Integrated Vehicle-Based Safety System

Heavy Truck Driver Vehicle Interface (DVI) Design Notes

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by

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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.

During the development of the DVI specification document, the heavy-truck DVI team addressed a number of issues by conducting short reviews or analyses on specific design topics. This report collates these "design notes" into a single report for easy reference.

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List of Acronyms and Abbreviations

DIU .... Driver Interface Unit
DVI .... Driver-Vehicle Interface
FCW .... Forward Collision Warning
FOV .... Field of View
IVBSS .... Integrated Vehicle-based Safety Systems
HT .... Heavy Truck
LCM .... Lane Change Merge
LDW .... Lane Departure Warning
LED .... Light Emitting Diode
NHTSA .... National Highway Traffic Safety Administration
POV .... Principal Other Vehicle
RT .... Perception-Reaction Time
SV .... Subject Vehicle
TBD .... To Be Determined
TTC .... Time-to-Collision
UMTRI .... University of Michigan Transportation Research Institute

Introduction

The Intelligent Vehicle-Based Safety Systems (IVBSS) Field Operational Test (FOT) project is being led by the University of Michigan Transportation Research Institute (UMTRI) team 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).

A key document developed by Battelle staff and others involved in the development of the DVI is a set of detailed specifications for the DVI. During the development of the DVI specification document, the HT DVI team addressed a number of issues by conducting short reviews or analyses on specific design topics. This report collates these “design notes” into a single report for easy reference.

The following design topics are included in this report:

- Warning Levels & Logic For The Side Sensor Display Unit.
- Viewing Angle Analysis.
- “Opening vs. Closing” Display Analysis.
- Cut-in Analysis.
- DIU Location Analysis.
- Approach for Dealing with the Presentation of Concurrent Alerts.

HT DVI Design Notes

1 Warning Levels and Logic for the Side Sensor Display Unit

1.1 Introduction

This paper briefly summarizes the current warning levels and logic for the Side Sensor Display Unit planned for implementation in the IVBSS HT system, and outlines recommended design changes in the warning levels and logic for the unit. Justifications for the changes are also provided.

1.2 Current Use of the Lights on the Side Sensor Display Unit

On the planned IVBSS HT system, the presence of side objects will be indicated using presence detector displays located nearby the driver and passenger side rear-view mirrors (e.g., the displays may be attached to the A-pillars on the vehicle). Figure 1 depicts the unit itself, while Table 1 shows the four states that will be communicated using the red and yellow LEDs on the unit.

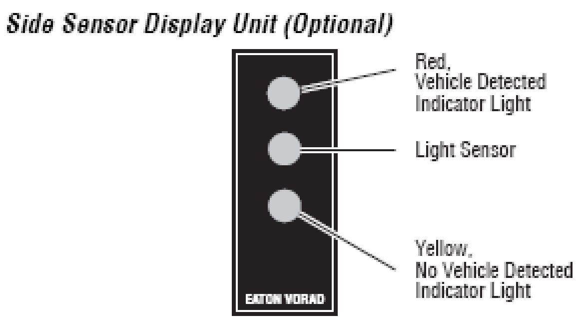


Figure 1. Side sensor display unit (current).

Table 1. Side sensor state table (current).

Red	Yellow	Interpretation
-	-	No power – fault condition.
-	On	No vehicle detected (use caution).
On	-	Vehicle detected (tone sounds if corresponding turn signal is active).
On	On	Startup self-test or failure detected.

1.3 Recommended Changes

Table 2 provides the recommended changes to the use of the red and yellow LEDs on the side sensor display unit. Currently, the BlindSpotter display has no way to inform the driver of a power failure to the display itself. We also recommend that, if possible, the DIU be used to inform the driver of a power failure to the BlindSpotter display.

Table 2. Side sensor state table (recommended).

Red	Yellow	Interpretation
-	-	No power or No vehicle detected.
-	On	Vehicle detected (use caution).
On	-	Vehicle detected + closing rate exceeds a TBD threshold and/or absolute distance between the SV and the POV is less than a TBD threshold (tone also sounds if corresponding turn signal is active).
On	On	Brief on, then off = Startup self-test. Steady on = Failure detected.

1.4 Justification for Recommended Changes

We have identified four (4) reasons that justify this change:

1. The color yellow is generally used to indicate “caution”. On the IVBSS, using the color yellow to indicate “no vehicle detected (i.e., no specific cautionary situation detected) will violate population stereotypes and driver expectations for the use of the color yellow.
2. Consistent with these same population stereotypes and driver expectations, the VORAD Driver Interface Unit (DIU) uses the color yellow to indicate “caution” related to vehicle headway (3 second following, 2 second following, and 1 second following). An inconsistent use of yellow associated with the LCW system could confuse drivers and would reflect a lack of attention to system integration across the various IVBSS subsystems.
3. The current logic for the side sensor LEDs may require drivers to make a difficult discrimination between the red and yellow LEDs. Specifically, discrimination between the presence and non-presence of an obstacle in the adjacent lane might be difficult if initial detection is in the peripheral visual field (where spatial resolution and color discrimination is poor). Under “no vehicle detected” conditions, additional eye glances may be required by the driver to make sure that it is the yellow LED - not the red LED - that is illuminated. Thus, the use of the yellow to indicate “no vehicle detected” could present a -distraction to the driver.
4. There are several IVBSS driving scenarios that will lead to a driver warning (FCW20, LDW3, LCM4, and LCM7)1 for which having an additional level of warning coding available would likely provide some benefits to drivers. These include conditions under which a vehicle is detected and the closing rate exceeds a TBD threshold or the absolute distance between the SV and the POV is less than a TBD threshold.

[1] These scenario designations reflect the scenarios included in the warning spreadsheet (ScenarioClassification_110906_HT.xls) distributed to the IVBSS HT DVI team on November 9, 2006.w

2 Viewing Angle Analysis

This brief memo identifies expected gaze angles for drivers of heavy trucks in car-following situations. It is intended to support human factors analyses being conducted to determine the appropriate location for the DIU display within the HT cab. The DVI Specification for the IVBSS HT recommends that the DUI display be located within 30 degrees from the driver's *expected gaze angle* or line-of sight-while driving. Given a nominal driver's eye height (i.e., approximately 8 feet ground-to-eye height) in a heavy vehicle, it is clear that many eye fixations will be below a horizontal plane of 0 degrees. Although drivers make eye movements to different parts of the visual scene, most of these eye movements are contained within a small area surrounding the expected gaze angle. The expected gaze angle is itself a function of how far ahead drivers typically look in the visual scene.

2.1 Objective

The HT driver's expected gaze angle relative to the horizontal plane was calculated for different time headways (i.e., how far ahead the driver looks down the road).

Car following situations were given special consideration, because under these conditions, expected gaze angle may be farther down from the horizontal plane and closer to the DIU than without a lead vehicle. The reasons for this are:

- Drivers spend most of their time looking at the region around the lead vehicle's tail lights in car-following situations and spend significantly less time scanning the visual scene (Tijerina, Barickman, & Mazzea, 2004).
- Time headway in car-following situations is likely to be shorter than if no lead vehicle is present, which translates to a lower expected gaze angle.
- Car following information is key information in the DIU, so it is reasonable to assume that drivers will be glancing at the DIU more frequently in car-following situations.

The functional implication of this is that the visual angle between the driver's expected gaze angle and the DIU position may be lower (and within the DVI specifications) in a subset of car-following situations. This possibility was tested in this analysis.

2.2 Methods

View angle was calculated for different time headways (0.5 to 3.0 sec) at different Subject Vehicles speeds (25-70 mph). Time headway was converted into distance based on the speed specified. Other assumed distance values are shown in Figure 2.

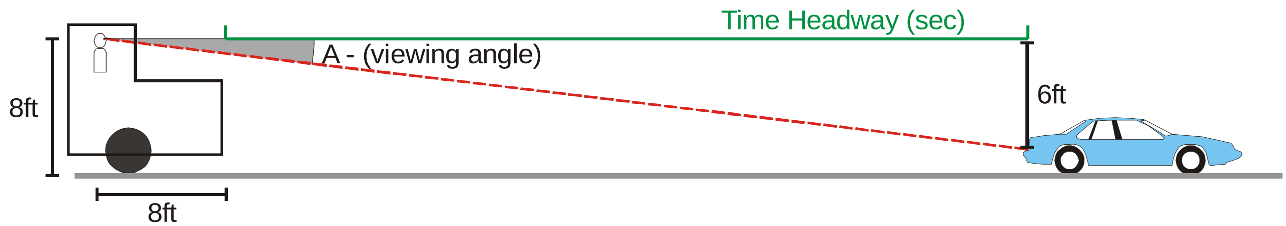


Figure 2. Values used to calculate viewing angle A. Note that the horizontal plane = 0 degrees.

2.3 Results

The results are shown below in Figure 3. Expected gaze angle is only more than 5 degrees below the horizontal plane at the closest time headways (e.g., < 1.5 sec) and slowest speeds (e.g., 25 mph). Also, because of the short headway in the few cases in which the expected gaze angle is significantly farther down than 5 degrees, a driver would have to have a great deal of confidence that the lead vehicle was not going to slow if he or she wanted to look away from the lead vehicle and towards the DIU. Furthermore, the time spend driving under these conditions is probably too small for drivers to gain a noticeable functional benefit from the reduced gaze angle to the DIU.

