Integrated Vehicle-Based Safety System

Heavy Truck Driver Vehicle Interface (DVI) Literature Review

Developed under
U.S. Department of Transportation
Cooperative Agreement DTNH22-05-H-01232

by
Battelle, Center for Human Performance and Safety
1100 Dexter Ave., Seattle, WA 98109

for
The University of Michigan Transportation Research Institute (UMTRI)
2901 Baxter Road, Ann Arbor, Michigan 48109-2150

June 2, 2006

This report was prepared in connection with the U.S. Department of Transportation,
National Highway Traffic Safety Administration, Office of Vehicle Safety Research,
1200 New Jersey Avenue, SE, West Building, Washington, D.C. 20590

Technical Report Documentation Page

1. Report No. UMTRI-2008-22	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Integrated Vehicle-Based Safety System Heavy Truck Driver Vehicle Interface (DVI) Literature Review		5. Report Date June 2006 6. Performing Organization Code
7. Author(s) Marvin McCallum, John L. Campbell, Christian Richard, and James L. Brown		8. Performing Organization Report No.
9. Performing Organization Name and Address Battelle, Center for Human Performance and Safety 1100 Dexter Ave. Seattle, WA 98109		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Cooperative Agreement DTNH22-05-H-01232
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered 14. Sponsoring Agency Code Office of Human Vehicle Performance Research – Intelligent Technologies Research Division, NVS-332

15. Supplementary Notes

This report was prepared by Battelle, Center for Human Performance and Safety, for UMTRI under contract to the U.S. DOT.

16. Abstract

The Integrated Vehicle-Based Safety Systems (IVBSS) program is a four-year, two phase cooperative research program conducted by an industry team led by the University of Michigan Transportation Research Institute (UMTRI). The program goal is to integrate several collision warning systems into one vehicle in a way that alerts drivers to potential collision threats with an effective driver vehicle interface (DVI), while minimizing the number of excessive warnings presented to the driver. Basic program strategies for meeting this objective include systematically managing and prioritizing all information presented to the driver, minimizing the number of system false alarms, and restricting auditory alarms to higher urgency collision conditions.

The report summarizes existing guidelines, data sources, and design principles relevant to the design of the IVBSS heavy-truck DVI; and discusses high-priority research issues relevant to the development and field testing of the IVBSS heavy-truck DVI.

17. Key Words IVBSS, literature review, driver-vehicle interface, DVI, vehicle safety research, crash avoidance research, verification testing, collision avoidance, crash warning systems	18. Distribution Statement Document is available to the public through the University of Michigan Transportation Research Institute, Ann Arbor, Michigan

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	71	

Authors

The primary authors of this document are Marvin McCallum, John L. Campbell, Christian Richard, and James L. Brown of Battelle. This material, however, reflects the work of many others including Michael Nowak, Michael Lesher, and John Kovacich of Eaton Corporation; Dean Pomerleau and Matt Troup of Cognex; and John Sullivan of the University of Michigan Transportation Research Institute (UMTRI). Jim Sayer, of UMTRI, serves as project director of the IVBSS team.

Acknowledgments

This research was sponsored by the National Highway Transportation Safety Administration (NHTSA), U.S. Department of Transportation, through cooperative agreement DTNH22-05-H-01232. The material contained herein does not necessarily reflect the opinions or policies of NHTSA.

Jack Ference is the contracting officer's technical representative at NHTSA. Wassim Najm and Sandor Szabo lead efforts at the Volpe National Transportation Systems Center and the National Institutes for Standards and Technology, respectively, to support NHTSA.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

ACC ....Automated Cruise Control
CAMP .... Collision-Avoidance Metric Partnership
CAS ....Collision Avoidance System
CCAW..Cautionary Crash Avoidance Warning
CVO ....Commercial Vehicle Operator
DVI...Driver Vehicle Interface
FCW..Forward Collision Warning
FMCSA ....Federal Motor Carrier Safety Administration
FMVSS .... Federal Motor Vehicle Safety Standard
FOT..Field Operational Test
HT ....Heavy Truck (aka Heavy Vehicle)
ICAS .... Intersection Collision Avoidance System
ICAW ....Imminent Crash Avoidance Warning
ISO..International Organization for Standardization
IVBSS ....Integrated Vehicle-Based Safety Systems
IVI ....Intelligent Vehicle Initiative
LCD.. Liquid Crystal Display
LCW...Lane Change/Merge Warning
LDW..Lane Departure Warning
LED..Light Emitting Diode
LTCCA ....Large Truck Crash Causation Study
MT... Masked Threshold
NHTSA.. National Highway Traffic Safety Administration
Radar ....Radio Detection and Ranging
RDW ....Road Departure Warning
SAE..Society of Automotive Engineers
SCW ....Side Collision Warning
TTC...Time-to-Collision
UMTRI ....University of Michigan Transportation Research Institute

Introduction

The Integrated Vehicle-Based Safety Systems (IVBSS) Field Operational Test (FOT) project is being led by the University of Michigan Transportation Research Institute (UMTRI). The purpose of this project is to develop and test new, integrated crash warning systems in fleets of 16 passenger cars and 10 heavy trucks. Battelle is supporting UMTRI in the development and field testing of the heavy truck (HT) driver vehicle interface (DVI). Battelle's first activity in support of UMTRI involves the identification of data sources and design principles relevant to the HT DVI for IVBSS and to summarize this information. This *IVBSS HT DVI Literature Review* is the product of Battelle's first activity. This section of the report describes the scope of Task 1, the literature review strategies, and the report organization.

Scope Of Task 1 Literature Review

The goal of Task 1 is to identify and summarize data sources and design principles relevant to the HT DVI for IVBSS. The majority of data sources relevant to IVBSS DVI guidance were previously identified during Battelle's recent draft of the *Human Factors Guidelines for Collision Avoidance Warning Systems* prepared for the National Highway Traffic Safety Administration (NHTSA) (Campbell, Richard, Brown, & McCallum, 2006). The present effort expands the scope of that recent effort and specifically addresses HT issues and IVBSS DVI applications. This report summarizes existing guidelines, data sources, and design principles relevant to the design of the IVBSS HT DVI; and discusses high-priority research issues relevant to the development and field testing of the IVBSS HT DVI.

Literature Search Strategies

In addition to the literature review conducted in support of Battelle's recent preparation of the Collision Avoidance System (CAS) human factors guidelines for NHTSA (Richard, Campbell, and Brown, 2005), two additional literature searches were conducted specifically for this Task 1 effort. The first literature search was conducted to update the NHTSA CAS literature search conducted in August 2005. This search update was conducted by replicating the search strategy and sources of the earlier search, but only searching the period between August 2005 and March 2006. The TRIS, NTIS, PsycINFO, INSPEC, and EI Compendex(R) publication sources were searched. Topics and keywords used in this search reflected the three types of collision warning systems in this project and included the following search terms.

1. CAS search terms: variants of collision, crash, warning, and avoid, in conjunction with variants of car, automobile, truck, bus, vehicle, road, and transit.

2. CAS device operation search terms: variants of collision, crash, warning, and avoid, in conjunction with variants of activation, testing, device controls, and device location.

3. CAS levels of warning search terms: variants of collision, crash, warning, and avoid, in conjunction with variants of imminent, urgent, and cautionary.

4. CAS warning presentation search terms: variants of collision, crash, warning, and avoid, in conjunction with variants of priority, multiple warnings, false warning, nuisance warnings, annoy, false alarm, and disturb.

The second literature search was conducted to identify documents that were relevant to HT operations. The TRIS, NTIS, PsycINFO, INSPEC, and EI Compendex(R) publication sources were searched for the period between 1990 and March 2006. Topics and keywords used in this search included reference to heavy vehicles in conjunction with operation or driver training or instruction, as summarized below:

1. Heavy vehicle search terms: variants of heavy vehicle, commercial truck, and combination unit.

2. Operation and workload search terms: variants of operation and workload.

3. Driver training and instruction search terms: variants of driver training and driver instruction.

Report Organization

This report is divided into five sections and one appendix, as summarized below.

Section 2, *IVBSS HT System Components*, provides an overview of the components that are being integrated into the IVBSS HT system.

Section 3, *Heavy Truck-Specific Issues*, provides a general discussion of issues specific to HTs that are pertinent to the IVBSS HT DVI design.

Section 4, *Design Guidance Applicable to IVBSS HT CAS*, summarizes available guidance that is intended specifically for HT CAS DVI design or adapted from applicable passenger vehicle CAS DVI design guidance.

Section 5, *IVBSS HT DVI Research Issues*, discusses unresolved IVBSS HT design issues that will require research and/or expert panel input.

Appendix A, *Completed Document Review Forms for Core HT References*, provides completed document review forms for core IVBSS HT DVI sources dealing specifically with CAS HV DVI issues.

1 IVBSS HT System Components

This section provides information on recent configurations of the IVBSS HT system components to be implemented and tested in the HT FOT. This information is provided as a reference to the scope of CAS technologies and the DVI options possible during the design of the IVBSS HT DVI. This section is based on information available to Battelle project staff through public resources and documents provided by UMTRI project staff. This information is provided as one reference point regarding the components and functionality of the IVBSS HT system components and it should be recognized that all or some of these systems will evolve during the two-year period of IVBSS system development.

1.1 Forward Collision Warning (FCW) System

FCW systems monitor the space in front of the host vehicle to detect objects in close proximity or those traveling at a relative speed slower than the host vehicle. Based on system thresholds and presentations, warnings can be given regarding a potential or imminent collision. The Eaton VORAD© Always Alert© FCW system will be implemented in the IVBSS HT FOT (Eaton, 2006). Features of this system include:

- Collision warning – audible and visual warnings are emitted when the potential for a collision is detected in rain, snow, fog, smoke, sun glare, or total darkness.
- Tail Gating – audible alerts are sounded when host vehicle is within one half (1/2) second of another vehicle.
- Slow Moving Vehicle – Audible and visual alerts issued.
- Fog Mode – Visual display indicates when objects are detected within 500 feet in front of the vehicle.
- Straight Ahead Same Lane Tracking – the system's same-lane target discrimination eliminates warnings for nuisance objects in adjacent lanes.
- Curved Same Lane Tracking – same lane target discrimination is maintained using host vehicle turn rate information and vehicle azimuth. Due to limitations of the Radio Detection and Ranging's (radar) field of view, maximum range is limited in sharp turns.
- Distance and Sensitivity Control – allows the operator to set forward object detection distance. This allows for a reduction in the distance thresholds for alarms and is intended for limited use in heavy traffic conditions.
- Proximity Alerts – audible and visual alerts issues when host vehicle is traveling below 5 mph and an object is within the threshold range (typically set at 15 feet).
- Display Intensity Adjustment – display light intensity is adjusted automatically in response to ambient light conditions.
- Object Tracking – simultaneously tracks up to 20 moving or stationary objects within range.
- Accident Reconstruction – can store host vehicle and other object data for several minutes prior to the time that data are saved.

- System Problems – notifies the driver when a failure is indicated.
- Self-Troubleshooting – provides onboard fault codes to help to diagnose a system problem.

1.2 Lane Change/Merge Warning (LCW) System

LCW systems use electronic sensors to monitor one or more blind spots of a vehicle. HTs have several noteworthy blind spots that predominate on the right sides of the cab and trailer. The Eaton VORAD© BlindSpotter© Side Sensor© Warning system will be implemented in the IVBSS FOT. This system consists of a radar transmitter and receiver mounted on the side of the vehicle that can detect objects from one (1) to twelve (12) feet from the side of the vehicle. The Side Sensor© can detect vehicles or objects unseen by the driver, moving or stationary, provided the vehicle or objects are in the radar coverage area adjacent to the vehicle. Side Sensor© units are typically mounted on the side of the cab, providing coverage for the area adjacent to the cab. As currently configured, the system provides a warning when an object is in the detection range of the radar. A visual display inside the vehicle indicates if there is an object in the detection area and an audible alert sounds when the turn indicator is activated and there is an object in the detection area (Eaton, 2006).

1.3 Lane Departure Warning (LDW) System

LDW systems monitor the position of a vehicle within a roadway lane and warn a driver if the vehicle deviates or is about to deviate outside the lane. Currently available LDW systems are forward looking, vision-based systems that use algorithms to interpret video images to estimate vehicle state (lateral position, lateral velocity, heading, etc.) and roadway alignment (lane width, road curvature, etc.). LDW systems typically warn the host vehicle driver when the vehicle is traveling above a certain speed threshold, the vehicle's turn signal is not in use and a lane departure is occurring or predicted to occur. The AssistWare SafeTRAC© LDW system (AssistWare, 2006) will be implemented in the IVBSS HT FOT. SafeTRAC© uses a forward-looking video camera to monitor the road ahead and track road features to determine a vehicle's position and trajectory. The system generates a warning if a vehicle begins to drift out of its lane. Figure 1 depicts the camera view used by the SafeTRAC© system to identify and define lane position. The three symbols in this figure ( ) are used to denote left lane, own vehicle center, and right lane positions, respectively, in some versions of the SafeTRAC© displays.

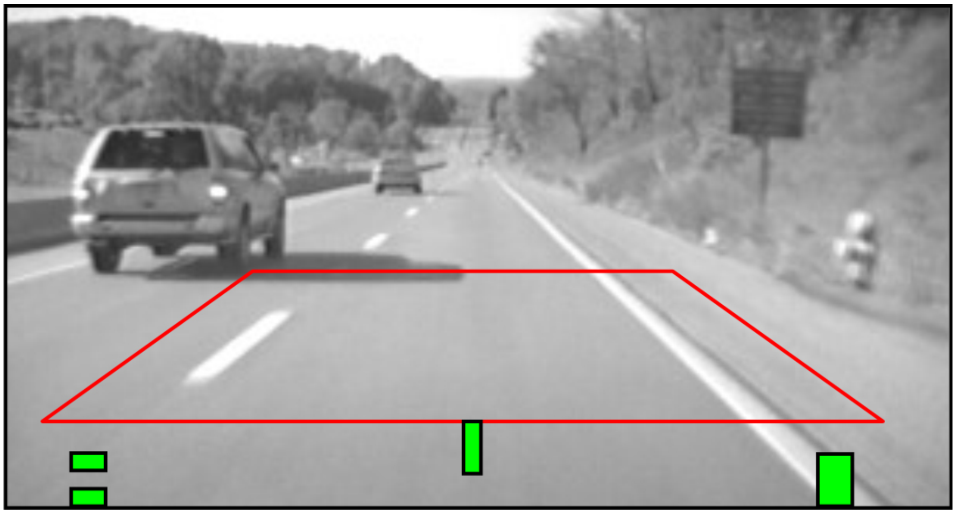

Figure 1. Camera view used to determine own vehicle's position in the road ahead (from AssistWare website).

Current installation options for SafeTRAC© include factory installation or fleet installation. Figure 2 presents a factory-installed system.

**Figure 2. Factory Installation of SafeTRAC©
(from AssistWare website).**

Key features of SafeTRAC© identified by AssistWare (2006) include the following.

- Warnings for roadway departure using audible, visual, or tactile modalities.
- Accurate operation in a wide range of driving situations including: night driving, snow, and rain.
- The detection of drowsy or distracted driving by sensing weaving or erratic lane keeping.

The SafeTRAC© lane tracker system was one of four fatigue management technologies employed in a pilot test recently reported by Dinges, Maislin, Krueger, Brewster, and Carroll (2005). In this implementation, SafeTRAC was used to provide alertness feedback to drivers, by providing a score between 0 and 99 that indicated lane tracking performance, where 0 indicated the most erratic lane tracking, and 99 indicated the least erratic lane tracking, using a proprietary algorithm. The system also provided a graphic image of the truck position in the lane (using the bars depicted in Figure 1), as well as an auditory warning signal if a driver made an abrupt deviation from the lane without signaling. The SafeTRAC alertness measure was shown to have some sensitivity to driver alertness levels in the pilot test.

1.4 Current Status of IVBSS HT System DVI

The Eaton VORAD DVI was undergoing substantial modifications as part of the IVBSS project concurrent with the preparation of this literature review. The primary FCW display was being modified from a light emitting diode (LED) display to a combined display that includes LED and a liquid crystal display (LCD) that can provide graphic information.[1] The adoption of an LCD will provide for flexibility in designing, testing, and implementing visually presented information as this project progresses. It should be noted that the central LCD provides a central display that could be used to display side collision warning (SCW) and LCW information as well as FCW information. A preliminary concept for the integrated display of all three IVBSS HT systems is currently under development by Eaton.

[1] Confidential Eaton VORAD *Summary of Human Factors* document dated February 22, 2006.

2 HT Factors to Consider in IVBSS DVI Design

Several aspects of HT characteristics and operation will influence the design of the IVBSS DVI. This section of the report reviews pertinent topics to ensure a common understanding of these factors. The section is divided into four subsections: HT characteristics; HT operational considerations; HT crash data; and HT driver tasks and workload.

2.1 HT Characteristics

The HT characteristics of physical dimensions, braking distances, and the truck cab environment will all influence the design of the IVBSS DVI and are reviewed in this subsection.

2.1.1 Physical Dimensions

A typical combination interstate tractor-semitrailer is 13.5 feet high, 8.5 feet wide, and between 68.5 and 73.5 feet in total length. The typical tractor-semitrailer has 5 axels and a maximum weight of 80,000 to 99,000 lbs. Figure 3 presents two common HT configurations. The single trailer on the left is the most common configuration, used extensively for long and short hauls in all urban and rural areas to carry and distribute all types of materials, commodities, and goods, and likely the configuration used for the IVBSS FOT.

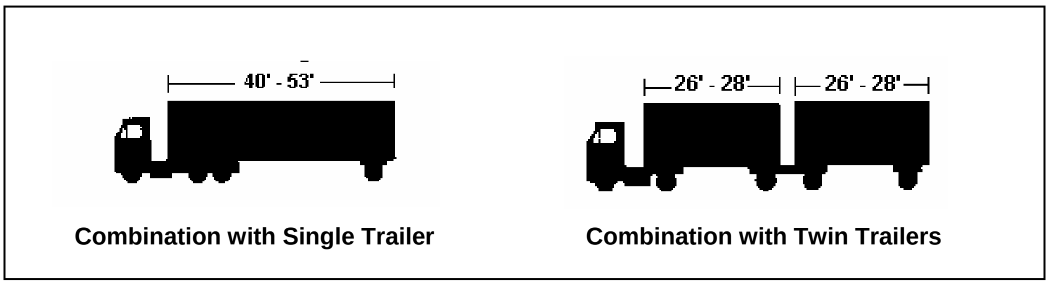

Figure 3. Typical tractor-semitrailer configurations
(adapted from Harkey, Council, & Zeeger, 1996)

2.1.2 Braking Distances

The braking distances of HTs relative to that of passenger vehicles is a primary factor in establishing FCW timing parameters. Braking distance is the distance needed to stop a vehicle from the time that brake application begins. It does not take into account the driver's perception-response time. HTs use both air and hydraulic brake systems, with air brake systems being much more common. HT braking involves either locked-wheel braking or controlled braking modes. Locked wheel braking occurs when the brakes grip the wheels tightly enough to cause them to stop rotating, or "lock," before the vehicle has come to a stop. HTs have much more difficulty than passenger or single unit trucks stopping in locked-wheel mode and, depending upon which axle is locked first, locked braking can result in skidding straight ahead, a "jackknife," or trailer swing. A skilled driver can recover from trailer swing, but a jackknife situation is unrecoverable.

