DEVELOPING AN EFFECTIVE MULTI-MODAL, MULTIPLE-WARNING SYSTEM: THE PROCESS USED FOR IVBSS

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ABSTRACT

This paper discusses the process employed to develop the driver-vehicle interface (DVI) for the light-vehicle platform of the Intelligent Vehicle-Based Safety Systems (IVBSS) project, a cooperative agreement between the private industry and the United States Department of Transportation. The goal is to develop an effective and easy-to-use DVI that alerts the driver of the possibility of rear-end crashes, road departures, and potentially hazardous lane changes and merges. The process included the integration of expert knowledge and focused simulator testing to generate an initial DVI. The steps involved in the development process included developing the engineering assumptions; creating an initial DVI option space; and the iterative process of testing and refining the DVI design by on-road testing with experts and pilot test subjects. The final DVI design will be deployed as part of a field operational test.

Keywords: driver-vehicle interface, human factors, field operational test

OVERVIEW OF IVBSS

The Integrated Vehicle-Based Safety Systems project seeks to develop and test an effective and easy-to-use driver-vehicle interface that warns the driver of potential rear-end, road departure, and lane change crashes. This project is conducted jointly by teams from the private sector, the United States Department of Transportation (U.S. DOT), and the National Institute of Standards and Technology. The U.S. DOT team is represented by the National Highway Traffic Safety Administration, the Research and Innovative Technology Administration (specifically, its Intelligent Transportation Systems Joint Program Office and the Volpe National Transportation Systems Center), and the Federal Motor Carrier Safety Administration. IVBSS prototypes are being developed on heavy-truck and light-vehicle platforms. IVBSS is broken up into 2 phases; phase I is the design and development phase and phase II is the deployment phase. The light-vehicle IVBSS prototype will be integrated into a 2007 Honda Accord. This paper addresses the process employed to design and integrate the DVI for the light-vehicle IVBSS platform.

The IVBSS for the light-vehicle platform is comprised of the following four warning subsystems:

1) Forward collision warning (FCW)
2) Curve speed warning (CSW)
3) Lateral drift warning (LDW)
4) Lane change merge warning (LCM)

FCW uses a long-range radar to detect the distance and calculate the time to collision for objects of interest directly in front of the host vehicle. CSW uses global positioning sensor (GPS) and map data along with other vehicle signals to warn if the vehicle speed is excessive for upcoming curves. LDW uses a forward-looking camera to monitor vehicle position within the travel lane and provides an alert if the driver crosses the lane boundary without signaling. LCM uses short-range radars mounted along the side of the vehicle to provide a visual cue if there is an object of interest in the detection zone, and alerts the driver in case of an imminent side collision.

COMPOSITION OF THE DRIVER VEHICLE INTERFACE TEAM

A DVI team was formed to make recommendations for the design of the IVBSS driver-vehicle interface, both for light vehicles and heavy trucks. The core team consisted of human factors engineers and subsystem design personnel from Visteon, UMTRI, and Takata (formerly Cognex). A key advantage of this team is that most of its researchers and engineers had worked together previously on the Road Departure Crash Warning (RDCW, LeBlanc et al., 2006) project, which included interface development, simulator testing, and on-road testing.

UMTRI was responsible for the definition of the human machine interface (HMI) for IVBSS. Visteon was responsible for the design and implementation of the DVI and was the main systems integrator for the light vehicle DVI. Visteon also developed the CSW, FCW, and LCM functions. Cognex implemented the LDW function.

LIGHT-VEHICLE IVBSS DVI DESIGN PROCESS

Figure 1 depicts the steps of the design process used for the development of the light-vehicle IVBSS DVI, This process included developing the engineering assumptions; creating the initial Stage-1 DVI option space; and the iterative process of testing and refining the DVI design by performing simulator studies, on-road testing with experts (jury drives), on-road testing with selected pilot subjects, and vehicle-level development.

