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Evaluation of Heavy-Vehicle Collision Warning Interfaces – Follow-On Testing

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16. Abstract This report describes a follow-on evaluation of heavy-vehicle collision warning interfaces as it pertains to the auditory and visual components of a forward collision warning system. The findings build on the results of the original 2015 study. This follow-on investigation examined human performance under nighttime conditions and assessed the impact of delaying the visual component of the alert. Consistent with the original study, drivers who received imminent collision warnings (regardless of time of day or visual alert timing) responded significantly faster to potential rear-end collision events compared to those who did not receive alerts. Comparison of brake response times between drivers alerted during daytime versus nighttime conditions revealed no statistically significant differences. Delaying the visual alert also resulted in 100 percent of drivers directing their attention first to the forward roadway upon alert activation. However, this alert configuration did not result in faster brake response times relative to alert configurations without a delayed visual alert.		
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Executive Summary

This report documents a follow-on study to continue to evaluate the effectiveness of heavy-vehicle crash warning interfaces (HV-CWIs) in heavy trucks, but with an expanded focus on two additional areas: (1) nighttime and (2) delaying the visual component of the alert. Evaluating HV-CWI performance requires the examination of aspects such as driver response characteristics and the design of displays and controls. This project focused on the visual and auditory alerts of a forward collision warning (FCW) that warned of an imminent collision. These particular components are of interest and will continue to help to inform manufacturers and industry partners as well as any potential future revisions of NHTSA's *Human Factors Design Guidance for Driver-Vehicle Interfaces* (Campbell et al., 2016).

This report covers the follow-on study of HV-CWIs; therefore, certain aspects of the original study are only summarized. Please refer to the original HV-CWI report (Tidwell et al., 2015) for a more detailed description of the background, scope, methodology, and pertinent literature.

The main objective of this project was to provide additional human performance experimentation examining HV-CWIs under different situations and to compare those results with what was found in the previous project. The research questions continue after the previous 3 research questions from the previous project:

> RQ#4: Based on a comparison of the previous findings from Experiment 3 (Daytime) to those from this experiment, are reaction times comparable when assessed during nighttime conditions?
>
> RQ#5: Based on a comparison of the previous findings from Experiment 3 and the new findings from Experiment 4 to the findings from Experiment 5, is a 1-second delay in the presentation of the visual component of the alert a benefit or disbenefit in terms of reaction time (i.e., upon FCW activation the auditory alert component is triggered followed by the visual alert 1 second later)?

Methods

Participants

Fifty-nine participants (56 were male, three were female) completed the study with valid test trials. Their mean age was 46.5 years (standard deviation [SD] = 13.1 years). All participants had valid CDL licenses (58 from Virginia and one from Indiana), valid DOT medical cards, and no DOT-reportable crashes within the past year. They are referred to here as the "driver."

Vehicles

The Class 8 truck used in this study was a 2007 Freightliner Cascadia with an Eaton-Fuller 10-speed non-synchronized manual transmission, electronic stability control (ESC), traction control, antilock braking system (ABS), and super-single tires on the rear drive axles. It is similar in design and operation to most Class 8 trucks in CMV operations today. Freightliner has the largest market share (37.4% in 2020) of Class 8 trucks in the United States (Statista, 2021).

Two confederate test vehicles driven by the research team as part of the scenarios were also used. A 2006 Cadillac CTS acted as the lead vehicle in front of the Freightliner. A 2010

Mercedes R-Class minivan acted as the side vehicle (driving in the left adjacent lane of the Freightliner).

Data Acquisition System

A data acquisition system (DAS) was installed in the truck to collect vehicle variables including speed, engine rpm, gas pedal position, brake application, following distance, and time-to-collision (TTC).

Heavy Vehicle Crash Warning Interface

The HV-CWI for this follow-on testing was the same as used in Experiment 3. It used an FCW single-stage alert system that gives an ICW alert when triggered. The system provided both an auditory and a visual alert with a tone sequence as the auditory alert coupled with a simple visual alert icon. Secondary audio sources (i.e., radio) were not muted with the onset of the alert. The ICW visual alert was displayed on a Samsung Galaxy Player 4.0 (Model YP-G1CWY/XAA) color display mounted on the instrument panel directly above the speedometer and tachometer.

Procedures

All testing occurred on the Virginia Smart Road test bed, a section of two-lane highway about 3.5 km long (2.2 miles) that meets Federal and State DOT standards. Only the test vehicle and two confederate vehicles were on the test track at the time of testing.