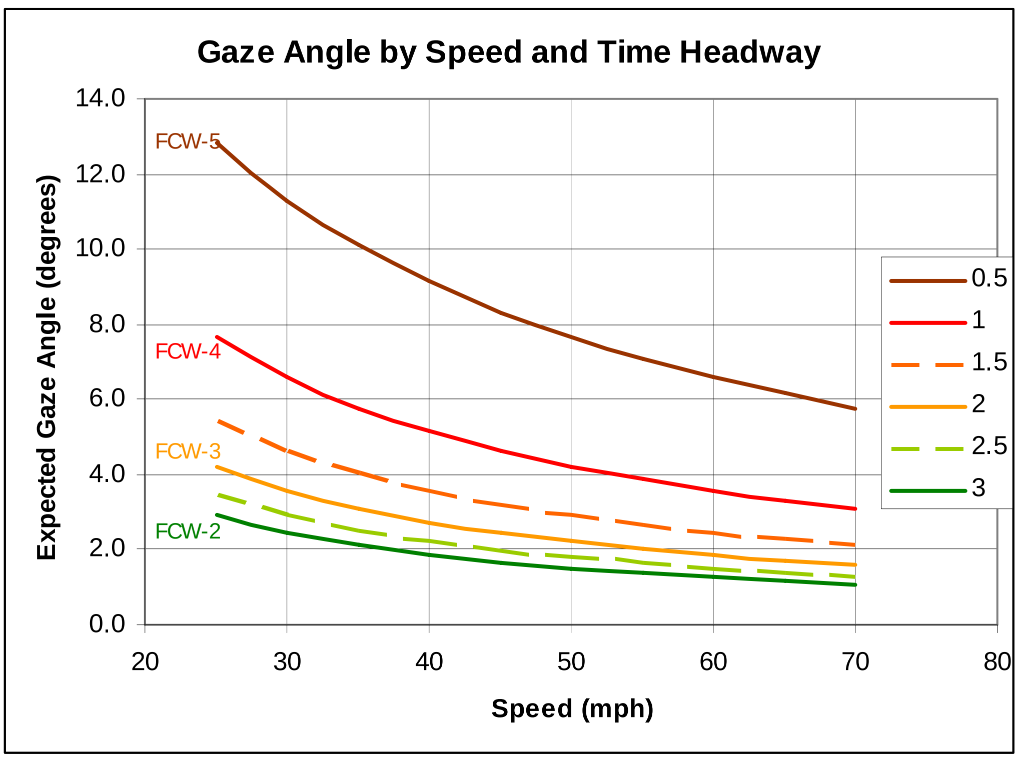


Figure 3. Expected gaze angle as a function of speed and time headway (colored lines). The time-headways corresponding with FCW alerts are shown in solid lines.

2.4 Conclusions

Assumptions about expected gaze angle of HT drivers during car following situations should be limited to, at most, 2-4 degrees down from the horizontal. Given the variability across drivers with respect to eye height, as well as the task-driven and therefore dynamic nature of eye movements while driving, this finding does not support changing the current DVI specification with respect to display location.

3 “Opening vs. Closing” Display Analysis

An important unresolved DVI issue is to determine the best warning approach for situations in which the lead vehicle has a short headway (within FCW-3 or 4 range) but is *opening* relative to the SV. The current IVBSS HT DVI specification provides for both visual and auditory warnings in FCW-3 and FCW-4 situations in which the SV is *closing* on the POV, but treats *opening* conditions as an FCW-1 situation. This memo describes an analysis conducted to compare two possible approaches, and provides a recommended approach based on this analysis.

The two different approaches considered were:

1. *Visual Opening Display*: This involves showing a visual FCW DIU message (but no auditory warning) under headway opening conditions. This display would continue until the headway conditions for that warning state are no longer met[2].
2. *No Visual Opening Display*: This involves terminating the visual FCW DIU message if the lead vehicle is no longer closing, even though reduced headway conditions persist (the “Object Detected”/FCW-1 message would be shown instead). This is the approach currently adopted in the DVI specification.

3.1 Methods

The two different approaches were compared and contrasted based on a variety of different aspects, such as the information they provide in general and under FCW conditions, assumptions about safety, and the mental models that describe them. These analyses were conducted in two different ways. The first identified general differences between each warning approach, and the second identified differences that occur specifically the context of relevant driving scenarios (e.g., going from FCW-2 to FCW-3 and back). The results are presented in separate tables corresponding to the General Analysis and the Scenario Analysis, respectively. Appendix B, provides details of the Scenario Analysis for each scenario considered.

3.2 Results

The results of the General Analysis are shown in Table 3.

[2] This approach further assumes that FCW-2 visual messages are presented in the DIU in the same manner as the FCW-3 and 4 visual messages in opening conditions. This is to maintain display consistency in terms of the system providing continuous headway information.

Table 3. General differences between the "Visual Opening Display" and the "No Visual Opening Display" warning approaches.

Type of Information	Description	Visual Opening Display	No Visual Opening Display
Warning Definition	How the threat is defined according to the feedback that drivers receive from the DVI. It reflects how the displays change with changing conditions.	Based on headway – the warning information (visual display) remains unchanged until the next-lower headway condition occurs.	Based on closing rate – the warning information (visual display) changes as soon as the headway is no longer closing.
Mental Model	The simplest plausible mental model that drivers could adopt based on how the system operates.	The visual display provides headway information and the auditory display provides additional information about closing threats.	Both the auditory and visual displays provide information about closing threats; headway information is only provided in closing situations.
Display consistency	The extent to which the system operates in a consistent manner across different situations.	Visual displays are sometimes associated with auditory displays and sometimes not.	Visual and auditory displays occur together, but the visual display will continue until the closing threat is eliminated. An inconsistent aspect of this display is that the FCW-1 message is shown under FCW-3 or 4 headway conditions if P1 is not closing.
Headway Info for Learning	Availability of headway information over time to help drivers learn what their current headway distance is.	Continuous	None/Indirect*

* Over time, drivers will get indirect information about headway because they will get repeated FCW-3 messages (due to speed variability) if headway is less than 2 sec, but not if it is greater)

The Scenario Analysis identifies differences between the each approach as evident in specific driving situations. The scenarios analyzed include:

1. *FCW-2 to FCW-3 Scenario:* The SV closes on P1 until the FCW-3 message is displayed, then the SV decelerates until a safe headway is obtained.
2. *FCW-2 to FCW-4 Scenario:* The SV closes on P1 until the FCW-4 message is displayed, then the SV decelerates until a safe headway is obtained.
3. *FCW-3 to FCW-3 Scenario:* The SV maintains a constant or opening headway of < 2 seconds, then P1 closes on the SV and the SV decelerates until a safe headway is obtained.

4. *FCW-2 to FCW-3 with Inadequate Response Scenario:* The SV closes on P1 until the FCW-3 message is displayed, then the SV decelerates but deceleration is initially insufficient to halt closing (i.e., P1 may be decelerating more) before opening up again.

The results of the Scenario Analysis are shown in Table 4.

Table 4. Differences between the "Visual Opening Display" and the "No Visual Opening Display" warning approaches as identified in the Scenario Analysis.

Type of Information	Description	Visual Opening Display	No Visual Opening Display
Warning-specific Information	The new warning information (change in Auditory/Visual display) that is specifically tied to the onset of the threat condition.	Mostly Visual and Auditory but sometimes Auditory only.*	Auditory and Visual
Threat Persistence Feedback	Information that indicates that threat conditions persist.	None	Visual warning display continues as long as the closing conditions persist.
Threat Resolution Feedback	Information that indicates that threat has ended.	None	Visual warding display is extinguished (goes to FCW-1).
Headway Info (for response)	Availability of headway information feedback that driver can use to reach a safer headway distance (e.g., > 2sec) during the driver's response.	Continuous headway information presentation.	None/Indirect**
Inherent Safety Risks	The primary safety risks associated with using one approach over the other.	Driver response is inadequate to eliminate the threat conditions and the DVI provides no indication of this.	FCW-3 or 4 opening is treated by the DVI as an FCW-1 even though the short headway leads to significantly reduced margin of error.
Key assumptions	Important assumptions that each approach makes regarding the driver's response to a warning message.	Driver is able to recognize if they have made an inadequate response, and will act promptly to rectify the inadequate response.	Driver will act safely and knowledgably and get to a safe headway without undue delay.

* Information is auditory only if the warning condition is triggered without a transition between different warning categories (e.g., FCW-4 when headway is already in FCW-4 range).

** Over time, drivers will get indirect information about headway because they will get repeated FCW-3 messages (due to speed variability) if headway is less than 2 sec, but not if it is greater).

3.3 Discussion

3.3.1 Visual Opening Display

This approach provides more continuous and higher resolution information about headway at the expense of less salient and potentially more ambiguous closing information about forward collision threats. This ambiguity occurs under some conditions (e.g., an FCW-4 when the already in FCW-4 range) because the only unique warning information is the auditory message. In addition, this approach does not provide feedback to the driver that the response was sufficient to address the closing aspect of the forward collision threat. That said, these limitations are tied to the definition of what the threat is. If the overriding threat is a short headway, then this approach provides clear information, however, if the overriding threat is confined to the closing rate, then this information is less precise.

Another potential concern associated with this approach is the apparent display inconsistencies that arise from visual warning messages not always being directly tied to auditory messages because the auditory messages do not occur under opening conditions. Note that this is not necessarily problematic because the overall system function can still be represented with a simple and intuitive mental model.

3.3.2 No Visual Opening Display

This approach maintains stricter display consistency in terms of visual and auditory message co-occurrence and provides higher resolution temporal information about when forward vehicles are no longer closing. However, the analyses identified several drawbacks with this approach. These include:

- Headway information is limited to closing situations. As soon as the lead vehicle is no longer closing, headway information becomes unavailable and it is up to the driver to determine the appropriate headway.
- Similarly, this overall approach relies heavily on the assumption that drivers are motivated and able to assume a safe headway on their own. If drivers do not consistently do this, it can lead to an increased crash risk (e.g., if the headway is at FCW-4 levels (>1sec) and the P1 vehicle decelerates abruptly).
- Although this approach maintains consistent use of auditory and visual messages in closing situations, there are still important ways in which this presentation approach leads to display inconsistencies. In particular, in non-closing situations, the FCW-1 message is presented even though the headway conditions are consistent FCW-3 and 4 conditions rather than FCW-1 headway conditions.

3.4 Conclusions

On balance the results of these analyses suggest that the “visual opening display” strategy is the best option in terms of providing clear headway information that supports safe driving practices, while—at the same time—not being overly complex or inconsistent. Consequently, it is recommended that the IVBSS HT DVI specification be revised to reflect this approach.

Note that if the information about when the SV is no longer closing on P1 is considered to be important (e.g., feedback that the speed-change response was sufficient), it may be useful to investigate alternative methods for providing this feedback to drivers. One option is to use the LED bands on the DIU to indicate closing information, while using the LCD display to present the headway conditions (e.g., use the LED as a “no visual display on opening” display, and the LCD as a “visual display on opening” display).

3.5 Next Steps

If the proposed change to the DVI specification is accepted, the following additional activities will have to be conducted:

1. Modify the DVI specifications.
2. Add new rows to the Permutations Table and revise the Worksheets document accordingly.
3. Look for new rule exceptions that arise from the changes (specifically with regard to concurrent LDW messages).

4 Cut-in Analysis

4.1 Executive Summary

This memo report discusses how cut-in FCW situations affect the usefulness of lower-level FCWs. The potential safety problem with cut-ins is that the P1 vehicle can come into conflict with the SV at a variable headway distance and with different kinematic conditions. This can undermine the effectiveness of lower-level FCW alerts because drivers could get FCW-1/2b/3b/4b alerts that have significantly less available response time than under typical FCW conditions.