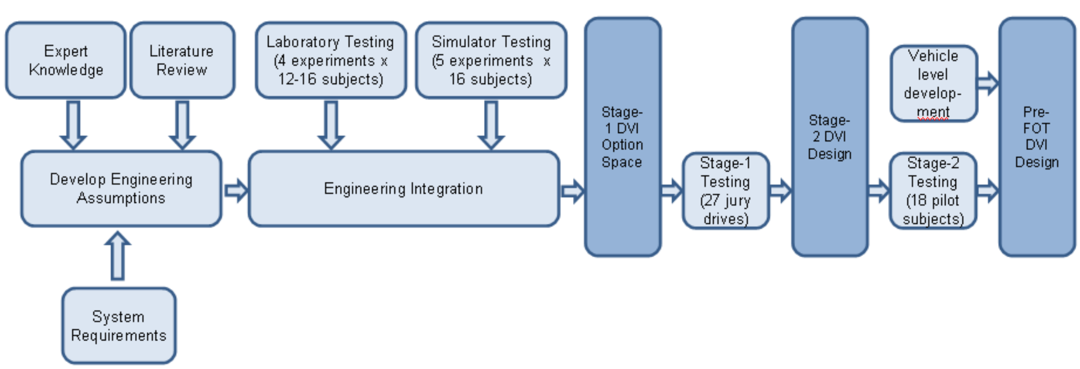


Figure 1 IVBSS Light Vehicle DVI Design Process

The following sections describe the key elements of the process.

Developing the Engineering Assumptions

A design of a complex alert system may have one unique alert for each subsystem and may also differentiate alerts based on the location of the threat (such as a lane-change merge left- or right-side warning). On the other hand, the simplest alerting system would consist of one master alert that would not vary by subsystem. The challenge in developing an effective and easy-to-understand interface is to assure that the warning(s) capture the driver's attention, convey the nature of the threat, and evoke the appropriate response.

To this end, the DVI team created a set of engineering assumptions to use throughout the process of designing and developing the DVI for the light-vehicle IVBSS system. The engineering assumptions were derived from literature on warnings systems and expert knowledge in the field (from IVBSS DVI team members).

While many human factors design guidelines were considered and reviewed in this process (e.g., Campbell et al., 2007), the following list of principles was culled out including simplicity, consistency, stimulus response compatibility, reducing confusion and annoyance, and user in control. Although these principles seem obvious, in some cases there was no research on an issue and these guidelines were used to make design decisions.

Based on the literature and human factors expertise, Table 1 shows the fundamental engineering assumptions that underlie the initial DVI design.

Table 1 Fundamental Engineering Assumptions

Assumption	Rationale
Warnings will alert the driver of potential safety threats and convey the nature of threats, but will not provide the driver with a recommended action (e.g., FCW warning to steer around vehicle vs. brake).	Systems may not be reliable enough to determine what the most appropriate action is. Further, taking over control from the driver, especially steering, may not be acceptable to customers.
Rely heavily on the auditory modality to warn the driver.	Looking away from the road draws driver attention away from where the critical event is taking place, and where they should be looking.
Visual displays are for additional system information such as early, on demand, or clarification information.	Visual displays (text or icons) are sometimes needed to explain the meaning of a warning. However, past FOT results indicate that visual cues were not used and should only be implemented to augment the warning, not as the main component of the warning. Furthermore, a visual cue used to validate the driver's understanding of the warning will aid in training the driver and improves warning effectiveness.
Have one warning level – imminent for each warning subsystem.	This will simplify an integrated warning system. There is a risk of overwhelming the driver with information if non-imminent warnings from several different systems are used.

The DVI system will not take control of the vehicle but may alter system dynamics (e.g., brake pulse).	The driver must remain in control.

The engineering assumptions led to the basic warning strategy and the goals for warning effectiveness, both of which are described below.