Four test conditions were examined, with two conditions each in Experiment 4 and Experiment 5. Experiment 4 evaluated the FCW alert in a nighttime setting. A baseline condition (i.e., no alert) was also evaluated. Experiment 5 evaluated the FCW in both daytime and nighttime; however, in this experiment, the visual alert component was delayed by 1 second from activation of the FCW auditory alert.

The experimental design was a between-subjects design with a single-exposure surprise event. All drivers made six test trials. These were the same across all test conditions and were always conducted in the same order. Each test trial was one full test track lap. The only test trial of interest for this study was Test Trial 6 (i.e., a near-crash rear-end event).

Results and Discussion

The first measure of interest was DV #1 (first response). The first response to the imminent collision warning (ICW) alert was categorized in one of three ways: (1) look to the forward roadway, (2) look to the visual alert, or (3) lift foot from the gas pedal.[1] The second measure of interest was DV #2 (reaction time).

The majority (90%) of drivers looked forward to the roadway as their first response after the FCW was activated. However, there were some differences between the first responses of drivers in the condition with a delayed visual alert component and those in the condition that did not delay it.

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[1] In this report the throttle is the same as the gas pedal, also sometimes called the accelerator pedal. Some people point out that the throttle is in the air intake, situated between the air cleaner (filter) and the intake manifold. It is in a metal housing of a butterfly valve that regulates airflow; therefore, the driver cannot literally "step on it" or release it by taking the foot off it. Without getting into the merits of that discussion, this report uses "gas pedal" for clarity. Some specific tests use the word "Throttle" in their formal names, so the word was kept in those figures and tables.

Under conditions with the FCW alert, both gas pedal release and brake response reaction times were significantly quicker than under baseline conditions. Overall, drivers who received alerts released the gas pedal 0.33 seconds quicker and depressed the brake pedal 0.34 seconds quicker than drivers not receiving alerts.

There was no significant difference in reaction time for gas pedal release or brake response when evaluating between each of the test conditions for delaying visual warning.

Looking at effects of day/night, the results showed significant differences among the brake response reaction times. Post hoc analysis indicated the FCW Alert – Night condition was significantly quicker than the Baseline – Day condition. No significant results were observed for gas pedal release reaction times.

The subjective data showed that most drivers rated the attention-getting qualities of the auditory alert between “moderate” to “very” attention-getting. Both FCW alert nighttime conditions were rated more attention-getting than either of the FCW alert daytime conditions. This can be explained by the increase in perceived contrast difference of the visual alert in the dark.

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Introduction

Overview

In 2018 the Federal Motor Carrier Safety Administration (FMCSA) reported that 530,862 large trucks were involved in crashes across all crash classifications (4,862 fatal, 112,000 injury only, and 414,000 property-damage-only). This represents a 6 percent increase in fatal crashes, a 9 percent increase in injury crashes, and a 15 percent increase in property-damage-only crashes since 2016; however, there was only a 6 percent increase in vehicle miles traveled (VMT) for large trucks from 2016 to 2018. Also, the rate of fatal large-truck crashes per million people in the United States was 13.5 in 2018, a 27-percent increase since 2010. Rear-end crashes with large trucks striking the rear of a passenger vehicles accounted for 11 percent of crashes involving large trucks in 2018 across all crash classifications (FMCSA, 2020).

One solution to mitigate the number and impact of large truck crashes is the implementation of active safety systems such as FCW and automatic emergency braking. Currently, active safety system manufacturers are rolling out the next generation of their systems, and in some cases third- or fourth-generation systems. As these newer systems available as original equipment manufacturer (OEM) or aftermarket installations, have entered the marketplace, it is expected that rear-end crash rates would decrease. However, this crash rate has remained stable since 2014.

A Class 8 truck typically has a three-phase, 15- to 20-year life cycle. According to Research and Markets (2019), owners of large fleets buy new trucks and operate them for about 480,000 miles. Second, long-haul owner-operators or owners of small fleets then purchase the used trucks and operate them for another 640,000 miles. Finally, smaller owner-operators drive them for another 400,000 miles. These long-life cycles keep many older large trucks without active safety systems on the road, missing out on the safety advancements of new technologies. According to FMCSA (2020), the majority (53%) of large-truck fatal crashes in 2018 each involved a large truck at least 6 years or older since date of manufacture. When breaking down large truck age further, 17 percent involved trucks at least 16 years old.[2]

