Fit test with an expected value of 3.4. Microsoft Excel, a spreadsheet application, was used as the simulation platform. The first step in the simulation was to generate a group of 24 (corresponding to the number of subjects in the actual study) simulated subjects. To each subject, one of the seven display conditions was randomly assigned, based upon a uniform distribution. For this group of 24 subjects, a Chi-Squared statistic was calculated using the expected value of 3.4. This process was repeated 2000 times to approximate a large value of N. The Chi-Squared statistics were then rank ordered in descending order. This process developed a distribution which reflected the use of 3.4 as an expected value, as opposed to the minimum suggested by Siegel and Castellan (1988) of 5. The p-value was calculated by determining where the Chi-Squared experimental value was found to be greater than the Chi-Squared simulated value (17) and then dividing by the number of Chi-Squared values simulated (2000). A flowchart of the simulation is given in Appendix J.

The results of the computer-based simulation ($p \leq 0.0085$) confirmed the demonstrated preference for a certain display configuration. The preferred display combination for the impending front-to-rear collision was the auditory and dash-mounted display, Figure 23. For the impending side collision, the preferred display combination was the mirrors, auditory, and dash-mounted visual display, Figure 24.

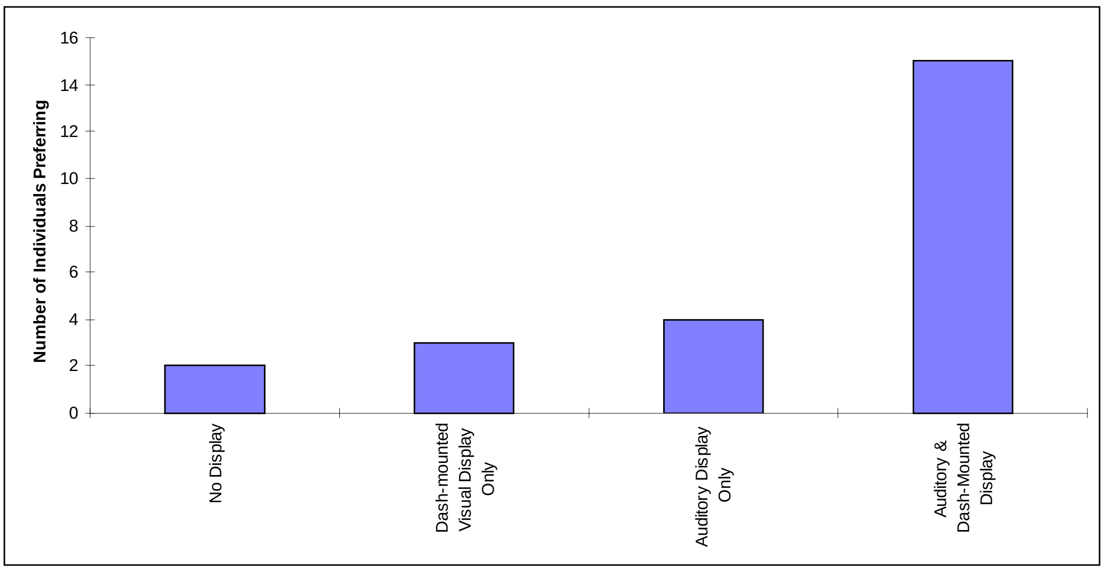


Figure 23. Responses Identifying a Preferred Display Combination for Front-to-Rear Collision Avoidance.

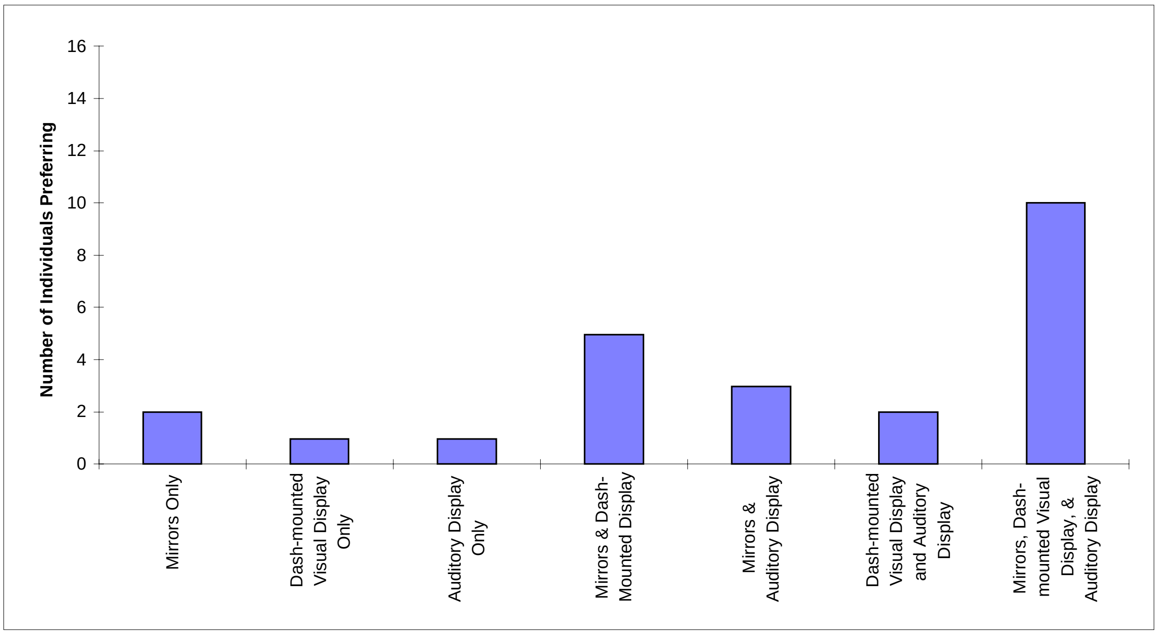


Figure 24. Responses Identifying a Preferred Display Combination for Side Collision Avoidance.

DISCUSSION

Auditory icons, have been recognized as having tremendous potential as warning signals. Until now, however, attempts to incorporate auditory icons as warning signals into complex systems have been largely unsuccessful. The impetus of this research was to determine if auditory icons were in fact genuinely useful as warning devices.

Front-to-rear impending collisions.

Two dependent measures, initial response time and overall brake response time were analyzed for the scenarios involving front-to-rear impending collisions. Since the patterns of significance were identical for both dependent measures and reducing cognitive processing is one hypothesis used to support the use of auditory icons, initial response time is believed to be the relevant dependent measure and the dependent measure around which the following discussion is framed.

It is worth mentioning, however, that the average overall brake response time for situations in which no collision avoidance display was active was found to be 1.01 seconds. This is comparable to the braking response times reported by Barrett, Kobayashi, and Fox (1968), and Lechner and Malaterre (1991). Table 22 compares the overall brake response times obtained in this research for scenarios which did not include a collision warning as compared to those reported in the literature.

Display main effect. Not all of the collision avoidance displays used in this study resulted in reduced response times. The dash-mounted visual display resulted in significantly longer initial response times than did any other display, or lack of a display altogether. That the visual display did not reduce initial response times is not surprising. The display, while centrally located on the dashboard, was outside of the driver's direct field of view of the roadway scene. The current simulator setup was not equipped to track the subject's eye movement; therefore, determining the exact reason for this increased response time is not feasible. Since the visual display was outside of the immediate field of view, the driver had to adopt a scanning pattern to attend each display. It is possible that the drivers' response time increased due to the latency between

TABLE 22

Overall Brake Response Time Compared to Previous Research Measuring Brake Response Time.

Year	Authors	Driving Environment	Brake Response Time Mean (s)	Brake Response Time Standard Deviation (s)
1968	Barrett, Kobayashi, and Fox	Simulator	1.00	Not Reported
1971	Johansson and Rumar	On-Road	0.90*	Not Reported
1991	Lechner and Malaterre	Simulator	1.00	0.22
1992	McKnight and Shinar	On-Road	1.18-1.86**	Not Reported
1996	Graham, Hirst, and Carter	Simulator	0.70 - 0.90	Not Reported
Current Study		*Simulator*	*1.01*	*0.28*

*Corrected for anticipation of subject.
**Did not control for headway.

scanning patterns. It is also possible that the visual display simply required a higher level of cognitive processing.

In either case, the operators' attention had to be diverted from the driving task in order to attend to the warning being presented. This alone provides valuable information to system designers that presenting collision avoidance information exclusively through the visual channel may not always be appropriate since it can distract the driver and may result in longer response times than those which exist without the use of a collision warning. In an exhaustive literature review, no other similar research was found to which a comparison of these results can be made. Since driving is primarily a visually intensive, manual-control tracking task, and the majority of the driver's attention must be focused toward the road, it is not surprising the visual display produces shorter response times. The omni-directional nature of auditory warnings lend themselves particularly well to a task such as driving where the operator's attention must be focused on the roadway ahead.

The auditory icon was found to elicit significantly faster brake response times than that of the conventional auditory warning (approximately 122 ms faster). As previously mentioned, initial response time is the measurable quantity which is most closely related to cognitive processing time. That the auditory icon produced statistically faster response times may support the theory since auditory icons are identified by their distal stimulus, they require less cognitive processing time than do conventional warnings.

Additionally, the differences found in initial response time (and overall brake response time as well) indicate that using the auditory icon as a warning device in the simulator environment was successful. The conventional auditory warning used in this study had been identified through previous research (Haas, 1993) as being relatively urgent, which in addition to its other characteristics would seem to make it an excellent choice for a traditional warning signal. Because the auditory icon was able to elicit significantly faster response times than this carefully designed conventional auditory warning indicates that auditory icons may be suitable warning signals.

No significant differences were found between the conventional auditory warning and the no-display conditions, despite the fact that auditory warning signals were generally expected to reduce operator response time. Two possible explanations are presented to explain the lack of differences. One possible explanation is the additional the time required to cognitively process the warning signal, decipher its meaning, and begin to react. Alternatively, given the high relative urgency of the warning signal, a startle response may account for the lack of differences. In an exhaustive literature review, no other similar research was found to which a comparison of these results can be made.

The auditory icon was found to reduce response time compared to both the no-display condition and the conventional auditory warning. This follows the aforementioned premise that properly designed auditory warning signals are intended to result in reduced response times. Unlike its conventional correlate, it is suspected that since the auditory icon was intended to be highly representative, the translation or deciphering of its meaning required less cognitive processing time. This would account for the reduced response times. No known research is available to verify this hypothesis, further research should be conducted to understand the cognitive processing of warning signals at a microscopic level.