The first priority was to design the DVI so that the driver will be warned of preventable crashes in a timely manner. Warnings should be easy to detect but not startling, be immediately understood with little or no training, not be confused with one another, and lead to the desired response in the requisite timeframe. The performance of existing warning systems has flaws due to technology limitations. Therefore, care was required in setting thresholds and criteria to balance the frequency of nuisance warnings (which can distract the driver) with those that are critical so as to not diminish drivers' trust and acceptance of the warning system.

A warning is only effective if the driver understands it and responds to it in a timely and appropriate manner. By increasing intuitiveness and familiarity, and, thereby, reducing confusion, it is possible to reduce the driver response time while maintaining accuracy (correct response to the warning). In addition, any system latency for warnings must be minimized to increase the time the driver has to respond to the threat.

DVI Design and Integration

The next step of the process is to create the DVI option space using the engineering assumptions, design strategy, and warning effectiveness goals. this process is iterative and requires evaluation of the options and selecting the best solution based on simulator testing, jury drives (stage-1 testing), accompanied pilot drives (stage-2 testing), and vehicle-level development.

The option space approach is a bottom-up approach in which many options are considered and then explored or eliminated by a team of experts. These experts make decisions based primarily on the design strategy for the desired product, complemented by human factors and technical expert opinions. The effectiveness of options is weighed against technical feasibility while applying human factors guidelines and following the design strategy. The process is iterative and requires input from all members of the DVI team, with input from other technical experts on an as-needed basis.

The DVI team used several different approaches to flush out the issues surrounding the integration of four warning subsystems and to evaluate potential solutions. These approaches included: (1) a matrix of warning zone combinations (where is the problem?), (2) a driver response/attention matrix (what should the driver do?), and (3) a warning presentation options matrix (which specific options were considered and accepted or rejected?), which are described in the text that follows.

A driver concept perspective was generated to evaluate whether any warnings could be combined to reduce the number of overall warnings. This perspective classified the potential warnings into six zones as depicted in Figure 2. Zone 1 was what the driver could see directly. Zones 2 and 6 corresponded roughly to the driver's blind spot. Zones 3, 4, and 5 divided the area behind the vehicle into left, center, and right. As shown in Table 2, the warning candidates that should be considered for each modality depended upon the number of zones to be differentiated and how those zones might be combined. As zones are combined, for example, the ability of the driver to understand an IVBSS alert is simplified but you trade off the ability to direct the attention of the driver to the location of the specific hazard or focus the driver's attention to a specific location to handle the threat.

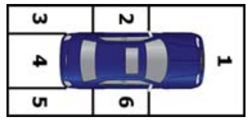
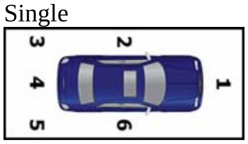
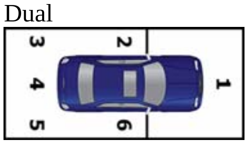
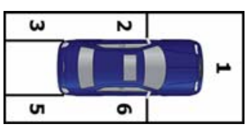
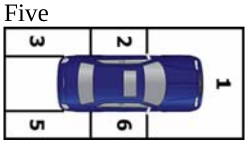


Figure 2 Warning Zones

Table 2 Possible warning zones around the vehicle

Zone Combinations	Zone Configuration	Haptic	Auditory	Visual
Single 	1,2,3,4,5,6	Seat Steering wheel Seatbelt Brake pulse	Tone Vocal	360 degree graphical
Dual 	1	Steering wheel	Lateral tones Vocal "Forward"	180/180 deg HUD Red light in fwd FOV Directional light flash
	2,3,4,5,6	Seatbelt	Lateral tones vocal "Rearward"	Red light in fwd FOV Directional light flash
Triple 	1	Steering wheel	Vocal "Fwd" Directional tone	Same as Dual
	2,3	Left seat	Vocal "Left" Directional Tone	Directional light flash Mirror Icon Zone display
	5,6	Right seat	Vocal "Right" Directional tone	Directional light flash Mirror Icon Zone display
Five 	1	Same as Triple	Same as Triple	Same as Triple
	2	Seat left bottom	Directional vocal Directional tone	Static display
	3	Seat left back	Directional vocal Directional tone	Rate of approach
	5	Seat right back	Directional vocal Directional tone	Rate of approach
	6	Seat right bottom	Directional vocal Directional tone	Static display