FCW systems have been available in heavy trucks for 25 years (Jones, 2001). The timeline in Figure 1 shows when active safety systems entered the heavy vehicle market in the United States and their continued development. However, most studies to date have been based on early field operational test data that assessed the effectiveness of early generation warning systems that were prone to frequent nuisance and false alarms. Two more recent studies evaluated active safety systems that were more recent. The earlier phase of this study was *Evaluation of Heavy Vehicle Crash Warning Interfaces* (Tidwell et al., 2015) and the *Field Study of Heavy-Vehicle Crash Avoidance Systems* (Grove et al., 2016) came later. To realize their potential benefits, these systems must generate appropriate driver responses to threats in a well-timed manner. However, crash warning interfaces (CWIs) must effectively convey the appropriate warning

[2] [Editor's Note: After this report was completed, an article in the Journal of the American Medical Association (Zhang et al., 2025, May 1) reported that each new driver assistance technology is associated with a 6-percent reduction in the risk of driver death in fatal crashes. That report focused on the difference between teenagers and older drivers, pointing out that younger people drive passengers vehicles more than 15 years old much more often than older people with higher incomes. The study did not mention truck fleets, but it is reasonable to see the corollary between young people driving older used cars – sometimes called "beaters" – with truck owner-operators who also cannot afford up-to-date vehicles with many of the new technologies.]

information to the driver for this to occur. Rapid evolution in these technologies has produced new challenges while bypassing some of the more basic concerns. There are many differences between OEM and aftermarket installations and between the different active safety systems manufactured by different companies. The characteristics of the individual components that compose an FCW alert, including auditory alert loudness, tone type, and duration, as well as the size, location, and color of the visual aspect, can vary markedly. These characteristics can affect driver responses to those alerts, especially in slip-seat operations (i.e., drivers assigned whatever trucks are available and share them with other drivers) or with newly hired drivers. According to the *Benchmarking Survey Report 2017* (National Private Truck Council, 2017), 59 percent of truck fleets in the United States employ slip-seat operations to boost efficiency. This underscores how important it is for active safety systems to be easily understood by drivers of all experience levels across many models of large trucks.

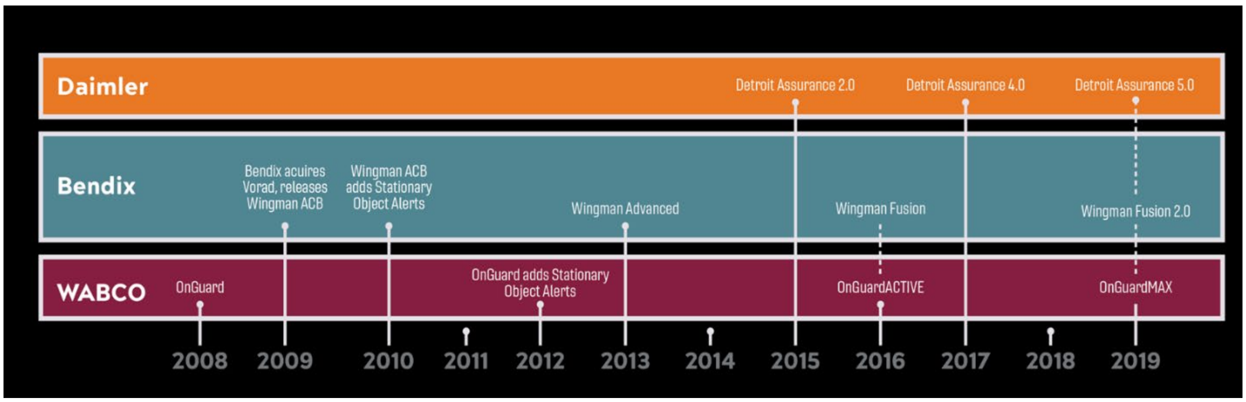

Figure 1. Active Safety System Timeline (Eaton Vorad released 1994)

Background

This report covers follow-on testing from the Heavy Vehicle Collision Warning Interfaces study (Tidwell et al., 2015). The goal of this follow-on effort, similar to the original testing, was to continue to evaluate the effectiveness of heavy-vehicle crash warning interfaces (HV-CWIs) in heavy trucks, but with an expanded focus on **two additional areas: (1) nighttime and (2) delaying the visual component of the alert**. Evaluating HV-CWI performance requires the examination of aspects such as driver response characteristics and the design of displays and controls. This project focused on the visual and auditory alerts of an FCW that warned of an imminent collision. These particular components are of interest and will continue to help to inform manufacturers and industry partners as well as any potential future revisions of NHTSA's *Human Factors Design Guidance for Driver-Vehicle Interfaces* (Campbell et al., 2016).

This report covers the follow-on study of HV-CWIs; therefore, certain aspects of the original study are only summarized. Please refer to the original HV-CWI report (Tidwell et al., 2015) for a more detailed description of the background, scope, methodology, and pertinent literature.