The expectation that the presentation of warning information through multiple modalities (visual and auditory) would lead to decreased brake response times when compared to either single component was partially realized. Both multi-modal displays (visual dash-mounted display and auditory icon and visual dash-mounted display and conventional auditory warning) were found to elicit response times which were significantly faster than the dash-mounted visual display. This was expected and is attributed to the fact that the multi-modal displays contained the omni-directional attribute of the auditory displays.

The dash-mounted visual display and conventional auditory warning combination was found to elicit initial response times which were significantly faster than the conventional auditory warning alone. One possible explanation for this result can be found by bringing together portions of the theories discussed previously. Combining the latency effect theory which accompanied the dash-mounted visual display discussion with the conventional auditory warning theory that slower response times can be explained by the time required to translate or interpret the signal prior to reacting offers a reasonable explanation.

Upon hearing the conventional auditory warning signal, participants must translate or interpret the signal before reacting; this is because the conventional auditory warning has no analog outside of the system in which it was used. This interpretation process is likely to involve some degree of uncertainty, therefore requiring additional time between signal presentation and the operator's first reaction. The addition of a visual display reduces this uncertainty. With the dash-mounted visual display and conventional auditory warning combination, the presentation of the auditory signal would have alerted the driver that 'something was happening'; however, the driver did not immediately interpret the meaning of the auditory signal but quickly glanced at the visual display for additional information. Because both of these signals were presented simultaneously, the driver did not need to rely solely on a scanning pattern in order to detect the visual warning signal.

No differences were found to exist between the multi-modal display (visual dash-mounted display and auditory icon) and the auditory icon alone. This can potentially be explained through the previously mentioned explanation of the auditory icon's performance. By its very nature, the auditory icon is already representative. Therefore, the incremental addition of the visual display to the conventional auditory warning is needed to provide an easily interpreted, highly representational image of the impending collision; the auditory icon already has this image 'built-in' to its structure.

That the dash-mounted visual display and auditory icon multi-modal display did not result in response times significantly different from the dash-mounted visual display and conventional icon multi-modal display may be explained by the limits of human response time. Little, if any, research has been done to determine the limits of human response time while simultaneously completing a secondary task, such as driving. Therefore, without further research, it is impossible to tell if the limits of human response time for performing a task in a complex driving environment are being reached.

These results can be related back to the model of human information processing presented by Wickens (1992) in Figure 1. Two major stages of this model appear to be affected by the different levels of displays presented in this study; the perception stage and the decision and response selection stage. Memory also appears to play a role (e.g. speed at which information can be recalled); however Wickens does not identify it as a separate stage; instead it is auxiliary to the perception and decision response selection stages. The distinction between warning signal modalities, such as the differences which exist between the visual display and the auditory warning displays may be most readily allocated through the perception stage of Wickens (1992) model of human information processing. The decision and response selection stage of Wickens (1992) model of human information processing, however, offers a more appropriate explanation of the notion of cognitive processing.

There is no clear answer to the problem of developing overall guidelines for the application of mixed-modality displays in motor vehicles. Both auditory icons and conventional warning signals, when added individually to an existing dash-mounted visual display resulted in decreased response times. However, use of the auditory icon alone achieved similar results. Therefore, consideration needs to be given to the users' acceptance of auditory icons. Approximately one-half of the participants in this study were skeptical of the auditory icons and indicated they did not sound like 'serious' warning signals. If the general opinion of the user population can be swayed to embrace the new technology, then the simplest design would involve one display which makes use of auditory icons. If the users remain skeptical and do not accept the technology, then a dual display utilizing conventional auditory warnings and a dash-mounted visual display should be employed.

Headway. A headway criterion of 3.5 seconds resulted in decreased initial response times when compared to a headway criterion of 2.5 seconds. That very short headways should elicit longer brake response times is a phenomenon documented in the literature (Hankey, McGehee, Dingus, Mazzae, and Garrott, 1996).   The nature of this phenomenon, however, is not well-understood and has not been clearly defined.

Before discussing the possible causes of this phenomenon it is important to summarize the methods of forward collision presentation. The method used by Hankey, et al. (1996) was slightly different from the method used in the present study. Hankey, et al. (1996) used a scenario in which a vehicle would pull out of an intersection at one of three predetermined headway values (2.85, 3.60, and 4.35 seconds) as the driver's vehicle approached the intersection. The mode of presentation for the current study made use of several different front obstructions (one of which was very similar to the method used by Hankey, et al. (1996) all of which appeared suddenly at the appropriate headway values (2.85, 3.60, and 4.35 seconds).

Hankey, et al. (1996) offered two possible explanations for the observation that very short headways should elicit longer brake response times. First, drivers may stay alert to the possibility of an impending collision up to a reasonable headway where the likelihood of an impending collision is deemed to be remote, then shift their attention to other driving tasks. This explanation lends itself particularly well to those situations which involve a visibly detectable, higher probability of collision (e.g. an intersection, playground). Unfortunately, it does not address those situations where the collisions may be deemed improbable (e.g. vehicle suddenly slowing on the interstate) due to a lack of surrounding visual cues. The hypothesis presented by Hankey, et al. (1996) can be expanded to include such collisions by rephrasing it in terms of headway. There is a region of headway, which can be defined temporally, which is very close to the front of the vehicle and therefore the driver lends less credibility to the probability of a collision occurring, or being able to react appropriately to an impending collision if it were to appear within this region and therefore devotes the vast majority of attentional resources beyond this region.

The second alternative presented by Hankey, et al. (1996) is, given the severity of the circumstance, that subjects may be evaluating the situation with greater scrutiny to determine the most appropriate response. Either of these proposals may be plausible. Unfortunately, this study can offer no evidence to support or refute either hypothesis and further study is needed to determine the effect of these hypotheses on impending forward brake response time.

Side Collision Avoidance

Auditory display. Participants had a lower occurrence of collisions when the auditory icon was used as a side collision warning as opposed to a conventional auditory warning. The reduction in accident occurrence attained with the auditory icon is attributed to the high salience and identification of the sound with the distal stimulus, thus reducing cognitive processing requirements.

Mirrors. It is not surprising the participants also had fewer collisions when mirrors were used as opposed to scenarios where they were absent. The reduction in accident occurrence attained with the presence of mirrors is attributed to the driver's current driving habits. Mirrors were included with the intent of evaluating the interaction effects of the other variables with mirrors; however, the reduction in the available degrees-of-freedom limited the number of interactions which could be included in the analysis. The only interaction, auditory display-by-mirrors, included in the analysis was not found to be statistically-significant.

Auditory icon-by-visual display interaction. The auditory-by-dash-mounted visual display interaction (AxDVD) is depicted in Figure 22. When no visual display is present, no differences were found between the traditional auditory warning and the auditory icon; however, with the addition of the visual display, the presence of the auditory icon resulted in significantly fewer collisions. The significance of the AxDVD interaction cannot be completely explained by the multiple resources model of information processing presented by Wickens (1992). Paivio's dual-coding theory; however, does provides a basis for understanding this interaction.

Dual coding theory, evolved from the role of imagery in associative learning, is supported by a large quantity of empirical evidence (Paivio, 1986, 1991). The theory assumes an orthogonal relationship between two functionally independent, yet interconnected, symbolic and sensorimotor systems. Table 23 shows the conceptual relationship between the symbolic and sensorimotor systems with examples of modality-specific information. The premise of the dual coding theory is that information is coded and processed by separate language (verbal) and non-linguistic (nonverbal) symbolic systems. The language, or verbal, sub-system is specialized for handling language or speech, while the non-linguistic is specialized for coding and processing non-verbal information such as background or environmental noise. Cognitive activity can take place concurrently in both symbolic systems since dual coding theory assumes that information is coded and processed by separate language and non-linguistic systems

(Paivio, 1986); presenting information concurrently to both systems will improve the efficiency and effectiveness of processing information.

Dual coding theory can be used to explain the current AxDVD interaction. The occurrence of the visual display is inherently a non-linguistic attribute of the visual sensorimotor system (by contrast, a linguistic visual display may consist of printed or displayed words) while the conventional auditory warning is a non-linguistic attribute of the auditory sensorimotor system. Because of its highly representative nature, the auditory icon may be argued to be more closely related to the language symbolic system than is the conventional auditory warning. As a result, in the "no visual display" condition, no significant differences were found between the traditional auditory warning (non-linguistic subsystem) and the auditory icon (language subsystem). When the visual display (non-linguistic subsystem) was added; however, the use of the auditory icon (language subsystem) was found to result in significantly fewer accidents than with the visual display and the conventional auditory warning (non-linguistic subsystem) used together. This result is supported by dual coding theory. The situation involving the visual display and auditory icon used warning stimuli from complementary symbolic systems, whereas the use of the visual display and the conventional auditory warning were from the same (non-linguistic) subsystems. The use of warning stimuli from complementary symbolic systems resulted in improved operator performance.

Subjective Preference

As was shown in Table 17, participants answered each of the questions regarding various aspects of the simulator using a five point Likert-type scale. The Likert-type scale was anchored at "1 - Strongly Agree" and "5 - Strongly Disagree." Several broad statements can be made. Generally speaking, the participants felt the collision warnings provided useful information, were easily understood, were not annoying, and did not distract them from driving. Furthermore, the majority felt that the system provided reliable information and that they were able to react more quickly to hazards with the system than without.

TABLE 23

Orthogonal conceptual relationship between the symbolic and sensorimotor systems with examples of modality-specific information (adapted from Paivio, 1989).

	Symbolic Systems	
Sensorimotor	Language (verbal)	Non-Linguistic (nonverbal)
Verbal	Visual Words	Visual Objects
Auditory	Auditory Words	Environmental Sounds
Haptic	Writing Patterns	“Feel” of objects
Taste		Taste memories
Smell		Olfactory memories

Participants conveyed a general willingness to support new technology which has the potential to increase their safety and productivity. Informally, several participants indicated very strong support for the current research being conducted in that it addressed several issues which they perceived to be significant. Whether these opinions are representative of the truck driver population as a whole cannot be determined from the responses of this relatively small group; however, the opinions do signal a marked willingness and openness to the consideration of new technology by at least a portion of the commercial motor vehicle operators currently on the nation's roadways.

Participants were also asked which auditory warning signal they preferred for a given collision scenario (either an impending front-to-rear or side collision), as shown in Table 19. For the front-to-rear collision scenario, fifteen of the individuals identified the auditory icon as the preferred auditory warning while the remaining nine chose the conventional auditory warning. For the impending side collision, only eleven individuals preferred the auditory icon, the remaining thirteen chose the traditional auditory warning.