The attention matrix in Table 3 is a useful decision aid for selecting warnings. The attention matrix considered what the system was communicating, what the driver was to do in response, and how warnings in various modalities might encourage that response. It was not easy to create this matrix for two reasons. First, there were shifts in what each warning system could do, in particular for LCM, where a change in the sensor suite changed what the warning could detect. Second, there was uncertainty about how to trade off communicating to the driver *what the threat was*, *where the threat was*, and *what to do about the threat*. One might argue that a fully informed driver is best. However, the more information the driver has to process, the slower the driver responds to the threat (Murray et al., 1995).

Table 3 Driver response/attention matrix

IVBSS Warning	Warning Direction	Desired Driver Response	Haptic	Auditory	Visual
LDW You are unintentionally drifting across a lane boundary.	Lateral	a. Attention forward b. Correct or maintain the vehicle heading in lane.	Directional haptic in seat bottom	Directional Tone wav file	Display: non-directional text or icon. Under investiga-tion.
LCM The lane you are intentionally entering is hazardous.	Lateral	a. Maintain current lane until hazard is not present. b. Check side for clearance and adjust vehicle heading.	Directional haptic in seat bottom	Directional Tone wav file	Icon in left/right mirror.
CSW You are entering a curve too fast.	Longitudinal	a. Attention forward b. Decelerate vehicle.	Throttle Back off transmission downshift	Directional Tone wav file	Text: "X MPH Curve"
FCW There is a hazard ahead.	Longitudinal	a. Attention forward b. Choose and execute appropriate action, e.g., brake or steer.	Throttle Back off transmission downshift	Directional Tone wav file	Light bar HUD advisory in center display

The warning presentations options matrix in Table 4 was part of the design and development process. This matrix is only shown partially in Table 4 with selected examples and has two main purposes. First, this matrix provides detailed modality-specific descriptions of warning candidate implementations. Second, it quantifies the criteria for selecting warnings and provides an initial assessment of their effectiveness.

Table 4 Examples from the Warning Presentation Options Matrix

Haptic Modality	Current Implementation Direction	Rationale for Decision	Vehicle Systems FMEA	Effectiveness
Directional Seat Bottom	☒Approved ☐Rejected ☐Investigate Primary haptic for LDW dashed lane change. Focus on positioning of transducers to increase directional sensation. Place transducers closer to rear tail bone.	Testing of placement configuration in seat bottom to be done on Honda seat. Place similar to RDCW or try a V pattern where the rear transducers are placed closer together.	Will not affect the vehicle system.	☐High ☒Medium ☐Low Seat bottom haptic may not be discernible by drivers wearing heavy coats. Front transducers may not be discernible by drivers with cruise control as their knees are elevated. This modality is only perceivable by the driver.
Steering Wheel	☐ Approved ☒ Rejected ☐Investigate Use a transducer mounted on the steering column or steering wheel to induce a desired vibration.	Low effectiveness. Implementation concerns.	Concern with injecting a vibration at the wheels. Visteon's technical expert on steering systems suggests that a minimum frequency of vibration of 50 Hz be used to eliminate vibration-induced steer inputs. The 50 Hz target is in the audible range and may not provide the desired tactile feedback as a 10 Hz vibration would.	☐High ☐Medium ☒Low Effectiveness is questionable. People steer in many different ways (e.g., with one hand or finger). Gloves would reduce and possibly eliminate the tactile sensation. Older drivers typically have reduced tactile sensation in their extremities. Using this modality may be less effective than other haptic modalities being considered.

