TEST AND EVALUATION OF THE COOPERATIVE INTERSECTION COLLISION AVOIDANCE SYSTEM FOR VIOLATIONS (CICAS-V) DRIVER-VEHICLE INTERFACE

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ABSTRACT

The Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was conducted to develop and field-test a comprehensive system to assist drivers in reducing the number and severity of crashes at intersections due to violations at stop-sign and signal-controlled intersections. One essential component of such a system is the Driver-Vehicle Interface (DVI) to warn a driver of an impending violation. A series of test-track studies was conducted to support the selection of a DVI for subsequent on-road tests of the CICAS-V. In these tests, 18 naive drivers per interface were placed in a surprise intersection violation scenario and provided with a precisely timed warning presented through a variety of DVIs. Driver braking profiles and vehicle stop locations were collected and analyzed, with particular emphasis on behaviors that resulted in avoiding entering the intersection DVIs included combinations of visual, auditory, and haptic (brake pulse) warnings. Results from the tests showed that drivers exposed to a brake pulse tended to stop more often and with lower decelerations than drivers that were not exposed to the brake pulse. The effectiveness of the brake pulse warning, however, was partly moderated by the type of auditory warning that accompanied the brake pulse warning. A baseline trial was conducted to determine the benefit of the DVI over a non-warning condition. Overall, results supported the recommendation of a DVI containing the simultaneous presentation of a flashing visual (red stoplight/stop sign icon), a 'Stop Light' speech warning, and a single brake pulse. The best-performing DVI resulted in an 88% improvement over the baseline condition. Project participants included offices of the United States Department of Transportation, Daimler, Ford, General Motors, Honda, Toyota, and the Virginia Tech Transportation Institute.

INTRODUCTION

The Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was conducted to develop and field-test a comprehensive system to assist drivers in reducing the number and severity of crashes at intersections due to violations of traffic control devices (TCD). These crashes account for almost 400,000 injuries and fatalities in the United States every year (National Highway Traffic Safety Administration, 2008). The approach selected to reduce these crashes is to present a timely and salient in-vehicle warning to those drivers predicted to violate a TCD. The warning is intended to elicit a behavior from the driver to avoid a potential violation.

Supporting the warning are several subsystems that exchange, process, and present the required information from both the vehicle and the intersection. The Driver-Vehicle Interface (DVI), which is the means through which the warning information is presented to the potential violator, is one of these CICAS-V subsystems. The importance of this particular subsystem is based on its function: prompting the driver to take the appropriate violation avoidance maneuver. For this reason, a series of Human Factors (HF) test track studies were executed during the CICAS-V project to determine the DVI that would be integrated into the CICAS-V system for further on-road testing. To this end, experimental scenarios were developed to attain a set of test conditions that simulated a "representative" signal violation environment. Naive drivers were exposed to these scenarios while being aided by one of several DVI alternatives. Based on knowledge gaps remaining after past research efforts, these test scenarios were designed to address the following research questions:

- Within the auditory modality, how does the effectiveness of speech warnings compare to non-speech warnings?

- Is scenario outcome improved by the addition of a brake pulse warning?
- Does the availability of Panic Brake Assist (PBA) functionality improve the scenario outcomes?
- Within the context of the experimental scenario, what is the effectiveness of each different DVI warning relative to when a warning was not presented?

Although interesting data were obtained during this research addressing signal violation alert timing, this timing issue was a secondary goal of this investigation. The range of alert timings examined in the current research (as they coupled with the examined DVI approaches) was initially based upon previous research and then was later modified based on the scenario outcomes as the studies progressed. It should be noted that the current research did not directly examine potential false alarm (annoyance) issues associated with the DVIs or alert timings examined.

This paper describes the effort to select a DVI that can be used to warn a driver that is predicted to violate an intersection TCD. The approach and candidate DVIs selected for these experiments were based on previous research and consensus of stakeholders within the CICAS-V project.

Description of Past Research

The magnitude and prevalence of intersection crashes have prompted a variety of research efforts in recent years. Within the context of crashes resulting from intersection TCD violations, most of these efforts have examined the effect of infrastructure-based systems in mitigating this problem. This limitation has mainly been due to constraints in technology, especially that which allows the vehicle and intersection to communicate and share information. However, new wireless communications technologies (e.g., Dedicated Short Range Communications - DSRC) have bridged some of these gaps and prompted research into vehicle-based countermeasures for addressing the intersection crash problem.

The most comprehensive examination of vehicle-based intersection TCD violation collision avoidance systems to date was the Intersection Collision Avoidance-Violation (ICAV) project (Lee et al., 2005). This effort examined auditory, visual, and haptic (in the form of brake pulses and soft braking) DVIs in the context of a surprise scenario presented to naive drivers, using a visual occlusion approach. Some of the key findings from the ICAV study with respect to an intersection TCD violation scenario include:

- The effectiveness of a particular DVI is dependent upon its timing; that is, the optimal warning presentation timing for one DVI is not necessarily the optimal timing for another DVI.
- Visual warnings should be accompanied by warnings in other modalities and, in the intersection TCD violation context, help explain the warning meaning.
- Speech-based ("Red Light") auditory warnings may elicit faster and more effective driver responses than non-speech (context-free) tones.
- Brake pulses and automated soft-braking appear to be effective warning methods in the intersection TCD violation context.
- Nuisance alarms are a key consideration in defining the warning type and timing to be used in these systems.

The ICAV project results were complemented by the Intersection Decision Support (IDS) project (Neale et al., 2006), which examined a wide range of infrastructure-based countermeasures in the context of similar intersection TCD violation scenarios. The IDS effort allowed for further development and refinement of the experimental protocols used in ICAV. Lessons from both of these projects provide a strong foundation of knowledge for the studies conducted as part of the CICAS-V effort. This investigation builds upon these two efforts in two distinct ways. First, it introduces a naturalistic testing approach that will aid in the estimation of safety benefits from the countermeasures tested. Second, the warnings that are considered are the result of consensus of the project team. As such, it is likely that possible implementations of the final system will be based on the general characteristics of these warnings.