A simple comparison between individuals who preferred the conventional auditory warnings and those who preferred the auditory icons shows that fewer individuals who preferred the conventional auditory warning were able to correctly identify that signal's meaning than were the individuals who preferred the auditory icon warning signal. For the impending front-to-rear impending collision, only five of the nine participants who chose the traditional auditory warning as their preference were able to correctly identify its meaning. For the side impending collision, only six of the thirteen participants who preferred the traditional auditory were able to correctly identify its meaning. For both the side and front-to-rear impending collisions, one-hundred percent of the individuals preferring the auditory icons were able to correctly identify the signal's meaning.

As mentioned previously, results indicated the presence of significant differences between the initial brake response times elicited by the auditory icon and conventional auditory warning for the front-to-rear impending collisions. This is an important result as it demonstrates the performance improvement that might be attained with auditory icons with respect to detectability and alertability over that of a conventional auditory warning signal. While this improvement in response times is important, another benefit of auditory icons became evident when participants were asked to identify the meaning of each warning signal. Participants were able to correctly identify the meaning associated with the auditory icon over 95% of the time; whereas, they were able to correctly identify the meaning associated with the conventional auditory warning signals less than 57% of the time. The percentage of individuals correctly identifying the meaning associated with the conventional auditory warning was not statistically different from randomly choosing one of the two meanings.

That individuals were able correctly identify the auditory icons while it appears they were guessing at the meanings of the conventional auditory warnings is important. While driving is representative of a relatively complex task, there were only two situations which would have resulted in an alarm, an impending front-to-rear collision or an impending side collision. As ITS systems become more prevalent, the number of displays in the vehicle are likely to increase and some of these may also make use of auditory displays. If a driver is unable to discern between two conventional warning sounds, it is unlikely that additional displays will improve performance. The ramification of incorrectly identify a warning increases when a driver misinterprets a relatively unimportant display (e.g. low fuel) for one of greater importance (e.g. impending front-to-rear collision), or vice-versa. Finally, if the driver is uncertain as to the meaning of an auditory display, his/her course of action may be to ignore it altogether, a factor which makes the value of such warning devices questionable.

Finally, individuals indicated a clear preference for multiple modality displays in both the front-to-rear and side collision scenarios. Results from the front-to-rear brake response times and side collision accident occurrence appear to confirm their perceptions of improved driver performance with the use of multi-modal displays. These results, however, should be used judiciously. One of the goals of this study was to determine how to improve driver performance. The evidence confirms that driver performance was generally improved with the use of multi-modal displays. However, since measures of operator workload were not recorded there is no evidence as to the effect of multi-modal displays on workload. Further research is needed, however, to determine where such displays are appropriate; it is unlikely that all displays would benefit from presentation through dual modalities and such a situation could likely result in excessive operator workload.

These results illustrate the preference and performance tradeoff issues; a salient issue in the design of human factors systems. While it is important to design technical systems such that they improve operator performance, consideration must also be given to the social system or operator preference. If such systems are perceived as frivolous then it is unlikely that operators will embrace such systems thus resulting in possible sabotage or a simple unwillingness to use the system. As a result, system design should consider both the social and technical aspects affecting a system and work to jointly optimize the pair. In this situation, where approximately one-half the operators preferred the traditional warnings over auditory icons, despite decreased performance that occurred with traditional warnings, a demonstration of the effectiveness of auditory icons may improve their acceptability among a skeptical population.

Experimental Limitations

Although the results of this study seem to support the use of multi-modal displays, the inclusion of auditory warning signals in the commercial motor vehicle, and the use of auditory icons over conventional auditory warnings, several items must first be considered. Driver workload and simulator fidelity are two such items which must be taken into account. Because driver workload was neither quantified nor measured, there was no way in which the workload experienced by the participants could be estimated. Further, there is no way to determine if the workload experience through the simulator was comparable to that of an actual driving task.

The second issue, which could limit the generalizability of the results as a whole, is that of simulator fidelity. Many drivers commented on the overall simplicity of the simulator. The deficiencies mentioned most often include the lack of a manual transmission, Jake brake, stereo, and citizens band radio. In addition, that the experiment was conducted in a non-smoking facility was mentioned by more than a few of the participants.

The lack of a citizens-band radio and/or stereo may have had an unintentional adverse effect on the results of the auditory alarms; specifically upon the discernability of auditory icons. The component auditory spectrum of auditory icons is generally wider than that of traditional auditory warnings and therefore is more susceptible to the effects of masking. Increased masking will potentially result in decreased detection which may adversely affect the utility of such warning signals. Unfortunately, there was no way in which these devices could be used which would increase the realism of the experience while at the same time maintaining experimental control. As a result, they were not incorporated into the simulator environment.

The results concerning the chosen dash-mounted visual display may limit the generalizability of these results. As only a single display was incorporated into the simulator, it is important to note that the results presented herein pertain only to the particular display used within the current study. While every effort was taken to utilize a display that efficiently conveyed the necessary information, the generalizability of these results to other visual displays may not be appropriate.

Another potentially limiting factor involves the subject participating in the study. Every effort was made to recruit subjects from a cross-section of the trucking population Given some of the informal conversations with the drivers involved in the current study, it is believed that this effort was realized. Since no formal metrics were acquired to verifying this belief; the population may have been unintentionally skewed. Specifically, the concern is such that individuals who are willing to participate in a simulator-based study at a university may not be representative of the population as a whole.

CONCLUSIONS

The most notable conclusion of the current study involves the use of auditory icons as warning signals. Previous attempts (Graham, Hirst, and Carter, 1995; Haas and Schmidt, 1995) to incorporate auditory icons as warning signals into complex systems have been largely unsuccessful. Based upon the decreased braking response times for impending front-to-rear collisions and a reduction in the occurrence of accidents for the impending side collisions, this research offers the first evidence that auditory icons, or representational warning signals, may in fact be useful as alarming devices. When compared to conventional auditory warnings, the results from this research also demonstrate that auditory icons are more easily remembered, and less likely to be forgotten.

This study yields some very salient results for the appropriate design of an impending collision warning system. Collision warning displays, as a whole, were found to improve driver performance over situations in which none were present. The potential benefit of improved driver performance in lives and dollars saved warrants the further design and development of collision warning devices.

Auditory displays yielded improved driver performance when compared to visual displays; however, visual displays were generally preferred to auditory displays when the display consisted of a single modality. Given the general discrepancy between operator performance and preference, no clear recommendations can be offered if the collision warning display is to consist of a single modality.

Multi-modal displays was found to be at least as effective as the single modality auditory warnings for both auditory icons and conventional auditory warnings. For both impending collision scenarios, front-to-rear and side, participants indicated a preference for the multi-modal display. The agreement between the operator preference and performance responses suggest that collision warning displays make use of multiple modalities.

Finally, dependent driving measures demonstrated that auditory icons yield improved performance over conventional auditory warnings. When considered in conjunction with the positive nature of the participant subjective responses, collision warning systems would benefit from the use of auditory icons.

SUGGESTIONS FOR FUTURE RESEARCH

While the research described herein was considered to be successful, the nature of the work undertaken has identified more questions than it has answered. That the use of auditory icons has been identified as effective warning signals opens an entire new field of warning signal design. Additional experiments should be conducted in order to refine the methodology developed for the selection and identification of auditory icons. Much has yet to be resolved regarding the roles of an individual's location, gender, vocation, or culture in sound identification.

Further research is also needed to determine what factors affect perceived urgency within an auditory icon. Is the distal stimulus the most influential feature? Or, is it the physical characteristics (e.g. frequency, amplitude, length) of the signal? The current literature (Patterson, 1982; Edworthy, Loxley, and Dennis, 1991; Haas and Casali, 1993; and Burt, Bartolome, Burdette, and Comstock, 1995) represents considerable effort to identify the effects of various physical characteristics on perceived urgency for conventional auditory warnings. No similar research is known to exist for representative auditory warnings such as auditory icons.

Since no effort was made to measure the workload experienced by the operator, a future study should concentrate on quantifying this value as a more complete evaluation of each of the different display combinations. Additionally, prior to implementing collision warnings based upon the information described herein, additional studies should be conducted using a higher fidelity environment, such as an actual commercial vehicle, which more closely resembles aspects of the driving task not incorporated into the simulator.

Additionally, the long-term effect of auditory icons as collision warning signals needs to be established. In particular, the effect of experience or familiarity through repeated presentation may affect the nature of the responses elicited. It is unknown at this time if a driver's perception of auditory icons is stable over the long-term. This is one area which should be more fully explored prior to widespread implementation of auditory icons.

Finally, the phenomenon of shorter times to collision yielding longer brake response time warrants investigation. At least two studies, the current study and Hankey, et al. (1996), have identified this phenomenon. Future efforts should concentrate on developing a model which uses the driving environment and conditions to predict the optimum time for which the presentation of a collision warning should occur.

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APPENDIX A

Informed Consent for Auditory Icon Pilot Study

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project:	Pilot Study for the Use of Auditory Icons in the Heavy Truck Cab Environment
Principle Investigators:	Dr. J. G. Casali, Professor and Department Head, ISE Dr. Gary S. Robinson, Senior Research Associate, ISE John J. Winters, Graduate Research Assistant, ISE Steven M. Belz, 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 construct a set of non-verbal auditory messages for use in heavy truck cabs. The information to be presented by these messages includes both information available in current commercial vehicles and information from potential Intelligent Transportation System (ITS) functions. To participate, you will be required to show a valid driver's license. If you choose to take part, you will be one of more than 40 participants in this study.

II. Procedures

Before the testing begins, you will participate in a short orientation session. You will be provided with a brief description of the functions and information that the auditory messages which you will hear in the study are intended to convey. The messages will relate to either current commercial vehicle functions or ITS functions that may be included in heavy trucks in the future. You will also receive instructions for free modulus magnitude estimation, a rating method you will be requested to use in this study. You will be asked to complete a short line length estimation task in order to practice the free modulus magnitude estimation method.