The objective of the current analysis is to determine if there are FCW-1/2b/3b/4b situations following cut-ins in which SV drivers could get more effective warning if the system escalated the initial FCW-1/2b/3b/4b immediately to an FCW-5/7 (referred to as the *Escalation Approach*) in comparison to the current FCW implementation (referred to as the *Typical FCW Approach*).

The potential benefits of using an Escalation Approach were examined for specific situations in which cut-ins produce different kinematic conditions than standard forward collision situations where the P1 vehicle originates in the SV lane. The conditions examined and their associated findings are summarized in the table below.

Table 5.. Conditions and finding for non-standard forward collision situations.

Situations/Conditions Examined	Findings
Cut-ins that cause reduced headway. - These are the same as constant-speed standard forward-originating FC situations but the cut-in point leads to a lower initial headway distance.	• Under worst case relative speeds (P1 = 80.1% SV speed), drivers should be able to avoid crashes for all but the shortest cut-in headways, and if crashes occur they are likely to involve low relative speeds. • An Escalation Approach does not seem to provide any significant advantages for cut-ins involving constant 80.1% relative speeds.
Cut-ins involving greater variability in P1 kinematics at the time of lane entry. - This specifically examined a P1 vehicle that was decelerating at the time of the cut-in.	• If the P1 vehicle is decelerating at a moderate or high level, bumper-kiss collisions can occur at relatively long headways, even if the SV driver responds immediately to the first FCW alert provided (Escalation Condition). • Potential crashes under these conditions are likely to occur at higher relative speeds. • An Escalation Approach is likely to provide a significantly better warning to an SV driver for the time headways examined.
Cut-ins that involve speed adjustments (e.g., P1 decelerating) shortly after the cut-in maneuver.	• Formal analyses were not conducted on these scenarios. • The worst case versions of these situations are likely to be worse than the worst-case decelerating P1 vehicles. • A complicating factor is that the P1 vehicle is likely to have been in SV lane for a short time before the speed adjustment, which means that these situations cannot be covered by the same rules as the strict cut-in situations described above.

4.1.1 Disadvantages of Accommodating Cut-ins with New FCW Rules

Although there appears to be a case for developing special procedures for addressing certain cut-in situations (e.g., decelerating P1), there are potential disadvantages to doing so. These include:

- Increased system complexity and corresponding increase in mental model complexity.
- Increased potential for false alarms.

Additional on-road data is required to conduct a proper analysis of the relative benefits of accommodating cut-in situations.

4.1.2 Conclusions

The findings from the current analyses are summarized below regarding the gaps in the current FCW approach and future data requirements.

Gaps/suboptimal aspects of the current FCW approach:

- Cut-ins involving a P1 that is decelerating at the time of lane entry.

- Cut-ins that are followed by a P1 vehicle speed adjustment (unconfirmed but likely).

Future data requirements:

- Frequency with which different cut-in situations occur.
- Information about how drivers respond to FCW alerts of different levels.
- Additional analyses of the impacts of FCW system changes on the driver mental model and on potential false alarm rates.

4.1.3 Recommendations

1. It is recommended that the current FCW rules not be changed to accommodate cut-ins at this time. Although potential gaps were found in the current approach with regard to decelerating P1 vehicles, it is not possible to evaluate whether or not changing the current FCW rules would yield a net improvement in FCW system effectiveness.
2. It is recommended that the on-road data specified under “Future Data Requirements” above be collected in order to enable an analysis of the whether or not changing the FCW rules would lead to an overall improvement in system effectiveness.

4.2 Cut-in Analysis

This memo report discusses how cut-in FCW situations affect the usefulness of lower-level FCWs.

Cut-in situations differ from the typical FCW situation in which the P1 (forward) vehicle hazard is initially in the same lane as the SV and closing. In this standard case, the warning levels will progress in an expected manner and with a predictable time course based on relative SV and P1 vehicle speeds. In contrast, with cut-ins, the P1 vehicle can come into conflict with the SV at a variable headway distance and with different kinematic conditions. This has the potential to undermine the effectiveness of lower-level FCW alerts because drivers could get FCW-1/2b/3b/4b alerts that have significantly less available response time than under typical FCW situations.

The objective of the current analysis is to determine if there are FCW-1/2b/3b/4b situations following cut-ins in which SV drivers could get more effective warning if the system escalated the initial FCW-1/2b/3b/4b immediately to an FCW-5/7 (i.e., rather than the current approach of presenting the lower level FCW alert initially, then waiting for the FCW-5/7 alert to occur based on evolving kinematic conditions). These situations are referred to respectively as the *Escalation* and *Typical FCW Approach*es in the remainder of this document.

Note that utility of escalating lower-level FCW alerts depends on how drivers’ respond to various warning levels. For example, if drivers consistently decelerate immediately following an FCW-4b involving a cut-in, there would be no benefit of escalating that FCW-4b to an FCW-5/7 because it already consistently elicits the optimal driving response. On the other hand, if the typical response to an FCW-4b following a cut-in is for drivers to look at the P1 but keep their foot on the accelerator pedal, then escalating the initial FCW-4b to an imminent warning could provide additional response time that allows drivers to avoid a collision under certain conditions.

The steps taken in the determining if there was any real safety advantage to escalating lower-level FCW alerts in cut-in situations are listed below.

1. Identify specific safety-relevant ways in which Cut-ins differ from standard FCW situations, and that can be addressed by changes to the warning rules.
2. Determine under which kinematic conditions the current set of FCW rules are suboptimal (i.e., if the SV driver would be better served by getting a FCW-5 immediately (Escalation Approach), instead of an FCW-2b/3b/4b (Typical FCW Approach)).
3. If the existing FCW rules are suboptimal, do the advantages of changing the rules outweigh the potential costs (e.g., increased false alarms)?

These steps are discussed in the following sections.

4.2.1 Identify Specific Safety-Relevant Ways In Which Cut-Ins Differ

Identifying the specific ways in which cut-in situations differ from standard FCW situations is a necessary first step because it indicates what driving conditions need to be investigated in order to find potential shortcomings of the Typical FCW Approach and/or define potential benefits of using an Escalation Approach. At the same time, not all conditions warrant further analysis if 1) they have no safety impacts or 2) cannot be addressed by altering the current FCW rules/algorithm.

Four ways in which cut-ins differ when compared with the standard FCW scenario ways were identified. These include:

1. The full progression of warnings may not be triggered (e.g., an FCW-4b can be the first warning that the driver receives).
2. The time before the next-higher warning level occurs can be reduced if the P1 vehicle cuts in partway through the time headway zone.
3. The P1 vehicle kinematics can be more varied at the time the first FCW alarm occurs (e.g., it can be accelerating, decelerating, going a constant but slower speed, etc.).
4. The P1 vehicle is more likely to make speed adjustments once established in the lane (e.g., if it has a vehicle in front of it).

The safety implications associated with each of the conditions described above, and potential FCW rule/algorithm changes to address them are shown in Table 6.

Table 6. Ways in which cut-in situations differ from standard FCW conditions, in addition to their associated safety implications, and ways that the FCW system can be altered to address them.

Conditions	Safety Implications	Potential FCW Changes
1. The full progression of warnings may not be triggered.	Less advance warning of emerging conditions.	None (but a cut-off detection warning system could be developed based on IVBSS sensor data).
2. The time before escalation to the next warning level may be reduced.	Reduction in available RT for a particular FCW level.	Lower-level FCW alerts can be automatically escalated to FCW-5/7.
3. The P1 vehicle kinematics can be more varied at the time the FCW alarm occurs.	Significant reduction in available RT for a particular FCW level if P1 is already decelerating.	Lower-level FCW alerts can be automatically escalated to FCW-5/7.
4. The P1 vehicle is more likely to make speed adjustments once established in the lane.	Reduction in available RT for a particular FCW level and lack of temporal cues that situation is the result of an earlier cut-in.	Exception to current arbitration rules that take into account the possibility of a cut-in within the last X seconds.

4.2.2 Determine Under Which Conditions The Typical FCW Approach Is Sub-Optimal

The Factors identified in the previous step describe potential conditions in which the currently implemented FCW system potentially provides sub-optimal warning in cut-in situations. Note that the first condition identified (i.e., the full progression of warnings may not be triggered) cannot be addressed by changes to the current rules, so it is not discussed further. For the remaining three conditions, we investigated whether or not SV drivers could get a meaningful increase in available RT using an Escalation Approach than the Typical FCW Approach. Specifically, the three conditions analyzed included:

- Cut-ins causing reduced headway.
- Greater variability in P1 kinematics at the time of the first FCW Alert.
- Cut-ins that are followed by P1 speed adjustments.

4.2.3 Cut-ins Causing Reduced Headway

The first set of situations examined are those that are similar to the standard FCW alert situations, except that the initial FCW alert is occurs with reduced headway because the cut-in occurs partway into the FCW zone (i.e., compared if the P1 vehicle was in front of the SV the entire time; see Figure 4). These situations occur when both the SV and the P1 vehicle are traveling at a constant speed at the moment that the P1 enters the FCW detection zone.

The primary condition of concern in this case is when the P1 vehicle has a constant speed that is between 80.1 to 100% of the SV speed. If the P1 is going the same speed or faster, the SV should be able to avoid a conflict by adjusting speed to regain adequate headway. These conditions would only become problematic if the P1 vehicle made an additional speed adjustment, and these situations are covered below. Furthermore, if the P1 is traveling at 80% of the SV speed or less, the first FCW alert is already the highest priority alert (e.g., FCW-5/7), so there would be no advantage to employing an Escalation Approach under these conditions.

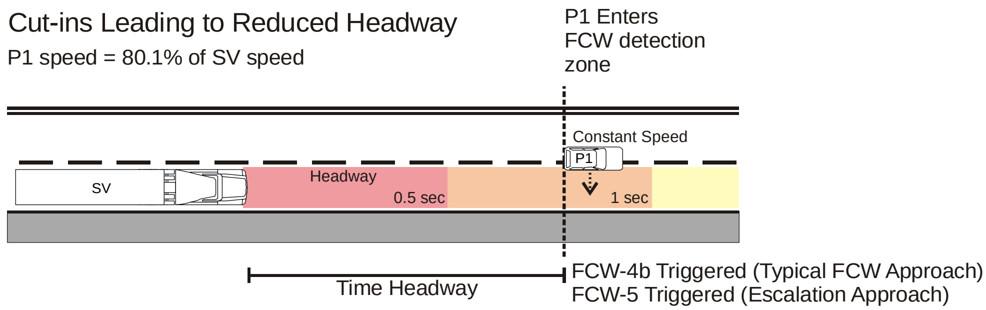


Figure 4. Example of a cut-in that leads to reduced warning headway for an FCW alert.