The literature examined to determine the collection of DVIs tested as part of this effort was not limited to these two projects. The types of warnings tested in this investigation have been examined, often with encouraging results, in other crash contexts. The literature examined described these previous tests and presented guidelines for the design of haptic, auditory, and visual warning systems in automotive applications (e.g., Campbell, 2004; Kiefer et al., 1999; Lee, McGehee, Brown, & Nakamoto, 2007; Lloyd, Wilson, Nowak, & Bittner, 1999; Noyes, Hellier, & Edworthy, 2006). The results of these efforts, along with the project team's experience

enabled the development of multi-modality approaches that were production-representative and technologically feasible.

Assumptions of CICAS-V Studies

To determine the most suitable DVI for inclusion in the CICAS-V system, a series of nine studies was conducted. There are three assumptions implicit in the results and discussion contained in this paper. First, it is expected that the surprise signal violation scenarios used in the experiments provide DVI effectiveness estimates that may approximate those that may be obtained in the real world. Furthermore, the assumption is made here that experimental rankings of warning effectiveness will be equivalent to rankings based on real-world use. Second, it was assumed that DVI rankings obtained for signalized intersection scenarios would be applicable to stop sign scenarios (stop signs were not tested as part of the experiments described in this paper). This assumption was supported by the findings of the ICAV and IDS studies, which showed equivalencies in driver stopping behaviors for surprise traffic signal and stop sign scenarios. Third, all studies used nominal intersection approach speeds of 35 mph (56.3 km/h) and one or more TTIs (times-to-intersection) at which warnings were presented (the warning presentation algorithm was based on TTI). The performance measures discussed herein are expected to be applicable to speeds that are close to the 35 mph nominal speed used, and might change at higher and lower approach speeds (in part because the alert timing approach may be influenced by driver speed). These performance measures were collected in these studies as a means of evaluating various DVIs rather than to characterize typical driver behavior across a range of intersection types. However, the DVI rankings obtained, which were the primary focus of the study, are expected to remain largely consistent across intersection approach speeds.

METHOD

In an effort to determine the best method to evaluate the DVIs, two protocols were developed that employed different methods to distract drivers' attention from the forward roadway. One protocol used visual occlusion, while the other protocol used a naturalistic distraction method. The ICAV and IDS studies used occlusion as the method to induce 'distraction' during the surprise trial. While the occlusion method worked well in the context of those studies (where it was sufficient to make relative comparisons between countermeasures under well-controlled experimental conditions), the question remained as to whether the output could be effectively used for the estimation of potential safety benefits (one of the goals of the CICAS-V effort). In addition, it cannot be stated with absolute certainty that the relative differences observed with the occlusion method would necessarily be preserved under more naturalistic distraction conditions. To address these issues, the occlusion approach was compared to a naturalistic distraction protocol. For a variety of reasons that are discussed in Maile et al. (in print), the naturalistic distraction method was selected as the approach of choice for the tests discussed in this paper. The nine studies conducted with this protocol, the DVI tested in each study, and the alert timings (i.e., TTIs) tested are shown in Table 1 and discussed in this paper.

Table 1.
CICAS-V Studies Conducted using the Naturalistic Driving Protocol

Study #	DVI*	Time to Intersection (TTI, s)
1	Collision Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) Tone	2.44
2	Speech	2.44
3	CAMP FCW Tone and Brake Pulse	2.44
4	Speech and Brake Pulse	2.44
5	Beep Tone and Brake Pulse with PBA	2.24
6	Speech and Brake Pulse with PBA	2.24
7	Speech and Brake Pulse with PBA	2.04
8	Speech and Brake Pulse with PBA	1.84
9	No warning	2.44**

*All of these studies featured a visual display that performed both advisory and warning functions (only the advisory function of this display was used in Study 9).
** The yellow light change occurred at 2.44 s TTI.

The method used to conduct this series of studies is summarized in this section. More comprehensive descriptions can be found in Perez et al. (in print).

Participants

Participants were recruited through the newspaper, broadcast media, word of mouth, and the Virginia Tech Transportation Institute's (VTTI) database of possible participants (based on their expressed

interest). On initial contact (usually over the phone), individuals were screened to ensure their eligibility for the study. Eligibility criteria included restrictions to exclude individuals who had previously participated in a surprise-scenario experiment at VTTI (which may have predisposed them to expect a surprise scenario), health conditions or medication intake that may interfere with their ability to operate a motor vehicle, and no more than two moving violations nor any at-fault accidents within the previous three years (for liability and safety reasons). Participants also had to possess a valid driver's license.

Most experimental groups contained 18 participants, counterbalanced for age and gender. However, when it was apparent that the DVI being tested would not yield favorable results, the study was stopped early in an effort to conserve resources. Participants across three age groups were recruited for all experiments: younger drivers aged 20-30 years, middle-aged drivers aged 40-50 years, and older drivers aged 60-70 years. Altogether, 195 participants were run for the nine studies, of which 136 provided valid data points. Invalid data points resulted from drivers for whom the naturalistic distraction technique did not work as intended (e.g., drivers were looking directly at the forward roadway on or before the time of warning or yellow light onset).

Testing Facility

The experiments were completed on the Virginia Smart Road, a 2.2 mile controlled-access research facility. The designated path driven by participants during this series of studies spanned the upper and third turnaround areas on the two lane test-bed. The path included a pass through one signalized intersection. At this intersection, the Smart Road intersects with an additional access road, which then connects to a road that runs parallel to the upper portion of the Smart Road.

Protocol

Upon arriving at the Institute, participants were asked to read an informed consent form which provided specific information about the study, including the procedures, risks involved, and measures for confidentiality. The participants were initially not told the true purpose of the study in order to gain information on how naive participants react to an intersection violation warning. The purpose stated in the form described the study as an evaluation of the effect of in-vehicle tasks on driving behavior. After agreeing to the study and signing the informed consent, participants completed a health screening, a visual acuity test, and a color vision test.