None of the locked-wheel stopping modes are considered safe for trucks (Harwood, Potts, Torbic, & Glauz, 2003).

Antilock brake systems have been developed for HTs to enable vehicles to make controlled stops without locking the wheels and losing vehicle control. Federal Motor Vehicle Safety Standard (FMVSS) 121 requires antilock brake systems on all new truck tractors manufactured after March 1, 1997 and all new trailers manufactured after March 1, 1998 (NHTSA FMVSS Air brake systems, 2003). Because their useful life is relatively short, nearly all truck tractors in the current fleet have antilock brakes or will soon be replaced by a tractor that does. A field study published by Harwood, Torbic, Richard, Glauz, and Elefteriadou (as cited in Harwood et al., 2003) found that approximately 43 percent of trailers in combination trucks were equipped with antilock brake systems and it can be expected that within 10 years nearly all trailers will be equipped with antilock brake systems.

The required braking distances for a loaded truck tractor with an unbraked control trailer equipped with antilock brakes specified in FMVSS Standard 121 is 299 feet at 55 mph and 355 feet at 60 mph. In the recently published *Highway/Heavy Vehicle Interactions* synthesis prepared for the Transportation Research Board, Harwood and his colleagues note that truck braking distances remain longer than passenger car braking distances on dry pavements; however, on wet pavements, which are the most critical to safety, the braking distances of trucks and passenger cars are nearly equal (Harwood et al., 2003).

NHTSA considers the difference in the regulated braking distance between HTs and passenger vehicles to represent a significant safety issue. Current regulations require passenger vehicles to stop within 216 feet at a speed of 60 mph (NHTSA FMVSS Light vehicle brake systems, 2003). NHTSA has recently been conducting studies to determine if it would be technically feasible to reduce the regulated stopping distances of HTs by 30 percent, which would result in a decrease from 299 to 209 feet at 55 mph and from 355 to 249 feet at 60 mph for a loaded truck tractor with an unbraked control trailer (U.S. Federal Register, December 15, 2005). As part of this effort, the braking distances of four production tractors with various brake configurations were tested (Ashley, Dunn, & Hoover, 2004). Mean stopping distances (across six tests for each vehicle) from 60 mph on a dry, level roadway of between 241 feet and 317 feet were obtained, with only one of the four vehicles consistently stopping within the contemplated reduced stopping distance. For the purposes of the present review, a reasonable and conservative assumption is that, at travel speeds of 60 mph, passenger vehicles are capable of stopping in 216 feet or less and gross vehicle weight rating (GVWR) trucks are capable of stopping in 355 feet following the HT driver's perception and reaction to a forward hazard.

2.2 HT Cab Environment

One starting point in considering the HF cab environment is the general vehicle interior. Figure 4 is a rendering of a current-model Kenworth truck. Truck cabs similar in layout and appearance to this cab will likely serve as the test vehicles in the IVBSS HT FOT. Following are brief descriptions of the HT auditory, visual, and haptic/tactile environments.

Figure 4. View inside a recent model Kenworth cab (accessed at http://www.kenworth.com March 2006)

2.2.1 Visual Environment

The HT cab visual environment presents special challenges to the HT driver who must continually monitor the roadway and traffic while controlling the truck on the road. One important aspect of the visual environment that is intended to be addressed by side-looking collision warning systems is the visual blind spots that surround a HT. Because of the location of the driver and configuration of the tractor and trailer, HT blind spots are not symmetrical on either side of the vehicle, with the driver's right side having more extensive unobservable areas.

The extent to which visual blind spots can be attenuated through the use of fender-mounted mirrors is an important consideration. In a study comparing early LCW systems, Mazzae and Garrott (1995) found that fender-mounted mirrors provided blind spot coverage superior to any other side object detection system that they tested.

One advantage that HT drivers have in terms of the cab visual environment is that they sit higher than passenger care drivers. As a result, they can see farther when there are vertical sight restrictions, such as hillcrests. This may permit truck drivers to see traffic conditions or objects in the road sooner and, therefore, begin braking sooner.

2.2.2 Auditory Environment

Robinson, Casali, and Lee (1997) provide a comprehensive, though somewhat dated, review of HV driver hearing requirements and truck cab noise levels. In reviewing earlier studies, they conclude that truck cab noise dramatically decreased from the 1970's to the 1990's. The researchers then measured noise levels in 10 “fairly high-mileage” 1990’s trucks under actual operational conditions and found on-road noise levels averaging 89 dBA. In discussing the implications of truck cab noise for in-cab warning signal design, Robinson et al. suggested the use of noise-sensing circuits that adjust alarm output levels as the truck cab noise level changes, thereby maintaining a desired signal-to-noise ratio.

2.2.3 Haptic/Tactile Environment

The truck cab haptic/tactile environment is of interest in the present review because the coding of IVBSS HT CAS warnings might potentially employ some form of haptic or tactile coding. Empirical studies of the haptic/tactile cab environment were not uncovered during the present literature search. However, Jiang, Streit, and El-Gindy (2001) reviewed HT ride comfort research and cab vibration estimation simulation approaches. These authors note that vehicle suspension is a very important factor in cab vibration. However, HT handling and rollover characteristics are the primary concerns in designing suspensions which leaves the cab suspension, seat suspension, and seat cushion as the components that can be modified to reduce driver vibration.

2.3 HT Operational Considerations

Four topics related to HT operations that will influence IVBSS development and testing are: the roadway environment, driver characteristics, the perceived importance of various safety issues within the commercial trucking community, and reactions by HT drivers to early tests of IVBSS HT CAS components. Each of these topics is briefly reviewed in this subsection.

2.3.1 The Roadway Environment

Kiger et al. (1992) surveyed 55 HT drivers to determine the relative perceived importance to safety of a range of driving condition factors. Table 1 presents the scaled relative importance to safety of these factors as judged by the sampled drivers. As can be seen in the table, each factor was scaled as being approximately twice as important as the next-most-important factor with the order of relative importance being, road traction, visibility, traffic density, roadway division, and lighting.

Table 1. Relative Driving Condition Factor Importance (from Kiger et al., 1992)

Driving Condition Factor	Levels	Relative Factor Importance
Road Traction	Good traction vs. poor traction (slippery ice, heavy rain, mud, snow)	51.6%
Visibility	Good vs. poor (e.g., foggy with visibility of barely one truck length ahead)	25.8%
Traffic Density	Light vs. heavy	12.9%
Roadway Division	Divided vs. undivided	6.5%
Lighting	Day (sunny) vs. night (moonless)	3.2%

The findings presented in Table 1 are consistent with crash data, which indicate that a higher percentage of HT crashes occur under poor weather conditions (winter, spring, and fall) than passenger vehicles (Staplin, Lococo, Decina, and Bergoffen, 2004). Thus, road conditions are an even more important safety factor for HTs than they are for passenger vehicles.

2.3.2 Driver Characteristics

HT drivers are quite different from the "typical" passenger vehicle driver. Perhaps the most noteworthy difference concerns the use of alcohol during driving. NHTSA's *Traffic Safety Facts 2004* (NHTSA, 2004) indicates that the percentage of drivers involved in a fatal accident who had a blood alcohol content level of .01 or higher was 26 percent for passenger vehicle drivers, 25 percent for light truck drivers, 34 percent for motorcyclists, and just 2 percent for large truck drivers.

Another important characteristic, driver training, appears to be quite variable within the HT driver community. There are limited federal standards for training, with only four topics requiring approximately 10 hours identified in current Federal Motor Carrier Safety Administration (FMCSA) training standards. Comprehensive training programs are available and the Professional Truck Driver Institute certifies courses, which must include training in safe and advanced operations practices, including: visual search, speed and space management, night operation, extreme driving conditions, hazard perception, emergency maneuvers and skid avoidance, and skid control and recovery. However, many of the larger carriers do not require driver training, but rather require minimum driving experience levels (e.g. two years) and a "clean" driving record (Staplin et al., 2004).

The professional status of HT drivers makes them susceptible to various incentive (bonus) schemes established by fleet management. Some of these incentive schemes are consistent with safe driving practices (e.g., maintaining a safe following distance and speed zone compliance) while others may be in conflict with safe driving practices (e.g., minimizing road time). The most basic incentive influencing driving performance probably continues to be the basis for pay for most HT drivers (number of miles driven) which is in conflict with slower driving and taking regularly scheduled breaks.

2.3.3 Perceived Importance of Safety Issues

In a recently completed study entitled *Effective Commercial Truck and Bus Safety Management Practices*, Knipling, Hickman, and Bergoffen (2003) reported the results of parallel surveys of commercial vehicle fleet safety managers and commercial vehicle safety experts. Table 2, excerpted from that report, summarizes the rank-order of safety manager's and safety experts' ratings of 20 identified "problem areas" – showing the ten highest-ranking problems identified by safety managers. Review of this table reveals that four of these top-10 problem areas are addressed by IVBSS HT CAS features, as summarized below.

- At-risk driving behaviors (e.g., speeding, tailgating) are partially addressed by the FCW feature that provides a warning when the host vehicle was following another vehicle too closely.

- Lack of defensive driving skills (e.g., space management around vehicle) is partially addressed by the LCW feature that provides a warning when a lane change or merge conflict is present.
- Driver fatigue/drowsiness is partially addressed by the LDW feature that provides a warning when actual or predicted lane excursions occur.
- Aggressive driving (i.e., “road rage”) on the part of either other vehicle drivers or host vehicle drivers is partially addressed by the FCW feature that provides a warning if a vehicle cuts in front of the host vehicle not allowing sufficient following distance or if the host vehicle is tailgating.

Table 2. Fleet Safety Managers and Safety Experts Importance Rating Ranks of Selected Problem Areas (adapted from Knipling et al., 2003)

	Importance Rating Rank (of 20)	
Problem Area	**Safety Managers**	**Safety Experts**
At-risk driving behaviors (e.g., speeding, tailgating)	1	3
High-risk drivers (i.e., the degree to which managers should focus on the worst 10-20% of their drivers)	2	1
Life style/general health-related (e.g., poor diet, smoking)	3	6
Lack of defensive driving skills (e.g., space management around vehicle)	4	8
Delays associated with loading and unloading (e.g., resulting in long working hours, tight schedules, and fatigue)	5	5
Driver fatigue/drowsiness	6	2
Aggressive driving (i.e., “road rage”)	7	11
Cardiovascular illness/heart disease	8	12
Poor attitude and morale, loneliness, alienation, unhappiness	9	9
Failure to inspect vehicle (e.g., pre-/post trip)	9	12

Knipling and his colleagues (2003) also report the responses by fleet safety managers and safety experts to a question regarding the effectiveness of 28 individual solution areas. Although the ratings in Table 2 indicate concern over problem areas addressed by IVBSS HT system features, such solutions were not highly-ranked by either safety managers or safety experts, as summarized in Table 3. In particular, the specific solution area of “Advanced technology collision avoidance systems (e.g., forward/rear obstacle detection)” received ratings that resulted in a ranking of 26 out of 28 by the fleet safety managers and a ranking of 19 out of 28 by the safety experts. Apparently, systems that share IVBSS functionality are not currently embraced as a leading safety solution among safety managers.

Table 3. Fleet Safety Managers and Safety Experts Effectiveness Rating Rank of Selected Solution Area Related to IVBSS HT Features (adapted from Knipling et al., 2003)

Solution Area	Effectiveness Rating Rank (of 28)	
	Safety Managers	Safety Experts
Basic safety-related equipment on new vehicles: basic equipment (e.g., engine specs, conspicuity lighting)	12	18
On-board computer monitoring devices with management review, feedback, and rewards/punishments for good/poor performance	18	16
Advanced technology collision avoidance systems (e.g., forward/rear obstacle detection)	26	19
On-board computer monitoring (e.g., speed monitoring) and feedback to drivers without management review	28	27

Dick, Murray, and Houser (2006) synthesized the results of "over 11 survey, interview, and focus group instruments" and reported their findings at the TRB annual meeting in January 2006. They identified three surveys that asked carriers to indicate which, if any, technologies they planned to install in some or all of their fleet vehicles in the future. The most commonly selected technologies and the percentage of carriers intending to implement them, presented below, suggest that carriers are planning to implement technologies related to IVBSS at modest levels.

- Automatic collision notification/mayday systems: 26%
- Remote diagnostic system that senses malfunction and notifies driver, company and/or repair station: 23%
- Load stability sensors/Roll over stability: 23%
- Radar-based collision warning system/Forward radar: 21%
- LDW/Lane change aid: 21%

Thus, it appears that a number of countermeasures other than in-vehicle safety systems are currently seen as providing more promise in improving HT safety and that the HT operational community is in an initial stage of adopting these technologies.

2.3.4 Driver Reactions to Early Tests of IVBSS HT CAS Components

Two recently completed projects have included on-road assessments of some of the technologies to be incorporated into the IVBSS HT system. Dinges et al. (2005) recently completed a pilot study of Commercial Vehicle Operator (CVO) fatigue management technologies that included the SafeTRAC LDW system. Battelle (2004) also recently completed the Volvo Intelligent Vehicle Initiative (IVI) FOT that included assessments of the Eaton VORAD side and FCW systems.

The recently-completed pilot study of CVO fatigue management technologies reported by Dinges et al. (2005) provides one opportunity to see how drivers respond to of the SafeTRAC technology. However, it should be noted that the implementation of SafeTRAC was most likely quite different from that to be implemented in the IVBSS field test. Table 4 provides a summary of Canadian and U.S. driver responses to selected survey questions from that pilot test. Only 58 percent of drivers agreed that the system was easy to adjust. The general agreement that the operation of the system was consistent and understandable was 77 percent among Canadian drivers and 58 percent among U.S. drivers. Drivers' ratings of displayed information reliability and appropriateness of warnings were slightly positive. Finally, a small majority agreed that the system helped them drive more safely and only a minority agreed that they would like the system installed in their truck. In reviewing the modestly favorable response to the SafeTRAC system, Dinges and his colleagues noted that one common comment by drivers was that the SafeTRAC volume control on the auditory alarm was set too high and not under their control, which was a feature of the pilot study protocol rather than the technology. It was concluded by these researchers that this negative reaction to the auditory alarm might have reduced overall driver acceptance of the system.

Table 4. Selected Driver Responses to SafeTRAC from the CVO Fatigue Management Technologies Field Test (adapted from Dinges et al., 2005)

	Driver Responses (Percent Agreement or Mean Rating)	
Survey Question	**Canadian Drivers (26 drivers)**	**U.S. Drivers (12 drivers)**
The SafeTRAC system was easy to adjust	58%	58%
Operation of SafeTRAC was consistent and understandable	77%	58%
SafeTRAC's crossing the lane alert feature could be trusted. 5=very helpful, 4=good, 3=neutral, 2=low value, 1=disappointing	3.36	3.25
Displayed information was reliable; the display usually accurately depicted my driving with regard to tracking the lanes on the road. 5=very helpful, 4=good, 3=neutral, 2=low value, 1=disappointing	3.50	3.25
SafeTRAC warned me of poor lane tracking only when I thought it was appropriate. 5=very helpful, 4=good, 3=neutral, 2=low value, 1=disappointing	2.96	3.25
SafeTRAC helped me drive more safely	69%	42%
I would like SafeTRAC installed in my truck	50%	42%

The recently-completed Volvo IVI FOT included an earlier version of the Eaton VORAD side and FCW system interface than the one to be implemented in the present effort. The reported Phase II driver survey results provide some information regarding drivers' reactions to this IVBSS technology (Battelle, 2004). Much of this feedback was quite favorable, although some specific issues in understanding some warning information was obtained. Following are some selected findings.

- 87 percent of drivers reported that the VORAD warning lights were "always" easy to see.
- 64 percent of drivers indicated that the VORAD audible alerts were "always" easy to hear.
- Most drivers said visual (78%) and auditory (84%) warnings "rarely" or "never" drew their attention away from their driving tasks.

- 62 percent of drivers indicated that they could “always” distinguish between the forward and side warnings.
- Of those drivers with other “warning or beeping” systems, 79 percent indicated that they could always distinguish between the auditory warning of those other systems and the VORAD system.
- Many drivers did not understand the intended meaning of imminent crash avoidance warning (ICAW), cautionary crash avoidance warning (CCAW), and advisory warning levels. Drivers’ responses to “What do you do when a single beep sounds?” were identical to those in response of the same question about three illuminated lights. Drivers’ responses to what to do when a double beep sounds were also identical to those in response of the three illuminated lights or the single beep.

On the whole, the findings from these earlier studies indicate that drivers previously exposed to earlier versions of the technologies to be implemented in the IVBSS HT system were split on their benefits and value. Quite a few drivers were willing to adopt these technologies while other drivers objected to the lack of display adjustment and/or had difficulty interpreting displayed information. Integration of all three of these technologies will obviously require careful consideration of the DVI to increase driver acceptance.

2.4 HT Crash Data

The HT driver has the demanding task of maintaining safe control of his/her vehicle while maintaining vigilance and awareness of other vehicles. Highway fatality data suggest that the defensive driving requirements are the most demanding, since the majority of fatal accidents involving trucks have been attributed to passenger vehicle driver actions. Blower (1998) presents dated indicating that in two-vehicle fatal crashes involving a medium-HT and a passenger vehicle, some error on the part of the passenger vehicle driver was identified much more frequently (80 percent of crashes) than on the part of the truck driver (26 percent of crashes).

FMCSA (FMCSA, 2006) recently provided a preview of results from their ongoing Large Truck Crash Causation Study (LTCCS). This study is an in-depth investigation and analysis of 967 HT crashes that occurred over a 33 months period between 2001 and 2003 at 24 sites and involved at least one fatality or at least one incapacitating on non-incapacitating but evident injury. This sample was used to calculate national estimates of similar accidents. A first, noteworthy finding reported by FMCSA in this report is that the “critical reason” for those crashes involving a HT and passenger vehicle was assigned to the passenger vehicle 56 percent of the time and the HT 44 percent of the time. This finding partially corroborates the general conclusion that HT drivers are put in danger by the drivers of other vehicles most frequently, although the absolute percentages differ from the Blower (1998) study.

Table 5 presents the estimated national percentage of crash types for similar crashes based on the LTCCS sample. Review of the first three most prevalent crash types provides the basic logic for the selection of FCW, LDW, and SCW systems for the HT IVBSS systems, as these three directly-related crash types account for over 51 percent of all estimated crash types.