Using a small speaker or pair of headphones, you will be presented with a set of short sounds. For each sound, you will be asked to give the perceived meaning of the sound as it relates to use in a heavy truck cab. You need not be overly specific in your responses; if your answers are too vague, the experimenter will prompt you for a more specific answer. A total of approximately 40 sounds will be presented. Once all of the sounds have been presented, you will be given a five to ten minute break. The set of sounds will then be presented a second time in a different order. During this set of presentations, each sound will be presented twice. For each presentation, you will be asked to use the free modulus magnitude estimation method to rate the perceived urgency by assigning a number to the sound. You may assign any number you think appropriate, but let high numbers represent high urgency, let low numbers represent low urgency, and try to make the ratios between the numbers correspond to the ratios between the urgencies of the sounds. Please attempt to rate the urgency of the sound itself and not the urgency of the function you perceive as being represented. The urgency rating presentations will be followed by a second short break, after which the set of sounds will be presented once again. Again, each sound will be presented twice. Following each of these presentations, the experimenter will inform you of the intended meaning of the presented sound. You will then be asked to again use the free modulus magnitude estimation method to rate the level of association of the sound with the provided meaning. The entire session is expected to last between an hour and a half and two hours.

III. Risks

There are no known risks associated with your participation in this project.

IV. Benefits of this Project

Your participation in this study will provide useful information about the perceived meanings and urgencies of auditory messages. There are no known direct benefits to you associated with your participation in this project other than the compensation discussed in Section VI.

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 provide. 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.

VI. Compensation

At the end of your participation in this session, you will be compensated at the rate of $5.00 per hour. If you complete the session in less than one hour, your compensation will be equal to the amount for one hour.

VII. Freedom to Withdraw

You are free to withdraw from this experiment for any reason at any time without penalty. If you choose to withdraw early, you will be compensated for the time you have spent in the study. If there are circumstances under which it is determined that your participation in this study should not continue, you will be compensated for the portion of the experiment completed.

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 know of no reason I cannot participate in this study. I have the following responsibilities:

To perform the tasks according to the instructions to the best of my ability.

To notify the experimenter at any time about discomfort or desire to discontinue participation.

____

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.

I have read and understand the informed consent and conditions of this project. All the questions that I have asked have been answered to my satisfaction. I hereby acknowledge the above and give my voluntary consent for participation in this project, 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 Casali, Director of the Auditory Systems Laboratory, Dr. Gary S. Robinson, Research Associate, and Steven M. Belz, Graduate Research Assistant. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory
Room 538 Whittemore Hall
VPI & SU
Blacksburg, VA 24061-0118
Dr. Casali: (540) 231-9081
Dr. Robinson: (540) 231-2680
Steven Belz: (540) 231-9087

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 B

Auditory Icon Pilot Study

The following is a detailed description of the auditory icon pilot study.

Background

Three major issues must be addressed in designing auditory icons. First, the signal must be easily detectable. Second, the signal must be distinct so as not to be confused with other signals. Finally, the perceived urgency of the signal should match the urgency of the event to which it corresponds. For example, a warning signal identifying a severe event (e.g. engine overheating) should sound more urgent than one which identifies a relatively minor event (e.g. pay toll ahead).

The issue of warning signal detection can often be accounted for by adjusting the sound level at which the signal is presented. Although other variables, such as the contrast of the signal to the background noise, may also influence detection of a warning signal. Established methods and standards such as ISO 7731-1986 are available which address the issue of setting signal levels in an objective and quantifiable manner.

The issue of warning signal identification or association of a signal with its intended meaning is not addressed in the current literature. Traditionally, warning signals have been developed and implemented into systems where operators would then be expected to commit the signal and its meaning to memory. Little consideration was given to the process of associating an alarm with a specific event. Further, identification of a warning signal which could be appropriately associated with the system was a major criticism of the doorbell icon within the BCIS (Haas and Schmidt, 1995).

Finally, the issue of matching the perceived urgency of a situation with that of an warning signal has received little attention. Gaver (1994) demonstrated the importance of matching the perceived urgency of a signal to its associated meaning when he noted that individuals in his study frequently neglected important tasks, directing their attention to tasks of lesser importance. A higher level of importance with respect to safety or system operation should result in a warning signal with a higher degree of perceived urgency. Likewise warning signals of low relative importance should be perceived as having a lesser degree of perceived urgency.

Methodology

Established guidelines suggest a maximum of five or six conventional warning signals be employed in a complex system (Patterson and Milroy, 1980); a number insufficient for many of today's complex systems. Auditory icons, however, may expand the current maximum to include fourteen or more such auditory warning signals (Gaver, Smith, and O'Shea, 1991). Previous research efforts (Graham, Hirst, and Carter, 1995; Haas and Schmidt, 1995) made use of expert opinion to identify and select auditory icons have largely ineffective because of conflicts between expert and end-user opinions as to the meaning and appropriateness of the auditory icons. As a result it was imperative to include a metric by which the level of association of an auditory icon with its intended meaning could be appropriately gauged.

The first step in developing the methodology for selecting auditory icons was to perform a rudimentary task analysis to identify those situations which would benefit from the auditory display of information. For the study described herein, these tasks included: low fuel, low air pressure, high engine temperature, poor weather ahead, and congested traffic ahead, among others.

After completing the task analysis, it was necessary to identify candidate sounds for each task. Although several candidate auditory icons were sought for each meaning group or task, in some cases only one suitable sound could be identified or obtained. The majority of the auditory icons used in this study were obtained from commercially available sound effect collections. Sounds not available on pre-recorded media were obtained by sampling actual events. All of the sounds were edited and filtered to remove as much background noise as possible and to ensure each auditory icon was presented at a uniform loudness.

Once the candidate auditory icons and their associated meanings had been identified, data collection began. Fourteen commercial vehicle operators (CVO) and twenty civilian drivers were recruited for the study. Each subject reported having normal hearing and no history of tinnitus. Participants were paid five dollars per hour as compensation for their time.

The experimental sessions were conducted in a quiet environment either in the Auditory Systems Laboratory or at the participant's place of employment. The auditory icons were presented using an Apple Powerbook 180 laptop computer and the participants listened to the sounds through a pair of lightweight stereo headphones. The experimenter monitored the presentation levels of the sounds at all times so as not to cause the participant any harm.

At the beginning of each experimental session, the participant took part in a pre-experimental line-length estimation task designed to familiarize the subject with free-modulus magnitude estimation. The auditory icon testing was divided into three segments. The first segment was designed to determine the meaning of each of the 51 auditory icons. The participants were encouraged to respond freely and were not restrained to a uniform set of responses. Each auditory icon was presented once during this segment. In the second segment, participants rated the perceived urgency of the auditory icons using free-modulus magnitude estimation. In the third segment, participants again used free-modulus magnitude estimation to rate the level of association each auditory icon had with an experimenter-assigned meaning. The subjects were instructed to use higher numbers to indicate greater levels of perceived urgency and association. In the second and third segments, each auditory icon was presented twice in random order and the average of the two ratings was used as the dependent measure.

Results

The subjects' free responses obtained during the first segment of the study were evaluated by grouping similar responses into categories to determine if the participants assigned the same or similar meaning to the auditory icons as had the experimenter. Due to the subjective nature of this process, no further statistical analysis was performed on this data. In order to compare the perceived urgency and association responses, it was first necessary to establish a uniform rating scale by removing the inter-subject variability attributable to the individual differences in scale selection. Each pair of responses was averaged and transformed using a procedure developed by Engen (1971) and explained in detail (with a correction) by Haas (1993). Separate transformations were completed for the ratings of perceived urgency and association.

As mentioned earlier, participants were given an opportunity to practice the free-modulus magnitude estimation procedure via a line-length estimation task since research has shown that practice tasks reduce the variability in later rating tasks (Zwislocki, 1983). However, the line-length estimation task also served a screening function. Zwislocki (1983) determined that individuals with poor rating skills for one type of stimulus exhibited similar behavior for other stimuli. For this reason, the free-modulus magnitude-estimation data for one CVO subject who exhibited difficulty with the line-length estimation task was eliminated. This subject's free response data, however, was retained since his inability to judge line length had no influence on his ability to interpret a sound's meaning.

Individual ANOVAs were performed for each set of auditory icons grouped by intended meaning to analyze perceived urgency and association, resulting in 70 individual analyses. Where there was only a single auditory icon within a meaning group, single factor (Driver Category) ANOVAs were performed. In groups containing more than one auditory icon, two factor (Auditory Icon by Driver Category) ANOVAs were performed. Newman-Keuls procedures were used for all post-hoc tests. Results of the analyses are presented in Table 2.

Only one auditory icon was rated significantly different ($p \leq 0.05$) for perceived urgency across driver categories. In this case, CVOs rated the back-up alarm (Group #19 - Vehicle/Object Behind) as being more urgent than did the civilian drivers. In several cases (Groups 2-4, 6, 10, 11, 13, 14, and 16-18), the perceived urgency of one or more of the auditory icons within a group differed significantly from the other auditory icons within that group (a main effect of Auditory Icon). Although the specifics of which auditory icons differed from which others (according to Newman-Keuls post-hoc tests) within these groups are not presented here, the practical implications of these findings are discussed in the next section.

Two of the auditory icon groups (Group #4 - Low Oil and Group #12 - Automated Toll Payment) differed in their perceived association with their intended meaning across driver category. For Group #4, a main effect of Driver Category indicated that CVOs rated the auditory icons in that group as having a significantly ($p \leq$ 0.05) greater

TABLE B.1

Summary of Individual Meaning Group ANOVAs

Group Number	Meaning Group *Description Of Candidate Auditory Icons*	Number of Auditory Icons	Urgency		Association	
			Auditory Icon	Driver Category	Auditory Icon	Driver Category
1	Low Fuel *Gurgling, Drain clearing*	2	N	N	N	N
2	Loss Of Air Pressure *Bottle rocket, Air leak, Air spurt*	3	Y	N	Y	N
3	High Engine Temperature *Teapot whistling, Boiling water, Wildfire*	3	Y	N	Y	N
4	Low Oil *Gears grinding, Grinding & squeaking, Grinding & whirring, Metal crushing, Rattle, Chain rumble*	6	Y	N	N	Y
5	Problem With Trailer *Squeaking trailer*	1	-	N	-	N
6	Incoming Voice Message *Analog ringer, Digital ringer*	2	Y	N	N	N
7	Place A Call To Someone *Touch-tone dialing*	1	-	N	-	N
8	Incoming Fax Message *Fax machine*	1	-	N	-	N
9	Incoming Text Message *Typewriter (w/ carriage return), Teletype*	2	N	N	N	N
10	Poor Weather (Rain) *Rainfall, Thunder, Rain w/ thunder roll, Rain w/ thunder clap*	4	Y	N	Y	N
11	Fog Warning *Foghorn (single tone), Foghorn (2-tone)*	2	Y	N	N	N
12	Automated Toll Payment *Coin dropped on table, Coin dropped in slot*	2	N	N	Y	Y
13	Emergency Vehicle Approaching *Siren (wail), Siren (fade), Siren (hi-lo)*	3	Y	N	Y	N
14	Roadwork Ahead *Jackhammer, Bulldozer*	2	Y	N	N	N
15	Roadside Mowing Ahead *Mower (high pitch), Mower (low pitch)*	2	N	N	N	N
16	Train Crossing Ahead *Train horn, Train crossing bell, Train (Doppler effect)*	3	Y	N	Y	N
17	Children / Playground Ahead *Giggling, Screaming*	2	Y	N	Y	N
18	Collision Avoidance Warning *Short honk, Long honk, Double honk, Short & long honk, Tire skid, Tire screech, Tire skid & crash, Tire screech & crash*	8	Y	N	Y	N
19	Vehicle / Object Behind *Truck back-up alarm*	1	-	Y	-	N
20	Congested Traffic Ahead *Congestion (coughing)*	1	-	N	-	N