Research Questions

This follow-on study provided additional human performance experimentation examining HV-CWIs. The original work addressed three research questions based on gaps identified through a prior comprehensive literature review. The original research questions (#1, #2, and #3) are presented below to provide context to this follow-on study and subsequent research questions.

Research Questions

Previous Testing (Tidwell et al., 2015)

Research Question #1 (Experiment 1): In terms of reaction time, is there a benefit to muting secondary audio sources (e.g., radio, etc.) during an imminent collision warning (ICW) alert?

Research Question #2 (Experiment 2): In terms of reaction time, is there a benefit to providing drivers with a simpler visual ICW alert (providing minimal information) over a more complex ICW alert (providing more in-depth information), or is having no visual alert the most effective method?

Research Question #3 (Experiment 3): Based on the findings of Research Questions 1 and 2, in terms of reaction time, is there a benefit to the final design ICW alert over a no-alert condition? Are the results obtained for Class 8 truck drivers applicable to motorcoach drivers?

Follow-On Testing

Research Question #4 (Experiment 4): Based on a comparison of the previous findings from Experiment 3 (Daytime) to those from this experiment, are reaction times comparable when assessed during nighttime conditions?

Research Question #5 (Experiment 5): Based on a comparison of the previous findings from Experiment 3 and the new findings from Experiment 4 to the findings from Experiment 5, is a 1-second delay in the presentation of the visual component of the alert a benefit or disbenefit in terms of reaction time (i.e., upon FCW activation the auditory alert component is triggered followed by the visual alert 1 second later)?

Experimental Approach

To evaluate Research Questions 4 and 5, two new experiments were performed. Experiment 5 assessed the FCW system using a Class 8 truck-trailer combination at night. This experiment used the same FCW alert configuration as Experiment 3: no muting of secondary audio sources (radio) combined with a simple visual alert. Experiment 5 assessed the FCW system using a Class 8 truck-trailer combination in both a nighttime and daytime setting. This experiment used the same FCW alert configuration as both Experiment 3 and Experiment 4; however, the visual component of the alert was delayed 1 second upon activation of the FCW (i.e., the auditory component is generated when the FCW alert was triggered followed by the visual component being displayed 1 second later).

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Methodology

Overview

The purpose of this follow-on testing was to further evaluate the targeted alert characteristics that were assessed in Experiment 3 (Tidwell et al., 2015). This HV-CWI incorporated the auditory alert with the simple visual alert and did not mute any secondary audio sources (i.e., radio). This configuration was evaluated in a nighttime condition (Experiment 4) and in both day and nighttime conditions with the visual alert component delayed by 1 second from the onset of the auditory FCW component (Experiment 5). A baseline condition (i.e., drivers did not receive an alert) under both day and nighttime conditions was also evaluated.

Participants

All drivers held valid Class A CDLs without air brakes restriction [K] or automatic transmission restriction [E] and possessed current State-issued Department of Transportation medical cards (medical examiner's certificate). They were not recruited based on age; however, while Federal regulations allow people 18 to 20 years old to qualify for and obtain intrastate CDLs, people must be 21 or older in order to qualify for and obtain interstate CDLs. Therefore, no drivers under 21 were included.

Participants were also not recruited based on gender. However, the Virginia Tech Institutional Review Board requires that any female who is pregnant to meet with her physician to ensure she is medically fit to participate or accept any additional risks due to pregnancy. Each female driver checks a box on the consent form documenting that she has read and understood this requirement.

Additional requirements to serve as a driver included:

- Currently or recently employed (defined as within the past 6 months) in truck operations as a driver;
- No DOT-reportable incident within the past year; and
- Never having participated in a study that involves a surprise (unanticipated) event.

While drivers had to show valid DOT medical cards, additional screening was conducted to ensure requirements set forth in the DOT regulations were met. This included vision acuity of at least 20/40, normal color vision, and hearing loss not greater than 40 decibels with or without a hearing aid in the best ear at 500 Hz, 1,000 Hz, and 2,000 Hz.

Apparatus

Truck-Tractor

The Class 8 truck used in this study was a 2007 Freightliner Cascadia (Figure 2 and Figure 3). The Cascadia has a wheelbase of approximately 6.1 m (20 ft) with an approximate tare weight of 5,443 kilograms (12,000 lb). The truck had an Eaton-Fuller 10-speed, non-synchronized, manual transmission, electronic stability control (ESC), traction control, antilock braking system (ABS), and super-single tires on the rear drive axles. This truck is similar in design and operation to most Class 8 trucks in CMV operations today. Freightliner has the largest market share (37.4% in 2020) of Class 8 trucks in the United States (Statista, 2021).