Participants were then led to the vehicle where they were given time to make the necessary adjustments to the seat, mirrors, and climate control. During the pre-drive vehicle orientation, different safety systems available in the experimental vehicle, including the CICAS-V system, were briefly mentioned (e.g., forward collision warning, backing aid). The availability of PBA (when it was made available) was never mentioned. Participants were told to follow all the normal traffic rules throughout the experiment and that maintenance vehicles would occasionally be entering and leaving the road at the intersection. Unbeknownst to the participants, these maintenance vehicles were staged confederate vehicles driven by VTTI on-road crew as part of the study. At this time, the participants were given a brief tutorial and demonstration of the in-vehicle systems they would be using to perform various tasks. Participants were also provided with the opportunity to practice one of these distraction task sequences while parked. They were told that information about their speed maintenance and lane position accuracy would be recorded, including during the execution of any in-vehicle tasks. They were asked to place the car in third gear and maintain 35 mph throughout the study.

During the experiment, the front-seat experimenter (FSE) triggered a pre-recorded message at predetermined landmarks on the Smart Road that instructed the participant to complete a certain task. These tasks were based on those developed for CAMP's Driver Workload Metrics project (Angell, Auflick, Austria, Kochhar, Tijerina, Biever, et al., 2006). Tasks the participants were asked to complete included changing the radio station, changing tracks on a CD, changing properties of the heating, ventilation, and air conditioning (HVAC) system, and turning on the vehicle's hazard lights. Each message ended with the word "Now." Participants were instructed to keep both hands on the steering wheel prior to hearing the word "Now." Upon hearing the word "Now," participants were to complete the task as quickly and as accurately as possible. Once the participant finished the task, they were to say "Done," as an indication to the FSE that they had completed the task. The procedure of keeping both hands on the steering wheel prior to hearing the word "Now" helped to minimize the frequency of early glances to the task area or quick return glances to the forward roadway. This in turn helped reduce the chance that participants would be glancing away from the forward roadway when the warning and/or green-to-yellow light change were presented during

the surprise trial. The participant had the option to quit or skip any task, or to ask the FSE to play the instructions again. Additionally, for safety reasons, the FSE could instruct the participant to stop or skip any task.

The first nine trials of the experiment (all of which involved intersection crossings, most under a green light) were scripted to build the expectation of possible cross traffic at the intersection, while the last trial was a surprise scenario. Throughout the experiment, tasks were initiated at predetermined landmarks. Each 2-3 minute drive (trial) up or down the Smart Road contained four or five tasks in total. On the first trial down the Smart Road, there was a "maintenance" vehicle (Principal Other Vehicle - POV) parked on a road parallel to the Smart Road. The POV driver appeared to be performing maintenance activities on the road. After the Subject Vehicle (SV) circled through the lower turnaround and approached the intersection for the second trial, the POV drove to the adjacent stop bar at the intersection. The signal, though triggered by the on-board computer in the SV, appeared to the participant to be triggered by the waiting POV. The participant then received a common yellow-red light sequence, during which the POV crossed and exited the road.

On the sixth intersection approach, the POV re-entered the road, crossing through the intersection towards the parallel road. Again, the light sequence was triggered by the on-board computer in the SV, though appearing to change because of the presence of the POV. When the SV continued to the lower turnaround during the seventh trial and was no longer in view of the POV, the POV inconspicuously exited the road. At the start of the SV's tenth (final) intersection approach, a second confederate vehicle (Following Vehicle - FV) followed the SV up the road at approximately a 1.5 to 2 s headway. Although participants might have believed that the maintenance vehicle was again entering or leaving the road, this maintenance vehicle was not near the intersection at this time.

During this final approach (the surprise trial), a recorded set of instructions was automatically triggered by the on-board computer at 24 s TTI. A separate audio file stating "Now" was triggered at 4 s TTI. This consistent timing of events helped to maximize the probability that participants would not be glancing at the forward roadway as the light turned yellow, before the warning and/or yellow light were presented. The light turned yellow about 0.1 s before the warning onset, which occurred at 2.44, 2.24, 2.04, or 1.84 s TTI (depending on the study).

After the surprise trial was complete and participants either stopped or crossed through the intersection, a brief questionnaire about the warning(s) just received was administered. Participants were then asked to read and sign a new informed consent form that explained the true purpose of the study. The experiment was then concluded and participants returned to the VTTI main building for payment, unless additional trials were performed (see below).

Each participant took approximately 75 minutes to complete the experiment, and up to six participants could be run per day, depending on weather and amount of daylight. The study was run only when the road was dry, since the experiment involved the potential for hard braking and risk of skidding on wet pavement.

Additional Trials

In order to obtain additional information on braking behavior and PBA activation thresholds, several participants in Studies 5 through 8 completed up to two additional trials using different PBA activation settings following the surprise trial. After the surprise trial questionnaires had been administered, and with the participant's consent, the participant completed one or two additional approaches to the intersection. The availability of PBA, or the fact that PBA activation was the main measure of interest from the additional trials, was not discussed during the orientation for these trials. As the SV approached the stop bar, the Collision Avoidance Metrics Partnership (CAMP) Forward Collision Warning (FCW) Tone warning (as used and described in Kiefer et al., 1999) was presented at 2.0 s TTI. Upon hearing the warning tone, the participant was asked to apply the vehicle brakes as if trying to avoid an intersection crash. The FSE instructed the participants on this procedure after the surprise trial and prior to asking for their consent to participate in these additional trials. Altogether, 53 participants were run through at least one additional trial, and 88 trials were conducted.

Instrumentation

As previously stated, experimental scenarios were developed to attain a set of test conditions that simulated signal violation scenarios. To support that effort, the test system emulated CICAS-V functionality, but was overbuilt to operate in a more precise manner than would be necessary for real-world implementation.

Two 2006 Cadillac STSs were equipped as the SVs in this set of studies. The vehicles were equipped with anti-lock brakes, dual front and side airbags, and traction control. To minimize risk for participants and experimenters, an emergency passenger-side brake was mounted such that the experimenter (seated in the front passenger seat) could brake if needed. The confederate vehicles used for these studies included a 1999 Ford Contour, posing as cross traffic, and a 2000 Ford Explorer as the following vehicle.