The analysis in this section compares the benefits of an Escalation Approach compared to the Typical FCW Approach. The objective of this analysis is to determine the maximum benefit obtained with Escalation Approach, in which the driver breaks immediately upon getting the first post-cut-in FCW alert, versus if the driver instead waits until the initial lower-level FCW alert becomes an FCW-5 before responding.

Escalation Approach: With the Escalation Approach, if a fixed RT (e.g., 1.5 sec) is assumed, it is possible to calculate the closest headway at which a cut-in can occur and that the SV driver still has time to just avoid a bumper-kiss collision. Note that this also assumes that the SV driver responds immediately following the cut-in (e.g., if the FCW-4 was automatically escalated to an FCW-5). The results for different SV absolute speeds and SV deceleration levels are shown in the “Time Headway” column in Table 7. For example, in the first row, if a P1 vehicle going 52 mph cuts in front of the SV traveling at 65 mph with a time headway of 0.58 sec, the SV will just avoid a bumper kiss if the driver can initiate breaking at 0.40g within 1.5 seconds of the cut in (see Figure 5A). If the P1 vehicle cuts in with less headway or if the SV driver takes longer than 1.5 seconds to respond, a collision will occur (although at low relative speed). Note that of the two SV deceleration levels shown in Table 7, the 0.4g level reflects a hard-braking response, while the lower 0.25g level reflects a more gradual response that is likely to be unrealistic under these urgent braking conditions, but was included for comparison purposes.

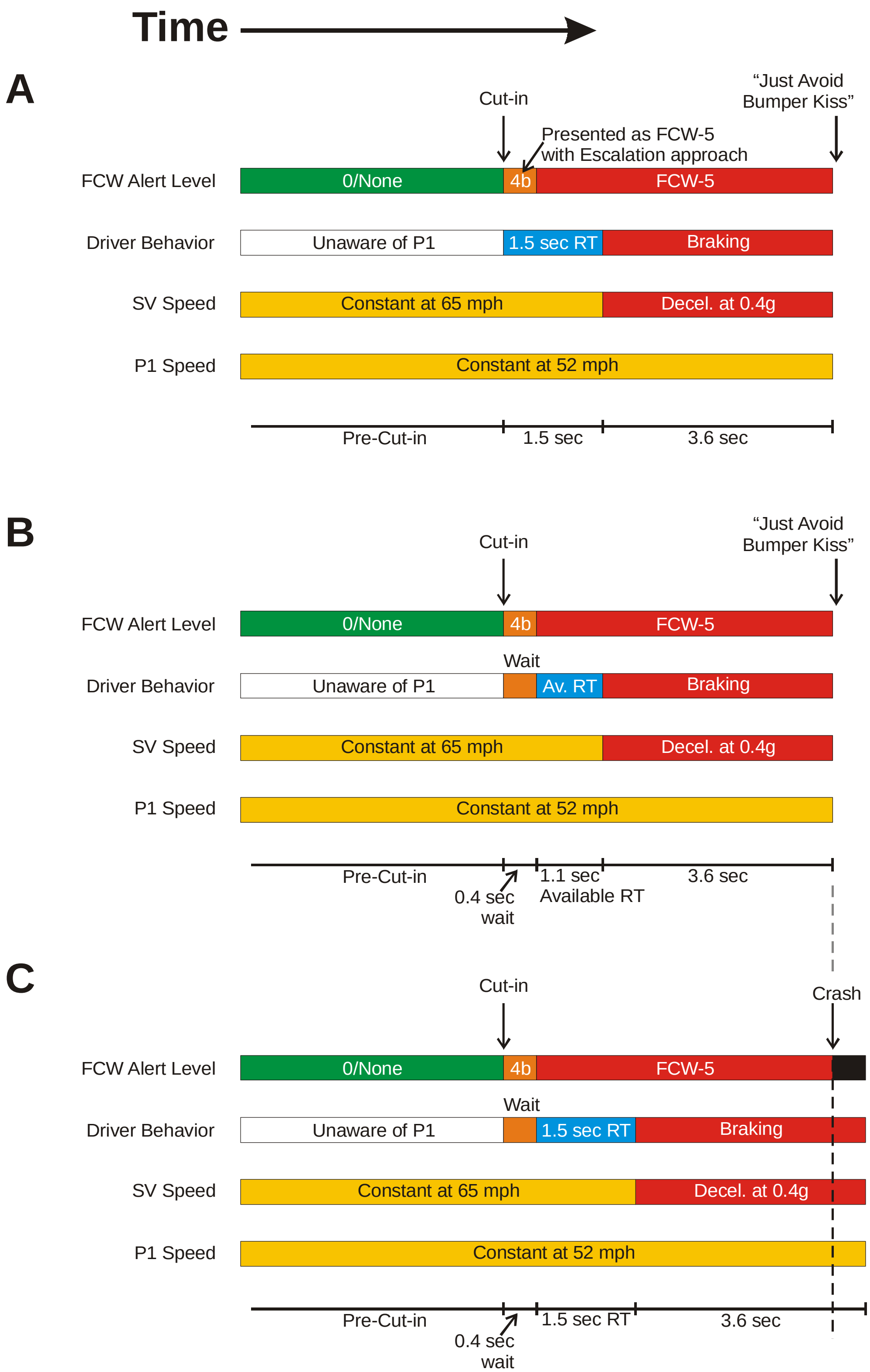


Figure 5. Time lines for cut-in situation in which the P1 vehicle enters the lane at the shortest headway at which a "bumper-kiss" collision can just be avoided. The different parts show: A) SV the driver breaking immediately after the first FCW alert onset, and B and C) the SV driver waiting until the FCW-5 before initiating a response (with different RT assumptions).

In Table 7, the P1 vehicle is assumed to be traveling at constant speed of 80.1% the SV speed, which represents the worst-case relative speed condition. Note also, that the assumed RT of 1.5 seconds is likely to be overly conservative, because if the alert that occurs at the time of cut in is an FCW-5 (Escalation Condition), and drivers know that it represents an imminent collision situation, they can initiate braking, saving response time that would otherwise have been taken up by assessing the situation and making a decision about how to respond.

Table 7. Shortest possible Time Headway at which a P1 vehicle traveling at 80.1% of SV speed can cut in and which the SV driver can just avoid a "bumper-kiss" collision.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2); A_{P1} = 0 g (-0 m/s^2); V_{P1} = V_{SV} x 80.1%

A_{SV}	V_{SV} (mph)	V_{P1} (mph)	Time Headway (sec)	Initial Warning
-0.4 g (-3.92 m/s^2)	**65**	**52**	0.58	FCW-4
	55	**44**	0.56	FCW-4
	45	**36**	0.53	FCW-4
	35	**28**	0.51	FCW-4
	25	**20**	0.49	FCW-5
-0.25 g (-2.45 m/s^2)	**65**	**52**	0.67	FCW-4
	55	**44**	0.63	FCW-4
	45	**36**	0.59	FCW-4
	35	**28**	0.56	FCW-4
	25	**20**	0.52	FCW-4

Typical FCW Conditions: The information about the shortest crash-avoidable headway in the Headway Time column of Table 8 can be used to estimate the maximum relative benefits provided by an Escalation Approach compared to if the driver does not begin responding until the conditions raise the warning level to FCW-5. This can be done by calculating the available RT following the onset of the FCW-5 assuming the same vehicle kinematic conditions and the same shortest crash-avoidable headway as in the Escalation-approach analysis above.

The "Available RT at FCW-5" column in Table 8 indicates how much time the driver has to initiate braking following the onset of the FCW-5 alert and still just avoid a bumper-kiss collision. The Available RT is equal to 1.5 sec (assumed RT in the Escalation Condition example) minus the duration of the FCW-4b alert ("Time before FCW-5 onset" column in Table 8), which represents the time that the driver waits before initiating a braking response following. Available RT can be calculated in this way because the SV driver has to initiate deceleration at the same time (as in the Escalation Approach) following the initial alert if the SV is to stop in time to avoid a collision. Thus, if drivers wait before initiating a response (for the duration of the FCW-4b), they have less available RT before they reach the required deceleration point. This is also illustrated by comparing Figure 5B with 2A. It should be noted that just because the available RT is less than in the Escalation Condition, it does not mean that the same driver would not be able to respond effectively with less time available. More specifically, if the duration *before* the FCW-5 is sufficiently long, drivers may have enough time become alerted and assess the situation, which could reduce the response time they need after the FCW-5 alert to initiate deceleration.

Table 8. Time before FCW-5 onset (aka FCW-4b duration) and Available RT after FCW-5 onset for a cut-in involving a SV driver just avoiding a "bumper-kiss" collision with P1 vehicle traveling at 80.1% of SV speed.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2); A_{P1} = 0 g (-0 m/s^2);V_{P1} = V_{SV} x 80.1%

A_{SV}	V_{SV} (mph)	V_{P1} (mph)	Time Headway (sec)	Initial Warning	Time before FCW-5 Onset (sec)	Avail RT at FCW-5
-0.4 g (-3.92 m/s^2)	65	52	0.58	FCW-4	0.41	1.09
	55	44	0.56	FCW-4	0.30	1.20
	45	36	0.53	FCW-4	0.15	1.35
	35	28	0.51	FCW-4	0.05	1.45
	25	20	0.49	FCW-5	0.00	1.50
-0.25 g (-2.45 m/s^2)	65	52	0.67	FCW-4	0.86	0.64
	55	44	0.63	FCW-4	0.66	0.84
	45	36	0.59	FCW-4	0.46	1.04
	35	28	0.56	FCW-4	0.30	1.20
	25	20	0.52	FCW-4	0.10	1.40

The Typical FCW Conditions analysis indicates that there is some reduction in available RT if drivers wait for the FCW-5 alert before initiating a response. However, the reduced available RT may be offset somewhat by the advanced warning time provided by the FCW-4b. An important question is whether or not this reduced available RT has significant safety consequences. This question can be answered by assuming a worst case scenario in which the driver waits for the FCW-5 onset before initiating a response, and then further assuming that the driver takes the full 1.5 response time before initiating braking (i.e., that there is no alerting benefit of the prior FCW-4b). Under these conditions there will always be a crash because the driver is unable to initiate braking by the time required by the given deceleration level (see Figure 5C). Thus, the severity of the crash can be indicated by the relative speed between the SV and the P1 vehicle at the time of contact. Table 9 is the same as Table 8, but with th addition of a final column in that shows the relative speed of the SV and P1 vehicles at the time of impact.