Table 5. Estimated Percentage of Trucks in Crashes by Crash Type
(adapted from FMCSA, 2006)

Type	Percent**
Rear End	23.1%
Ran off Road/Out of Lane	17.8%
Side Swipe, Same Direction	10.3%
Rollover	8.9%
Turning across Path/into Path	8.0%
Intersecting Vehicles, Straight Paths	5.8%
Side Swipe, Opposite Direction	4.6%
Head-on	3.0%
Hit Object in Road	1.8%
No Impact (fire, jackknife, other,)	0.9%
Backing into Other Vehicle	0.3%
Other Crash Type	15.5%
Total Trucks	100.0%

In all of the 967 crashes included in the LTCCS, a “critical reason” was assigned to a truck (rather than another vehicle) to an estimated 55 percent of crashes corresponding to the national population, with the remaining 45 percent being assigned to the other vehicle. A single “critical event” was assigned to each of these crashes, providing a valuable tool for considering the type of crashes that could be avoided most directly by HT drivers. Table 6 presents these findings, which indicate that driver-related critical reasons account for over 87 percent of these crashes (48 percent of all crashes), with vehicle conditions and the environment accounting for the remainder. Review of this table reveals that “Driver Decision” was assigned the critical reason in an estimated 38% of such crashes. Here, Driver Decision refers to the situations of driving too fast for conditions, misjudging the speed of other vehicles, following other vehicles too closely, or made false assumptions about other driver’s actions. The second-most frequent critical reason was “Driver Recognition,” which refers to the driver not recognizing the situation by not paying proper attention, being distracted by something inside or outside the vehicle, or failing to adequately observe the situation. Note that many of the situations associated with critical events involving driver decision or recognition could trigger an IVBSS HT alert.

Table 6. Estimated Number of Trucks in All Crashes by Critical Reasons
(adapted from FMCSA, 2006)

Critical Reasons	Percent of Crashes Assigned to HT
Driver Decision	38.0%
Driver Recognition	28.4%
Driver Non-Performance	11.6%
Vehicle	10.1%
Driver Performance	9.2%
Environment	2.3%
Unknown	0.3%
Total – Assigned to HT	100.0%

2.5 Driver Tasks and Driver Workload

Two related topics that are central to IVBSS DVI design are: (1) the tasks other than IVBSS operation that are being performed by HT drivers; and (2) the driver workload associated with these tasks. Each of these topics is reviewed in this final subsection of HT factors.

2.5.1 Driver Tasks

Turanski and Tijerina (1992) conducted an extensive study of HT driver workload with the objective of providing methods and preliminary results regarding the implications of introducing advanced technologies into the HT cab. Early during that project, a set of driving tasks was identified, a subset of which were selected for the focus of workload assessment. The standard and non-standard driving tasks identified by Turanski and Tijerina are provided in Table 7, which are organized into the categories of basic driving tasks, parking and related activities, lane changes and passing/overtaking, turns and curves, intersections and crossings, and non-standard (emergency) tasks. Tasks with an asterisk were identified as those most relevant to in-cab device interaction.

Tijerina, Kiger, Rockwell, Tornow, et al. (1995) measured following distance and lead time with an experimenter present in the cab during structured, instrumented observation of 30 professional drivers over a pre-defined 285 mile course. Observed mean following distance and headway time were found to be comparable, though statistically different, across urban and rural freeways for both measures. Observed headway distances were 44.90 meters and 49.73 meters for urban and rural freeways, respectively, and 1.93 seconds and 2.06 seconds, for urban and rural freeways, respectively. For this observational setting (with an experimenter/observer present in the cab driving on a prescribed route) it appears that drivers adopted what are generally considered safe car following behaviors.

An understanding of both the nature and modality of ongoing driver tasks is essential in the design of the IVBSS HT DVI, therefore, the following discussions outline HT driver visual, auditory, and haptic/tactile tasks.

Table 7. Standard and Nonstandard Driving Tasks
(from Turanski & Tijerina, 1992)

Basic Driving Tasks
Start vehicle in motion
Shift gears
Reach desired speed in each gear
Reach desired cruise speed
Control truck speed to allow for safe stopping distance*
Brake under normal circumstances*
Maintain safe following distance*
Control direction via the steering wheel*
Maintain lane position and spacing, straight road*
Be aware of changes in the road scene [the primary visual task*
Glance at gauges
Glance at mirrors*
Drive on a downgrade (steep gradient)
Drive on an upgrade

Lane Changes and Passing/Overtaking
Change lanes*
Pass on the left, cars (multi-lane, divided road)
Pass on the left, other trucks (multi-lane, divided road)
Pass on the left, cars (two-lane, undivided road)
Pass on the left, other trucks (two-lane, undivided road)
Pass construction zones
Merge*
Exit using an exit ramp

Turns and Curves
Make a left turn
Make a right turn
Negotiate a curve and remain in your lane*
Negotiate a curve and change lane in a multi-lane divided highway*
Turn your tractor-trailer around

Intersections and Crossings
Travel through intersections (You have right-of-way)
Stop at intersections (They have right-of-way)
Start truck in motion from a stop at an intersection
Cross railway grade crossings
Negotiate l-lane and narrow 2-lane bridges*
Negotiate narrow lane tunnels*
Stop at and start from narrow-lane toll plaza

Nonstandard Driving
Recover from locked brakes due to extreme loss of air pressure
Make a quick stop (Put a lot of pressure on brakes, but with no
smoking tires, no danger of losing control)
Make a hard braking stop (smoking tires, danger of losing control)
Stop due to lighting problem (e.g., trailer lights go out)
Stop due to engine problem (e.g., high engine coolant temperature, low oil pressure)
Recover from tire failure, front tire(s)
Recover from tire failure, other tire(s)
Steer to avoid something on the road
Recover from a tractor/trailer skid
Respond to cargo or tire fire
Execute off-road recovery (veer off the road to avoid collision, then immediately return to roadway)

Parking and Related Activities
Park tractor-trailer
Back-up

2.5.2 Visual Tasks

Tijerina and his colleagues conducted an on-the-road study of driver glance behavior with 30 professional truck driver participants who each drove a single vehicle (a 1992 Volvo/White GMC conventional tractor with sleeper compartment and a 1993 Fruehauf dry freight van semi-trailer loaded with ballast to bring gross vehicle weight to 76,300 pounds) on a fixed route of 285 miles that was divided between daytime and nighttime driving. Table 8 summarizes the obtained glance times, which are divided by road type, since analyses indicated that observed glance times significantly differed by road type for each of these glance measures (Tijerina, Kiger, Rockwell, Tornow, et al.). The reader should note that absolute observed glance times were generally shorter in this study than glance times obtained in prior studies. Because of the larger sample and increased rigor of the observations by Tijerina, Kiger, Rockwell, Tornow, et al. (1995), they should be considered to provide valid approximations to glance times under actual operational conditions.

Table 8. Driver Glance Times of Observed Tasks
(adapted from Tijerina, Kiger, Rockwell, Tornow, et al., 1995)

Glance Measure	Urban Freeway	Rural Freeway	Rural Road
Left Mirror average duration (sec)	1.00	1.01	0.87
Right Mirror average duration (sec)	0.96	1.05	0.90
Mean Mirror glance duration (sec)	1.02	1.04	0.89
Instrument Panel average duration (sec)	0.84	0.93	0.76
Off-road average duration (sec)	0.97	1.01	0.87
On-road average duration (sec)	2.64	2.43	5.27
Proportion of Time Spent	0.083	0.092	0.047

As part of their on-the-road study of driver glance behavior, Tijerina, Kiger, Rockwell, Tornow, et al. had a ride-along experimenter ask the driver participant to perform several tasks found in normal, everyday truck driving at a time when headway from another vehicle was a minimum of 200 feet (Tijerina, Kiger, Rockwell, Tornow, et al. (1995). Table 9 summarizes the video data analyzed during performance of seven of these requested tasks. The resulting measures provide a good index of the individual and combined amount of time that HT drivers take their eyes off the road to perform these common tasks which, in turn, is useful in estimating overall perception times in response to roadway hazards.

Table 9. Driver Glance Times of Directed Tasks
(adapted from Tijerina, Kiger, Rockwell, Tornow, et al., 1995)

Requested Task	Mean Device Glance Duration	Mean No. of Glances to Device	Average Time Off Road	Average Road Glance Duration During Task
Adjust Radio Volume	0.76	1.10	0.90	1.65
Right Mirror Detect	1.37	1.05	1.43	0.64
Read Air Pressure	1.57	1.16	1.80	0.61
Tune Radio	1.22	5.61	6.75	0.89
Tune CB	0.95	3.23	2.99	1.04
Read Clock	1.20	1.03	1.23	0.66
Left Mirror Detect	1.21	1.05	1.27	0.69

In summarizing their visual allocation data analyses, Tijerina, Kiger, Rockwell, Tornow, et al. noted that drivers adapted well to workload induced by the environmental factors of road type, lighting, and traffic (car following). Drivers allocated 90 percent of their visual resources to road sampling for night 2-lane highways vs. 70 to 75 percent for day 4-lane rural expressways. When required to sample for information off the roadway, e.g., mirrors and gauges, drivers limited their average time off the roadway to between 0.85 and 1.03 seconds. Drivers showed a tendency to quicken glances off the roadway for 2-lane vs. the freeways. Conversely, mean “on road” glance durations were longer for 2-lane roads and night operations (Tijerina, Kiger, Rockwell, Tornow, et al., 1995).

2.5.3 Auditory Tasks

Robinson et al. (1997) developed a comprehensive list of commercial vehicle operations driving tasks that were “hearing critical” which included the categories of: routine driving tasks, communication, detection of mechanical problems, detection of internal (inside cab) warning signals, detection of external (outside cab) warning signals, engine, drive train, air system, tires and wheels, trailer, electrical system. Detection of warning signals is probably the most relevant to the present review, as these are signals that could compete with collision warning signals. Warning signals identified in the review were:

- Low oil pressure
- High oil pressure
- Low water
- Low air pressure
- Engine temperature
- Approaching trains
- Emergency vehicles
- Automobile horns
- Truck horns
- Car in blind spot
- Car coming up on right side
- Car coming up on left side
- Pedestrians, animals, and other unmarked road hazards
- Rumble strips
- Lane deviation
- Lane edge bumps

2.5.4 Haptic (Tactile) Tasks

Just as there is little information available regarding the haptic/tactile cab environment, limited research has focused on the haptic/tactile nature of driver tasks. A number of tasks obviously fall into this category, including use of foot controls and shifting transmission gears. Tijerina and his colleagues observed that when asked to tune a radio, HT drivers initially located the control visually, then minimized their time glancing at the radio, relying primarily upon tactile sensation to turn the knob and hearing to identify stations (Tijerina, Kiger, Rockwell, Tornow, et al., 1995).

2.5.5 Driver Workload

The workload demands of HT driving are typically viewed as higher than passenger vehicles, due to more complex vehicle control operations (steering, shifting, and braking). Driver opinion appears to be consistent with this general view. The recently completed Battelle report of the Volvo IVI FOT asked drivers to rate the perceived mental workload of driving using a 10-point scale. Mean ratings and 95 percent confidence intervals for the 86 respondents were: driving a personal automobile under normal conditions (mean = 4.38, 95% CI = 0.52), driving a HT in good conditions (mean = 5.44, 95% CI = 0.48), driving a HT in heavy traffic (mean = 7.84, 95% CI = 0.48); and driving a HT in low visibility conditions (mean = 8.67, 95% CI = 0.38) (Battelle, 2004). These findings indicate that experienced HT drivers perceive that driving a HT is more demanding than driving a personal automobile and that traffic and weather conditions increase the perceived mental workload.

Kiger et al. (1992) conducted a task analysis and initial assessment of HT driver workload as part of their larger effort to develop measures of driver workload. As part of a larger survey, drivers were asked to rank eight common tasks from “1” to “8” in order of increasing workload where a “1” means the task has the lowest workload, while an “8” means the task has the highest workload. Table 10 presents the mean rank orders (n=21). Again, we see that drivers are sensitive to the workload demands of driving and that common driving tasks vary substantially in the amount of workload perceived to be involved.

Table 10. Mean Rated Workload of Common Driving Tasks
(adapted from Kiger et al., 1992)

Task	Mean	Std. Dev.
Check your mirrors	2.33	1.35
Eat or smoke while driving	2.42	1.94
Change lanes	3.57	1.53
Pass another vehicle on the left	4.24	1.48
Enter a freeway	4.48	2.20
Negotiate a curve and stay in your lane	5.14	1.68
Make a turn at an intersection	6.62	1.24
Driving through a construction zone	7.19	1.25

Kiger et al. (1992) also conducted a series of interviews to gain a more complete understanding of how HT operators defined workload and the factors that they viewed as affecting workload levels. These researchers found that operational and driving environment factors combined to induce stress and workload. They concluded that it would be essential to control these factors in any studies attempting to assess driver workload. Tijerina and his colleagues also anticipated the implications of these factors in an assessment of in-vehicle safety systems, noting that an evaluation of such systems would best be conducted under demanding conditions, including inclement weather, congested traffic, and roadway construction zones.

3 Selected Design Guidance Applicable to IVBSS HT DVI

The preponderance of CAS DVI research has been focused on passenger vehicle applications. Although only a few studies have specifically investigated HT CAS DVI issues, this research does provide a source for some design guidance specific to the IVBSS HT DVI. In addition, much of the passenger vehicle CAS DVI research is applicable to the IVBSS HT DVI design. The following selected design guidance draws upon research and previous guidance from both the passenger vehicle and HT domains. This guidance, as well as the associated discussions, rely heavily upon the CAS human factors guidelines recently prepared by Battelle; more detailed guidance and discussions can be found in that document (Campbell et al., 2006). Seven IVBSS HT DVI design topics are addressed by these guidelines:

1. Warning Levels Specification
2. Warning Prioritization
3. Warning Integration
4. Warning Modality Selection
5. Display Location
6. Warning Signal Specification
7. Warning Adjustments and False Alarms

3.1 Warning Levels Specification

In the context of IVBSS HT DVI, warning levels refers to the type and number of CAS warnings or informational displays provided to drivers to alert them to a potentially hazardous driving situation. There are four warning types that must be considered in the design of each IVBSS HT CAS component. These are summarized in Table 11 in order of their relative urgency.

Table 11. CAS Warning Types and Functions

Warning Types	Warning Functions
Imminent collision avoidance warning (ICAW)	Alert driver regarding required immediate corrective action
Cautionary collision avoidance warning (CCAW)	Alert driver regarding required immediate attention and possible corrective action (may be followed by a separate ICAW)
Advisory warning	Provide driver information about a specific condition of the current roadway situation
Informational display	Provides driver information about his/her current or recent driving performance (e.g., FCW system headway distance and LDW system lane keeping performance score)

The four types of warnings can be combined in various ways to provide warnings with successive levels of priority (see the following warning prioritization discussion) or to provide a combination of warnings and informational displays. Table 12 summarizes the currently available guidance for selecting warning levels for the separate IVBSS HT component systems and is followed by a discussion of this guidance.

Table 12. Warning Stages Design Guidance

- FCW systems should include a minimum of two levels of warning (CCAW and ICAW) to provide HT drivers sufficient time to assess the roadway situation and respond to a forward hazard. Additional advisory or informational displays may be valuable.
- LCW systems can provide an informational display or advisory warning, in addition to an ICAW, if this information is provided visually in a location that is consistent with (and would promote) use of side-view mirrors in assessing clearance of the roadway prior to a lane change/merge maneuver.
- LDW systems can provide an information display or advisory warning, in addition to an ICAW, if this information is provided in a non-distracting manner that minimizes the driver's glance time away from the roadway.

The braking distance discrepancy between HTs and passenger vehicles is a sufficient basis for providing HT drivers with multiple levels of FCW to ensure adequate time to assess and respond to the forward hazard. Figure 5 provides a comparison of passenger vehicle and HT braking distances, based on regulated maximum braking distances on a dry, level surface with good traction (NHTSA FMVSS Air brake systems, 2003; NHTSA FMVSS Light vehicle brake systems, 2003). These braking distances represent the braking distance after brakes have been actuated and do not take into account the driver's perception-response time. Braking distance for the truck tractor reflects current regulations, which call for testing using only the tractor brakes and do not directly reflect the on-road performance of a combination HT that has braking at all wheel positions. The longer braking distance and resultant earlier required response by HT drivers to forward hazards has led to recommendations that HT CAS should use progressive warnings to provide drivers with sufficient time to avoid forward crashes.

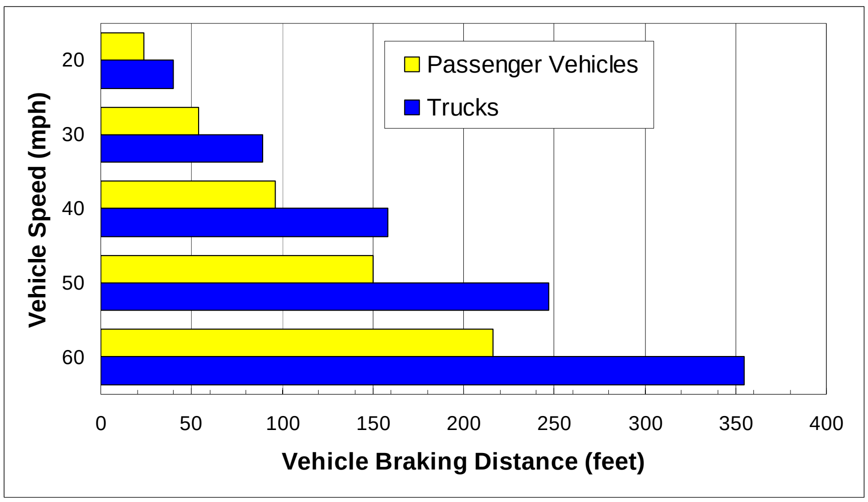

Figure 5. Comparison of passenger and HT regulated braking distances.

FMCSA recently published voluntary operational requirements for HT FCW and Automated Cruise Control (ACC) (Houser, Pierowicz, & McClellan, 2005) that include recommendations for three levels of warning for FCW systems, as depicted in Figure 6.

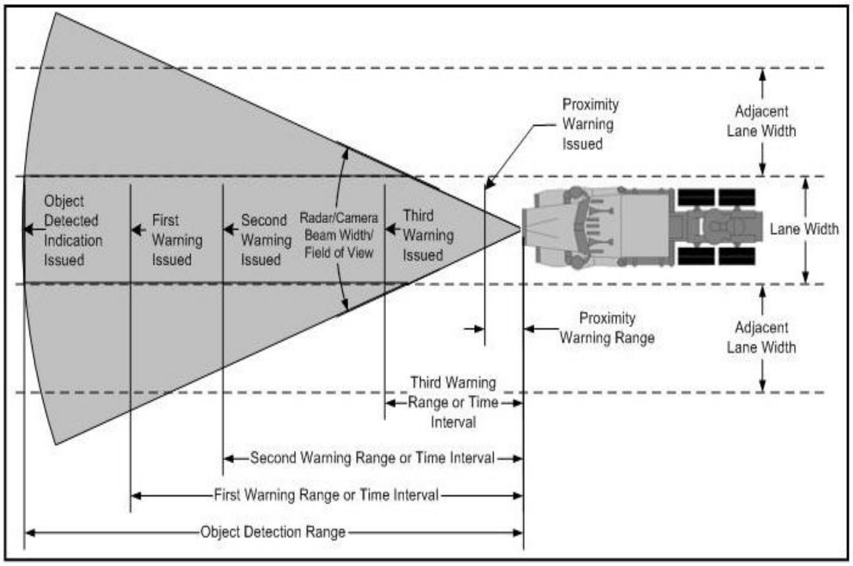

Figure 6. FMCSA recommended FCW three-stage warning thresholds and warning threshold placement zones (from Houser et al., 2005).

Research regarding appropriate levels for LCWs are limited, although available passenger vehicle data are consistent with the use of a CCAW or information display to provide information regarding the presence of other vehicles in adjacent lanes.