The information from these matrices led to the development of the initial DVI option space. The option space was refined, based on the testing described in the following sections, resulting in the DVI design.

Laboratory and Simulator DVI Testing

UMTRI carried out laboratory and simulator testing to support design of the driver vehicle interface (Green et al., 2008). After considering the warning design research (in general and specific to crash warnings for drivers), expert human factors judgment, and discussions with those overseeing the engineering efforts of subsystem development and integration, the DVI team identified seven research questions that warranted study (Table 5). The human factors experts designed five experiments to answer these seven questions with particular interest towards recommending how the DVI should to be implemented in the IVBSS program.

Table 5 Seven Research Questions Addressed in the Simulator DVI Testing

Issue	Comment
Q1. Shared warnings (When and how should warnings be shared or differentiated, (e.g., FCW and CSW, LDW and LCM?))	In response to warnings, drivers can return to their lane, steer out of it, or slow down. Warnings can indicate what is wrong (so each warning is unique), what to do (which suggests common warnings based on desired actions), or both.
Q2. Sequencing co-occurring warnings (Should warnings occurring at the same time be presented together or with a delay between them?)	Presenting two warnings at the same time (e.g., forward collision warning and lateral drift) could confuse drivers as they will not be able to determine what each warning is, or which to respond to first.
Q3. Warning set/confusion (Are warnings in the IVBSS sets confused with one another?)	Warnings that look or feel alike could be confused. But, what constitutes "alike"?
Q4. Time course of driver actions (What is the process by which drivers respond to warnings?)	To design warnings, the sequence of how drivers respond to warnings needs to be known – in particular where and when they look, when they release the throttle, and when they brake or steer.
Q5. Warning processing time/accuracy tradeoff (How does the tradeoff between warning system processing time [to start to inform the driver] and warning accuracy affect driver responses to warnings?)	For some systems, waiting to respond improves warning accuracy, for example allowing a radar unit to make more sweeps and increase threat identification accuracy. However, that delay gives the driver less time to respond.
Q6. Auditory characteristics of warnings (How does auditory warning effectiveness vary with warning sound characteristics [loudness, pitch, speed] in sound environments of each vehicle platform?)	Although there are basic data on auditory discrimination, their application to multidimensional variations found in real warnings is difficult. In real systems, due to signal generator limitations and the desire for warning sounds to resemble particular real-world sounds, there are constraints on which sounds can be used.
Q7. Influence of pauses and repetitions (For sounds that involve periods of silence [or pauses], are responses deferred to coincide with silence? What is the optimal number of repetitions?)	For lateral drift, sounds resembling a rumble strip are sometimes used. That sequence takes time to play, potentially delaying a driver response. Can the sequence be sped up?

The testing included laboratory studies to examine the association between candidate auditory warnings and the threats they could represent and driving simulator evaluations in which multiple scenarios could trigger each warning. The simulator setting made it possible to collect driver response to many warnings in a very short period of time (once a minute). The scenarios were sequenced so that drivers were less likely to be able to predict which scenario would appear next. The simulator testing provided results that influenced the design of the DVI. The most significant finding is the lack of a difference as to whether or not warnings should be shared (e.g., a single master warning, a warning for each type of response, or a single warning for each system). Selected simulator results appear in Table 6.

Table 6 Selected Simulator DVI Results

Issue	Comment
Q1. When and how should warnings be shared?	There were no performance differences due to sharing. Accordingly, and for technical reasons, a hybrid interface with a limited number of warning signals was used in post-simulator testing.
Q2. Should warnings occurring at the same time be presented together or with a delay between them?	In general, the answer did not matter very much. As co-occurring warnings are rare in real-world driving, considerable creativity was required to force them to occur, and most often the situation was of near occurrence (e.g., in responding to FCW, the subject changed lanes without signaling, so LDW triggered).
Q3. What warning set should be selected to increase effectiveness?	Based on the testing, some adjustments were made to the warning content. This included the choice of sounds and the visual indications provided.