Note: Y denotes significance at $\alpha = 0.05$, N denotes no significance, and '-' is not applicable, because of one-way ANOVA. Italicized text denotes a brief description of the individual icons beneath each Meaning Group.

association with their intended meaning (Low Oil) than did the civilian drivers. In Group #12, a breakdown of the two-way interaction revealed that the sound of a coin being dropped onto a table had a significantly greater ($p \leq 0.05$) association with its intended meaning (Automated Toll Payment) for civilian drivers whereas the sound of a coin being dropped into a slot exhibited no difference between the two Driver Categories. In several instances (Groups 2, 3, 10, 12, 13, and 16-18), a main effect of Auditory Icon was present indicating that the icons within those groups
differed in their perceived association with their intended meanings. As with perceived urgency, the specific differences will not be presented but the practical implications will be discussed.

Discussion

For the majority of the auditory icons, there were no significant differences in the responses given by civilian drivers and commercial vehicle operators. The CVO population rated one auditory icon, the back-up alarm, as having significantly greater perceived urgency than did the civilian population. For civilian drivers, backing a car is a relatively simple task; however, the task faced by commercial vehicle operators is non-trivial given the increased size and reduced visibility in the rearward direction of travel as well as the close proximity of other large trucks that may be backing up as well. Furthermore, since many trucks are equipped with back-up alarms and drivers consider backing to be so important, then it stands to reason that they would rate the back-up alarm as having a higher perceived urgency than would the civilian driving population. Previous research (Lee, Robinson, and Casali, 1996) conducted using subject matter experts confirms, at least qualitatively, the importance of backing to the commercial motor vehicle operator.

There were also differences in the perceived urgencies of the auditory icons within meaning groups. Knowing that some auditory icons within a group of auditory icons with the same or similar meanings elicit a greater (or lesser) response in terms of their perceived urgency will allow designers to more appropriately match the warning to the situation. However, to quantitatively match a warning to a specific situation would require that the urgency of both the situation and warning be quantifiable using comparable measures. This has yet to be addressed in the literature.

The differences between the CVO and civilian ratings of perceived association for Group #12 (Automated Toll Payment) illustrate how the results of a study such as this may be applied towards implementation of an auditory icon in a complex system. Two auditory icons, a coin being dropped on a table and a coin being dropped in a slot, were intended to represent an automated toll payment. Results indicate that commercial vehicle operators found the sound of a coin dropping on the table to have less association with an automated toll payment than the sound of a coin dropping into a slot. There was no significant difference between the perceived associations of the two auditory icons among civilian personnel. The practical implication for interface designers, when choosing auditory icons that must apply to both the CVO and civilian environments, is to choose an auditory icon which is accepted equally by both user populations. In this situation, that auditory icon would be the coin being dropped in the slot.

While there were few instances where ratings of perceived urgency and association differed between driver categories, the differences that do exist are important since they represent differing attitudes towards some situations. It is important to note that where cross-population differences are likely to occur, it is of paramount importance to uncover these differences in order to avoid a catastrophic error.

In evaluating which auditory icons are suitable for use in a given system, it is first necessary to determine if any of the auditory icons proposed by the experimenter are suitable for the task. Given the nature of the free responses in the first segment of the experimental sessions (subject-assigned meaning) and the inability to perform quantitative statistical analyses on the allocated groups (G. R. Terrell, personal communication, July 8, 1996), the method for determining the suitability of auditory icons is somewhat capricious.

In this study, Meaning Group #4 (Low Oil) represents a situation in which the experimenters determined that none of the proposed auditory icons suitably represented the task and that further development was needed. For example, very few of the auditory icons in Group #4 elicited free responses representing the experimenter's intended meaning. Furthermore, the perceived association scores were generally low, indicating that the auditory icons within the group may not be suitable for their intended purpose. In such situations, it would be prudent for system designers to pursue other sounds. Perhaps the sound of an antique oil can or a grease gun would be more appropriate as a low oil display. This should not be viewed as a failure of the methodology. To the contrary, the methodology was able to identify these unsuitable auditory icons before they were implemented in a complex system.

As mentioned previously, results from the simulator-based, commercial motor vehicle study indicated a significant difference between the overall brake response times elicited by the auditory icon and conventional warning. The performance of the auditory icons with respect to detectability and functionality was superior to that of the conventional warning signals. Further, when participants were asked to identify the meaning of each warning signal, the real benefit of auditory icons became evident. Participants were able to correctly identify the meaning associated with the auditory icon over 95% of the time; whereas, they were only able to correctly identify the meaning associated with the conventional warning signals less than 57% of the time. The percentage of individuals correctly identifying the meaning associated with the conventional warning was not statistically different from what would have been observed had the subjects been guessing at their meaning. In a safety-critical task, such as avoiding an impending collision, uncertainty about an alarm's meaning could be disastrous.

Conclusion

The science relating to the selection and implementation of auditory icons is relatively undeveloped. One of the driving forces behind this study was to develop a systematic methodology for selecting and evaluating auditory icons. Previously, researchers relied on expert opinion to establish an auditory icon's meaning. Unfortunately, this method lacked statistical rigor.

The method described herein is a first step towards establishing a methodology not solely dependent on expert opinion. The systematic approach used in this study is an improvement over previous efforts to identify and validate auditory icons. Further, this study partially validates the proposed methodology in that it was able to identify a situation in which commercial vehicle operators, as a result of their increased vehicle size and differences in equipment find to be more critical than do civilian drivers operating much smaller vehicles. The method described herein is being further evaluated in an on-the-road study to determine if environmental factors are significant in the evaluation and selection of appropriate auditory icons.

APPENDIX C

One-Third Spectral Band Of Warning Signals
And Background Noise

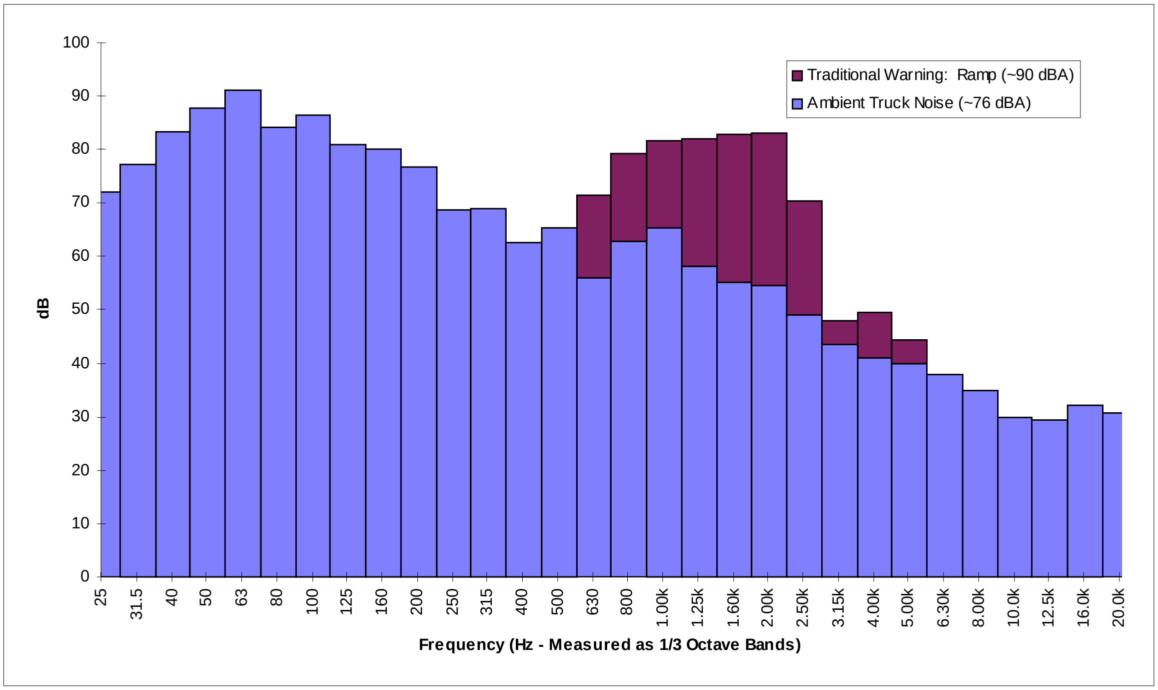

Figure H.1. One-Third Octave Band of the Front-to-Rear Collision Traditional (Ramp) Warning and Ambient Truck Noise.