Recent pilot testing of a HT LDW system that incorporated continuous feedback found it to be acceptable by many drivers (Dinges et al., 2005), suggesting the possible benefit and acceptance of a lane tracking performance informational display as part of the IVBSS HT LDW system.

3.2 Warning Prioritization

Establishing priorities for the individual IVBSS HT CAS warnings provides a basis for defining system algorithms that control warning precedence, attenuation, or delay within individual IVBSS systems, across the three IVBSS HT CAS systems, and across all HT warning systems. It is recommended that priorities for these warnings be established for the IVBSS HT DVI by applying procedures that are modeled after International Organization for Standardization (ISO) Technical Specification 16951 *Procedures for Determining Onboard Messages Presented to Drivers* (ISO, 2004). The warning prioritization design guidance in Table 13 and the subsequent discussion is adapted from Campbell et al. (2006).

Table 13. Warning Prioritization Design Guidance

- CAS warnings, whether they are ICAW or CCAW, should have priority over all other in-vehicle messages.
- When determining priority among multiple CAS warnings, the procedures outlined in Figure 8 should be used (adapted from ISO 16951, refer to this data source for additional details).

Given the safety relevance of CAS warnings, it is important to emphasize the priority of CAS warnings over non-CAS warnings, and to establish precedence rules for the each of the warning levels (e.g., ICAW and CCAW) and the three IVBSS HT CAS systems (FCW, LCW, and LDW). The recently-developed ISO standard (ISO, 2004) for prioritizing messages provides two different procedures for determining the relative priority of all in-vehicle messages based on assessed criticality and urgency. In the *Priority Index Method*, expert evaluators rate both criticality and urgency on a 0-3 scale and develop a priority index for each message based on weighted criticality and urgency factors. In the *Priority Matrix Method*, expert evaluators make pair-wise comparisons among all possible pairs of messages, to determine which of the two messages should receive priority, or whether the messages should have the same priority.

Because one objective of the IVBSS program is to serve as a broader catalyst for industry-wide implementation of an integrated system, it would be appropriate to investigate fleet-specific versus broader industry perspectives on the relative priorities of FCW, LCW, and LDW warnings. In addition, since priorities are likely to be established by fleets, but dealt with on a daily basis by drivers, it will be important to understand the perspectives of safety experts, fleet operational personnel, and HT drivers.

Figure 7 outlines a recommended approach (from Campbell et al., 2006) that reflects the procedures suggested for the Priority Index Method from ISO 16951.

Prepare to Prioritize Messages	• Identify at least 5 examiners to conduct the evaluations. • Identify and assemble messages that are to be prioritized. • For each message, describe the driving scenario; i.e., context, conditions, and situation associated with the message. This might include trip type, roadway type, speed, weather, traffic situation, vehicle type, vehicle condition (note that if the same message could be presented in more than one condition/situation, it should be prioritized separately for each condition/situation).
Select Desired Weights for Criticality and Urgency	• Assign relative weights, k_c and k_u to, respectively, the criticality and urgency criteria. Selecting, for example, a 1 for each of these values would mean that the contribution of criticality and urgency to final priority values would be the same. Selecting a 1 for k_c and a 2 for k_u would mean that urgency was given twice the weight as criticality. Common weights can be selected for the entire evaluation, or individual evaluators can select their own weights, though the final priority calculations will become more complex if this is done.
Evaluate Criticality and Urgency for each Message	• Assess risk to vehicle, occupants, and/or pedestrians using the following 4-point scale for criticality: 3 = severe or fatal injury, 2 = injury or possible injury, 1 = no injury (vehicle damage), 0 = no injury (no vehicle damage). • Assess the urgency of the situation using the following 4-point scale: 3 = immediate response required (0-3 seconds), 2 = response required within 3-10 seconds, 1 = response preparation needed, action needed between 10 and 120 seconds, 0 = information only, no direct action required by the driver.
Calculate Priorities Among CAS Messages	• For each message, calculate the priorities assigned by individual evaluators: $p_{ij} = k_c c_{ij} + k_u u_{ij}$ (1) where: p_{ij} = the priority value for an individual message from an individual evaluator c_{ij} , u_{ij} = individual scores for, respectively, criticality and urgency k_c, k_u = individual weights for, respectively, criticality and urgency • For each message, calculate the average priority value across evaluators.
Develop Prioritized List of CAS Messages	• Before finalizing the priorities, verify that there was sufficient agreement across the evaluators to be confident of the quality of the data. For example, check to see if at least half of the evaluators agreed on the criticality and urgency of individual messages or calculate the standard deviation of the priority values across evaluators and verify that the standard deviation is less than 1.0 (see also ISO 16951 for more details). • If confidence in the data is low, make sure common procedures and heuristics were used across the evaluators and either adjust scores by consensus or repeat Steps 2-4 above until adequate confidence in the data is achieved. • Once adequate confidence in the data is achieved, rank order the messages from highest to lowest priority value; when items have the same priority values, the message with the highest criticality score should have a higher priority.

Figure 7. Recommended warning prioritization (adapted from Campbell et al., 2006).

3.3 Warning Integration

There is limited research that is directly applicable to CAS warning integration and the data that are available are not entirely consistent. Table 14 (adapted from Campbell et al., 2006) provides general guidance regarding issues that should be considered when integrating the warnings from IVBSS HT CAS devices.

Table 14. System Warning Integration Guidance

- Maintain identity of the warning nature through signal features and location.
- Determine how to present warnings from simultaneous hazards (e.g., forward collision plus a potential side object collision). Establish and implement rules for warning presentation based on warning priority, including warnings of equal priority.
- Consider suppressing and subsequently delaying intrusive ICAWs (e.g., auditory, haptic, HUD visual) following driver action in response to the initial ICAW.
- Physical Integration of IVBSS warnings will include decisions about whether to use a centralized display to present visual warnings associated with two or more CAS devices or to use distributed displays. Physical integration might also include decisions about whether the controls associated with a CAS device or devices (e.g., on/off, warning intensity, warning sensitivity) are co-located in a single interface or separated.
- Complete CAS integration can occur at the software, hardware, and component level. If integration of multiple CAS devices takes place, this integration will likely need to occur at the sensor, vehicle information processing, warning algorithm, vehicle component, and DVI levels.

Research involving driver responses to FCW and LCW in a passenger vehicle simulator (Chiang, Brooks, and Llaneras, 2004) and a HT simulator (Belz, Robinson, & Casali, 1999) support the value of providing warnings that allow drivers to discriminate the nature and location of the hazard by providing distinct auditory warnings that are spatially separated.

For the purpose of CAS DVI design, concurrent hazards involve those situations where a second hazard co-occurs or immediately following an initial hazard before the driver has completed his/her response to the first hazard. The following concurrent hazard scenarios have been identified for the three HT IVBSS CAS system components[2]:

FCW-LDW: Host vehicle is moving at a constant speed and leaves its lane unintentionally at the same time or just before it encounters a lead vehicle moving at a lower constant speed, slowing down, or stopped.

FCW-LCW: Host vehicle is moving at a constant speed and encounters a lead vehicle moving at a lower constant speed, slowing down, or stopped. The host vehicle attempts to move into an adjacent lane, which is occupied by another vehicle.

LDW-LCW: A vehicle is driving in an adjacent lane. The host vehicle drifts and departs its lane.

Determining how to present warnings for concurrent hazards (e.g., FCW-LCW) is a crucial design question that has not been satisfactorily answered by past research. A key concern is whether warnings for concurrent hazards should ever be presented simultaneously, or if the

[2] These three scenarios were identified in the draft UMTRI *DVI and Human Factors Interim Task Report* dated March 27, 2006.

initially detected hazard should be cleared before a warning for the next hazard is presented. If simultaneous warnings are presented and both the timing of the concurrent hazards and CAS processing speed allow for flexibility in warning modality, then consideration should be given to the modalities used for the different warnings. The limited available data suggest that the driver should be warned about the highest priority hazard with an auditory tone and that warnings for concurrent hazards with a lower priority should be presented visually. Research by Tan and Lerner (1996) indicates that suppressing an auditory warning as soon as the driver takes action, followed by a period of delay after the driver's action before reactivating the ICAW can reduce or eliminate unwanted auditory alarms.

3.4 Warning Modality Selection

A warning modality can be selected early in the CAS DVI design process. Modality selection should consider the capabilities of auditory, visual, and haptic signals to fulfill the message function (i.e., alerting the driver and conveying the corresponding message content in a timely manner) while minimizing potential negative effects of increased driver workload, startle response, misunderstanding, or annoyance. Table 15 presents guidance on the selection of warning modality, followed by discussions of issues specific to the selection of auditory, visual, and haptic modalities for HTs IVBSS CAS warnings. The guidance and discussion draw upon relevant content from the recent CAS guidelines prepared by Battelle (Campbell et al., 2006).

Table 15. Warning Modality Selection Guidance

- All ICAWs that have priority for display should include an auditory or haptic modality that supports rapid and intuitive identification of the nature and location of the hazard by the driver.
- All ICAWs that have priority for display should include a secondary visual mode that supports rapid identification of the nature and location of the hazard and requires a minimal – or no – glance time away from the imminent roadway hazard.
- System limitations or malfunction status should be initially identified by an auditory signal and accompanied by a visual signal that provides further explanatory information.
- Avoid control-based haptic ICAWS (i.e., brake pulse and steering wheel torque) if it is determined that they will interfere with driver control of the HT.
- A haptic seat vibration LDW ICAW should only be considered if it is determined that an auditory warning is unlikely to be effective due to:
  - Excessive HT cab noise levels and an inability to mute or attenuate the source of the conflicting noise;
  - Unacceptable auditory signal localization; or
  - Poor driver recognition of other auditory warnings.
- Use of auditory and haptic CCAWs, advisory warnings, and informational displays should be avoided in order to minimize unnecessary driver startle responses, distraction, or annoyance to frequent (and possibly false) warnings.

Avoiding the disruption of drivers' visual scanning and focus through the use of non-visual CAS display modalities is a central theme throughout the recently prepared CAS DVI guidelines

(Campbell et al., 2006). Figures 6A and 6B present selected results from naturalistic observations of HT drivers' glances reported by Tijerina, Kiger, Rockwell, Tornow, et al. (1995). These data represent summaries based on the observations of 30 HT drivers making over 30,000 individual glances during representative periods of day and night driving on urban freeway, rural freeway, and 2-lane rural roads. Figure 8A shows that HT drivers allocate approximately 75% of their total visual resources looking at the forward road scene. Figure 8B shows that HT drivers' individual glances at the forward road scene typically vary from less than one second to almost eight seconds, while individual glances away from the forward road scene seldom extend longer than 1.6 seconds.

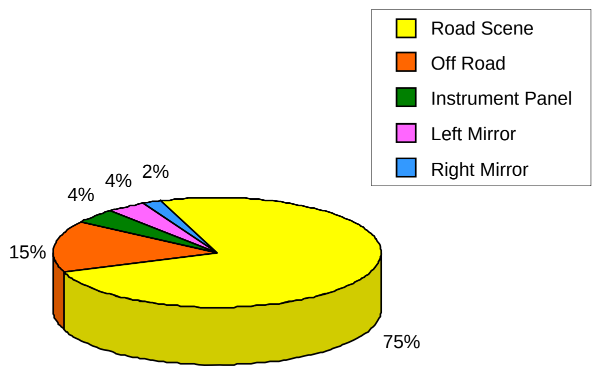

Figure 8A. Percentage of HT driver total glance time shared among five locations.

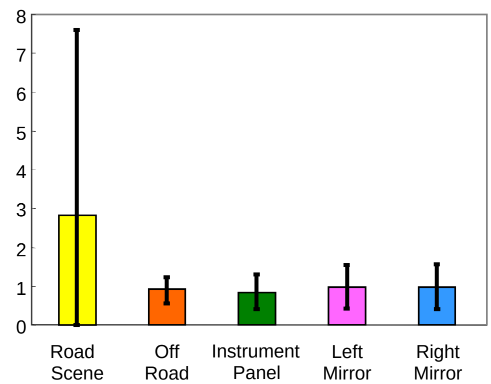

Figure 8B. Means and estimated 95% confidence intervals for HT driver glance times across five locations.

The amount of visual scanning between the forward road scene, mirrors, and instrument panel required for safe monitoring while driving HTs suggests that an exclusively visual ICAW could be distracting or not attended to by the driver. Belz et al. (1999) demonstrated that auditory displays can result in better HT driving simulator brake response time than dash-mounted visual displays out of driver's direct field of view and that, in some circumstances, visual displays can result in slower brake response time than no display. These researchers interpreted their latter finding as indicating that presenting collision avoidance information exclusively via a visual display could distract the driver and result in longer response times than no collision warning. Finally, these researchers found that combined visual and auditory displays were generally more effective than visual- or auditory- only displays in FCW systems for commercial driver participants in their HT driving simulator study.

3.4.1 Auditory Warning Modality

HT cab noise was reported to approach 90 dBA in a study reported by Robinson et al. (1997). These authors recommended the use of noise-sensing circuits to maintain a constant signal-to-noise ratio with these high ambient noise levels. Informal discussions with UMTRI and Eaton IVBSS team members suggests that current noise levels in HT cabs are substantially lower than the levels reported by Robinson et al. in 1990's truck cabs. If this is the case for most HTs that would potentially have IVBSS-type systems installed, then the absolute decibel level of IVBSS HT alarms could be reduced, while ensuring an adequate level above the current cab noise levels.

Available research provides consistent support for the adoption of auditory signals as the primary ICAWs modality. The advantage of auditory warnings is that they are omnidirectional signals that can command attention regardless of where the driver is looking. In addition, most of the relevant literature suggests that operator performance can be further improved by combining auditory and visual messages (e.g., Belz et al., 1999; König & Mutschler, 2002; Kiefer et al., 1999; Campbell, Carney & Kantowitz, 1998; Campbell, Richman, Carney, & Lee, 2002). In particular, redundant visual displays that are visually conspicuous can serve as a backup method for drawing the driver's attention to a warning if the auditory signal is masked by in-vehicle noise. A visual signal may also have an additional advantage of clarifying the nature of the hazard by providing a readily comprehended icon or message.

A final use of auditory IVBSS HT warnings can be to alert drivers to abnormal CAS system status. Kiefer et al. (1999) recommend that a brief auditory tone should indicate the onset of a system limitation or malfunction (i.e., the CAS ceases to provide some or all of its designed capability), and a visual display should continually indicate the limitation or malfunction.

3.4.2 Visual Warning Modality

Visual warnings are not recommended as the primary source of information for time-critical warnings, since there is a good possibility that drivers will not receive the information in a timely manner. Because visual warnings are not omnidirectional, they must appear in the driver's field of view. Thus, a visual warning presented on the left side of the instrument panel likely will not be seen in a timely manner if the driver is looking down at the radio or performing a shoulder check. In addition, drivers who are actively focusing their attention on a specific area of the visual scene can still miss a visual warning displayed in the general location of the focused viewing.

Trade-offs between warning urgency and driver annoyance can lead to the selection of exclusively visual warnings. If drivers could be expected to consistently attend directly to or near the warning information as a part of their normal driving activities, then visual display could be the most appropriate in such cases. Talmadge, Chu, Eberhard, Jordan, and Moffa (2000) provide an example of a system that would warrant consideration for exclusively visual warnings in a LCW system designed for "parallel usage." The primary objective of this system was to provide information that augmented driver decision making when clearly understood that they were responsible for actively acquiring information from the warning system. In the system field test, 88 percent of test drivers reported that the exclusively visual lane change warning provided adequate warning of potential hazards. However, available data suggest that passenger vehicle drivers only look at the rear-view or relevant side-view mirror approximately 50 percent of the time (compared to 99 percent for glances towards the forward center) prior to a lane change/merge, which means that they could otherwise miss critical visual-only warning information presented at the mirror locations (Lee et al., 2005). The necessary HT naturalistic driving data are not available to determine if a comparable trend might preclude use of exclusively visual ICAWs for HT IVBSS LCWs.

3.4.3 Haptic Warning Modality

Two advantages of haptic warnings are: (1) possible faster braking response times (Shutko, 2001); and (2) the omnidirectional properties of properly implemented haptic signals. An appropriate haptic warning can be effective in communicating time-critical information to a driver who may not be paying attention to the driving task or who, for some reason, cannot be expected to hear an auditory warning. This feature makes haptic warnings potentially appropriate for ICAWs. Some guidelines recommend that haptic warnings can be appropriate for both ICAWs and CCAWs (Campbell, Bittner, Lloyd, Mitchell, & Everson, 1997; Wilson et al., 1998); however, these and other sources recommend not using haptic warnings for CCAWs with high false alarm rates because haptic warnings can be annoying to drivers under these conditions. Most of the empirical studies reviewed used haptic warnings for ICAWs only (Kiefer et al., 1999; General Motors Corporation and Delphi-Delco Electronic Systems, 2002; Manser, Ward, Kuge, and Boer, 2004; Tijerina, Jackson, Pomerleau, Romano, and Petersen, 1996; Shutko, 2001). For now, there is insufficient data to make the claim that haptic ICAWs are equally effective as auditory ICAWs, however, it is possible that further research involving haptic warning signals with more optimal characteristics could change this conclusion.

Jiang et al. (2001) identify HT suspension as an important factor in cab vibration. However, they go on to note that handling and rollover characteristics are the primary concerns in designing vehicle suspensions, leaving the cab suspension, seat suspension, and seat cushion as the components that can be modified to reduce driver vibration. This suggests that foot pedal and steering wheel vibration coding could be masked by ambient vibration levels in HTs. The COMSIS Corporation (1996) CAS DVI guidelines caution that use of haptic warnings in HTs should be avoided because they may lead to driver responses that are incompatible with appropriate safety-related actions, citing earlier studies identifying potential disruptions with commercial transport driving activities; although it was noted that the extent of such possible disruption was not known (COMSIS, 1996).

Data about the interactions between haptic warnings and driver responses are limited. Specifically, some research sources raise important safety issues regarding haptic warnings that remain unanswered, such as the potential loss of vehicle control on slippery surfaces, onset delays, consequences of moving the driver’s foot from its “normal” position in the vehicle, inhibiting of more appropriate driver responses, driver annoyance, confusion of a haptic brake pulse with fuel line clogging, and drivers mistakenly assuming that brake pulse warnings will automatically mitigate an unsafe situation (Kiefer et al., 1999; Tijerina, et al., 1996).

3.5 Display Location

Display location refers to the spatial placement of HT IVBSS warning, informational, and system status displays in the cab. The guidance provided in Table 16 is adapted from Campbell et al. (2006). Separate discussions are provided on auditory, visual, and haptic display location considerations.

Table 16. Display Location Design Guidance

- Do not use virtual speakers – sound images that are perceived to emanate from between two or more physical speakers – to provide localized auditory warnings. Use discrete speakers aimed directly at the driver's head to localize sound in the direction of the crash threat.
- The visual warning display should be located within 15 degrees of the drivers' expected line sight so that it does not direct the driver's gaze away from important visual information.
- If a visual warning is selected for HT IVBSS FCW, the recommended visual display is a head-up display (HUD) or high head-down display (HHDD) directly in front of the driver.
- The type of haptic display used should be intuitively associated with the situation it represents and, if possible, it also should be compatible with the driver response appropriate for the driving situation and hazard (e.g., steering wheel torque applied in the direction that moves the vehicle away from a hazard in a LCW system).
- The haptic display should present information in a form that the driver is physically able to perceive (e.g., accelerator pedal displays are riskier because drivers may not be in contact with the accelerator—i.e. if the cruise control is engaged).