Table 9. Relative SV-P1 speed at impact in a cut-in situation, assuming that the SV driver takes the full 1.5 second RT to initiate response following the onset of the FCW-5 alert.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2);A_{P1} = 0 g (-0 m/s^2); V_{P1} = V_{SV} x 80.1%

A_{SV}	V_{SV} (mph)	V_{P1} (mph)	Time Headway (sec)	Initial Warning	Time before FCW-5 Onset (sec)	RT (sec)	Relative Speed at Impact (mph)
-0.4 g (-3.92 m/s^2)	**65**	**52**	0.58	FCW-4	0.41	1.5	9.15
	55	**44**	0.56	FCW-4	0.30	1.5	6.98
	45	**36**	0.53	FCW-4	0.15	1.5	4.70
	35	**28**	0.51	FCW-4	0.05	1.5	1.85
	25	**20**	0.49	FCW-5	0.00	1.5	—
-0.25 g (-2.45 m/s^2)	**65**	**52**	0.67	FCW-4	0.86	1.5	10.7
	55	**44**	0.63	FCW-4	0.66	1.5	8.69
	45	**36**	0.59	FCW-4	0.46	1.5	6.62
	35	**28**	0.56	FCW-4	0.30	1.5	4.50
	25	**20**	0.52	FCW-4	0.10	1.5	2.15

4.3 Reduced Headway Cut-ins Summary and Conclusions

The preceding analysis examined the magnitude of potential safety benefits that could be gained by using an Escalation Approach following cut-in rather than the Typical FCW Approach. The key findings are as follows:

- Under worst-case relative speed conditions, cut-ins can occur relatively close to the FCW-4b/FCW-5 boundary and a driver responding within 1.5 seconds will typically be able to just avoid a bumper-kiss collision
- Under high-speed conditions, an Escalation Strategy provides longer available RTs at the same time headway in comparison to the Typical FCW Approach, however, these benefits are likely offset somewhat with the Typical approach because drivers gain an alerting benefit from the FCW-4b.
- Under the worst-case response time conditions (i.e., no FCW-4b alerting benefit), the resulting crashes occur at slow relative speeds (e.g., < 10 mph).

Based on the findings described above, the benefits of implementing an Escalation Approach do not appear to be significant.

4.3.1 Greater Variability in P1 Kinematics at Time of First FCW Alert

Another important difference between cut-in situations and standard FCW situations in which the P1 vehicle originates in the SV lane is that, with cut-ins, the P1 vehicle can have greater variability in terms of its speed and acceleration/deceleration at the time the first FCW alert is presented. This is compounded by the fact that the time headway when the first FCW alert occurs can be reduced, which can make more difficult or impossible for the SV driver to avoid a crash. Examples of some of these variable kinematic situations are shown in Table 10.

Table 10. Examples of cut-in scenarios involving a different P1 kinematics at the time of the first FCW alert.

Cut-in Scenario	P1 Kinematics at Lane Entry (first FCW)
P1 entering a gap in traffic in SV lane from a faster moving lane.	Decelerating from greater than SV speed.
P1 cutting in at last minute to get over to a quickly passing highway exit.	Decelerating from slightly greater, same, or less speed than SV.
P1 changes into SV's lane from a slower-moving lane.	Accelerating from less than SV speed.
P1 passing in open road.	Accelerating or traveling at a constant speed that is greater than the SV.

Cut-ins with Decelerating P1

A analysis similar to the one conducted in the previous section was used to investigate whether or not SV drivers would be better served by an Escalation Approach compared to the Typical FCW Approach with cut-ins associated with greater variability in P1 vehicle kinematics at the time of lane entry. Given the large number of different P1 vehicle speed and acceleration/deceleration combinations that are possible, the analysis focused on the worst-case scenario, in which the P1 vehicle is already decelerating at the time of lane entry. These situations yield the shortest Time-To-Collision values given the same time headway conditions.

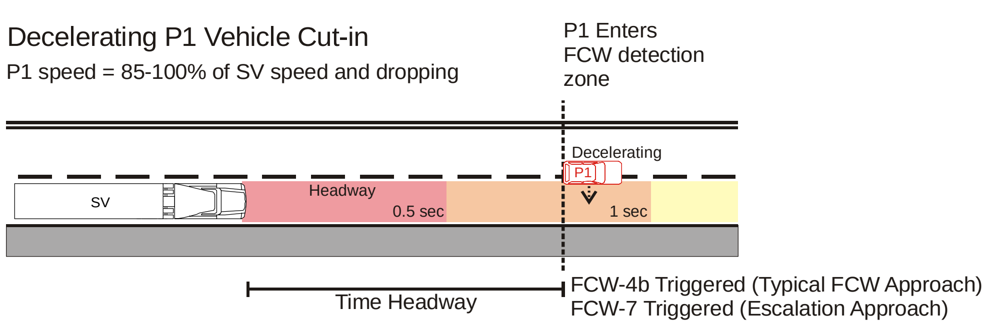


Figure 6. Example of cut-in situation involving a decelerating P1 vehicle.

In the current analysis, the minimum cut-in time headway was calculated for different SV and P1 deceleration rates. One aspect of the current analysis that was different than in the previous analysis was that the relative speed of the SV and P1 vehicles was varied from 85 or 90% to 100%. The reason for this is that the 80.1% relative speed used in the constant-speed analysis above would immediately lead to the highest level FCW alert if the P1 vehicle is decelerating. Using P1 speeds that were closer to the SV speed provides a more sensitive analysis of the potential benefits of an Escalation Approach because it focuses more on the lower-level FCW alert duration.

The kinematic analysis results are shown in Table 11, Table 12, and Table 13. Each of these tables combines the three analyses conducted in the previous section in separate rows, including:

- *Analysis 1*: Determine the shortest cut-in headway for which the SV driver can just avoid a bumper-kiss collsion (assuming a 1.5 second RT initiated immediately following the first FCW alert)
- *Analysis 2*: Determine the available RT if the SV driver waits until the FCW-5/7 before initiating a response
- *Analysis 3*: Determine the relative speed at impact, assuming that the SV driver waits until the FCW-5/7 before initiating a response, and that the response time is 1.5 seconds

Error! Reference source not found., Table 12, and Table 13 below show the results of the kinematic analyses for three P1 deceleration conditions. In the first, the P1 decelerates hard and faster than the SV, in the second table, the P1 decelerates at a moderate level, but less than the SV, and in the third table, the P1 decelerates gradually.

Table 11. Results of the kinematic analyses in conditions in which the P1 vehicle decelerates hard and at a greater level than the SV for various relative speed conditions at time of lane entry.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2); A_{P1} = -0.46 g (-4.51 m/s^2)

V_{REL}	V_{SV}	V_{P1}	*Analysis 1:* Time Headway (sec)	Initial Warning	*Analysis 2:* Time before FCW-7 Onset (sec)	*Analysis 2:* Avail RT at FCW-7	*Analysis 3:* Relative Speed at Impact (mph)
90%	65	59	3.24	FCW-1	2.89	0.00*	57.3
	55	50	3.07	FCW-1	1.47	0.03	37.6
	45	41	2.91	FCW-2	0.45	1.05	18.6
	35	32	2.74	FCW-2	0.35	1.15	14.4
	25	23	2.57	FCW-2	0.25	1.25	10.2
95%	65	62	2.94	FCW-2	2.59	0.00	52.3
	55	52	2.82	FCW-2	0.83	0.67	28.2
	45	43	2.70	FCW-2	0.68	0.82	23.0
	35	33	2.57	FCW-2	0.52	0.98	17.9
	25	24	2.45	FCW-2	0.37	1.13	12.7
100%	65	65	2.63	FCW-2	2.05	0.00	44.8
	55	55	2.56	FCW-2	1.09	0.41	32.3
	45	45	2.48	FCW-2	0.89	0.61	26.5
	35	35	2.40	FCW-2	0.70	0.80	20.6
	25	25	2.33	FCW-2	0.50	1.00	14.7

Available RT is actually less than zero, which means that a crash is unavoidable under these conditions.

Table 12. Results of the kinematic analyses in conditions in which the P1 vehicle decelerates hard and at a greater level than the SV for various relative speed conditions at time of lane entry.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2); A_{P1} = -0.35 g (-3.43 m/s^2)

V_{REL}	V_{SV}	V_{P1}	*Analysis 1:* Time Headway (sec)	Initial Warning	*Analysis 2:* Time before FCW-7 Onset (sec)	*Analysis 2:* Avail RT at FCW-7	*Analysis 3:* Relative Speed at Impact (mph)
90%	65	59	2.42	FCW-2	0.85	0.65	25.3
	55	50	2.38	FCW-2	0.72	0.78	23.9
	45	41	2.34	FCW-2	0.59	0.91	21.5
	35	32	2.30	FCW-2	0.46	1.04	16.7
	25	23	2.25	FCW-2	0.33	1.17	11.9
95%	65	62	2.03	FCW-2	1.27	0.23	26.5
	55	52	2.05	FCW-2	1.08	0.42	24.8
	45	43	2.06	FCW-2	0.88	0.62	23.2
	35	33	2.08	FCW-2	0.69	0.81	20.5
	25	24	2.10	FCW-2	0.49	1.01	14.6
100%	65	65	1.62	FCW-3	1.70	0.00*	27.5
	55	55	1.69	FCW-3	1.44	0.06	25.6
	45	45	1.78	FCW-3	1.12	0.38	23.7
	35	35	1.86	FCW-3	0.91	0.59	22.0
	25	25	1.94	FCW-3	0.65	0.85	16.9

* Available RT is actually less than zero, which means that a crash is unavoidable under these conditions.

Table 13. Results of the kinematic analyses in conditions in which the P1 vehicle decelerates at a gradual level that is less than SV deceleration for various relative speed conditions at time of lane entry.