The SVs were equipped with visual, auditory, and haptic warning displays. The visual display consisted of a non-reprogrammable single-icon light-emitting diode (LED) screen located in a high head-down (top of dashboard) position on the vehicle centerline near the center speaker and oriented towards the driver (Figure 1). The display was in a hooded enclosure with a low-reflection diffusion glass panel. The visual icon consisted of an outlined traffic signal and stop sign, which was developed via open-ended icon comprehension and rank order testing (Campbell, Kludt, & Kiefer, 2007). The icon was 11.6 mm (0.46 inches) high and 11.6 mm (0.46 inches) wide. Including the additional 1 mm background on all sides, the total icon size was 13.6 mm (0.54 inches) high and 13.6 mm (0.54 inches) wide. At a pre-established TTI, the figures would become blue and steady. On warning activation, the figures would become red, and flash at 4 Hz with a 50% duty cycle (125 ms on, 125 ms off).

Figure 1. High head-down visual display LED screen.

In addition, the vehicles had an integrated loudspeaker (located in the dashboard above the instrument cluster) used to present the auditory warnings independently of the vehicle's sound system. The sound was directed toward the driver from the location of interest (i.e., forward windshield). Three different auditory warnings were tested. The initial warning tested was the CAMP FCW Tone (Kiefer et al., 1999). The CAMP FCW Tone was presented at 74.6 dBA. A second speech warning was tested consisting of a female voice stating the word "Stop Light," presented at 72.6 dBA. A third auditory warning was a Beep Tone, which consisted of three high-pitched beeps. The Beep Tone was presented at 75.0 dBA. All sound level measures were taken at the approximate location of the driver's head.

When used, the Brake Pulse was triggered immediately before the onset of the visual and auditory warnings such that deceleration would reach ~0.10 g at approximately the same time as the visual and auditory warning onset. Total pulse duration was approximately 0.6 s. Deceleration produced by the pulse peaked around 0.25 g, and was reached between 0.25 and 0.35 s after the onset of the visual and auditory warnings. The brake pulse command was not issued if deceleration over 0.1 g and/or brake activation were detected by the on-board processing unit. The system was implemented entirely within the brake controller using the existing Anti-Lock Braking System (ABS) pump hardware.

The Data Acquisition System (DAS) contained within the vehicle was custom-built by VTTI. The DAS was located inside the trunk and out of the participant's view. Attached to the system bus was a series of custom-designed circuit boards that controlled the various functions of the acquisition device. This system included video grabbers, accelerometer/gyroscope (Crossbow VG400), a vehicle network sniffer (to pull variables from vehicle network), and power management boards. It also received data from a Differential Global Positioning System (DGPS, Novatel OEM4-G2L), which was used to acquire vehicle position (using an internal intersection map for reference) and speed. The alignment and time-stamping data retrieved from these boards was choreographed by a customized VTTI proprietary software package, which collected non-video data at 100 Hz. Hardware was contained in a custom-mounting case designed to affix instrumentation in orientations necessary for accurate measurement and durability.

The video grabbers installed in the DAS converted the National Television System Committee (NTSC) signal from the cameras into Motion Picture Experts Group 4 (MPEG-4) compressed video, which was recorded to the hard drive in real time. Small cameras (1" square by ¼" deep, seeing through a 1/32" aperture) were mounted inconspicuously within

the vehicle and collected the video data. For the current study, four cameras were installed. The camera views included the driver's face (to record eye glances), the forward road view, the driver's hand placement, and the driver's feet (to show accelerator and brake activation). Video data were recorded on the DAS computer at 30 Hz. For analysis, video data were multiplexed in a four-quadrant, split-screen display (Figure 2).

Figure 2. Four-quadrant, split-screen video data display.

Wireless communications needs were addressed via a second computer connected to the distributed DAS network and linked to a Denso® Wave Radio. In addition to coordinating wireless communications, this computer provided the experimenter interface, computed the algorithm, and supplied algorithm data to the DAS for synchronization with the video and driver performance data. DSRC equipment in the vehicle provided signal phase and timing information from the intersection's DSRC transceiver to the DAS and sent control commands to the intersection. Antennas were mounted underneath the front vehicle bumper and on top of the controller cabinet. VTTI developed platform-specific software to address all of these communication needs.

The DAS was independent of the CICAS-V test-bed system but remained linked as necessary to record and time-stamp key events (e.g., warning onsets). The entire DAS was unobtrusive and did not limit visibility or create a distraction.

A 700 MHz PC104 computer was used at the intersection to manage the signal configuration and wireless data transfer tasks. The PC104 received commands over the wireless communication system with regard to signal change sequence, timing, and phase change initiation. The computer physically controlled the signal state through a 110 V interface built in-house at VTTI.

Study Variables

The primary independent variable was DVI Type. In cases where multiple timings were tested for the same DVI, Warning Timing (i.e., TTI) was also used as a factor. A substantial number of dependent variables were collected across the studies. The majority of these variables were objective measures, but some subjective data were also collected through questionnaires. The following dependent variables were selected or derived from the raw data available from the vehicle DAS:

- Avoidance: Avoidance was determined based upon whether the driver stopped and where. Four different zones were defined, depending on the vehicle's distance with respect to the stop bar, measured from the front of the vehicle. These zones are specific to the Smart Road intersection and its approach configurations (although they could be defined for any intersection). Areas prior to the collision zone included the 'No Violation', 'Violation', and 'Intrusion' zones. Stopping in any of these zones was considered as successfully avoiding entering the intersection. If the driver did not stop or stopped in the 'Collision Zone' the result was considered unsuccessful. The zones are defined below and illustrated in Figure 3.

    - Did not Stop – Vehicles that did not stop.
    - Collision Zone – Vehicles that stopped at 9.1 m (30.0 ft) or more beyond the stop bar. For the Smart Road intersection, this distance represented the location at which crossing traffic could be expected to be first encountered.
    - Intrusion Zone – Vehicles that stopped between 4.6 m (15.0 ft) and 9.1 m (30.0 ft) beyond the stop bar. (Since the test bed vehicles measured close to 4.6 m in length, at this distance the rear end of the vehicle would be completely over the stop bar.)
    - Violation Zone – Vehicles that stopped within 4.6 m (15.0 ft) beyond the stop bar.
    - No Violation Zone – Vehicles that stopped at or before the stop bar.