3.5.1 Auditory Display Location

Auditory signals can be spatially localized to draw the driver's attention in the direction of a visual display or a hazard, but with some element of risk. Localization acuity is generally poorer for sounds on the median plane (0- and 180-degrees azimuth). Also, sound images that are generated using virtual speakers tend to be associated with poorer localization acuity, particularly with low-bandwidth signals under high noise conditions (Ericson, Bolia, & Nelson, 1999; Tan & Lerner, 1996). In the HT IVBSS system that integrates multiple CASs, localization may be necessary to differentiate warnings generated from each system (by using an auditory signal presented in front for FCW systems, and on the side of the hazard for LCW and LDW systems (König & Mutschler, 2002; Lee et al., 2004; Chiang et al., 2004).

3.5.2 Visual Display Location

Figure 9 (adapted from Transports Quebec, 2006) depicts a typical configuration of blind spots around a combination tractor-trailer. The extent of these blind spots has led at least one supplier of HT LCW systems to provide the option of multiple sensors on one side of the vehicle (Eaton, 2004). COMSIS (1996) cites crash analysis findings indicating that 63.1 percent of lane change/merge crashes involving HTs occurred on the right side of the vehicle, while only 18.5 percent occurred on the left side, as support for the recommendation that sensors may monitor the blind spot only on one side (the right side) of HTs. However, a sensor on both sides was identified as the preference in that earlier set of CAS DVI guidelines. This more conservative approach is supported by 2004 HT multiple vehicle crash statistics that indicate that left-side impacts represented 19.1 percent of all HT multiple vehicle crashes and right-side impacts represented 22.8 percent of such crashes (NHTSA, 2004).

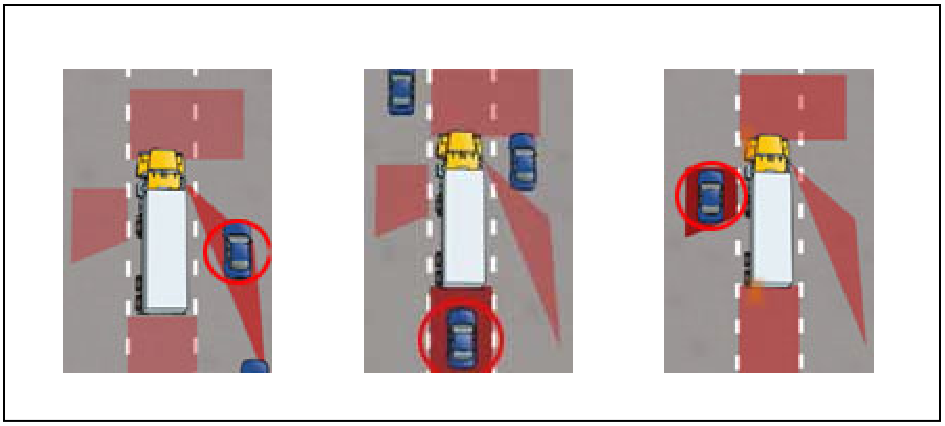

Figure 9. Depiction of HT blind spots and passenger vehicles in each of three danger zones (adapted from Transports Quebec, 2006).

Because of the multiple blind spots around HTs, drivers must actively scan the area surrounding their vehicle, leading the authors of the earlier version of the CAS DVI guidelines (COMSIS, 1996) to recommend that primary lane change displays should not be located on the vehicle dashboard but, rather, on each of the side view mirrors within 15 degrees vertically and within 15 degrees horizontally of the driver's line of sight of the mirrors.

In general, locating the visual warning near the line of sight will increase the likelihood that it will be seen, in addition to reducing the time needed to glance at that information (König & Mutschler, 2002). The specific design value of 15 degrees within the line of sight is taken from COMSIS (1996). This source also recommends that the visual display be located such that it draws the driver's gaze towards the hazard.

3.5.3 Haptic Display Location

If a haptic warning is selected, the haptic signal source must be in continual contact with the driver's body. The consideration of locations and signals are generally limited to the following, which will be discussed in greater detail in the following discussion of warning signal specification.

- Driver's seat – either general or lateral vibration;
- Accelerator – pedal movement accompanied by deceleration;
- Brake – brake pedal movement and corresponding vehicle brake pulsing; and
- Steering wheel – lateral vibration and/or increased lateral resistance.

3.6 Warning Signal Specification

Design guidance and discussions regarding the specification of warning signals is provided separately for auditory, visual, and haptic signal modalities in this subsection.

3.6.1 Auditory Warning Signal Specification

Table 17 presents guidance to support the specification of auditory warning signals for HT IVBSS applications. This table and the subsequent discussion are adapted from Campbell et al. (2006).

Table 17. Auditory Warning Signal Specification Design Guidance

- Use simple tones and auditory icons when an immediate response is required.
- Carefully designed and selected auditory icons can be more effective than conventional, urgent-sounding simple tones. Commonly-considered auditory icons include: brake squeal (FCW), prolonged horn honk (LCW), and rumble strip sound (LDW).
- The amplitude of an auditory ICAW signal should be in the range of 10-30 dB above the masked threshold; however, the signal should not exceed an absolute maximum of 90 dBA.
- Automatic adaptive control of auditory signal intensity, taking into account current ambient noise level, is recommended.
- When possible, any in-vehicle system or device that introduces conflicting auditory signals into the vehicle should be reduced in volume—and ideally should be muted—during the presentation of an auditory warning.

Auditory icons (tire skidding for FCW and long horn honk for LCW) were found to elicit better collision avoidance performance by commercial drivers in a HT driving simulator than conventional, urgent-sounding simple tone displays. The meaning of the auditory icon was recognized by almost all drivers (93%), whereas the meaning of the conventional auditory warning was recognized no better than chance (Belz et al., 1999).

The sources reviewed generally agree that auditory warnings should be distinctive, be used in high priority situations, and be reserved for use in ICAWs only. Auditory warnings should also convey the high level of urgency associated with an imminent crash. In addition, they should capture the driver's attention to increase awareness of a potential crash threat or of necessary visual information. However, auditory warnings should not startle or annoy the driver (e.g., Campbell et al., 2002; König & Mutschler, 2002). To improve distinctiveness and conspicuity, some sources recommend that continuous pure tones should be avoided and that tones should be intermittent with short intervals. Temporal attributes of effective tones include intermittent patterns of pulses with various fixed widths, pulses with widths that vary with time, and tones with frequencies that increase or decrease with time (e.g., warbling sounds) (Campbell, et al., 2002; König & Mutschler, 2002; Lee et al., 2004; Kiefer et al., 1999).

The 1996 COMSIS Guidelines recommend that the warning intensity should be at least 20 dB and no more than 30 dB above the masked threshold (MT). The masked threshold of a sound represents the intensity level at which a sound presented among masking "background" noises first becomes audible to a listener, after accounting for sound aspects such as pitch and harmonics, etc. Current sources indicate that drivers can discern auditory warnings at a level of less than 20 dB above the MT. Several sources suggest that the minimum intensity of auditory

ICAWs should be 10–15 dB above MT in order for the warning to be detectable (Campbell et al., 2002; König & Mutschler, 2002; MIL-STD-1472F, 1998). However, Lee et al. (2004) agree with the lower limit of 20 dB above MT recommended in the COMSIS (1996) Guidelines. Most sources agree that the amplitude of auditory signals for ICAWs should not exceed the MT by more than 30 dB and that the maximum amplitude of the warning should be limited to 90 dB. Note that muting of any in-vehicle systems that generate competing auditory information or noise (e.g., stereo system and fan) may also be appropriate (Kiefer et al., 1999).

Current sources indicate that drivers can discern auditory warnings at a level of less than 20 dB above the masked threshold (MT). Several sources suggest that the minimum intensity of auditory ICAWs should be 10–15 dB above MT in order for the warning to be detectable (Campbell et al., 2002; König & Mutschler, 2002; MIL-STD-1472F, 1998). However, Lee et al. (2004) and COMSIS (1996) agree with the lower limit of 20 dB above MT. Most sources agree that the amplitude of auditory signals for ICAWs should not exceed the MT by more than 30 dB and that the maximum amplitude of the warning should be limited to 90 dB. Note that muting of any in-vehicle systems that generate competing auditory information or noise (e.g., stereo system and fan) may also be appropriate (Kiefer et al., 1999).

3.6.2 Visual Warning Signal Specification

Visual signals include a wide range of visual display characteristics, which are addressed comprehensively by Campbell et al., (2002). Table 18 provides design guidance that specifically addresses IVBSS visual warning characteristics.

Visual symbols and icons appear to be effective as both ICAWs and CCAWs, provided that the alerting display is sufficiently conspicuous. For example, in one study, a low-conspicuity ICAW that was identical to the CCAW (except that it flashed at 4 Hz), was less effective than the same stimulus presented as a single-stage ICAW-only alert. In contrast, ICAW and CCAW icon displays were used effectively in another system that clearly differentiated the icon displays in terms of color, size, and form (General Motors, 2002).

Discrete displays (e.g. simple LEDs) that lack symbolic content also can be used effectively as CCAWs. While no performance data are readily available on the effectiveness of these displays, they have been implemented in CCAW-like LCW displays for HTs (Eaton, 2006). Note, however, that there is currently insufficient data available to evaluate the effectiveness of discrete displays for ICAWs.

Table 18. Visual Warning Signal Characteristics Design Guidance

- Visual ICAWs should be accompanied by an auditory or haptic warning.
- Visual ICAW attention-capturing properties should be maximized by having it appear abruptly within the relevant field-of-view and possibly by making it flash at a rate of 4 Hz.
- Primarily red visual ICAWs and primarily yellow/amber visual CCAWs are most consistent with drivers' stereotypes of warning levels, however other considerations about warning conspicuity may necessitate using a different color.
- Visual ICAWs should be visually distinct and more salient than the corresponding CCAW, if a CCAW is also implemented.
- Visual CCAWs should appear abruptly (include a luminance change component) so that it is noticeable to the driver.
- Visual CCAWs should be presented as a steady indicator (not flashing).
- Visual CCAWs may present analog, discrete, or symbol displays, provided that they are clearly distinguishable from ICAW displays and do not add distracting visual clutter to the overall display.

Visual ICAWs, should be accompanied by a simultaneous auditory or haptic ICAW signal. The visual ICAW should provide redundant and complementary information about the nature of the warning either directly through its associated visual icon/symbol or indirectly through the context (e.g., indicator on side-view mirror if intent to change lanes is detected). This is particularly important if the auditory signal is non-specific/non-descriptive (e.g., the Collision-Avoidance Metric Partnership (CAMP) warning sound), if there are multiple warning systems that may not be intuitively distinguishable, or if ICAWs are infrequently encountered. In these cases, the visual warning can provide specific information about the nature of the hazard (König & Mutschler, 2002). Existing icon design guidelines provide a good reference for developing and testing visual icons that are intuitive, meaningful, and simple (Campbell et al., 2002).

Drivers typically have inherent color stereotypes for different levels of warning urgency (Braun, Sansing, Kennedy, & Silver, 1994). The color red is usually associated with critical, high priority information (e.g., danger), and it is appropriate for use as part of a visual ICAW. The color yellow is typically associated with "caution" type messages. Note that there is some debate regarding whether the color orange represents "danger" or something less critical, such as "warning" or "caution" (Leonard, 1999). To reduce potential ambiguity, and to maximize perceived color distinctiveness, yellow should be used to indicate a discrete CCAW visual warning. The color green should not be used as a CCAW because it is associated with safe or normal operating conditions (Reference 2).

Considerations about warning conspicuity may override standard color choice. Red is best for communicating danger, however, red icons are also used in instrument panel indicators (e.g., emergency brake and seat belt icons) that drivers see frequently. If the visual warning is displayed in close proximity and is similar enough in size and shape that it can be confused with these non-warning icons, then an alternative color (e.g., yellow/amber) may be more appropriate (Kiefer et al., 1999). This could potentially lead to confusion between the ICAW and a yellow

CCAW, and possibly to inappropriate responses (e.g., drivers braking hard because they think the CCAW is actually an ICAW). Although how to address this issue is unresolved, potential approaches to this problem include changing the color set, making ICAWs and CCAWs more discriminable in terms of their other visual characteristics, or eliminating the CCAW altogether.

3.6.3 Haptic Signal Specification

It is important to recognize that haptic warnings are **not** recommended for the IVBSS HT DVI, unless it is determined that an auditory warning is likely to be ineffective. Table 19 (adapted from Campbell et al., 2006) identifies haptic warning characteristics that are associated with the best performance (from among alternative haptic signals) for each indicated IVBSS HT CAS. The discussion following Table 19 (also adapted from Campbell et al., 2006) provides the basis for these recommendations.

Table 19. Haptic Warning Signal Characteristics Design Guidance

Display	System	Guideline
Brake Pulse	FCW	Use three 0.160 sec pulses (separated by 0.100 sec) that yield a 3 g/s jerk with a total deceleration of -0.3 g.
Steering Wheel Torque	LCW	Use a single triangle wave at 2.0 Nm of torque with a half-period 0.5 sec. The torque should be applied in the direction needed for recovery.
Steering Wheel Torque	LDW	Use a single triangle wave at 2.0 Nm of torque with a half-period 0.5 sec. The torque should be applied in the direction needed for recovery.
Steering Wheel Vibration	LCW LDW	Steering wheel vibration parameters in following ranges will yield equivalent performance: Frequency 4-12 Hz; Amplitude 1.2-2.2 Nm; Duration 1.2-2.2 sec. Note: Although some evidence suggests that this display may work, it is not the recommended display for time-critical situations.

For FCW systems, the recommendations come from a recent study on intersection collision avoidance systems (ICASs), which evaluated a variety of brake-pulse warning parameters (Lee et al., 2005). The recommended pulse warnings yielded the best performance in terms of compliance and short braking distance. While these recommended values are in agreement with some brake-pulse guidelines (Campbell et al., 1997), earlier parametric studies recommend using a brake pulse with different characteristics—e.g., 0.600 second 0.32 g mono-pulse (Tijerina, Johnston, Parmer, Pham and Winterbottom, 2000). The data from the intersection collision avoidance study were selected for the current guideline recommendations because that study also evaluated the effectiveness of the alternative 0.600 second mono-pulse signal and found that it yielded significantly worse performance in terms of driver compliance and brake distance.

For LCW and Road Departure Warning (RDW) systems, there have not been any direct comparisons of haptic warning signals with different characteristics. However, for both systems, haptic warnings comparable to the recommended signal characteristics were effective in prompting appropriate corrective actions in RDW systems (Tijerina et al., 1996) and in prompting drivers to quickly and consistently cancel unsafe lane changes (Farber, Naab & Schumann, 1991; Schumann, Godthelp, Farber and Wontorra, 1993).

With regard to warnings based on steering wheel vibrations, one parametric study with a small sample size found that performance was basically the same for steering wheel vibrations indicated in the guideline recommendation. Note however, that although steering wheel vibrations have been shown to provide some response time advantages under conditions requiring minor steering corrections, they seem to be ineffective when more time-critical responses are required (Tijerina et al., 1996). Also, it should be noted that 1.2 Nm of amplitude likely represents a minimum acceptable value, because other FCW research involving smaller forces found that a 1.0 Nm amplitude was too weak to capture the driver's attention (Schumann et al., 1993).

One caution that should be considered when designing CAS warnings is to ensure that they cannot be misconstrued as system malfunctions or some other vehicle-related or environment-related problem. In particular, a haptic brake pulse warning was misconstrued by at least three of 20 commercial drivers in a closed-track HT study (Shutko, 2001). One participant in that study indicated that the brake pulse led him to interpret the warning as a vehicle malfunction, which caused him to look at the instrumentation instead of the roadway and to depress the accelerator rather than braking (thinking that it was a fuel line blockage).

3.7 Warning Adjustments and False Alarms

Warning adjustments include five IVBSS HT CAS functions that have been identified in both empirical studies and design guideline documents. Table 10 (modified from Campbell et al, 2006) provides recommendations for these adjustments based on the results of empirical studies, discussions and recommendations in guideline documents, and expert judgment. The recommendation column in Table 11 reflects available empirical data, guidelines, and expert input. The third and fourth columns identify control types that may be used for each CAS function. A dash in the third or fourth column of the table indicates that no data were found to either support or reject the use of this control type for the corresponding CAS function. The following discussion of warning adjustments is adapted from Campbell et al. (2006).

The On/Off recommendation in Table 20 reflects the unique position of commercial vehicle operations. Specifically, it is likely that these systems will provide fleet owners with reduced insurance rates and/or operational costs. Therefore, it is expected that HT drivers will not be given the option of disabling any IVBSS HT CAS capability.

Almost all sources recommend that controls be provided for adjusting both auditory warning intensity and visual warning display luminance. However, there are two approaches that may be particularly appealing to commercial applications. One source recommends that alarms should not be adjustable or defeatable, but that other auditory display systems (e.g., radio, navigation system) should not be capable of producing uncontrollable volume levels that mask interior or exterior alarms (Japan Automobile Manufacturers Association, 2004). A second source recommends that sensing devices monitor the ambient noise level in the HT cab and adjust the auditory level to match an established difference threshold.

Table 20. Warning Adjustment Design Guidance

IVBSS CAS Function	Recommendation	Use Discrete Control	Use Continuous Control
On/Off Enables and disables the CAS.	Not Recommended	—	—
Auditory Intensity Controls the intensity of the auditory warning display.	Highly Recommended	—	Yes Gross Adjustment
Master Intensity Master control for intensity of all (i.e., visual, auditory, and haptic) displays.	Recommended	—	Yes Gross Adjustment
Visual Display Luminance Controls the intensity of the visual warning display.	Highly Recommended	—	Yes Gross Adjustment
Sensitivity (Warning Timing, Warning Threshold, Range, Time-to-Collision) Controls the physical or temporal proximity threshold for which warnings are activated.	Recommended	Yes Multi-Position	Yes Precise Adjustment

Headway/Time-to-Collision (TTC) and sensitivity controls generally determine some threshold at which the warning display is activated. In order to accommodate personal driving styles and prevailing driving conditions, drivers may prefer to adjust the headway/TTC settings. Likewise, drivers might prefer to adjust the sensitivity to reduce the occurrence of false and nuisance alarms. The risk involved in providing these adjustments is that drivers may inappropriately adjust the controls to settings that reduce or eliminate the effectiveness of the CAS (i.e., alerts are presented too late to effectively warn the driver of an imminent collision) (Campbell et al., 1996). Nonetheless, these adjustments have been successfully implemented in empirical passenger vehicle studies. In FOTs of passenger vehicle FCW systems, drivers used the full range of these adjustments (six discrete values each for headway and warning timing). In addition, drivers tended to adjust the sensitivity to settings that produced fairly early presentation of cautionary warnings, even though the “later” setting would completely suppress the cautionary warnings (General Motors Corporation, 2005). An alternative to this approach would call for driver-specific thresholds that are determined by the CAS on the basis of driving performance (Dingus et al., 2006).