Initial Conditions: A_{SV} = -0.40 g (-3.92 m/s^2); A_{P1} = -0.18 g (-1.76 m/s^2)

V_{REL}	V_{SV}	V_{P1}	*Analysis 1:* Time Headway (sec)	Initial Warning	*Analysis 2:* Time before FCW-7 Onset (sec)	*Analysis 2:* Avail RT at FCW-7	*Analysis 3:* Relative Speed at Impact (mph)
85%	65	55	0.99	FCW-4	0.83	0.67	16.9
	55	47	1.02	FCW-3	0.70	0.80	14.7
	45	38	1.06	FCW-3	0.58	0.92	12.7
	35	30	1.14	FCW-3	0.45	1.05	10.6
	25	21	1.30	FCW-3	0.32	1.18	8.47
90%	65	59	0.71	FCW-4	1.65	0.00	20.2
	55	50	0.75	FCW-4	1.39	0.11	18.9
	45	41	0.81	FCW-4	1.15	0.35	17.3
	35	32	0.90	FCW-4	0.89	0.61	14.6
	25	23	1.08	FCW-3	0.64	0.86	11.6
95%	65	62	0.47	FCW-5	0.00	1.50	—
	55	52	0.51	FCW-4	0.18	1.32	5.95
	45	43	0.58	FCW-4	0.90	0.60	13.9
	35	33	0.68	FCW-4	1.33	0.17	13.8
	25	24	0.86	FCW-4	0.96	0.54	13.1
100%	65	65	0.26	FCW-5	0.00	1.50	—
	55	55	0.30	FCW-5	0.00	1.50	—
	45	45	0.37	FCW-5	0.00	1.50	—
	35	35	0.47	FCW-5	0.00	1.50	—
	25	25	0.66	FCW-4	1.27	0.23	11.4

Cut-ins with Decelerating P1 Summary and Conclusions

Similar to the analysis in the first section, the current analyses provide information about whether or not there could be meaningful benefits to escalating lower-level FCW alerts to an imminent FCW-5/7 alert in cut-in situations involving a decelerating P1 vehicle. The key findings are as follows:

- If the P1 vehicle is decelerating at a moderate or high level, bumper-kiss collisions can occur at relatively long headways, even if the SV driver responds immediately to the first

FCW alert provided. This reflects the severity of these situations and how headway can be reduced very quickly if the P1 vehicle is already decelerating.

- If the P1 vehicle is decelerating at a moderate or high level, using an Escalation Approach is likely to provide a significantly better warning to an SV driver for the headways examined. One finding that underscores this point is that compared to constant P1 speed conditions analyzed above, with a decelerating P1 vehicle, the first FCW alert is often an FCW-1 or FCW-2b, which has no auditory component. Consequently, if the driver is not paying attention to the road, the high-speed crashes shown in the Analysis 3 column of each tables is much more likely to occur because drivers get no auditory warning prior to the FCW-7. Even with more gradual P1 deceleration levels (Table 13), if the SV driver does not respond immediately to the FCW-3b/4b alert, they run the risk of crashing, and at higher absolute speeds, the resulting crashes can occur with more than 10 mph relative speed at impact.

Based on the findings described above, there appears to be the potential for significant and meaningful benefits associated with using an Escalation Approach when the P1 vehicle is decelerating at the time it cuts in.

4.3.2 Post-cut in Speed Adjustments by P1

The last important difference identified between cut-in situations and standard FCW situations is that the P1 vehicle is more likely to make speed adjustments once it is established in the lane (e.g., if it has a vehicle in front of it). Under the worst case scenario, this could involve a decelerating P1 vehicle that decelerates even faster, which is just a more extreme case as the decelerating P1 vehicle case analyzed above. However, where these situations become qualitatively different is when the P1 cuts in with a small headway, but is traveling at the same speed as the SV or opening up on it. Initially, this situation is associated with a low safety margin/headway, but the situation is probably improving because the P1 would be pulling away (i.e., if P1 is going faster or if the SV driver slows in response). However, because there is an increased likelihood of a speed adjustment, the P1 could decelerate quickly if traffic conditions ahead require it. Thus, in this case, the P1 that has been in the forward lane with lower headway for some time period begins decelerating (see Figure 7).

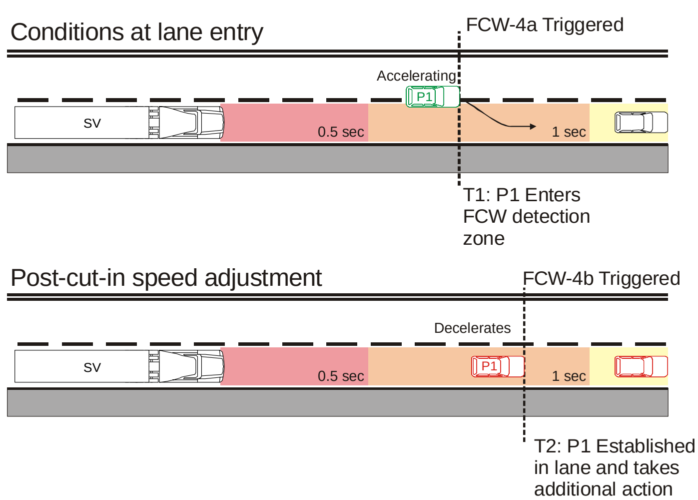


Figure 7. Example of P1 post-cut in action that starts from an reduced initial headway because of the earlier cut-in.

The warning conditions in the example above would involve a combination of both cut-in and standard FCW conditions. More specifically, it would have the low headway associated with cut-ins, but the P1 would also have a “history” in the forward lane, so it might not be as clearly identifiable as vehicle that just cut in. Consequently, if an Escalation Approach is used in these situations, it may be necessary to include an additional set of triggering conditions that reflect the fact that key FCW alert did not coincide directly with a cut-in but that a cut-in did occur within some number of seconds.

These post-cut-in deceleration scenarios were not analyzed in the present investigation. They involve more complex and time-consuming versions of the analyses described in the preceding sections. At this point in time, it probably makes sense to wait until questions about whether or not cut-ins should be treated as special conditions are resolved, before embarking on these analyses. Nevertheless, it is important to identify these situations as relevant to possible FCW changes based on cut-in situations if data about cut-ins will be collected in the future.

4.4 Determine if Advantages of Changing FCW Rules Outweigh the Potential Disadvantages

The kinematic analyses conducted above suggest that there might be some safety advantages to changing the current FCW rules for cut-in situations (especially those involving decelerating P1 vehicles). Although potential benefits were identified, the question of whether or not the FCW system as a whole would be improved if these changes were made is still an open question. These changes are also likely to come with certain disadvantages as well. These include:

1. Increased system complexity, which may also results in increased complexity of the driver’s mental model, and
2. A potential increase in false alarms depending on how additional cut-in-related rules are implemented.

With regard to false alarms, if critical hazard conditions only occur with cut-ins under certain speed and deceleration conditions, providing escalated FCW-5/7 warnings under all conditions could result in an excessive number of these alerts when drivers otherwise have ample time to avoid a collision.

Thus, the key question regarding whether or not the FCW system should be modified to handle cut-in situations differently depends of if the safety benefits associated with doing so significantly outweigh the potential loss in system effectiveness because of increased complexity and false alarms.

Unfortunately there are insufficient data at this time to reliably answer this question. The key missing information is the frequency with which the critical cut-in situations occur under real-world driving conditions. This requires on-road data over an extended period of time to capture the likely low-frequency events. Other information that is needed is an analysis of how the increase in system complexity changes the drivers mental model and an analysis that estimates the impacts of possible FCW changes on false alarm rates.

Another empirical question revolves around how drivers respond to the various FCW warning levels. If drivers consistently respond to FCW-3b and FCW-4b alerts in the same way as FCW-5/6/7 alerts, then an Escalation Approach would be unnecessary in under these conditions. This requires on-road data about driver behavior over an extended period of time given that FCW-3b and FCW-4b alerts are likely to occur infrequently.

4.5 Summary and Conclusions

The findings from the current analyses are summarized below regarding the gaps in the current FCW approach and future data requirements.

Gaps/suboptimal aspects of the current FCW approach:

- Cut-ins involving a P1 that is decelerating at the time of lane entry.
- Cut-ins that are followed by a P1 vehicle speed adjustment (unconfirmed but likely).

Future data requirements:

- Frequency with which different cut-in situations occur.
- Information about how drivers respond to FCW alerts of different levels.
- Additional analyses of the impacts of FCW system changes on the driver mental model and on potential false alarm rates.

4.6 Recommendations

1. It is recommended that the current FCW rules not be changed to accommodate cut-ins at this time. Although potential gaps were found in the current approach with regard to decelerating P1 vehicles, it is not possible to evaluate whether or not changing the current FCW rules would yield a net improvement in FCW system effectiveness.
2. It is recommended that the on-road data specified under "Future Data Requirements" above be collected in order to enable an analysis of the whether or not changing the FCW rules would lead to an overall improvement in system effectiveness.

5 DIU Location Analysis

5.1 Introduction

This document provides an initial identification of driver performance/driver behavior issues relevant to the recently-proposed location for the IVBSS HT DIU. The recently-proposed location of the DIU for the IVBSS HT falls outside of the location recommended in the current Driver-Vehicle Interface (DVI) Design Specification. Section 2.2.1.1 of the Specification indicates:

> *"The display unit should be mounted in a driver's forward visual field, not more than 30 degrees (ideally, no more than 15 degrees) of visual angle off the forward line of sight. The display unit must also be within easy reach of the driver so that pushbuttons can be operated without changing seated position."*

Recent project documentation (i.e., *633 HVAC/Radio Control Visibility Angles*) provided by International indicate that the look-down angle associated with the recently-proposed location would range from 36 degrees to 43 degrees for – respectively – a 5th percentile female driver and a 95th percentile male driver (see Figure 8 below).

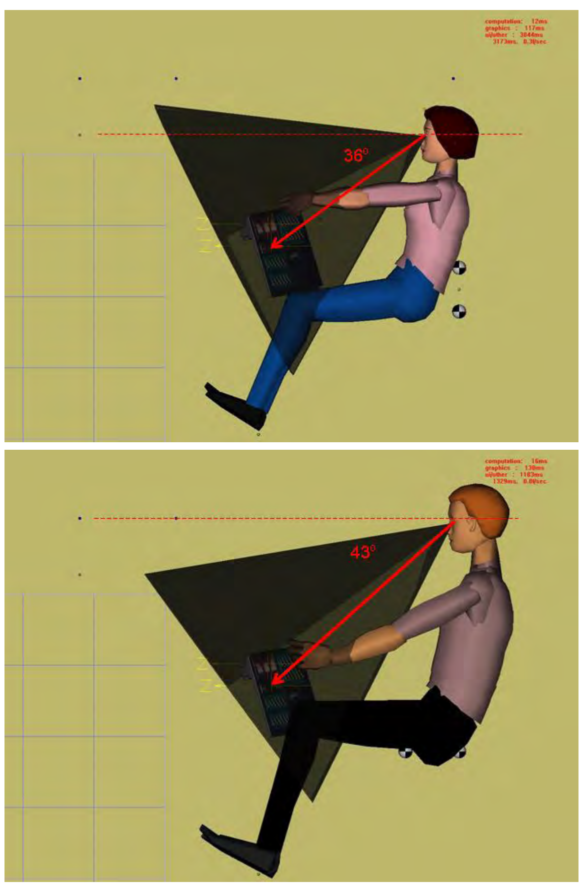


Figure 8. Look-down angles associated with the recently-proposed location for the IVBSS HT DIU.