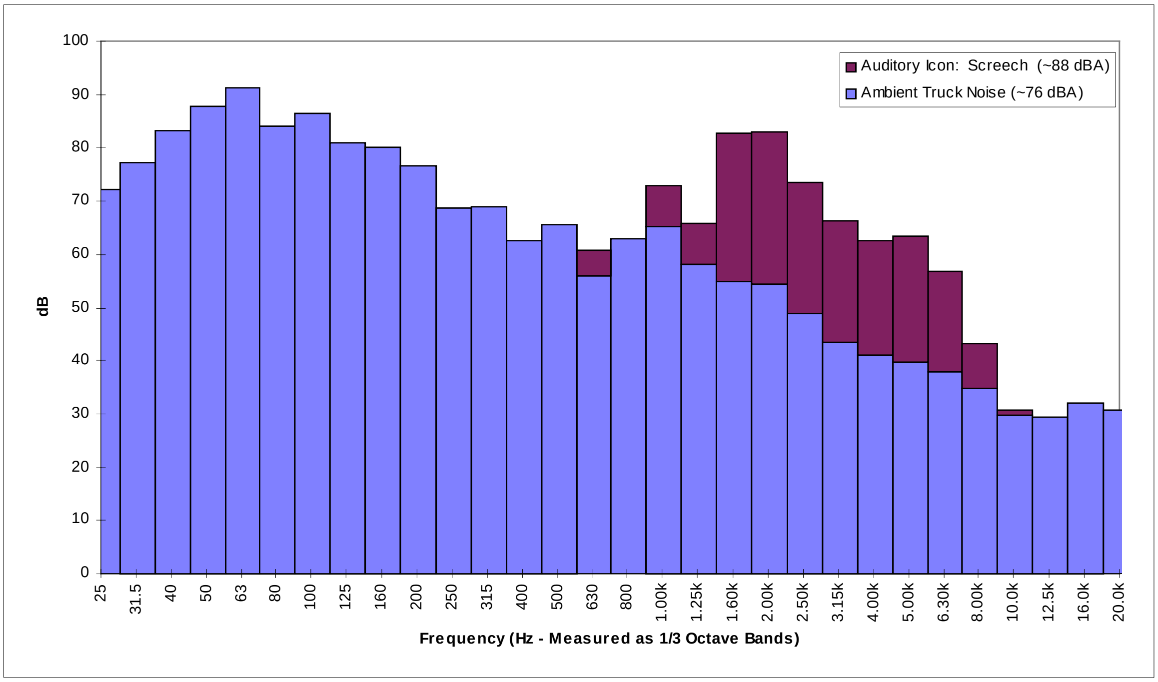

Figure H.2. One-Third Octave Band of the Front-to-Rear Collision Auditory Icon (Tire Screech) Warning and Ambient Truck Noise.

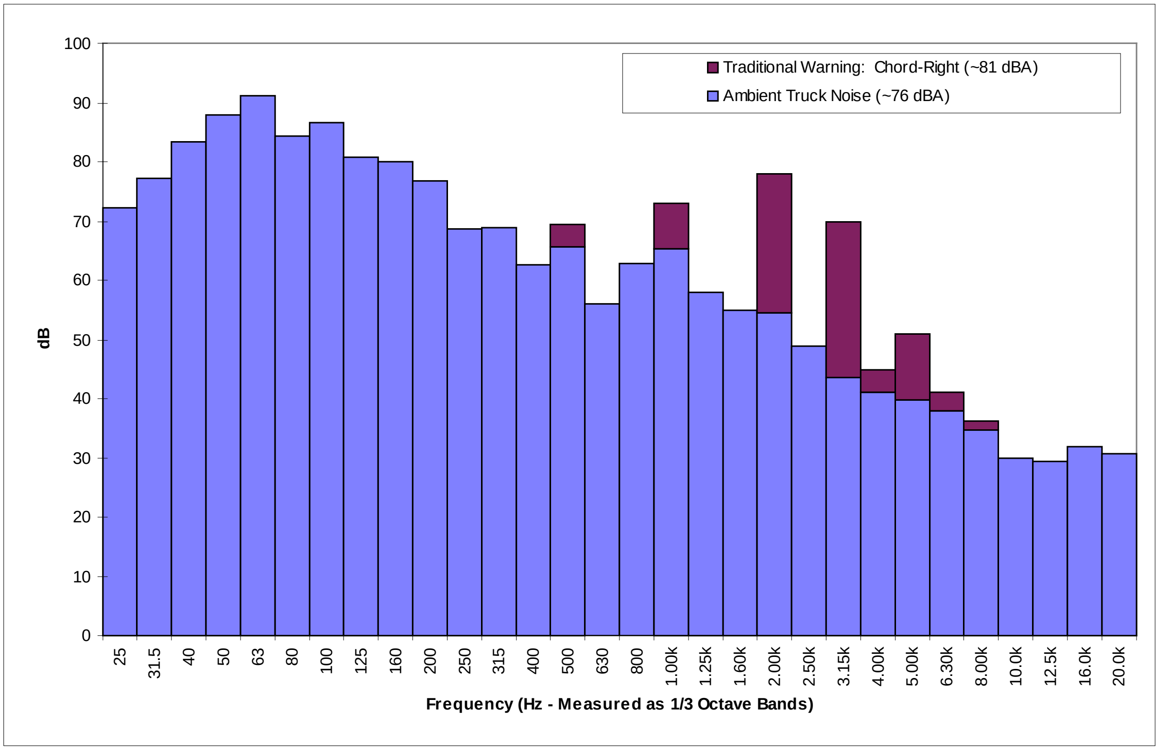

Figure H.3. One-Third Octave Band of the Side Collision Traditional Auditory (Right - Chord) Warning and Ambient Truck Noise.

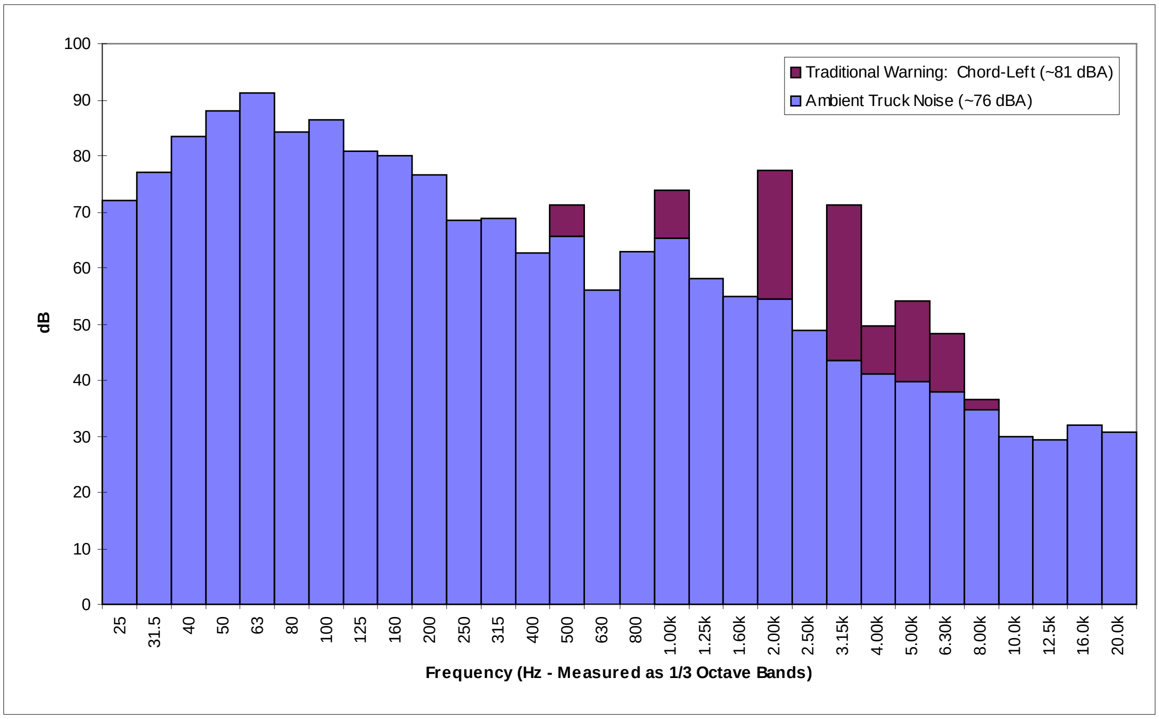

Figure H.3. One-Third Octave Band of the Side Collision Traditional Auditory (Left - Chord) Warning and Ambient Truck Noise.

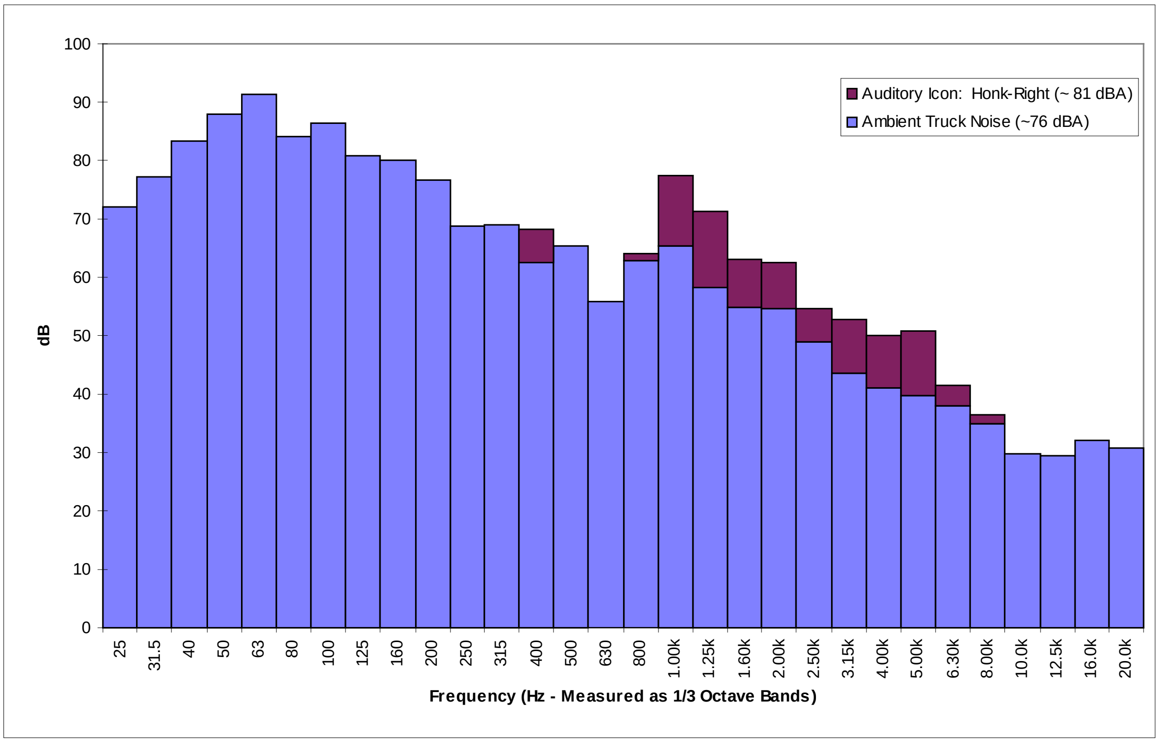

Figure H.5. One-Third Octave Band of the Side Collision Auditory Icon (Right - Honk) Warning and Ambient Truck Noise.