The majority of recent studies and discussion about CAS control has focused on what controls to provide. Recommendations for discrete versus continuous controls reflect more traditional human factors design principles and are based on the type of adjustment required for a particular function. Controls for CASs can be categorized into two classes: discrete controls and continuous controls. Some CAS controls (e.g., on/off) require discrete controls (controls that provide distinctive, individual values), while others are more suited for implementation with continuous controls (controls that provide a continuous range of values). Many CAS controls, however, may be implemented using either class of control. For example, Kiefer et al. (1999) recommend that warning timing should be adjusted with a rotary control, slide, or thumbwheel control that is either discrete or continuous. The designer must determine which class of control will most benefit the driver while best fitting the overall vehicle control strategy.

Research Issues

Table 11 provides a summary of IVBSS HT design issues identified on the basis of the current literature review and preliminary discussions with other members of the IVBSS UMTRI team. The identified design issues represent questions that are not adequately addressed by available empirical data or design expertise.

It is recommended that the identified design issues be reviewed and prioritized by UMTRI team members. Following prioritization of the design issues, separate research activities and phases could be identified by grouping high-priority Design Issues that fall under each Research Setting that has been identified -- Expert panel review, Expert panel survey input, Limited naturalistic driving study, low-fidelity simulation, high-fidelity simulation, modeling, and early on-road pilot testing.

Table 11. Summary of Identified Design Issues and Suggested Research Approaches

Design Issues	Research Approach		
	Independent Variables	**Dependent Variables**	**Research Setting**
Inclusion of a third advisory warning or informational display level in the FCW	ICAW timing threshold CCAW timing threshold Presence/timing of advisory warning Content of informational display	Braking response latency Headway distance User acceptance ratings	Early expert panel review High fidelity simulation study to establish display options and timing boundaries Early on-road pilot testing to select preferred option
Use of auditory warning to augment visual LCW CCAW	Presence/absence of auditory LCW CCAW to signal occupied lane FA rate	Percent of lane change/ merge maneuvers involving side mirror use Lane change/merge crash outcomes User acceptance ratings	Limited naturalistic driving study to obtain preliminary estimates of side mirror use Early on-road pilot testing select preferred option
Use of auditory warning to augment visual LDW CCAW	Presence/absence of auditory LDW CCAW to signal erratic lane keeping[3] CCAW criteria: past performance and/or predicted lane excursion	Lane excursion rate User acceptance ratings	Early on-road pilot testing to select preferred option
Warning priorities for integration	Expert panel source (safety research, fleet operations, drivers)	Warning ratings	Expert panel input adapted from ISO 16951 format
ICAW priority implementation	Simultaneous ICAW scenario ICAW attenuation, delay, or over-ride	Scenario-specific driving response User acceptance ratings	Early expert panel review Low-fidelity simulation study to establish display options and timing boundaries

[3] Because it is anticipated that the Always Alert system will include a continuous information display as a component of the LDW system, it is expected that this will not be included as an independent variable.

Design Issues	Research Approach		
	Independent Variables	**Dependent Variables**	**Research Setting**
Auditory ICAW signal characteristics	Iconic versus tone ICAWs	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics
Minimization of FCW FA rates	Algorithm parameters – headway threshold?	Mean glance time away from roadway Mean perception-response time Braking force profile Hit, Miss, FA rates	Limited naturalistic driving study to obtain preliminary estimates of driving behavior Modeling to estimate FA rates
FCW ICAW FA rates	FCW ICAW FA rates	Braking response latency Headway distance User acceptance ratings	Early expert panel review High fidelity simulation study to establish FA rate options Early on-road pilot testing to select preferred option
Minimization of LCW FA rates	Algorithm parameters – radar sensitivity threshold?	Mean glance time to side-view mirrors Mean turn signal onset prior to lane change initiation	Limited naturalistic driving study to obtain preliminary estimates of driving behavior Modeling to estimate FA rates
LCM ICAW FA rates	LCM ICAW FA rates	Lane change/merge crash outcomes User acceptance ratings	Early expert panel review High fidelity simulation study to establish FA rate options Early on-road pilot testing to select preferred option
Minimization of LDW FA rates	Algorithm parameters/ threshold for predicting lane excursion	Center-lane deviation variance Steering wheel lateral movement variance	Limited naturalistic driving study to obtain preliminary estimates of driving behavior Modeling to estimate FA rates
LDW FA rates	LDW ICAW FA rates	Center-lane deviation variance Lane excursions User acceptance ratings	Early expert panel review High fidelity simulation study to establish FA rate options Early on-road pilot testing to select preferred option
FCW active braking	Presence/absence of active braking Brake pulse timing Braking force	Braking response latency Headway distance User acceptance ratings	Early expert panel review Simulation study to establish display options and timing boundaries Early on-road pilot testing to select preferred option

Design Issues	Research Approach		
	Independent Variables	**Dependent Variables**	**Research Setting**
Auditory warning dB levels	Set warning dB level Muting of other systems Adaptive dB difference level	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics
CAS adjustment levels: Master level adjustment range	Master level adjustment range	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics
CAS adjustment levels: Auditory level adjustment range	Auditory level adjustment range	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics
CAS adjustment levels: Visual display luminance range	Visual display luminance range	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics
CAS adjustment levels: Sensitivity adjustment range	Sensitivity adjustment range	CAS recognition Response latency Driving response consistency User acceptance ratings	Expert panel and pilot studies to select best auditory and tone sets Low-fidelity simulation study to select ICAW characteristics

References

NOTE: References noted with an asterisk are core IVBSS HT DVI sources (those dealing specifically with: (1) CAS HV DVI issues; (2) the integration of FCW, LCW, and/or LDW systems; or (3) noteworthy aspects of HV characteristics or operations have a completed document review form in Appendix A.

* Ashley, L., Dunn, A., and Hoover, R. (2004). *Class 8 Truck Tractor Braking Performance Improvement Study, Report 1, Straight Line Stopping Performance on a High Coefficient of Friction Surface* (DOT HS 809 700). Washington, DC: Department of Transportation.

AssistWare (2006). *SafeTRAC Lane Tracker* (Product Description Information). Retrieved on March 13, 2006 from www.assistware.com

Battelle. (2004). *Phase II Driver Survey Report: Volvo Intelligent Vehicle Initiative Field Operational Test*. Columbus, OH: Author.

* Belz, S.M., Robinson, G.S., and Casali, J.G. (1999). A New Class of Auditory Warning Signals for Complex Systems: Auditory Icons. *Human Factors, 41*(4), 608-618.

Blower, D. (1998). *The Relative Contribution of Truck Drivers and Passenger Vehicle Drivers to Truck-Passenger Vehicle Traffic Crashes*. Ann Arbor, Michigan: University of Michigan, Transportation Research Institute.

Braun, C.C., Sansing, L., Kennedy, R.S. and Silver, N.C. (1994). Signal word and color specification for product warnings: An isoperformance application. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting*, 1104-1108.

Campbell, J.L., Bittner, A.C., Jr., Lloyd, M., Mitchell, E., and Everson, J.H. (1997). *Driver-vehicle interface (DVI) design guidelines for the intersection collision avoidance (ICA) system* (*Final Report)*. Seattle, WA: Battelle Human Factors Transportation Center.

Campbell, J.L., Carney, C., and Kantowitz, B.H. (1998). *Human factors design guidelines for advanced traveler information systems (ATIS) and commercial vehicle operations (CVO)* (FHWA-RD-98-057). Washington, DC: Federal Highway Administration.

Campbell, J.L., Hooey, B.H., Carney, C., Hanowski, R.J., Gore, B.F., Kantowitz, B.H., et al. (1996). *Investigation of alternative displays for side collision avoidance systems* (Final Report). Seattle, WA: Battelle Seattle Research Center

Campbell, J., Richard, C., Brown, J., and McCallum, M. (2006). *Human Factors Guidelines for Collision Avoidance Warning Systems (Draft)*. Seattle, WA: Battelle Center for Human Performance and Safety.

Campbell, J.L., Richman, J.B., Carney, C., and Lee, J.D. (2002). *In-vehicle display icons and other information elements. Task F: Final in-vehicle symbol guidelines* (FHWA-RD-03-065). Washington, DC: Federal Highway Administration.

* Chiang, D., Brooks, A., and Llaneras, E. (2004). *Final Task Report: Investigation of Multiple Collision Alarm Interference Driving Simulator Study* (Report for the National Highway Safety Administration). Torrance, CA: Dynamic Research, Inc.

COMSIS Corporation. (1996). *Preliminary human factors guidelines for crash avoidance warning devices* (NHTSA Project No. DTNH22-91-07004). Silver Spring, MD: COMSIS.

* Crum, M.R., Morrow, P.C., Olsgard, P., and Roke, P.J. (2001). Truck driving environments and their influence on driver fatigue and crash rates. T*ransportation Research Record, 1779*, 125-133.

Dick, V., Murray, D., and Houser, A. (2006). A synthesis of commercial motor vehicle safety technology surveys: What have we learned? [CD ROM]. *Transportation Research Board 2006 Annual Meeting*.

* Dinges, D., Maislin, G., Krueger, G., Brewster, R., and Carroll, R. (2005). *Pilot Test of Fatigue Management Technologies* (RN-FMCSA-RT-05-002). Washington DC: Federal Motor Carrier Safety Administration.

Dingus, T., Klauer, S., Neale, V., Petersen, A., Lee, S., Suidweeks, J., et al. (2006). *The 100-Car Naturalistic Driving Study, Phase II – Results of the 100-Car Field Experiment.* Washington, DC: National Highway Traffic Safety Administration.

Eaton. (2006). *VORAD Collision Warning System* (Product Descriptions). Retrieved March 2006 from www.vorad.com

Eaton. (2005). *VORAD Driver Instructions* (VORAD-0035). Retrieved February 2005 from www.vorad.com

Eaton. (2004). Roadranger Driver Instructions (VODR-0030). Retrieved February 17, 2006 from www.roadranger.com

Ericson, M.A., Bolia, R.S. and Nelson, W.T. (1999). Operational constraints on the utility of virtual audio cueing. *Proceedings of the Human Factors and Ergonomics Society 43rd Annual Meeting*, 1206-1209.

Farber, B., Naab, K., and Schumann, J. (1991). *Evaluation of prototype implementation in terms of handling aspects of driving tasks* (Deliverable Report DRIVE V1041/GIDS CON3). Haren, The Netherlands: Traffic Research Institute, University of Groningen.

Federal Motor Carrier Safety Administration. (March 2006). *Report to Congress on the Large Truck Crash Causation Study*. Washington, DC: Author.

General Motors Corporation and Delphi-Delco Electronic Systems. (2002). *Automotive collision avoidance system field operation test, warning cue implementation summary report* (DOT HS 809 462). Washington, DC: National Highway Traffic Safety Administration.

General Motors Corporation. (2005). *Automotive Collision Avoidance System Field Operational Test (ACAS FOT) Final Program Report* (DOT HS 809 886). Washington, DC: National Highway Traffic Safety Administration.

Harkey, D., Council, F., and Zegeer C. (1996). Operational Characteristics of Longer Combination Vehicles and Related Geometric Design Issues. *Transportation Research Record, 1523*, 22-28.

* Harwood, D.W., Potts, I.B., Torbic, D.J., and Glauz, W.D. (2003). *Highway/Heavy Vehicle Interaction*. (Commercial Truck and Bus Safety Synthesis Program CTBSSP-SYN-3); ISBN-0-309-08756-2. Washington, DC: Transportation Research Board.

Harwood, D.W., Torbic, D.J., Richard, K.R., Glauz, W.D., and Elefteriadou, L. (2003). *NCHRP Report 505: Truck Characteristics as Factors in Roadway Design*. Washington, DC: Transportation Research Board of the National Academies.

* Houser, A., Pierowicz, J., and Fuglewicz, D. (2005). *Concept of Operations and Voluntary Operational Requirements for Lane Departure Warning System (LDWS) On-board Commercial Motor Vehicle*. Washington, DC: Federal Motor Carrier Safety Administration.

* Houser, A., Pierowicz, J., and McClellan, R. (2005). *Concept of Operations and Voluntary Operational Requirements for Automated Cruise Control/Collision Warning System (ACC/CWS) On-board Commercial Motor Vehicles*. Washington, DC: Federal Motor Carrier Safety Administration.

* ISO 16951. (2004). *Road vehicles – Ergonomic aspects of transport information and control systems (TICS) – Procedures for determining priority of on-board messages presented to drivers*. Geneva: International Organization for Standardization (ISO).

Japan Automobile Manufacturers Association (JAMA). (2004). *JAMA guidelines for in-vehicle display systems—version 3.0*. Tokyo: Author.

* Jiang, Z., Streit, D., and El-Gindy, M. (2001). Heavy vehicle ride comfort: Literature review. Heavy Vehicle Systems. *International Journal of Vehicle Design, 8*(3/4), 258-284.

Kiefer, R., LeBlanc, D., Palmer, M. Salinger, J., Deering, R. and Shulman, M. (1999). *Development and Validation of Functional Definitions and Evaluation Procedures for Collision Warning/Avoidance Systems* (Final Report DOT HT 808 964). Washington, DC: National Highway Traffic Safety Administration.

* Kiger, S., Rockwell, R., Niswonger, S., Tijerina, L., Myers, L., and Nygren, T. (1992). *Heavy Vehicle Driver Workload Assessment. Task 3: Task Analysis Data Collection*. (DOT HS 808 467 (3)). Washington DC: National Highway Traffic Safety Administration.

Knipling, R.R., Hickman, J.S., Bergoffen, G. (2003). *Effective Commercial Truck and Bus Safety Management Techniques.* (Commercial Truck and Safety Synthesis Program RN- CTBSSP-SYN-1; ISBN-0-309-08754-6). Washington, DC: Transportation Research Board.

König, W. and Mutschler, H. (2002). *MMI of warning systems in vehicles.* (Technical Report, Draft, Reference No. ISO/TC22/SC13/WG8). International Organization for Standardization (ISO).

Lee, S.E., Knipling, R.R., DeHart, M.C., Perez, M.A., Holbrook, G.T., Brown, S.B., et al. (2004). *Vehicle-Based Countermeasures for Signal and Stop Sign Violations: Task 1. Intersection Control Violation Crash Analyses, Task 2. Top-Level system and Human Factors Requirements* (DOT HS 809 716). Washington, DC: National Highway Traffic Safety Administration.

Lee, S.E., Perez, M.A., Doerzaph, Z.R., Brown, S.B., Stone, S.R., Neale, V.L., et al. (2005). *Intersection collision Avoidance – Violation Project: Final Project Report* [Draft Final Task 5 Report DTNH22-00-C-07007]. Washington, DC: National highway Traffic Safety Administration.

Leonard, S.D. (1999). Does color of warning affect risk perception? *International Journal of Industrial Ergonomics, 23*, 499-504.

* Mazzae, E. and Garrott, W. (1995). *Human Performance Evaluation Heavy Truck Side Object Detection Systems* (SAE Technical Paper Series No. 951011). Warrendale, PA: Society of Automotive Engineers.

MIL-STD-1472F. (1998). *Human engineering*. Washington, DC: Department of Defense.

National Highway Traffic Safety Administration. (2004). *Traffic Safety Facts 2004: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System.* Washington, DC: Author.

NHTSA FMVSS Air brake systems, 49 C.F.R. § 571.121 (2003).

NHTSA FMVSS Light vehicle brake systems, 49 C.F.R. § 571.135 (2003).

Richard, C., Campbell, J., and Brown, J. (2005). *Human Factors Guidelines for Collision Avoidance Systems. Task 1: Literature and Technology Review/ Assess Current State of Knowledge and Lessons Learned (Draft)*. Seattle, WA: Battelle Center for Human Performance and Safety.

* Robinson, G., Casali, J., and Lee, S. (1997). *The Role of Hearing in Commercial Motor Vehicle Operation: An Evaluation of the FHWA Hearing Requirement. Final Report*. Blacksburg, VA: Auditory Systems Laboratory, Virginia Polytechnic Institute and State University.

Schumann, J., Godthelp, H., Farber, B., and Wontorra, H. (1993). Breaking up open-loop support for the driver's lateral control task. In A. G. Gale et al. (Eds.) *Vision in Vehicles IV* (pp. 321-332). London: Taylor and Francis.

* Shutko, J. (2001). *An investigation of collision avoidance warnings on brake response times of commercial motor vehicle drivers*. Unpublished master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

* Staplin, L., Lococo, K.H., Decina, L.E., and Bergoffen, G. (2004). *Training of Commercial Motor Vehicle Drivers*. Washington DC: Transportation Research Board.

Talmadge, S., Chu, R., Eberhard, C., Jordan, K., and Moffa, P. (2000*). Development of Performance Specifications for Collision Avoidance Systems for Lane Change Crashes* (DOT HS 809 414). Washington, DC: National Highway Traffic Safety Administration.

Tan, A.K. and Lerner, N.D. (1996). *Acoustic Localization of In-Vehicle Crash Avoidance Warnings as a Cue to Hazard Direction* (DOT HS 808 534). Washington, DC: National Highway Traffic Safety Administration.

Tijerina, L. Jackson, J., Pomerleau, D., Romano, R., and Petersen, A. (1996). Driving simulator tests of lane departure collision avoidance systems. *Proceedings of ITS America Sixth Annual Meeting, Houston, TX.*

Tijerina, L., Johnston, S., Parmer, E., Pham, H.A., and Winterbottom, M.D. (2000). *Preliminary studies in haptic displays for rear-end collision avoidance system and adaptive cruise control system applications* (DOT HS 808(TBD)). Washington, DC: National Highway Traffic Safety Administration.

* Tijerina, L., Kiger, S., Rockwell, T., and Wierwille, W. (1995). *Heavy Vehicle Driver Workload Assessment. Task 5: Workload Assessment Protocol* (DOT HS 808 467 (5)). Washington DC: National Highway Traffic Safety Administration.

* Tijerina, L., Kiger, S., Rockwell, T., Tornow, C., Kinateder, J., and Kokkotos, F. (1995). *Heavy Vehicle Driver Workload Assessment. Task 6: Baseline Data Study* (DOT HS 808 467 (6)). Washington DC: National Highway Traffic Safety Administration.

Transports Quebec. (2006). *Heavy vehicle blind spots, collision danger zones*. Accessed on April 6, 2006 at http://www.mtq.gouv.qc.ca/en/camionnage/lourds/campagne/index.asp.

* Turanski, A. and Tijerina, L. (1992). H*eavy Vehicle Driver Workload Assessment. Task 2: Standard Vehicle Configuration/Specifications* (DOT HS 808 467 (2)). Washington DC: National Highway Traffic Safety Administration.

Wilson, T., Miller, S., Burns, M., Chase, C., Taylor, D., Butler, W., et al. (1998). *Light vehicle forward-looking, rear-end collision warning system performance guidelines* (DOT HS 808 948).Washington, DC: National Highway Traffic Safety Administration.

Appendix A: Completed Document Review Forms for Core IVBSS HT References

Completed document review forms are provided in this appendix for core IVBSS HT DVI sources, which are those dealing specifically with: (1) CAS HV DVI issues; (2) the integration of FCW, LCW, and/or LDW systems; or (3) noteworthy aspects of HV characteristics or operations.