Stage-1 Testing (Jury Drives)

The results of the laboratory and simulator studies helped to define the DVI option space used for stage-1 testing (jury drives). The jury drives were used to target specific areas of the option space for evaluation by experts, particularly when the laboratory or simulator study results were inconclusive. The results of stage-1 testing lead to a narrowing of options on the path to a fully defined DVI. The stage-1 testing involved a total of 27 human factors experts and IVBSS engineers. The stage-1 test was split into two segments. During the first segment the experts drove a predetermined route and performed scripted maneuvers in a controlled environment in each of three vehicles. These vehicles differed in the DVI design elements. In the second segment the experts drove a two-hour period of naturalistic driving around the Detroit metro area in one of the three vehicles.

The jury drives were designed to address the following issues:

1. How many unique warnings should be included in the IVBSS warning suite? As the results from the simulator experiment did not definitively identify one of the four options tested, and given the importance of this question, this question was revisited in the jury drives. Three development vehicles with unique warning suites were tested:
    a. Four-Warning Suite: FCW, CSW, LCM/LDW imminent, LDW cautionary
    b. Two-Warning Suite: FCW/CSW and LCM/LDW
    c. One-Warning Suite: Master alert for all warnings
2. What is the preferred visual cue: text, icons, or both? Two of the vehicles had warning text accompanied by a warning icon (a different icon for each warning function). The third vehicle had warning text only.
3. Which of the two proposed side threat (LCM/LDW) tones is preferred? The alert sound was changed during the scripted portion of the test such that each participant experienced both audio cues for the same warning scenario.

The experts were asked to evaluate the appropriateness of aspects of the prototype system: warning timing and duration, volume control, mute (IVBSS system off) button, display legibility, haptic brake pulse intensity, haptic seat intensity, and ease of left/right discrimination.

Stage-2 Testing (Accompanied Pilot Subjects)

The results of the jury drives were used to design the stage-2 testing of the DVI design (Green et al., 2007; UMTRI, 2008). Stage-2 testing was intended to assess the effectiveness and customer acceptance of the proposed DVI design. In stage-2 testing, 18 laypeople were recruited to drive a vehicle equipped with the prototype IVBSS system accompanied by a researcher and they were asked for their subjective feedback and first impressions of IVBSS. These subjects drove a 90-mile prescribed route, which was a mix of surface streets and highways. Objective measures of warning type and frequency and subjective acceptance data were collected.

Vehicle-Level Development

Subject matter experts were exposed to the stage-2 DVI design for extended periods of time. In addition, system developers gained a valuable experience during the course of developing the IVBSS warning functions. Feedback from this exposure as part of the in-vehicle development also had impact on the final DVI design. For example, the haptic brake pulse was deleted from the CSW warning solely based on feedback from the engineering community.

DVI-Design for Field Operational Test

The results from the laboratory and simulator testing, stage-1 and stage-2 testing, and vehicle-level development culminated in the DVI design to be implemented in the field operational test (FOT) during Phase II of the IVBSS program. Table 7 shows the DVI suite resulting from this process. The block diagram in Figure 3 illustrates the hardware configuration required to implement the DVI.

Table 7 Pre-FOT DVI Warning Suite

	Forward Alerts		Lateral Alerts		
	FCW	CSW	LCM	LDW Imminent	LDW Cautionary
Auditory	Tone 1		(L) (R) Tone 2		____
Haptic	Brake Pulse	____	____		Haptic Seat L/R
Visual	____		Blind/Closing Zone: Yellow		____
Warning Text	Hazard Ahead	Sharp Curve	Left/Right Hazard		Left/Right Drift