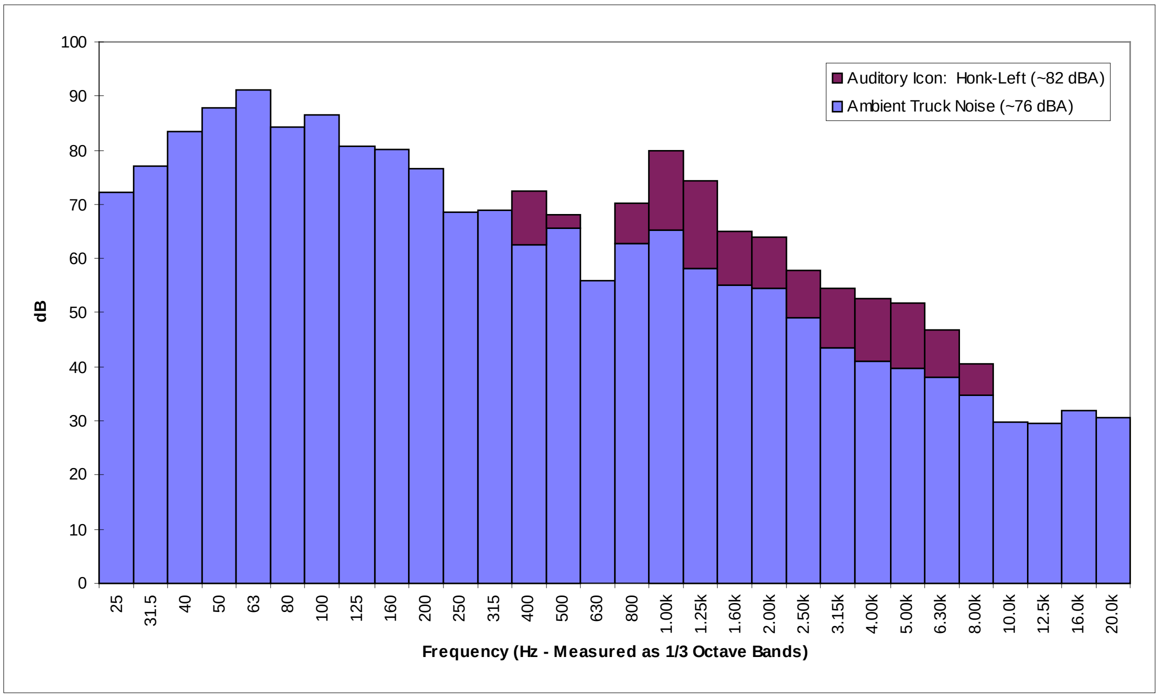

Figure H.6. One-Third Octave Band of the Side Collision Auditory Icon (Left - Honk) Warning and Ambient Truck Noise.

APPENDIX D

Telephone Screening Questionnaire for Main Experiment

PRE-EXPERIMENT/TELEPHONE SCREENING QUESTIONNAIRE

Name ____

Phone _________________

Age ___________

Male _____

CVO License: _____ Class A Class B

General

Tinnitus or head noises?	Y	N
History of excessive ear wax?	Y	N
Hearing or vision problems?	Y	N
Glasses/Contacts	Y	N
Hearing Aid	Y	N

Employment History

Years of experience driving commercial vehicles? ___________
Years of experience driving? ___________
Approximate distance regularly traveled: ___________
Type of vehicle normally driven: ____________________________
Type of company (e.g. private carrier, owner/operator): ___________

If Acceptable

The total experimental time will be about three to three and one-half hours

When you first arrive, we will test your hearing and vision to ensure that you can hear and see each part of the experiment. If you do not qualify, you will be paid $5 and thanked for coming in. Please realize that the initial hearing and vision tests are not designed to assess or diagnose any hearing or vision problems, they will only be used to determine whether or not you can participate in the experiment.

Experimental Session: Time: _____ Date: _____

This office phone number is 231-9087 and my home number is 951-8061. Please call me if you have any questions or need to reschedule.
REMIND THEM TO BRING THEIR CVO LICENSE

APPENDIX E

Description of Main Experiment

DESCRIPTION OF THE COLLISION AVOIDANCE SYSTEM EXPERIMENT WRITTEN INSTRUCTIONS TO THE PARTICIPANT

This experiment is intended to determine if different warning signals will help the driver avoid collisions. If you become a participant in this experiment, you will be asked to participate in one screening session (about 30 minutes), one training session (about 20 minutes), and one experimental session (about 2 hours).

In the screening session, you will be asked to read and sign an informed consent form and to receive a hearing and vision test. If you qualify as a participant, the experimenter will show you the equipment to be used in the experiment, and give you instructions concerning how to operate it. If you have any questions, please ask the experimenter at any time. The experimenter will provide the best answer possible; however, some questions regarding the specifics of the study can only be fully answered after you have completed your participation.

In the first portion of the training session, you will be asked to familiarize with the operation of the driving simulator. The experimenter will show you the controls, consisting of a steering wheel, brake pedal, and accelerator pedals. The controls work in the same way as normal vehicle controls. Even though the simulator is designed to drive like a normal vehicle, it does take some getting used to. You will be asked to drive the simulator for about five minutes to become accustomed to the driving task. **It is very important that you follow the rules of the road, adhering to the speed limit signs and laws, as you would normally drive.**

The second portion of the training session will be conducted while the simulator is stationary (in park). Each of the warning signals will be demonstrated and their meanings explained. Visual messages will come from the collision display located on the simulator's dash. Auditory messages will come from the two small loudspeakers mounted behind your head. Listen closely to the auditory messages; some sounds come from only one loud speaker, others come from both speakers. When you hear a warning coming from only one loudspeaker, the impending collision is on the same side of the vehicle from which you heard the message. For instance, if the message is presented to the right ear, then the impending collision is on the right side of the vehicle; messages presented to the left ear signal an impending collision on the left side of the vehicle. Messages presented to both ears will signal that the impending collision is in front of the vehicle.

In each of the experimental sessions you will perform the driving task while appropriately reacting to the warning signals as they are presented. It is extremely important that you drive as though this was an actual vehicle and maintain control of your vehicle at all times. Experimental sessions will be broken up to allow for several short breaks. You will have the opportunity to ask questions at any time during the experiment. If at all possible once the simulation has begun, please try to wait until a scheduled driving break before asking a question.

Please print and sign your name below to indicate that you have read and understand these instructions.

______________________________ ______________________________

Participant’s Printed Name | Participant’s Signature

APPENDIX F

Informed Consent Form for Main Experiment

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

Informed Consent for Participants of Investigative Projects

Title of Project: A Simulator-Based Investigation of Visual, Auditory, and Mixed-Modality Display of Vehicle Dynamic State Information to Commercial Motor Vehicle Operators.

Principal Investigators: Dr. John G. Casali, Professor and Department Head, ISE
Dr. Gary S. Robinson, Senior Research Associate, ISE
Steven M. Belz, Graduate Research Assistant, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a study which will investigate the use of different warning signals for the purpose of helping a driver avoid collisions while driving.

II. PRE-EXPERIMENTAL PROCEDURES

The procedures to be used in this research are as follows. If you wish to become a participant after reading the description of the study and signing this form, you will begin with a screening session. The screening session will check to see if your hearing and vision ability today qualifies you to participate in the experimental session.

First, your right and left ear hearing will be tested with very quiet tones played through a set of headphones to ensure that you can hear the auditory messages as they are presented during the experiment. You must be very attentive and listen carefully for these tones. **You will be asked to depress the button on the hand switch and hold it down whenever you can hear the tone and release it whenever you do not hear the tone.** The tones will be very faint, and you will have to listen very carefully to hear them. The hearing test will be conducted in a sound-proof booth with the experimenter sitting outside. 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. The is also an intercom system through which you may communicate with the experimenter by simply talking (there are no buttons to push).

During the experimental session, you will be asked to listen for to warning signals guiding your next course of action; however, at other times during the session, there will be only visual warnings given. Therefore, your vision will also be tested to ensure that you will be able to see the visual warnings involved in the experiment. Your vision will be tested using a Stereo Optical 2000 vision tester. This is a test similar to the vision test adminsitered by the Department of Motor Vehicles during driver's license examinations. If qualified, you may participate in a research experiment which will investigate the effect of different types of alarms to assist the driver in avoiding collisions while driving.

There is no known risk to your well being posed by this experiment. Also, the initial hearing and vision tests are not designed to assess or diagnose any physiological or anatomical hearing or vision problems. The tests will be used to determine whether or not you will be able to continue to the main part of the experiment.

III. EXPERIMENTAL PROCEDURES

Upon qualifying for the experiment, you will have the opportunity to test drive the commercial-truck simulator. Although the simulator will react in a similar manner to driving a commercial truck, there may be some minor differences you will be able to become accustomed to during the test drive. Following the first test drive, you will be introduced to the warning signals and their meanings. When you are comfortable with both driving the simulator and the warning signals, the experimental sessions will begin.

During the experimental segments, prerecorded truck noise will be presented at levels ranging from 72 - 76 dBA to simulate background noise levels found in currently available commercial trucks. Auditory warning signals will be presented at levels ranging from 78 - 80 dBA. None of these levels exceed the Occupational Safety and Health Administration (OSHA) legal limit for noise exposure. OSHA regulations allow U.S. industrial workers to be exposed to 90 dBA time-weighted average (TWA) noise level for an 8-hour workday (corresponding to a 100% dose). In this experiment, the maximum levels to which participants will be exposed will be well below 90 dBA for no longer than 4 hours. In fact, OSHA does not even include levels below 80 dBA in its noise exposure calculations.

The experiment will be broken up into several 20 - 30 minute sessions, with short rest breaks between the sessions. Each experimental session will consist of driving the simulator and responding appropriately to the warning signals as they are presented. The total time to complete the pretesting and experimental sessions will be no greater than three hours.

IV. BENEFITS OF THIS RESEARCH

Your participation in this project will provide the following information that may be helpful. First, data taken from the telephone screening questionnaire will establish certain characteristics of the sample of the population being studied (licensed, male commercial truck drivers). Second, it is the ultimate goal of this experiment to improve the safety and efficiency of commercial trucks. This experiment represents a small step in the pursuit of such a goal. It is expected that the results of this study will lead to further topics of research which will continue to improve driving safety for all road users.

No guarantee of benefits has been made to encourage you to participate. You may also receive a summary of the results when completed. Please leave a self-addressed envelope. **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 individuals working on the project without your written consent. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports of the research.

VI. COMPENSATION

For participation in this project, you will receive a total of $50.00. This amount will be adjusted if you are unable to complete the entire study. This payment will be made to you in cash immediately following your participation in the experiment.

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 project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT'S RESPONSIBILITIES

I know of no reason I cannot participate in this study. I have the following responsibilities:

To perform the tasks according to the instructions to the best of my ability.

To notify the experimenter at any time about discomfort or desire to discontinue participation.

____

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.