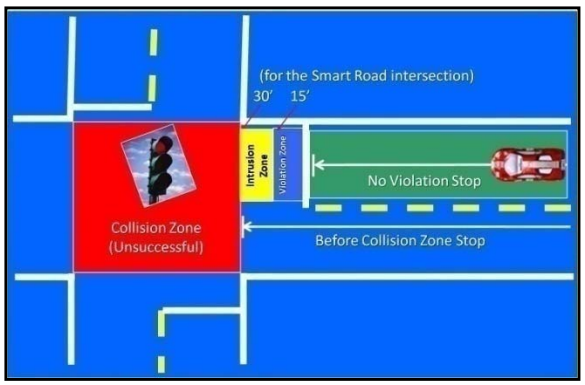

Figure 3. Illustration of the four stopping zones on the Smart Road.

- Distance Before the Stop Bar (ft): Vehicle distance to intersection once its speed was less than 0.2 ft/s (0.4 mph). The threshold was selected to eliminate incorrect triggers due to noise in the speed data.
- Peak Deceleration (g): Raw (i.e., non-smoothed) maximum driver-induced deceleration during the intersection stop.
- Constant Deceleration (g): Required constant deceleration to yield the observed stopping distance based on the observed brake onset distance, as calculated in Equation 1:

$$a = \frac{V^2}{2 \times g \times (D_i - D_f)} \qquad (1).$$

Where:
a = constant deceleration as a proportion of gravitational acceleration (*g*)
V = vehicle speed at the point when the driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s2)
Di = distance to intersection when the driver initiated braking (m)
Df = distance to intersection at which the vehicle stopped (m)

- Required Deceleration Parameter (RDP) from Braking Onset to Stop Bar (g): Required constant deceleration to come to a stop at the stop bar based on the observed brake onset distance, as calculated in Equation 2:

$$a = \frac{V^2}{2 \times g \times D_j} \qquad (2).$$

Where:
a = constant deceleration as a proportion of g
V = vehicle speed at the point when driver initiated braking (m/s)
g = gravitational acceleration constant (9.81 m/s2)
Dj = distance to intersection at braking onset (m)

For the following variables, note that stimulus onset for conditions in which a warning was issued was the warning onset. For the no-warning condition, the stimulus was the presentation of the yellow light. Note that for conditions where a warning was issued, the warning timing coincided with the presentation of the yellow light, making both warning and no-warning conditions equivalent in terms of timing.

- Time to Accelerator Release (s): Time from the onset of the stimulus to the onset of accelerator pedal release (operationally defined as the first decrease in accelerator position, after stimulus onset, of more than 2.5% in 0.1 s).
- Time to Brake (s): Time from the onset of the stimulus to the onset of brake application (operationally defined as the first increase in brake position, after stimulus onset, of more than 5% in 0.1 s).
- Time to Peak Deceleration (s): Time from the onset of the stimulus to maximum driver-induced deceleration.

Data Reduction and Analysis Techniques

The dependent variables for the study were examined for consistency prior to the analysis process. Custom software was created in the MATLAB® environment (MathWorks, Natick, MA) to identify the surprise trial within the data, calculate the dependent variables of interest, and produce plots that aided in data integrity verification and identification of the data that should be excluded. Figures created in MATLAB® illustrated all essential aspects of the intersection approach, and allowed the identification of incorrectly processed, incomplete, or corrupt data.

Upon completing each experiment, video collected by the on-board DAS was analyzed using VTTI's data analysis and reduction tool (DART). Participants who were not glancing down or otherwise obviously distracted were excluded from data analysis. Participants were also excluded from the study if they were traveling, at warning or yellow light onset, more than 7.9 km/h (5 mph) over or under the nominal speed for the warning condition.

Conceptually, there are two steps required for a successful intersection stop. These aspects are: (Step

1) analyze, formulate, and initiate a response plan to the stimulus requiring the stop, and (Step 2) adapt and complete the execution of the plan based on any sensory feedback. Put in another way, assuming a driver decides to stop, Step 1 characterizes pre-braking behavior and Step 2 characterizes the braking behavior.

Both steps can be quantified using different dependent variables; however, the dependent variables that characterize the second step might not be independent of those that characterize the first step. For example, it is possible that a driver that takes longer to react to the warning stimulus (Step 1) would brake harder (Step 2) in order to compensate and stop at the same point as a driver with a faster reaction time. All of the dependent variables described above can be classified according to the step that they quantify:

- Analysis, formulation, and initiation of the response plan (Step 1, plan initiation)
  - Time to accelerator release
  - Time to brake
- Adaptation and completion of the response plan (Step 2, plan execution)
  - Time to peak deceleration
  - Distance before the stop bar
  - Peak deceleration
  - Constant deceleration
  - RDP from Braking Onset to Stop Bar

In order to determine the need for correction factors, a correlation analysis was performed between the Step 1 and Step 2 variables. Given that correlation analysis quantifies the degree of linear relationship between variables, transformation of variables was also examined in this process, as a means of maximizing the correlations.

Once the correlations were completed and any relationships between Step 1 and Step 2 variables established, statistical analysis of variance (ANOVA) was performed. Dependent variables for which correction was not needed (i.e., all Step 1 variables and Step 2 variables that did not exhibit correlation with Step 1 variables) were analyzed using traditional ANOVA techniques. Dependent variables that required a correction were analyzed using Analysis of Covariance (ANCOVA).

When significant main effects were found, Student-Newman-Keuls (SNK) tests were performed to further determine the source of those differences. Significant interaction effects were examined with post hoc t-tests using the Tukey correction for multiple comparisons. A Type I error level of 0.05 was assumed for all tests.

Finally, the "Avoidance" variable was considered and analyzed separately since it was a discrete variable which did not require correction. This variable was analyzed based on proportion of occurrence for each trial. Confidence intervals (95%) were established to determine overlap between different experimental groups and infer statistically significant differences. These confidence intervals were based on the binomial distribution, which describes the probability of discrete outcomes when observations are independent.