Document:
Ashley, L., Dunn, A., and Hoover, R. (2004). *Class 8 Truck Tractor Braking Performance Improvement Study, Report 1, Straight Line Stopping Performance on a High Coefficient of Friction Surface* (DOT HS 809 700). Washington, DC: Department of Transportation

Source type:	Method/Study Type:	Relevance for IVBSS HV:
Empirical Study	Closed Track Braking Performance	HT Operations

General Approach:
Four configurations of pneumatic foundation brakes were evaluated and compared for high-speed stopping performance on two Class-8 6X4 truck tractors to assess the feasibility of reducing FMVSS No. 121 stopping standards by 30 percent.

Methods:
Independent variables
BRAKE CONFIGURATIONS:
1. Standard S-cam drums on steer and drive axles
2. Hybrid drum: larger capacity S-cam drums on steer, standard S-cam drums on drive axles
3. Hybrid disc: air disc brakes on steer, standard S-cam drums on drive axles
4. Air disc brakes on steer and drive axles

TRACTOR: 1996 Peterbuilt 377 and a 1991 Volvo WIA64T

Dependent variables
STOPPING DISTANCE

Quality: High	This is an engineering study that provides a comprehensive consideration of the effect of brake configurations on stopping distance for GVWR (full) and LLVW (light) loads.
Applicability: Medium	Directly applicable to HT characteristics.
Relative Impact: Medium	The study demonstrates the current stopping distances of trucks on dry pavement.

Key Findings and Recommendations:
- Compared to a possible 30% reduction in current FMVSS No. 121 standards at LLVW, margins of compliance for the minimum stopping distance (of six stops) at the LLVW load exceeded 10% for all non-standard brake configurations. Margins of compliance for the “hybrid-disc” and “all-disc” configurations exceeded 20% for both tractors at LLVW. Only one tractor-brake configuration (all disc) had a margin of compliance that exceeded 10%. Other brake configurations tested at GVWR had low or nonexistent margins of compliance for the considered reduced standard.

- Significant differences in mean stopping distances were obtained for all foundation brake configurations. Combining results for both tractors tested, an “all disc brake” configuration could yield a 20% improvement in stopping distance at GVWR over standard “all S-cam” brakes, and a 16% improvement at LLVW. With the hybrid disc brakes, the improvements were 12% and 19% for GVWR and LLVW, respectively. For the hybrid drum brakes, the improvements were 10% for both GVWR and LLVW.

Key Graphics: Fig. 8, p.22 Mean Stopping Distance for Combined Tractors with GVWR Load Configuration. (Shows better performance than 355 ft standard for all cases, but only one configuration meeting the 30% reduction standard of 249 ft.)

Caveats/Comments:
- The study highlights the reduced reliability in measuring the minimum of six stopping distances for the standard, versus using the mean stopping distance for a series of stops.
- The authors noted that further refinement of the control and actuation systems might result in both hybrid braking systems being able to achieve the target 30% improvement in stopping distance.

<table>
<tr><td colspan="3">Document:
Belz, S.M., Robinson, G.S., and Casali, J.G. (1999). A New Class of Auditory Warning Signals for Complex Systems: Auditory Icons. Human Factors, 41(4), 608-618.</td></tr>
<tr><td>Source type:
Empirical Study</td><td>Method/Study Type:
HT Simulator Study</td><td>Relevance for IVBSS HV:
<HV CAS/Integration/HF Ops></td></tr>
<tr><td colspan="3">General Approach:
24 male commercial truck drivers (aged 19 to 51) drove in a driving simulator modified to reproduce the acoustical and driving characteristics of a commercial truck. Drivers were presented conventional auditory warnings (multi-tone signal) and auditory icons (tire skid for FCW, long horn honk for SCW) alone and in combination with a dash mounted visual display (flashing icon) to warn of impending forward and side collisions.</td></tr>
<tr><td colspan="3">Methods:
Forward collision variables:
Independent variables
- DISPLAY PRESENTATION MODE (no display, visual display only, auditory icon only, conventional auditory warning only, auditory icon + visual display, conventional auditory + visual display): Wi/Ss
- VEHICLE SPEED (35 mph, 55 mph): Wi/Ss
- VEHICLE HEADWAY (2.5 sec., 3.5 sec.): Wi/Ss
Dependent variables
- INITIAL RESPONSE TIME, BRAKE RESPONSE TIME

Side collision variables:
Independent variables
- VISUAL DISPLAY (present, not present): Wi/Ss
- MIRRORS (present, not present): Wi/Ss
- AUDITORY DISPLAY (conventional, auditory icon): Wi/Ss
- VEHICLE SPEED (35 mph, 55 mph): Wi/Ss
Dependent variables
- OCCURANCE OF ACCIDENTS</td></tr>
<tr><td>Quality:
Medium</td><td colspan="2">While the methodology produced some statistically significant results, the results do not support clear guidance regarding use of mixed-modality displays vs. auditory icons alone.</td></tr>
<tr><td>Applicability:
High</td><td colspan="2">The findings directly apply to FCW and LCW systems using a HT simulator and licensed commercial drivers.</td></tr>
<tr><td>Relative Impact:
Medium</td><td colspan="2">The data are highly applicable to FCW and LCW systems; however, methodological limitations and difficult to-interpret results diminish the utility of the information provided.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
- Auditory icons (long horn honk) were found to be more effective than a conventional, urgent-sounding auditory warning (but not if presented in conjunction with a visual display).
- Additionally, a “tire skid” auditory icon also yielded effective driving performance as a single-modality display.
- The meaning of the auditory icon was recognized by almost all drivers, whereas, drivers recognized meaning of the conventional auditory warning no better than chance.
- Combined visual and auditory displays were generally more effective than visual- or auditory- only displays.</td></tr>
<tr><td colspan="3">Key Graphics: Fig 1 – pg 611</td></tr>
<tr><td colspan="3">Caveats/Comments:
- Each driver experienced a very high crash event rate (40 imminent-collision conditions in 60 scenarios) which could cause drivers to focus on the collision avoidance system rather than on driving.
- There is no control condition for the auditory display presentation
- Results are somewhat inconsistent concerning the effect of auditory alarms when added to visual displays.
- Results regarding the dash-mounted visual display may not be generalizable to other types of displays, given the unique visual display.</td></tr>
</table>

Document:
Crum, M.R., Morrow, P.C., Olsgard, P., and Roke, P.J. (2001). Truck driving environments and their influence on driver fatigue and crash rates. *Transportation Research Record, 1779*, 125-133.

Source type: Empirical Study	Method/Study Type: Survey	Relevance for IVBSS HV: HV Operations

General Approach:
502 commercial drivers were surveyed regarding operational factors hypothesized to be related to fatigue, reported indicators of fatigue, and reported and chargeable crashes.

Methods:
Independent variables
- 25 POSSIBLE INDICATORS OF ENVIRONMENTAL CHARACTERISTICS

Dependent variables
- 15 ITEMS RELATED TO FATIGUE AND CRASH BEHAVIOR

Quality: Medium	This is a good survey and correlational analysis providing useful descriptive information concerning driver environments and association with fatigue indicators.
Applicability: Medium	Directly applicable to understanding commercial vehicle operational conditions, which are tangentially related to IVBSS DVI design.
Relative Impact: Medium	See Applicability comment.

Key Findings and Recommendations:
REFINED MODEL OF DRIVING ENVIRONMENT FACTORS AND FATIGUE AND CRASH OUTCOMES
- CMV Driving Environments:
    - Regularity of Time
    - Trip Control
    - Quality of Rest
- Fatigue and Crash Outcomes
    - Frequency of Close Calls
    - Self and Other Perceptions of Fatigue
    - Crash Involvement

Individually significant correlations between driving environment indicators and one of more fatigue or crash outcomes were:
- Driving the same hours/Self and others Perception of Fatigue = -.10
- Number of driving "time zones" (6-hour periods)/Close Calles = -.11
- Regularity of Route/Self and others Perception of Fatigue = -.09
- Long Load Time/Close Calls = .12 and / Self and others Perception of Fatigue = .18
- Average Stops per Day/Crash Involvement = .10
- Uninterrupted Hours of Sleep/ Self and others Perception of Fatigue = -.09
- Start Workweek Tired/Close Calls = .18; /Fatigue Perception = .29; and /Crash Involvement = .09

Key Graphics: None

Caveats/Comments:
- The final set of regression models of environment factors and fatigue indicators were not remarkably large (even though reported *F* statistics were significant), with adjusted R^2 of .05 (Close Calls), .23 (Perception of Fatigue), and .02 (Crash Involvement).

- Greatest value is providing a reliable source of information regarding working schedules and conditions, in conjunction with poor rest/sleeping schedules/conditions, that likely lead to high levels of driver fatigue; which, in turn, argues for alertness monitoring capabilities.

<table>
<tr><td colspan="3">Document:
Dinges, D., Maislin, G., Krueger, G., Brewster, R., Carroll, R. (2005). Pilot Test of Fatigue Management Technologies (RN-FMCSA-RT-05-002). Washington DC: Federal Motor Carrier Safety Administration.</td></tr>
<tr><td>Source type:
Empirical Study</td><td>Method/Study Type:
On-road Study</td><td>Relevance for IVBSS HV:
HV CAS (LDW)</td></tr>
<tr><td colspan="3">General Approach:
Four technologies (sleep need, drowsiness, lane tracking monitoring, and vehicle stability aid) were provided to 38 Canadian and US commercial drivers, who drove for two weeks with no technology feedback followed by two with technology feedback.</td></tr>
<tr><td colspan="3">Methods:
Independent variables
- FEEDBACK: (feedback from each technology or no feedback)
- SleepWatch actigraphy “fuel gauge” activated or not
- CoPilot PERCLOS system “0-99” alertness indicator
- SafeTRAC lane tracker “0-99” lane tracking performance and auditory alert on unsignaled lane changes
- Howard Power Center Steering System (on or off)
Dependent variables
- TRUCK MOTION VARIABLES: speed, lateral acceleration
- Lane Tracking
- Eyelid Closure
- Actigraphy records
- Performance Vigilance Test score
- Human Factors Structured Interview Questionnaire</td></tr>
<tr><td>Quality:
Low</td><td colspan="2">This was a very well conducted field test, but has the limitations of any field test with bundled technologies – it’s impossible to attribute results to any one system.</td></tr>
<tr><td>Applicability:
Medium</td><td colspan="2">This provides one of the few field tests of an IVBSS HV system component.</td></tr>
<tr><td>Relative Impact:
Low</td><td colspan="2">Limited due to bundled technologies.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
IMPROVEMENT OF DRIVER ALERTNESS
- With the combined Canadian and US data, during night driving, feedback significantly reduced slow eyelid closures, increased SafeTRAC driver alertness estimates, and decreased lane tracking variability.

NO IMPROVEMENT IN DRIVER SLEEP TIME

DRIVERS GAVE HIGHER PREFERENCE RATINGS TO SAFETRAC, MEDIUM RATINGS TO SLEEPWATCH, AND LOW RATINGS TO COPILOT.</td></tr>
<tr><td colspan="3">Key Graphics: NA – it does provide photos of the technologies.</td></tr>
<tr><td colspan="3">Caveats/Comments:
- All four technologies were bundled and tested simultaneously, providing no controls for the effects of individual technologies.
- Canadian (n=27) driving was primarily daytime (74%) and US (n=12) driving was primarily nighttime (93%) under different regulatory hours of service rules.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Harwood, D.W., Potts, I.B., Torbic, D.J., and Glauz, W.D. (2003). Highway/Heavy Vehicle Interaction. (Commercial Truck and Bus Safety Synthesis Program CTBSSP-SYN-3); ISBN-0-309-08756-2. Washington, DC: Transportation Research Board.</td></tr>
<tr><td>Source type:
Analytical Study</td><td>Method/Study Type:
Literature Review and industry survey</td><td>Relevance for IVBSS HV:
HV Characteristics</td></tr>
<tr><td colspan="3">General Approach:
The synthesis addresses commercial truck and bus interactions with highway features based on a literature review and survey of highway agencies and the trucking industry.</td></tr>
<tr><td colspan="3">Methods:
NOT APPLICABLE</td></tr>
<tr><td>Quality:
Medium</td><td colspan="2">No original data and some expert opinion, but conclusions are generally supported by data.</td></tr>
<tr><td>Applicability:
Low</td><td colspan="2">This is only tangentially applicable to HV IVBSS DVI design, providing an overview of HT road handling characteristics.</td></tr>
<tr><td>Relative Impact:
Low</td><td colspan="2">See Applicability comment.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
PROVIDES USEFUL REFERENCE INFORMATION ON THE FOLLOWING TOPICS
- Vehicle types and configurations
- Vehicle weights and dimensions
- Turning radius
- Braking distance
- Driver eye height
- Truck acceleration characteristics
- Rollover threshold
- Roadway sight distance</td></tr>
<tr><td colspan="3">Key Graphics: Some useful truck dimension diagrams on Figures A-9 through A-16, pp 68-70.</td></tr>
<tr><td colspan="3">Caveats/Comments:
- This is a useful document to obtain an authoritative summary on HT characteristics.
- The authors indicate that truck braking distance are nearly equal to those of passenger vehicles on wet pavements (identified as most critical to safety) without providing a supporting source.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Houser, A., Pierowicz, J., and Fuglewicz, D. (2005). Concept of Operations and Voluntary Operational Requirements for Lane Departure Warning System (LDWS) On-board Commercial Motor Vehicle. Washington, DC: Federal Motor Carrier Safety Administration.</td></tr>
<tr><td>Source type:
Review and Commentary</td><td>Method/Study Type:
Design Guideline/Standard</td><td>Relevance for IVBSS HV:
Voluntary HV LDWS Functional and DVI Requirements are provided</td></tr>
<tr><td colspan="3">General Approach:
Technology survey and limited literature review provides a basis for a definition of the concept of operations and voluntary operational requirements, including the DVI.</td></tr>
<tr><td colspan="3">Methods:
NOT APPLICABLE</td></tr>
<tr><td>Quality:
Low</td><td colspan="2">Basis for specific DVI requirements not identified.</td></tr>
<tr><td>Applicability:
High</td><td colspan="2">Not research, but directly relevant to IVBSS HV DVI.</td></tr>
<tr><td>Relative Impact:
Medium</td><td colspan="2">Because this was published by FMCSA, the DVI recommendations should be carefully considered.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
LDWS VOLUNTARY FUNCTIONAL REQUIREMENTS ARE LISTED

LDWS VOLUNTARY DVI REQUIREMENTS ARE LISTED, INCLUDING THE FOLLOWING NON-OPTIONAL REQUIREMENTS:
1. LDWS should issue an audible or tactile warning when the vehicle crosses the warning threshold.
2. LDWS should include a visual indicator to indicate when the system is not tracking the vehicle’s position in the lane. This status may be indicated by an instrument panel warning light or an indicator that is integral to LDWS.
3. LDWS should use a visual indicator to indicate that the system is operational and ready to function. This status may be indicated by an instrument panel warning light or an indicator that is integral to LDWS.
4. LDWS should use a visual or audible indicator to indicate a system failure or malfunction. This status may be indicated by an instrument panel warning light or an indicator that is integral to LDWS.
5. LDWS indicators should be clearly discernable in direct sunlight and at night.</td></tr>
<tr><td colspan="3">Key Graphics: Page 10, Fig. 1: LDWS Warning Thresholds and Warning Threshold Placement Zones</td></tr>
<tr><td colspan="3">Caveats/Comments:
- This document is intended to provide motor carriers with system guidelines for voluntary adoption of an LDWS. The level of detail is insufficient to support detailed DVI design and development.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Houser, A., Pierowitz, J., and McClellan, R. (2005). Concept of Operations and Voluntary Operational Requirements for Automated Cruise Control/Collision Warning System (ACC/CWS) On-board Commercial Motor Vehicles. Washington, DC: Federal Motor Carrier Safety Administration.</td></tr>
<tr><td>Source type:
Review and Commentary</td><td>Method/Study Type:
Design Guideline/Standard</td><td>Relevance for IVBSS HV:
Voluntary HV FCW Functional and DVI Requirements are provided</td></tr>
<tr><td colspan="3">General Approach:
Technology survey and limited literature review provides a basis for a definition of the concept of operations and voluntary operational requirements, including the DVI.</td></tr>
<tr><td colspan="3">Methods:
NOT APPLICABLE</td></tr>
<tr><td>Quality:
Low</td><td colspan="2">Basis for specific DVI requirements not identified.</td></tr>
<tr><td>Applicability:
High</td><td colspan="2">Not research, but directly relevant to IVBSS HV DVI.</td></tr>
<tr><td>Relative Impact:
Medium</td><td colspan="2">Because this was published by FMCSA, the DVI recommendations should be carefully considered.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
LDWS VOLUNTARY FUNCTIONAL REQUIREMENTS ARE LISTED

LDWS VOLUNTARY DVI REQUIREMENTS ARE LISTED, INCLUDING THE FOLLOWING NON-OPTIONAL REQUIREMENTS:
1. CWS should utilize different audible tones (e.g., different pitches, patterns, lengths, etc.) or tactile warnings to provide multiple warnings as an object crosses the warning thresholds.
2. CWS and ACC systems should include a visual indicator when no vehicles or objects are in the lane. The indication may be provided by an instrument panel warning light or an indicator that is integral to each system.
3. CWS and ACC systems should use a visual indicator to provide system operational status. This status may be indicated by an instrument panel warning light or an indicator that is integral to each system.
4. CWS and ACC systems should use a visual or audible indicator to indicate a system failure or malfunction. This status may be indicated by an instrument panel warning light or an indicator that is integral to the system.
5. CWS and ACC system indicators should be clearly discernable in direct sunlight and at night.
6. CWS should utilize combinations of audible, visual and tactile indicators to provide multiple warnings of object detection and impending collision. (Optional)
7. CWS may allow the volume of the audible warnings to be adjusted, but not below a minimum sound level of 65 dBA7. (Optional)
8. CWS and ACC systems may provide operational or diagnostic messages or codes, such as “System Operational” on an alphanumeric display to alert the driver of specific faults, conditions, or concerns. (Optional)</td></tr>
<tr><td colspan="3">Key Graphics: Page 10, Fig. 1: CWS Object Detection Ranges and Collision Warning Thresholds</td></tr>
<tr><td colspan="3">Caveats/Comments:
- This document is intended to provide motor carriers with system guidelines for voluntary adoption of CWS and ACC. The level of detail is insufficient to support detailed DVI design and development.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Jiang, Z., Streit, D., and El-Gindy, M. (2001). Heavy vehicle ride comfort: Literature survey. International Journal of Vehicle Design, 8, (3/4), 258-284.</td></tr>
<tr><td>Source type:
Analytical Study</td><td>Method/Study Type:
Literature Review and Data Modeling</td><td>Relevance for IVBSS HV:
HV Characteristics</td></tr>
<tr><td colspan="3">General Approach:
Literature review of ride comfort issues and increasingly complex models intended to simulate driver vibration and comfort.</td></tr>
<tr><td colspan="3">Methods:
NOT APPLICABLE</td></tr>
<tr><td>Quality:
Medium</td><td colspan="2">The methods are applicable to the topic, but validation of the model outputs is a challenge.</td></tr>
<tr><td>Applicability:
Low</td><td colspan="2">This provides tangential information regarding cab and driver vibration.</td></tr>
<tr><td>Relative Impact:
Low</td><td colspan="2">See Applicability comment.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
INTRODUCTION TO RIDE COMFORT

RIDE COMFORT ASSESSMENT METHODS REVIEW
- Subjective
- Shaker table tests
- Ride simulator tests
- Ride measurement in vehicles

REVIEW OF RIDE COMFORT CRITERIA, INCLUDING CURRENT ISO STANDARDS

REVIEW OF RIDE COMFORT SIMULATION MODELS</td></tr>
<tr><td colspan="3">Key Graphics: A few useful diagrams of driver vibration and comfort models.</td></tr>
<tr><td colspan="3">Caveats/Comments:
- This is a useful review of modeling approaches towards the study of HT driver vibration and comfort.</td></tr>
</table>

Document:
Kiger, S., Rockwell, R., Niswonger, S., Tijerina, L., Myers, L., and Nygren, T. (1992). *Heavy Vehicle Driver Workload Assessment. Task 3: Task Analysis Data Collection* (DOT HS 808 467 (3)). Washington DC: National Highway Traffic Safety Administration.