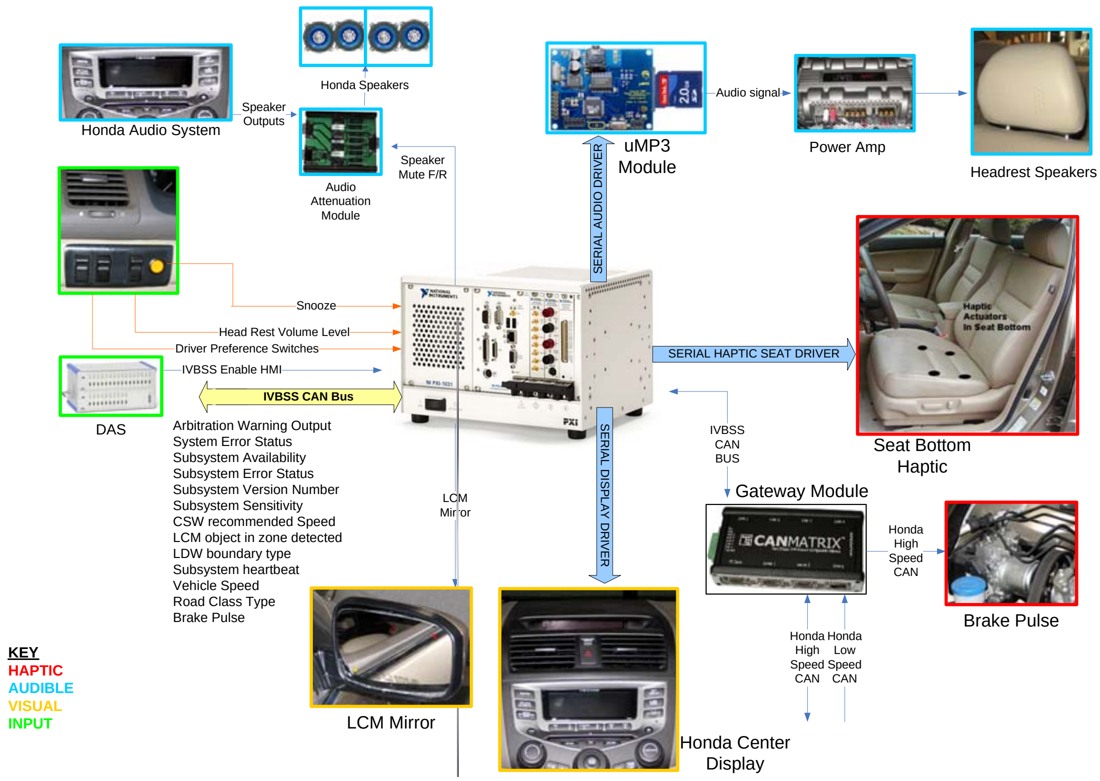


Figure 3 Pre-FOT DVI Hardware Design

SUMMARY

This paper describes the process of developing the DVI for the light-vehicle platform of the IVBSS program. This DVI design will be deployed during Phase II of the IVBSS program where a field operational test will be conducted.

The process was comprehensive and multifaceted, involving team members with varied backgrounds and technical perspectives. The process used expert opinions, surveys and analysis of literature. The team identified gaps in knowledge that had to be addressed. A variety of tools was utilized to plan and design experiments for this project. Some decisions were based on conceptual or analytical models of driver performance (e.g., with respect to human response times and the allocation of driver attention and resources). Some experiments were conducted in the laboratory and others required the use of a driving simulator. Finally, there was extensive on-road testing using both experts and laypeople drivers. The combination of these tools and testing provided an effective design and development process.

As evident from the design matrices shown in the body of the paper, many decisions had to be made to reduce the option space to a single DVI configuration for the IVBSS light-vehicle platform. The approach used is an example of a well-planned process, but no claim is made and no scientific justification is given for the advantage of this process over other possible processes. Furthermore, the success of the final product in the form of system effectiveness and driver acceptance during the field operational test will confirm the effectiveness of the process.

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