RESULTS AND DISCUSSION

The primary goal of these experiments was to develop a recommendation for the DVI to be integrated into the CICAS-V system for further on-road testing. In support of this goal, Table 2 shows a summary of the results obtained for each of the 9 studies; note that studies 4, 6, 7, and 8 are shown in bold. These studies used the Visual icon + Speech ('Stop Light') + Brake Pulse warning, which was ultimately recommended for use based on the observed patterns of driving behavior in reaction to this warning, including driver's success in avoiding entering the intersection.

Table 2.
Summary of Results*

Study	DVI**	TTI (s)	N and % Avoided	N and % Not Avoided	95% Confidence Interval (Avoided)	N Avoided Activating PBA
1	CAMP FCW Tone	2.44	7 (39%)	11 (61%)	16.4%-61.4%	--
2	Speech	2.44	7 (39%)	11 (61%)	16.4%-61.4%	--
3	CAMP FCW Tone with Brake Pulse	2.44	14 (78%)	4 (22%)	58.6%-97.0%	--
4	**Speech with Brake Pulse**	**2.44**	**17 (94%)**	**1 (6%)**	83.9%-100%	**--**
5	Beep Tone with Brake Pulse and PBA	2.24	5 (50%)	5 (50%)	26.9%-73.1%	0
6	**Speech with Brake Pulse and PBA**	**2.24**	**16 (89%)**	**2 (11%)**	74.4%-100%	**1**
7	**Speech with Brake Pulse and PBA**	**2.04**	**7 (78%)**	**2 (22%)**	58.6%-97.0%	**0**
8	**Speech with Brake Pulse and PBA**	**1.84**	**3 (33%)**	**6 (67%)**	11.6%-55.1%	**1**
9	Baseline	2.44***	1 (6%)	17 (94%)	0%-16.1%	--

* Note: Studies in bold investigated the warning recommended based on the results presented in this paper.
**All of these studies featured a visual display that performed both advisory and warning functions (only the advisory function of this display was used in Study 9).
*** Yellow light change occurred at 2.44 sec.

Key Study Comparisons

<u>Differences between CAMP FCW Tone and Speech Warnings and the Influence of a Brake Pulse</u> - This section compares the results of four studies testing four different DVI Types at a 2.44 s TTI and another baseline study where a warning was not provided but a traffic light change occurred at a similar timing:

- Visual icon + CAMP FCW Tone (Study 1)
- Visual icon + 'Stop Light' Speech Warning (Study 2)
- Visual icon + CAMP FCW Tone + Brake Pulse (Study 3)
- Visual icon + 'Stop Light' Speech Warning + Brake Pulse (Study 4)
- Baseline with no warning presented (Study 9)

The Baseline condition avoidance percentage (6%) was substantially (and significantly) lower than that observed for any of the other warning conditions (which ranged from 33% to 94%). Although no other significant differences in avoidance were observed between the remaining groups that experienced warnings, there was a trend for participants who experienced the Brake Pulse as a component of the warning approach to stop more often than participants receiving a warning that did not include a Brake Pulse.

In discussing the following plan initiation and plan execution variable results, it should be noted that only one participant responded to the traffic signal during the Baseline condition. Therefore, although the performance values for this participant are provided, statistical comparisons of these values with those obtained for other conditions with substantially larger avoidance percentages was not possible. The following statistically significant results are summarized in Table 3.

Analysis of plan initiation variables showed some significant main effects:

- Time to accelerator release ($F[4,42]=11.21$, $p<0.0001$): On average, participants who experienced the Brake Pulse released the accelerator 0.42 s faster than those who did not experience the Brake Pulse.
- Time to brake ($F[4,42]=6.28$, $p=0.0005$): Participants that experienced the Brake Pulse had faster brake onset times (by 0.30 s).

Analysis of plan execution variables showed several significant main effects as well, which are mainly attributed to the presence of the Brake Pulse (since the effects were not present when auditory warnings were presented in isolation):

- Distance before stop bar ($F[5,40]=10.94$, $p<0.0001$): This variable was significantly correlated with time to brake. After accounting for the effect of this plan initiation variable, results showed that participants who received the Brake Pulse stopped roughly 6 to 7 ft closer in front of the stop bar than those who did not receive a brake pulse.
- Constant deceleration ($F[5,40]=9.77$, $p<0.0001$): This variable was significantly correlated with time to brake. Conditions with a brake pulse resulted in slightly (approximately 0.02 g) lower

constant decelerations than other conditions when the influence of Time to Brake was removed.

- RDP from braking onset to stop bar (F[5,40]=43.78, p<0.0001): After considering the large correlation of this variable with time to brake, significant differences (about 0.04 g) between the Brake Pulse and non-brake pulse conditions remained.
- Time to peak brake (F[5,40]=3.13, p=0.0176): This variable was significantly correlated with time to brake. After considering the effects of this plan initiation variable, participants who experienced the Brake Pulse reached peak deceleration faster (approximately 0.4 s) than those who did not.

Table 3.
Means of Significant Main Effects of DVI Type and Brake Pulse Presence

Variable (N)	CAMP FCW Tone, No Brake Pulse (7)	Speech, No Brake Pulse (8)	CAMP FCW Tone with Brake Pulse (14)	Speech with Brake Pulse (17)	Baseline (1)
Time to accelerator release (s)	0.69	0.62	0.24	0.26	0.69
Time to brake (s)	1.11	1.08	0.82	0.74	1.06
Distance before stop bar (ft)	-9.9	-8.64	-2.04	-0.67	-9.63
Constant decel (g)	0.44	0.46	0.42	0.42	0.38
RDP from brake to stop bar (g)	0.48	0.48	0.44	0.45	0.40
Time to peak brake (s)	2.76	2.8	2.39	2.49	2.78

These results indicate that the presence of the Brake Pulse appears to directly contribute to quicker reactions, harder decelerations, and stops that were farther away from the intersection crash box (i.e., the collision zone). Most importantly, participants who experienced a warning that included the Brake Pulse tended to be more likely to respond to that warning. This evidence strongly suggests that the brake pulse should be considered an integral, primary part of the CICAS-V field test DVI.