The location recommended in the current DVI Design Specification reflects a guideline within the human factors literature for the presentation of warning information that goes back at least since 1973. This long-standing principle reflects a simple desire to provide users with time- or safety-critical information in a location as close to the nominal line-of-sight as possible, without interfering with primary task performance. From our reviews of the literature, it seems that this guideline was originally intended for use in workstation environments in control rooms or on the decks of naval vessels. This guideline is also consistent with experimental results from laboratory studies in which the perception and legibility of visual stimuli and associated eye movements have been investigated as a function of display distance relative to point-of-gaze. We are unaware of any studies examining these issues under environmental and task conditions directly comparable to those we are examining in the IVBSS HT program.

We should also recognize that the lower, recently-proposed location of the DIU could very well provide some advantages to the overall HT effort, including ease of production and aesthetic (i.e., fit and finish) improvements. Moreover, a “low center stack” location would certainly ensure that the DIU does not obstruct the driver’s view of the forward driving scene and would reduce or eliminate potential “distraction” effects associated with a changing visual display near the driver’s forward field-of-view. However, lowering the DIU relative to the driver’s seated position is also likely to impact how drivers would use the system, and could potentially impact driver safety. The objective of this document is to provide a quick evaluation of the specific impacts on safety, and driver use of the system associated with the recently-proposed location of the DIU, relative to the location recommended in the draft DVI specification.

5.2 Approach

The general approach was to evaluate the recently-proposed location of the DIU across a set of different design factors to determine how driver safety and use of the system might be impacted by placing the DIU at a location lower in the cab than that recommended in the draft DVI specification. Several years ago, Battelle conducted a project for the FHWA in which we developed a design tool for conducting a systematic trade-off analysis of different display locations. We used this tool as a basis for identifying the design factors that are relevant to safety and ease-of-use, and then estimated the corresponding impacts of the current proposed DIU location. Both visual/perceptual and manual control factors were examined. At this point in time, the impacts we have identified are presented in qualitative, not quantitative terms; quantitative data would require additional time to obtain, either through the literature or direct measurement.

5.3 Visual/Perceptual Design Factors

Table 14 shows the visual/perceptual issues associated with the recently-proposed location of the DIU, relative to the location recommended in the draft DVI specification. The predicted impact of these issues on the driver’s task or on driving behavior is also presented. These impacts are based on existing research and on expert judgment.

Table 14. Potential impacts of identified visual/perceptual design factors.

Design Factor	Issue	Potential Impact
Legibility	1) For drivers of certain size dimensions, the DIU may be visually occluded by the driver's arm. 2) DIU contrast may be reduced because of the higher relative angle between the face of the DIU and the driver. 3) The absolute distance to the DIU will make the text appear smaller and may be harder to read for taller drivers.	1) Drivers may look at the display less often if they have to move their arm out of the way in order to see the display 2) Reduced contrast can be addressed by adjusting display properties. Also, this location may be less susceptible to glare from the sun than higher locations. 3) This may not be significantly worse compared to other locations, and the DIU text can be designed to accommodate farther viewing distances.
FOV Compatibility	If drivers look at the DIU that far down, little or none of the forward field of view will remain in their peripheral vision.	This will likely reduce the time that drivers want to spend looking at the display, and may impact lane position control.
Visual Accommodation Time	Accommodation time would likely be similar for any in-cab display location	None
Gaze Shift Distance	It will take longer to view the display because drivers must make additional eye movements that are also slower to execute, plus they will likely need to make head movements.	Drivers will have less time to view the displays. This is compounded by the finding that drivers in car-following situations tend to limit the time they are looking away from the road to under 1.5 sec (mean=0.6, 95th percentile=1.5; Reference 1).
Display Integration	Display integration would not be affected by display location.	None
Passenger Availability	Passengers participation is likely to be minimal or none at any location.	Minimal to None

5.4 Manual Control Factors

Table 15 shows the manual control issues associated with the recently-proposed location of the DIU, relative to the location recommended in the draft DVI specification. The predicted impact of these issues on the driver's task or on driving behavior is also presented. These impacts are based on existing research and on expert judgment.

Table 15. Potential impacts of identified manual control design factors.

Design Factor	Issue	Potential Impact
Movement Distance	The movement distance for the current display may be farther than alternative locations.	Drivers could take more time to operate the DUI and/or make more button-press errors. This has safety implications for some message arbitration situations (see Discussion below).
Accessibility	There do not appear to be any access restrictions for this location.	None
Location Familiarity	The center console is a typically a familiar location, however, it is unknown to us how familiar these drivers are with the lower position.	Drivers could take more time to operate the DUI and/or make more button press errors. This has safety implications for some message arbitration situations (see Discussion below), and for driver satisfaction.
Reach Envelope	The location is appears to be beyond the reach envelope of most drivers.	Drivers could under-use some functions when it is appropriate to do so (e.g., “mute” function in work zones), leading to lower satisfaction with the system. However, the reach difficulty metric that International typically applies to evaluate control locations indicates that this location is well within reach curves corresponding to reach difficulty ratings of 5 (on a scale from 5 – 11.2, with 11.2 corresponding to ratings of “unreachable.” (See Figure 9 below.)
Movement Stereotypes	This is a property of the DIU and not the location.	None
Passenger Availability	Passengers participation is likely to be minimal or none at any location.	Minimal to None

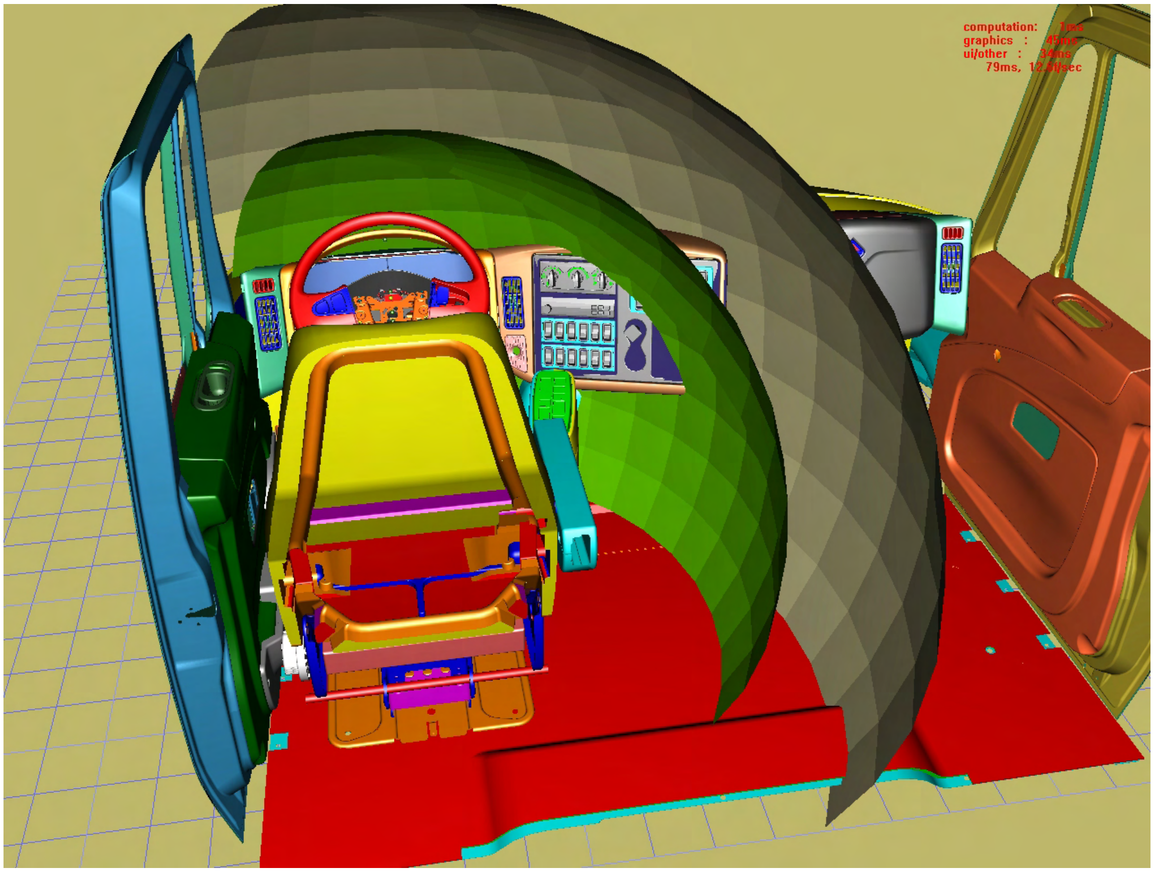


Figure 9. Reach envelopes in the International 8600 corresponding to rating difficulty curves of 5 for a large male (gray) and small female (green).

5.5 Discussion

The potential impacts on safety and driver use related to the different design factors differ across warning message conditions. A summary of these impacts is provided below.

Safety-critical messages (FCW-5, 6, and 7, some LDW). Because the primary warning information in safety-critical conditions is presented using the auditory mode, direct safety impacts of this particular display location are likely to be small. However, there is a small chance a driver confused about the nature of an auditory message could look to the DIU for clarification, which would take his or her eyes away from the driving environment at a critical time.

Messages presented in non-critical situations (e.g., FCW-1, 2, 3, 4 and some LDW, LDW availability). The primary concern with the proposed display location is that it is likely to lead to drivers looking at the DIU less often than if it were located closer to the driver's line-of-sight. In particular, the occlusion by the driver's arm, incompatibility with the driver's FOV, and longer eye movement time all discourage voluntary eye glances to the DUI. This generally has important implications for how drivers use the overall system. Some of these implications are that:

- - Drivers may use the display less to get feedback about what just happened, which diminishes their ability to learn how the system works and to develop a mental model of system operation.

- - Drivers may become less aware of LDW availability information, which could ultimately undermine their confidence in this system.
- - Drivers may not get regular information about lower priority situations (FCW-1 and 2), and may not adjust their driving accordingly.

Critical messages conditions requiring manual response (e.g., LCM-X2 concurrent with FCW-4). Some arbitration rules (e.g., LCM-X2 vs. FCW-3 and 4) rely on assumptions about driver response time for acknowledging a system failure (e.g., RT < 2 sec). The lower DUI location can lengthen these response times, so some of these assumptions may have to be re-evaluated.

Manual interactions with the DIU in general. The recently-proposed location may be associated with longer movement distances and operation times, which could impact both driver performance and driver satisfaction with the system. However, other locations may not provide a significant improvement over the current proposed location. This may be an issue that requires further investigation irrespective of display location.