I have read and understand the informed consent and conditions of this project. All the questions that I have asked have been answered to my satisfaction. I hereby acknowledge the above and give my voluntary consent for participation in this project, 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 Casali, Director of the Auditory Systems Laboratory, Dr. Gary S. Robinson, Research Associate, and Steven M. Belz, Graduate Research Assistant. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory
Room 538 Whittemore Hall
VPI & SU
Blacksburg, VA 24061-0118
Dr. Casali: (540) 231-9081
Dr. Robinson: (540) 231-2680
Steven Belz: (540) 231-9087

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 G

Pre-experiment Visual and Auditory Screening

PRE-EXPERIMENT CHECKLIST

Name ____

CVO License: ______ Class A Class B

VISUAL ACUITY ASSESSMENT (Far):
Using the OPTEC 2000 Vision Tester

1. NEAR/FAR point switch in the UP position
2. RIGHT and LEFT eye switches in the DOWN position
3. Dial Test Number on the TAUPE INDICATOR KNOB

Ask the question: Look in the first target, is the ring in the TOP broken like the other rings, or is it unbroken? Where is the unbroken ring in target #5? Is it in the BOTTOM, LEFT, RIGHT, or TOP? Continue until they miss TWO CONSECUTIVE answers. If the participant cannot identify #5, go back to #4 or #3 until they can correctly identify the broken ring.

Test No.		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
3	**Right**	**T**	**L**	**T**	**T**	**B**	**B**	**L**	**B**	**R**	**T**
4	**Left**	**L**	**R**	**L**	**B**	**R**	**T**	**T**	**B**	**R**	**T**
		20/200	20/100	20/70	20/50	20/40	20/35	20/30	20/25	20/22	20/20

Visual acuity of 20/40 in each eye is required by the Code of Federal Regulations (49 CFR Ch. III - Subpart E - Pysical Qualifications and Examinations)

AUDIO ACUITY ASSESSMENT:
Using the Beltone 19 Portable Audiometer

1. Turn on unit and allow to warm up for at least 20 minutes prior to use.
2. Set TONE SWITCH MODE to ‘PULSED’
3. Set OUTPUT SWITCH to ‘RIGHT’ for right ear and switch to ‘LEFT’ for left ear.
4. Follow modified Hughson-Westlake procedure.

Right Ear:

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	Final Threshold
500	_____	_____	_____	_____	_____	_____	_________
1000	_____	_____	_____	_____	_____	_____	_________
2000	_____	_____	_____	_____	_____	_____	_________

Left Ear:

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	Final Threshold
500	_____	_____	_____	_____	_____	_____	_________
1000	_____	_____	_____	_____	_____	_____	_________
2000	_____	_____	_____	_____	_____	_____	_________

Hearing loss in the better ear cannot exceed 40dB at the above frequencies as required by the Code of Federal Regulations (49 CFR Ch. III - Subpart E - Pysical Qualifications and Examinations).

Because the cues are being presented dichotically to display directional information, for this study, hearing loss in either ear cannot exceed 40 dB at the above frequencies.

APPENDIX H

Likert-type Subjective Preference Questionnaire

POST - STUDY QUESTIONNAIRE

The information communicated by the collision warning system was useful.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The collision warning system did not negatively change my driving behavior

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The information presented by the collision warning system helped me drive more safely.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The collision warning system seemed to give unreliable information; therefore, I paid little attention to it.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

I was able to react more quickly to potential hazards because of the collision warning system.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The collision warning system distracted me from driving properly.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The driving simulator seemed very realistic.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The collision avoidance system was annoying.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The collision warning system was easy to understand.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

If a collision warning system were available as a $1000 option on a vehicle, I would be unlikely to purchase it.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

If a collision warning system were available as a $500 option on a vehicle, I would be unlikely to purchase it.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

The following warning was easy to understand.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

What does the auditory warning signify? ______________________________

The following warning was easy to understand.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

What does the auditory warning signify? ______________________________

The following warning was easy to understand.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

What does the auditory warning signify? ______________________________

The following warning was easy to understand.

1	2	3	4	5
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

What does the auditory warning signify? ______________________________

APPENDIX I

Subjective Preference Questionnaire

SUBJECTIVE PREFERENCE QUESTIONNAIRE

For the situations involving a **front-to-rear collision**, which of the following warning signals did you prefer?

No Display
Dash-Mounted Visual Display ONLY
Auditory Warning Display ONLY
Dash-Mounted Visual Display AND Auditory Warning Display

For the situations involving a **front-to-rear collision**, two different auditory warnings were presented. Of the two different auditory warning displays, the conventional warning and the auditory icon (Tire Skid), which did you prefer?

Conventional Warning
Auditory Icon

For the situations involving a **side collision**, which of the following warning signals did you prefer?

Mirrors ONLY
Dash-Mounted Visual Display ONLY
Auditory Warning Display ONLY
Mirrors and Dash-Mounted Visual Display ONLY
Mirrors and Auditory Warning Display ONLY
Dash-Mounted Visual Display AND Auditory Warning Display
Dash-Mounted Visual Display AND Auditory Warning Display, AND Mirrors

For the situations involving a **side collision**, two different auditory warnings were presented. Of the two different auditory warning displays, the conventional warning and the auditory icon (long horn honk), which did you prefer?

Conventional Warning
Auditory Icon

APPENDIX J

Chi-Squared Statistic Simulation

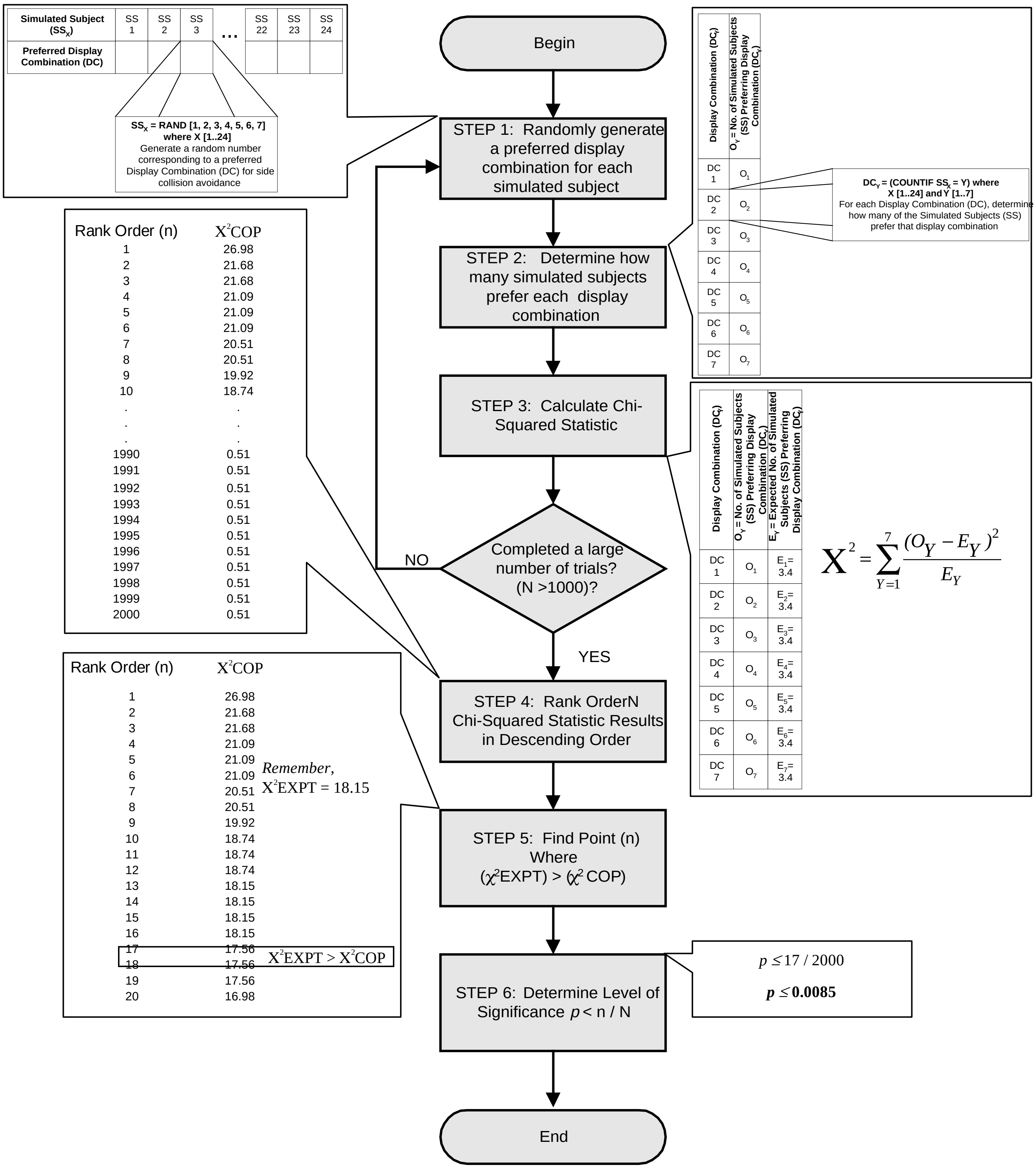

Figure J.1. Flow chart of chi-squared statistic simulation. Flow chart shows simulation logic; callout boxes show specific calculations pertainent to this study.

VITA

Steven M. Belz was born on February 25, 1973 in Eau Claire, Wisconsin. He received his Bachelor of Science degree in Industrial and Systems Engineering from Virginia Polytechnic Institute and State University in May 1995. Upon completion of the Master of Science in Industrial and Systems Engineering at Virginia Polytechnic Institute and State University, he intends to pursue a Doctorate of Philosophy in the same program.

Before he began work on his Master of Science degree at Virginia Polytechnic Institute and State University he worked for Montgomery County Public Schools as an assistant engineer where his primary responsibility was updating facility designs to be in compliance with the Americans with Disabilities Act. During his Master's degree, he also spent a summer working for the Wireless Consumer Product Group at Lucent Technologies. While at Lucent Technologies, his primary responsibility was to develop and test level and pattern characteristics of the auditory alterter in new mobile telecommunications devices. He was also responsible for designing and developing GUI interfaces for intranet sites and developing initial system requirements for intranet-based reporting of competitive product analyses.

As a graduate student, he was awarded a graduate fellowship for Intelligent Vehicle Highway Systems by General Motors and was a recipient of the Pratt Fellowship. His research interests include transportation systems, telecommunications, human-computer interaction, multimedia development, and organizational design. He is a member of Alpha Pi Mu and the Human Factors and Ergonomics Society.