Differences in Timing - Differences in timing were assessed by using the Visual icon + Speech ('Stop Light') + Brake Pulse warning at four different timings: 2.44 s TTI (Study 4), 2.24 s TTI (Study 6), 2.04 s TTI (Study 7), and 1.84 s TTI (Study 8). (Note that although the absence/presence of the PBA system and the PBA entrance criterion differed across these studies, the PBA system ultimately played a negligible role in the results since so few subjects activated the PBA system under these intersection approach experimental conditions.)

Analysis of avoidance percentages for these conditions showed that participants in the 1.84 s TTI condition responded to the warning at a much lower percentage (33%) than participants experiencing the warning at longer timings (overall, >79%). Other conditions were not statistically different, but there is a clear trend toward increased avoidance as the TTI warning timing occurred earlier (i.e., farther from the intersection).

Analysis of plan initiation variables showed no significant main effects. However, some main effects were observed for plan execution variables, which are illustrated in Table 4 and described below:

- Distance before stop bar (F[4,39]=7.78, p<0.0001): This variable was significantly correlated with time to brake. After accounting for the effects of this variable, results showed that participants in the 2.44 s group stopped significantly closer in front of the stop bar (by at least 3 ft) than all other groups. Although not significantly different, there was a tendency for participants to stop farther beyond the stop bar as the timings became shorter.
- Peak deceleration (F[3,40]=6.0, p=0.0018): Larger peak decelerations were observed as the timings became shorter. Participants in the intermediate 2.24 and 2.04 s timing groups showed statistically similar peak decelerations. However, the 1.84 s (the latest timing condition) and 2.44 s (earliest timing) groups exhibited approximately 0.17 g larger and 0.13 g smaller peak decelerations than the intermediate timing groups, respectively.

- Constant deceleration (F[3,40]=7.47, p=0.0004): Incrementally larger constant decelerations (between 0.02 and 0.06 g for each 0.2 s change in TTI warning timing) were observed as timings became shorter.
- RDP from braking onset to stop bar (F[4,38]=19.99, p<0.0001): Time to accelerator release was strongly correlated with RDP. After accounting for this variable, larger RDPs were observed as timings became shorter.
- Time to peak deceleration (F[4,38]=5.02, p=0.0024): This variable was significantly correlated with time to brake. After considering the effects of this variable, it was observed that participants in the 1.84 s timing reached peak deceleration faster (by at least 0.3 s) than participants experiencing other timings.

Table 4.
Means for all Significant Main Effects of Timing

Variable (N)	1.84 s TTI (3)	2.04 s TTI (7)	2.24 s TTI (16)	2.44 s TTI (17)
Distance before stop bar (ft)	-9.23	-7.31	-2.25	1.37
Peak decel (g)	0.9	0.74	0.72	0.6
Constant decel (g)	0.5	0.48	0.42	0.4
RDP: brake to stop bar (g)	0.55	0.51	0.43	0.39
Time to peak decel (s)	1.94	2.38	2.34	2.37

As suggested above, although PBA was available to participants in the 2.24 s, 2.04 s, and 1.84 s conditions, only two participants engaged this system. One participant did so in the 2.24 s condition and stopped 13.89 ft before the stop bar. The second participant engaged PBA in the 1.84 s condition and stopped 17.28 ft after the stop bar. Statistical analysis of these observations was not possible due to the small representation of PBA engagement within the study sample.

Overall, these results suggest that although shorter timings elicit slightly quicker reactions and significantly harder decelerations from drivers, this does not necessarily translate to a stop that is farther away from the crash box. This suggests that there is a discretionary element that drivers use when deciding exactly where to stop relative to the stop bar. The most important observation in the timing comparison was related to response to the warning, which showed a trend toward dropping as the timings became shorter, particularly at the 1.84 s TTI warning timing condition.

Furthermore, it appears reasonable to assume that, as the TTI warning timing decreases, more drivers will decide to continue through the intersection since they may feel that it is not possible to safely stop in the distance remaining. Therefore, warnings should be presented as early as possible to the extent that their earlier presentation does not result in an unacceptable number of warnings perceived by the driver as "too early" or unnecessary.

Differences between Speech and Beep Tone Warnings - This section compares the results obtained for the Visual icon + Speech ('Stop Light') + Brake Pulse warning and the Visual icon + Beep Tone + Brake Pulse warning at the 2.24 s TTI warning timing (Study 5 and Study 6, respectively). The motivation for this comparison was to continue to evaluate the hypothesis that the Brake Pulse was the dominant factor behind the favorable driver behavior results obtained when a warning was presented. If this hypothesis was true, perhaps a less salient (hence, potentially less annoying) auditory warning could be coupled with the brake pulse warning without degrading warning effectiveness. (It should be noted that although PBA was active for both of these comparison studies, only one participant activated PBA during either condition [this participant was in the Speech condition and stopped 13.9 ft before the stop bar].)

Analysis of avoidance percentages indicated a trend toward participants experiencing the Speech warning avoiding at a higher percentage (89%) than participants who experienced the Beep Tone warning (50%), a difference that approached statistical significance (p=0.0940).

While analysis of plan initiation variables failed to indicate significant main effects, analysis of plan execution variables showed some significant main effects, as described below and summarized in Table 5:

- Distance before stop bar (F[2,19]=6.42, p=0.0074): Time to brake was significantly correlated with this variable. After considering the effects of this plan initiation variable, participants in the Beep Tone group were observed to stop at longer distances before the stop bar than participants in the Speech warning condition.
- Constant deceleration (F[1,20]=8.84, p=0.0075): Participants in the Beep Tone group yielded larger constant deceleration values

(approximately 0.07 g) than those in the Speech group.

- RDP from braking onset to stop bar ($F[2,18]=5.98$, $p=0.0105$): This variable significantly correlated with time to brake. After accounting for the effect of this plan initiation variable, participants in the Beep Tone group were observed to exhibit a slightly greater average RDP from braking onset to stop bar (roughly 0.05 g) than those in the Speech group.
- Time to peak deceleration ($F[2,18]=7.85$, $p=0.0035$): This variable was correlated with time to brake. After accounting for the effect of this plan initiation variable, participants in the Beep Tone group were observed to achieve peak deceleration faster (by roughly 0.15 s) than those in the Speech group.