Source type:	Method/Study Type:	Relevance for IVBSS HV:
Empirical Study	Survey, Scaling, On-road Observation	<HV CAS/Integration/HF Ops>

General Approach:
Several efforts were conducted to understand vehicle driver tasks and workload, involving task analysis, surveys, and on-road observation of driver, including an initial assessment of driver visual allocation (glance times).

Methods:
DIMENSIONS OF TRUCK DRIVER WORKLOAD
- 34 drivers interviewed to identify how they define workload and what factors they perceive as affecting it.
- 21 drivers rank-ordered the judged workload of eight common tasks

DRIVING CONDITION DEMAND
- 55 drivers evaluated the relative demand associated with 10 pairs of conditions – selected to allow subsequent conjoint analysis

DIFFICULTY AND IMPORTANCE RATINGS OF TASKS UNDER VARYING DRIVING CONDITIONS
- 30 drivers rated the difficulty and importance to safety of a subset of tasks and driving conditions

FIELD OBSERVATION OF TRUCK DRIVERS
- These were preliminary efforts that established the methodology that was later applied by this team in a in a larger study

Quality: High	This study established much of the basis for HT driver workload assessment.
Applicability: Medium	Provides context for IVBSS DVI design and provides the foundation for rigorous driver workload assessment methodologies, but provides limited specific DVI information.
Relative Impact: Medium	See Applicability comment.

Key Findings and Recommendations:
DIMENSIONS OF TRUCK DRIVER WORKLOAD
- Drivers often identified workload as stress. Stress results from delays. Delays can only be dealt with by increasing workload.
- An initial rank-order rating of eight common task workload levels are provided.

DRIVING CONDITION DEMAND
- Scaled perceived workload for each of 32 unique driving conditions
- Approximate relative importance of five factors: Traction (51.6%), Visibility (25.8%), Traffic Density (12.9%), Highway Division (6.5%), and Day/Night (3.2%)

DIFFICULTY AND IMPORTANCE RATINGS OF TASKS UNDER VARYING DRIVING CONDITIONS
- Most difficult tasks: lane changing, recovery from locked brakes, making hard braking stops, recovery from tire failure, recovery from skids, and executing off-road recovery.
- Several most important tasks, including changing lanes, passing cars on left, merging from entry ramp, making left turn, turning trailer around, starting from stop at intersection, making railway crossing, and negotiating narrow bridge.

Key Graphics: None

Caveats/Comments:
- See Tijerina, L., Kiger, S., Rockwell, T., and Wierwille, W. (1995) for methodological details
- See Tijerina, L., Kiger, S., Rockwell, T., Tornow, C. (1995) for results of the larger observational study

<table>
<tr><td colspan="3">Document:
Mazzae, E. and Garrott, W. (1995). Human Performance Evaluation of Heavy Truck Side Object Detection Systems (SAE Technical Paper Series No. 951011). Warrendale, PA: Society of Automotive Engineers.</td></tr>
<tr><td>Source type:
Empirical Study</td><td>Method/Study Type:
On-road Study</td><td>Relevance for IVBSS HV:
HV CAS Effectiveness Comparison</td></tr>
<tr><td colspan="3">General Approach:
Eight professional drivers drove a tractor-trailer equipped with four different LCW system hardware or side view mirror configurations on a set route.</td></tr>
<tr><td colspan="3">Methods:
Subjects drove the same 5.5 hour route with different LCW configurations on four different days

Independent variables: 4 X 2 X 3 within subjects design
- DEVICE (4 levels)
1. Standard Side View Mirrors Only
2. Right Fender-mounted moderately convex mirror
3. Radar-based Side Object Detection prototype
4. Ultrasonic-based Side Object Detection prototype
- ROAD (2 levels): arterial or freeway
- TRAFFIC (3 levels): beside the tractor, beside the trailer, or no vehicle present.

Dependent variables
- Driver response to in-cab researcher question: “Is the right clear?”
- Glance times
- System performance questionnaire</td></tr>
<tr><td>Quality:
Low</td><td colspan="2">This was an early study with a number of methodological confoundings.</td></tr>
<tr><td>Applicability:
Medium</td><td colspan="2">Device display and performance differences make comparisons of potential differences difficult.</td></tr>
<tr><td>Relative Impact:
Low</td><td colspan="2">Lack of study sensitivity limited the need to attempt comparisons.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
RIGHT CLEAR RESPONSE CORRECTNESS: No overall effect of device
MEAN VERBAL RESPONSE TIME: Standard system significantly slower than others (which were all comparable)
NUMBER AND DURATION OF GLANCES DURING RIGHT LANE CHANGES: No overall effect of device

System performance was not consistent:
<table><tr><th>System</th><th>% Vehicles Undetected</th><th>Ratio of Inappropriate to Appropriate Alarms</th><th>Average Minutes Between Inappropriate Alarms</th></tr><tr><td>Radar</td><td>3.2</td><td>0.22:1</td><td>15</td></tr><tr><td>Ultrasonic</td><td>6.3</td><td>0.03:1</td><td>126</td></tr></table>
Participants preferred the fender mounted mirrors to the prototype SODS devices</td></tr>
<tr><td colspan="3">Key Graphics: Figures 6 and 7 showing disparate system driver displays.</td></tr>
<tr><td colspan="3">Caveats/Comments:
- Primary finding here was that drivers preferred fender-mounted mirrors, although that preference was not supported by significant differences in performance between the mirror-based and other SOD configurations.
- Lack of significant differences in performance raise questions of study sensitivity
- Both prototype systems relied primarily upon a centrally located visual display – which were very different between the two systems
- Only the radar-based system had an auditory warning</td></tr>
</table>

Document:
Robinson, G., Casali, J., and Lee, S. (1997). *The Role of Hearing in Commercial Motor Vehicle Operation: An Evaluation of the FHWA Hearing Requirement*. Final Report. Blacksburg, VA: Auditory Systems Laboratory, Virginia Polytechnic Institute and State University.

Source type:	Method/Study Type:	Relevance for IVBSS HV:
Empirical Study	Literature review, survey, on-road	HV operational conditions

General Approach:
Addressed commercial driver hearing requirements through task analysis and survey of 80 drivers; and cab noise environment through literature review and on-road in-cab measurements. Additional research (not reviewed here) looked at driver hearing decrement issues.

Methods:
TASK ANALYSIS
Independent variables: Task Analysis Questionnaire Items
Dependent variables: Task Importance Rating, Hearing Importance Rating, Other responses

CAB NOISE SPECTRAL MEASUREMENTS
Independent variables: Windows up/down; Ventilation on/off; and radios on/off
Dependent variables: one-third octave band in-cab sound pressure levels in dB(linear), dBA, and dBC
NOTE: *Truck Cabs* (one Volvo 1997, two Kenworth [1992 and 1993], six unspecified Internationals)
Cargo, cargo weight, and vehicle age not controlled

Quality: High	Good, comprehensive literature review and valuable on-road data.
Applicability: High	Provides best available cab noise data.
Relative Impact: High	Directly relevant to the design of auditory warnings in HTs.

Key Findings and Recommendations:
FINAL LIST OF HEARING-CRITICAL CVO DRIVING TASKS
- Routine Driving Tasks (22)
- Communication (6)
- Detection of Mechanical Problems (9)
- Detection of Internal (inside cab) warning signals (5)
- Detection of External (outside cab) warning signals (11)
- Engine [problems] (6)
- Drive Train [problems] (6)
- Air System [problems] (7)
- Tires and Wheels [problems] (2)
- Trailer [problems] (2)
- Electrical System [problems] (1)

OBTAINED CAB NOISE LEVELS WERE SUBSTANTIALLY HIGHER THAN OTHER RECENT STUDIES
- 89.1 dBA, whish is just below the OSHA permissible exposure level of 90 dBA for an eight-hour period taken when vehicle was traveling at full highway speed (not taking into account rest stops)

Key Graphics: Figure 8, p. 120: Trend for Interior Truck-Cab Noise from the 1960's to the 1990's, Including this Study.

Caveats/Comments:
- Cab noise measurements were taken on actual commercial runs, with trucks both loaded and unloaded, and most vehicles were fairly high-mileage (over 200,000 miles).
- These measurements likely represent the high end of cab noise that can be expected in newer model trucks.
- It may be necessary to measure the cab noise levels in the trucks to be used in IVBSS prior to establishing signal decibel levels.

<table>
<tr><td colspan="3">Document:
Shutko, J. (1999). An investigation of collision avoidance warnings on brake response times of commercial motor vehicle drivers. Unpublished master’s thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.</td></tr>
<tr><td>Source type:
Empirical study</td><td>Method/Study Type:
Closed Track Study</td><td>Relevance for IVBSS HV:
HV CAS Warning Type</td></tr>
<tr><td colspan="3">General Approach:
33 participants drove around a closed track in a HT equipped with auditory and haptic forward collision warnings. During performance of a distracter task, drivers experienced a collision warning coupled with plastic barrels being rolled into the path of the vehicle. Performance measures and subjective observations were collected.</td></tr>
<tr><td colspan="3">Methods:
Independent variables
- WARNING [no warning, auditory icon (tire skid), haptic (one-second brake pulse)]: B/t Ss

Dependent variables
- RESPONSE TIME (accelerator reaction time + movement time, brake reaction time + movement time, time to maximum brake depression, time to full stop)
- COLLISIONS (collision with barrels, speed at collision)
- EYE GLANCE
- SUBJECTIVE QUESTIONAIRRE</td></tr>
<tr><td>Quality:
Medium</td><td colspan="2">While not a definitive work, the study employs sound methodology based on precedent.</td></tr>
<tr><td>Applicability:
High</td><td colspan="2">The study directly addresses the use of forward collision warnings in commercial vehicles.</td></tr>
<tr><td>Relative Impact:
Low-Medium</td><td colspan="2">These results are highly applicable to FCW system in HTs; however, the methodological approach failed to yield statistically significant results.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
HAPTIC WARNING
- Break-pulse haptic warnings did not affect driver performance; however, they did lead to fewer collisions—probably due to the initial reduction in speed.
- The haptic warning was misconstrued by one driver that was naïve regarding the existence of the brake pulse system. The driver interpreted the warning as a vehicle malfunction (fuel line blockage), which caused him to look at the instrumentation instead of the roadway and to depress the accelerator rather than braking.
- The authors suggest that commercial vehicle drivers may have “learned” or conditioned responses to haptic warnings that may interfere with intended evasive safety actions.

AUDITORY WARNING
- Auditory warnings led to faster driver response times relative to no warning, but this difference only approached statistical significance.
- There was no significant reduction in the number of collisions for the auditory icon warning condition relative to the no warning condition.</td></tr>
<tr><td colspan="3">Key Graphics: Fig 16 – pg 40: Mean responses of reduced data set across alarm groups</td></tr>
<tr><td colspan="3">Caveats/Comments:
- This study was modeled after a similar study by Winters (1997).
- The long duration of the braking pulse may have encouraged confusion of the haptic display with a fuel system or braking malfunction.
- Brake Reaction Time was measured from signal onset for warning conditions and moment of hazard visibility for the no-warning conditions. Details on when the warning was triggered are not clear.
- Time to Collision at warning/hazard visibility varied between subjects <u>and</u> was so brief that 25/33 distracted drivers had collisions.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Staplin, L., Lococo, K.H., Decina, L.E., Bergoffen, G. (2004). Training of Commercial Motor Vehicle Drivers. Washington DC: Transportation Research Board.</td></tr>
<tr><td>Source type:
Analytical Study</td><td>Method/Study Type:
Literature Review and Limited Survey</td><td>Relevance for IVBSS HV:
HV Operations – Driver Training</td></tr>
<tr><td colspan="3">General Approach:
Literature review of driver training (28 technical documents) complemented by a survey of selected truck (n=3)and bus companies (n=1), industry associations, and public and private driving schools (n=5).</td></tr>
<tr><td colspan="3">Methods:
NOT APPLICABLE</td></tr>
<tr><td>Quality:
Low</td><td colspan="2">This is an adequate analytical effort, but is not empirically-based.</td></tr>
<tr><td>Applicability:
Low</td><td colspan="2">Focus is on entry-level driver training standards and practices.</td></tr>
<tr><td>Relative Impact:
Low</td><td colspan="2">Only tangential relationship to HT DVI design.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
SUMMARY OF CURRICULUM TOPICS RECOMMENDED BY DUEKER (1995) FOR “ADEQUATE” TRAINING (TABLE 2)

RECOMMENDED PRACTICES FOR IMPROVING ENTRY-LEVEL DRIVER TRAINING EFFECTIVENESS
- Industry-wide adherence to Professional Truck Driver Institute minimum standards for entry driver certification
- Finishing training for 1st seat (solo) drivers
- Substitution of CD/DVD instructional materials for traditional classroom presentations relying on printed materials.
- Introduction/expansion of appropriate and affordable simulation training’
- Expansion of the use of skid pads to train beginning drivers
- Videos with testimonials regarding health, wellness, lifestyle, and fitness-to-drive topics</td></tr>
<tr><td colspan="3">Key Graphics: None</td></tr>
<tr><td colspan="3">Caveats/Comments:
- Does not cite Tijerina task analyses

- A general understanding of entry driver training may be useful in developing the IVBSS DVI, but it is probably unlikely that many novice drivers would be hired by companies that field these systems.</td></tr>
</table>

<table>
<tr><td colspan="3">Document:
Tijerina, L., Kiger, S., Rockwell, T., and Wierwille, W. (1995). Heavy Vehicle Driver Workload Assessment. Task 5: Workload Assessment Protocol (DOT HS 808 467 (5)). Washington DC: National Highway Traffic Safety Administration.</td></tr>
<tr><td>Source type:
Methodological</td><td>Method/Study Type:
Methodology for on-road study</td><td>Relevance for IVBSS HV:
HV DVI Evaluation</td></tr>
<tr><td colspan="3">General Approach:
The report presents a description of a prescriptive workload assessment protocol for use in evaluation in-cab devices in HTs.</td></tr>
<tr><td colspan="3">Methods:
This document is primarily a methodological guide for assessing in-cab devices on the basis of driver workload. Workload measures include visual allocation, lane keeping, speed measures, and headway. Detailed procedures are described for:
1. Workload assessment approach development
2. Workload assessment detailed evaluation plan development
3. Workload assessment test execution, analysis, and reporting</td></tr>
<tr><td>Quality:
High</td><td colspan="2">There are no empirical data here, but the procedures provide a good standard for the conduct of assessments.</td></tr>
<tr><td>Applicability:
Medium</td><td colspan="2">The methods described in this report are applicable for IVBSS DVI assessment, but do not provide design guidance.</td></tr>
<tr><td>Relative Impact:
Medium</td><td colspan="2">See Applicability comment.</td></tr>
<tr><td colspan="3">Key Findings and Recommendations:
SEE METHODS ABOVE</td></tr>
<tr><td colspan="3">Key Graphics: Fig. 1-4, p. 1-20: Flow Diagram of Device Assessment Process From Driver Workload Perspective.</td></tr>
<tr><td colspan="3">Caveats/Comments:
- Many of the measures described in this report required apparatus developed specially for such assessment at the time that the report was prepared. The methods are still appropriate, but now many of the workload measures can be captured and stored by off-the-shelf CAS and driver monitoring equipment.</td></tr>
</table>

Document:
Tijerina, L., Kiger, S., Rockwell, T., Tornow, C., Kinateder, J., and Kokkotos, F. (1995). *Heavy Vehicle Driver Workload Assessment. Task 6: Baseline Data Study* (DOT HS 808 467 (6)). Washington DC: National Highway Traffic Safety Administration.

Source type:	Method/Study Type:	Relevance for IVBSS HV:
Empirical Study	On-road Observational	HV Operations – Baseline Driver Workload

General Approach:
Thirty professional drivers were observed during normal driving and while performing requested tasks over a range of roadways and light conditions and performance measures were assessed for their sensitivity to varying driver workload.

Methods:

Independent variables	*Dependent variables*
- ROAD TYPE (Rural Freeway, 2-Lane Rural Road, Urban Freeway) - LIGHTING (Day, Night) - REQUESTED TASKS 1. Right mirror – detection 2. Right mirror – discrimination 3. Left mirror – detection 4. Left mirror – discrimination 5. Turn CB volume up/down 6. Change CB frequency 7. Manually tune FM radio 8. Turn AM/FM radio volume up/down 9. Read clock 10. Read air pressure 11. Turn heater/AC temp up/down 12. Calculate available driving hours	- VISUAL ALLOCATION MEASURES - DRIVER STERING, ACCELERATOR, AND BRAKE INPUTS - SPEED AND HEADWAY MEASURES - LANEKEEPING MEASURES

Quality: High	This work set the standard and provided a baseline for HV driver workload research.
Applicability: High	Some of these results provide baseline data that can aid in setting CAS warning timing and location.
Relative Impact: High	See Applicability comment.

Key Findings and Recommendations:
IDENTIFICATION OF A SUBSET OF SENSITIVE DRIVER WORKLOAD MEASURES
- The researchers stressed the priority of visual allocation measures and also identified the following preferred measures: steering holds, steering position variance, steering velocity variance, steering reversals, speed variance, lane position variance, and lane exceedences

IDENTIFICATION OF A SUBSET OF REQUESTED TASKS THAT CAPTURE WORKLOAD
- Adjust radio volume, Right mirror detection, Read air pressure, tune radio manually, change CB frequency, read clock, left mirror detection

BASELINE DATA ON GLANCE LOCATION, FREQUENCY, AND DURATION FOR VARIOUS ROADWAYS AND REQUESTED TASKS
- This also provides a good baseline for on-road and off-road glance duration. Glance duration averages between 1.0 and 1.2 glances fro all off-road glances (except radio and CB tuning)
- Drivers glance back at the road in about 0.8 to 1.60 seconds regardless of the glance location.

Key Graphics: Table 3.6.1, p. 40: Visual Allocation of HV Drivers by Location

Caveats/Comments:
- Analyses include a comprehensive analysis of the intercorrelations among dependent measures, which provides a good basis for the selection of an efficient set of dependent measures.