6 Approach for Dealing with the Presentation of Concurrent Auditory Warning Messages

6.1 Problem

What approach should be taken for dealing with warning situations in which an alert needs to be presented while a previous alert is still being presented?

6.2 Conditions under which concurrent messages occur

- Typically between forward collision warning (FCW) alerts and lateral (LCM, LDW), and or system failure messages.
- Can occur between different FCW alert levels in cut-in situations when the headway is near an FCW alert level boundary.

6.3 Possible Approaches

Different approaches for addressing new alerts to be presented during an earlier alert are shown in the following table:

Table 16. Possible approaches for new alerts to be presented during an earlier alert presentation.

Approach	Description	Disadvantages
Suppression	Suppress the presentation of the second message until the first message is complete.	The additional time required to complete the initial alert could significantly reduce the available RT for responding to the second alert.
Preemption	The second message completely interrupts the first message if it has a higher priority.	The resulting "mixed-alert" audio stream could sound confusing or be difficult to interpret because of perceptual artifacts.
Hybrid Preemption and Suppression	The second message completely interrupts the first message if it has sufficiently high priority, or it is suppressed if to has a lower priority.	Same as with the straight Preemption approach, but these conditions should occur less frequently.
Suppression with shorter messages	Suppress the presentation of the second message, but use shorter messages so that the suppression is limited to a short duration.	Overall audibility/effectiveness of particular alerts may be reduced because the sound is less "hearable."

6.4 Recommended Approach

The hybrid preemption and suppression approach is recommended because:

1. It avoids significant reductions in available RT.
2. It reduces the occurrence of potentially confusing "mixed-alert" sound combinations.

3. It avoids the possibility that alert effectiveness is reduced for the majority of alert presentation just to accommodate highly infrequent circumstances.

6.4.1 When to preempt and when to suppress

To minimize the occurrence of potentially confusing “mixed-alert” audio streams, the use of preemption should be limited to situations in which a lower-priority initial message consumes a significant amount of the Available RT needed to avoid a crash.

6.4.2 Factors to consider when determining whether or not an alert should preempt or suppress an initial message

- *Alert priority*: Priority based on the existing Arbitration Rules table.
- *Duration of the initial alert*: How much of available RT will be taken up by the initial message.
- *Available RT*: Amount of time that the SV driver has to respond to the conditions indicated by the second message.

Table 17. Recommended presentation approach for different combinations of factors described above.

Alert Priority	Duration of Initial Alert	Available RT	Presentation Approach*	Confidence
High	High	High	Suppress	High
High	High	Low	Preempt	High
High	Low	High	Suppress	High
High	Low	Low	Preempt	High
Medium	High	High	Suppress	High
Medium	High	Low	Preempt	Medium
Medium	Low	High	Suppress	High
Medium	Low	Low	Suppress	Medium
Low	High	High	Suppress	High
Low	High	Low	Suppress	High
Low	Low	High	Suppress	High
Low	Low	Low	Suppress	High

*Preempt means that the second message preempts the first message;
Suppress means that the second message is suppressed by the first message.

Table 18. Characteristics of current alert messages.

	Priority	Avail RT	Alert Duration
FCW3	Medium	High	Low
FCW4	Medium	High-Med	Low
FCW567	High	Low	High
LCM3	High	Low	TBD
LDW	Medium	High-Med	High
LCMX2	High	Low	TBD
Fault	Low	High	Long

6.4.3 Recommended presentation approach for the various pairings of auditory alerts

Recommended presentations for pairing auditory alerts is given in Table 19 below. Note that these are preliminary recommendations because the alert sounds have not yet been finalized and a closer analysis of some combination may be required.

Table 19. Preliminary recommendations for pairing of auditory alerts.

		Message 2						
		FCW3	**FCW4**	**FCW567**	**LCM3**	**LDW**	**LCMX2**	**Fault**
Message 1	**FCW3**		Suppress	Preempt	Preempt	Suppress	Suppress	Delay
	FCW4	NA		Preempt	Preempt	Suppress	Suppress	Delay
	FCW567	NA	NA		Cancel	Cancel	Cancel	Delay
	LCM3	Suppress	Suppress	Preempt		Cancel	NA	Delay
	LDW	Suppress	Preempt	Preempt	Preempt		Preempt	Delay
	LCMX2	Suppress	Suppress	Preempt	Preempt	Suppress		Delay
	Fault	Suppress	Preempt	Preempt	Preempt	Suppress	Suppress	

Preempt: The second message preempts the first message.

Suppress: The second message is suppressed by the first message.

NA: The second message should not occur because it is an impossible sequence.

Cancel: Message 2 is cancelled by the Message 1 conditions until the situation represented by Message 1 is resolved.

Delay: It may be useful to delay non-critical status messages for an extended duration to ensure that the SV driver has adequately addressed an potential safety-related situations.

NOTE: Highlighted cells indicate that a closer examination of these conditions may be required.

References

1. Tijerina. L., Barickman, F.S., and Mazzea, E.N. (2004). Driver Eye Glance Behavior During Car Following (DOT HS 809 723). Washington DC: National Highway Traffic Safety Administration.

Appendix A: Prioritizing IVBSS Warnings

When determining priority among multiple IVBSS warnings, the following procedures should be used:

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 IVBSS 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 IVBSS 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.
- 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.

Appendix B: Scenario Analyses

Each scenario describes the progression of warning/sensor conditions over time and the corresponding visual and auditory messages displayed under those conditions for each of the two approaches.

Scenario 1: FCW-2 to FCW-3:

Description: SV closes on P1 until FCW-3 message displayed, then SV decelerates until safe headway is obtained.

Table 20. Progression of warning/sensor conditions over time and the corresponding visual and auditory messages displayed under those conditions for each of the two approaches in Scenario 1: FCW-2 to FCW-3.

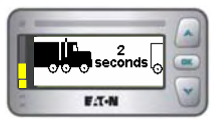
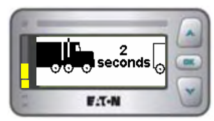
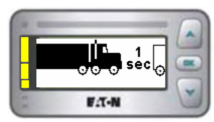
Conditions at Time (t)	Condition Code	Opening Display		No Opening Display	
		Visual Display	Auditory Display	Visual Display	Auditory Display
Forward object < 3 sec headway and closing	FCW-2		None		None
Forward object < 2 sec headway and *closing*	FCW-3		Short alert		Short alert
SV decelerates: < 2 sec headway but *opening*	FCW-3 (Opening)		None		None
SV decelerates: > 2 sec headway and *opening* or constant	FCW-2* (Opening)		None		None

* If and FCW-2 (Opening) visual display was not implemented, the "Object detected" display would be presented.

Scenario 3: FCW-2 to FCW-4

Description: SV closes on P1 until FCW-4 message displayed, then SV decelerates until safe headway obtained.

Table 21. Progression of warning/sensor conditions over time and the corresponding visual and auditory messages displayed under those conditions for each of the two approaches in Scenario 1: FCW-2 to FCW-4.

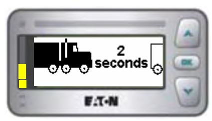
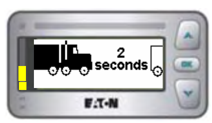
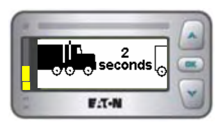
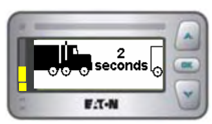
Conditions at Time (t)	Condition Code	Opening Display		No Opening Display	
		Visual Display	Auditory Display	Visual Display	Auditory Display
Forward object < 3 sec headway and closing	FCW-2		None		None
Forward object < 2 sec headway and *closing*	FCW-3		Short alert		Short alert
Forward object < 1 sec headway and closing	FCW-4		Double alert		Double alert
SV decelerates: < 1 sec headway but *opening*	FCW-4 (Opening)		None		None
SV decelerates: < 2 sec headway but *opening*	FCW-3 (Opening)		None		None
SV decelerates: > 2 sec headway and *opening* or constant	FCW-2* (Opening)		None		None

* If and FCW-2 (Opening) visual display was not implemented, the "Object detected" display would be presented.

Scenario 3: FCW-3 to FCW-3

Description: SV maintains a constant or opening headway of < 2 sec then P1 closes on P1, and SV decelerates until safe headway obtained.

Table 22. Progression of warning/sensor conditions over time and the corresponding visual and auditory messages displayed under those conditions for each of the two approaches in Scenario 1: FCW-3 to FCW-3.

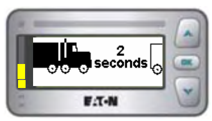
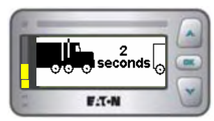
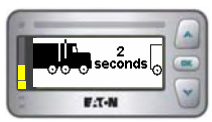
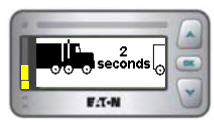
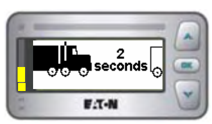
Conditions at Time (t)	Condition Code	Opening Display		No Opening Display	
		Visual Display	Auditory Display	Visual Display	Auditory Display
Constant or opening headway that is < 2 sec	FCW-3 (Opening)		None		None
P1 decelerates: Forward object < 2 sec headway and *closing*	FCW-3		Short alert		Short alert
SV decelerates: < 2 sec headway but *opening*	FCW-3 (Opening)		None		None
SV decelerates: > 2 sec headway and *opening* or constant	FCW-2* (Opening)		None		None

* If and FCW-2 (Opening) visual display was not implemented, the "Object detected" display would be presented.

Scenario 4: FCW-2 to FCW-3 with Inadequate Response

Description: SV closes on P1 until FCW-3 message displayed, then SV decelerates but deceleration is initially insufficient to halt closing (i.e., P1 may be decelerating more), before opening up again.

Table 23. Progression of warning/sensor conditions over time and the corresponding visual and auditory messages displayed under those conditions for each of the two approaches in Scenario 1: FCW-2 to FCW-3 with Inadequate Response.

Conditions at Time (t)	Condition Code	Opening Display		No Opening Display	
		Visual Display	Auditory Display	Visual Display	Auditory Display
Forward object < 3 sec headway and closing	FCW-2		None		None
Forward object < 2 sec headway and *closing*	FCW-3		Short alert		Short alert
SV decelerates but not enough: < 2 sec headway and closing	FCW-3		None		None
SV decelerates: < 2 sec headway and now *opening*	FCW-3 (Opening)		None		None
SV decelerates: > 2 sec headway and *opening* or constant	FCW-2* (Opening)		None		None

* If and FCW-2 (Opening) visual display was not implemented, the "Object detected" display would be presented.