Table 5.
Means of Significant Differences between the Speech and Beep Tone Warning Conditions

Variable (N)	Speech Warning (16)	Beep Tone Warning (5)
Distance before stop bar (ft)	-4.22	1.88
Constant deceleration (g)	0.42	0.49
RDP from brake to stop bar (g)	0.43	0.48
Time to peak deceleration (s)	2.43	2.25

The most intriguing result of this comparison was the relative difference in avoidance percentages. Although participants in the Beep Tone group reacted more quickly and stopped farther away from the crash box, participants in the Speech group responded to the warning at a much higher percentage. It should be noted that the unbalanced number of participants across the comparison studies used for this Beep Tone versus Speech warning analysis necessarily confounds the analysis of stopping distance and deceleration behavior (which is based only on compliant participants). Hence, the main conclusion from this comparison is the observed tendency for the Speech warning, which suggests an increase in warning effectiveness relative to a Beep Tone warning when both are coupled with the brake pulse warning.

CONCLUSIONS AND IMPLICATIONS

The results presented in the previous section showcase the substantial differences in driver performance and behavior that can result from the use of different DVIs and the timing at which those DVIs are presented for TCD violation warning. These differences were present during both plan initiation (i.e., pre-braking behavior) and plan execution (i.e., braking behavior) stages and in some cases resulted in significant differences in avoidance with the different warning combinations. In many instances, observable, sensible, and orderly trends suggested that additional statistically significant differences may have been found with larger sample sizes than those employed in the current studies. This section summarizes the key differences and trends observed in the current studies and suggests future research directions.

The main implication of the results from the nine studies is the selection of a DVI for on-road testing of the CICAS-V system. Driver behavior, performance, and response to the warnings (as well as subjective data not reported here) suggest that the Visual icon + Speech ('Stop Light') + Brake Pulse warning has the highest probability of success amongst the warnings tested. Therefore, this warning is recommended for further on-road testing of the CICAS-V system. The warning, which contains elements from the visual, auditory, and haptic modalities, also performed well across a number of relatively late presentation timings. Since both brake pulse and speech warnings have the potential to be annoying to drivers if false alarms occur too frequently (Kiefer et al., 1999), a Field Operation Trial with the CICAS-V system would provide useful information regarding user acceptance of these warnings. The following sections describe the conclusions reached for each of the four research questions that the series of studies was intended to address.

Within the auditory modality, how does the effectiveness of speech warnings compare to non-speech warnings?

There were two auditory warnings of primary interest, the CAMP FCW Tone and the Speech ('Stop Light') warning. There were no significant differences observed between the CAMP FCW Tone and Speech ('Stop Light') warnings with or without the brake pulse warning. However, avoidance rates suggested there may be a slightly increased likelihood of stopping before the intersection 'collision zone' with the Speech ('Stop Light') warning over the CAMP FCW Tone.

A third auditory warning, in the form of a Beep Tone, was also tested on an exploratory basis in an attempt to potentially reduce potential driver annoyance issues associated with the CAMP FCW Tone. This tone was accompanied by a brake pulse. The main

goal of using this tone was to determine if the lack of observable differences between the CAMP FCW Tone and the Speech ('Stop Light') warnings also transferred to a less urgent (hence, less annoying) sound. Since the tone was accompanied by a brake pulse, this would also determine the extent to which the Brake Pulse was the main factor in eliciting an avoidance response (see the next section for further discussion of this topic). Results showed that the Beep Tone elicited a significantly lower avoidance percentage than the Speech warning. Although participants that responded to the traffic signal after receiving the Beep Tone stopped slightly harder than those in the Speech warning condition, these differences are small from a practical perspective and may be the result of unbalanced data. Therefore, the Beep Tone was considered a less effective warning alternative and its use did not extend beyond the initial exploratory study.

Is scenario outcome improved by the addition of a brake pulse warning?
Results suggested that the brake pulse warning (i.e., a single, brief vehicle jerk cue) substantially improved driver performance with the warning (relative to conditions without a brake pulse). This tendency towards improved avoidance appears to be due to significant differences in plan initiation (i.e., pre-braking behavior) and plan execution (i.e., braking behavior) variables. Drivers receiving a brake pulse were faster to react and reached peak deceleration faster than drivers who did not experience a brake pulse warning. This, in turn, required slightly less braking effort from drivers receiving a brake pulse warning than for drivers not receiving a brake pulse, even though drivers receiving a brake pulse were also able to brake to a stop in less distance.

Given that these results were observed across two different types of auditory warnings (CAMP FCW Tone and Speech), it appears that the Brake Pulse was indeed a primary elicitor of response. However, recall that results with a Beep Tone auditory warning showed lower avoidance levels than those observed for the Speech auditory warning. Therefore, although the Brake Pulse warning appears to be the primary factor in eliciting an avoidance response, it is recommended based on the observed results that this warning be paired with a speech warning rather than a non-speech auditory warning (since the former provides more specific warning context to the driver).

Does the availability of Panic Brake Assist (PBA) functionality improve the scenario outcomes?
The availability of the PBA system, as well as the alteration of the PBA system entrance criterion across studies, had either a negligible or no effect towards improving the avoidance rates. Across the studies in which it was available, PBA was seldom activated by drivers. Although every instance of PBA system activation resulted in avoidance, it usually resulted in drivers stopping well short of the intersection stop bar. This suggests that the driver may have also avoided without assistance from the activated PBA system. Therefore, PBA was not recommended as a feature of the CICAS-V DVI.

Within the context of the experimental scenario, what is the effectiveness of each different DVI warning relative to when a warning was not presented?
This question would ideally be answered by examining driver performance and behaviors during the surprise trial. However, comparisons of driver performance and behaviors beyond avoidance were not possible, since only one driver responded to the traffic signal when a warning was not presented. This result, however, produced a significant difference in avoidance between the Baseline condition (in which drivers did not receive a warning) and all other similarly timed warning conditions. As shown earlier in Table 2, baseline drivers were substantially less likely to respond to the traffic signal. While the real-world magnitude of these differences is subject to statistical confidence, differences in avoidance rates suggest substantial improvements for most of the warnings, especially those employing a brake pulse. Future research should use data from real-world exposure to these systems to validate the avoidance levels and performance measures obtained in these test track experiments.

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