Figure 2. The 2007 Freightliner Cascadia

Figure 3. The 2007 Freightliner Cascadia Interior View

Utility Trailer

The trailer was a 2007 Utility 4000D-X trailer with a tare weight of 5,960 kilograms (13,139.55 lb). The trailer is a 16.15-meter (53 foot) long dry van[3] equipped with ABS and was used in an empty configuration.

[3] [Editor's Note: Commonly called a "53-er" and "Big Box" in the trucking industry; in other words, the most common industry standard box that replaced the previous 48-footer. They are estimated to make up about 98 percent of over-the-road dry van and refrigerated fleets and some 30 to 40 percent of all van trailer types, including dry and reefers. While hundreds of small companies build or modify trailers, about 25 major manufacturers dominate 90 percent of the domestic market, led by the "Big Five."]

Confederate Vehicles

Two confederate vehicles were also used, a 2006 Cadillac CTS lead vehicle in front of the Freightliner, and a 2010 Mercedes R-Class, "side vehicle" driving in the left adjacent lane.

Data Acquisition System

A Virginia Tech Transportation Institute data acquisition system (DAS) was installed in the experimental truck in order to collect a number of vehicle variables, including speed, engine rpm, gas pedal position, brake application, following distance, and TTC. The DAS records five or more channels of time-synchronized video. The video views for this experiment included a view of the forward roadway, a wide angle of the driver's face, a wide-angle over-the-shoulder view of the driver and truck cabin, the driver's foot well (oriented toward the pedals), and a view of the visual display that generates the collision warning alert (Figure 4). The DAS is unobtrusive and does not interfere with the driver. The data and video were recorded and encrypted on a removable hard drive in the DAS.

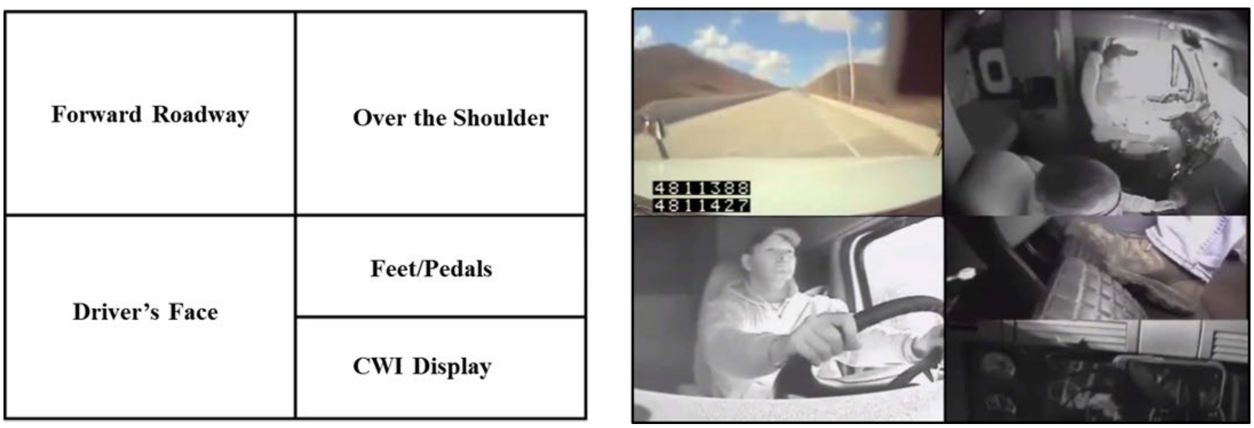

Figure 4. Video Layout as Recorded by the DAS

Heavy Vehicle Crash Warning Interface

The HV-CWI for this follow-on testing was the same as used in Experiment 3. It consisted of an FCW single-stage alert system that gives an ICW alert when triggered. The system provided both an auditory and a visual alert with a tone sequence as the auditory alert coupled with a simple visual alert icon. Secondary audio sources (i.e., radio) were not muted with the onset of the alert. The ICW visual alert was displayed on a Samsung Galaxy Player 4.0 (Model YP-G1CWY/XAA) color display mounted on the instrument panel (IP) of the vehicle directly above the speedometer and tachometer. This area was chosen to represent the location of an integrated display that many suppliers and manufacturers have implemented (Figure 5). The display location is based on existing guidelines (COMSIS Corporation, 1996; Campbell et al., 2007) that suggest a position within 15° of the driver's vertical and horizontal line of sight should, upon activation, direct the driver's attention to the forward roadway.

Figure 5. Placement Comparison With OEM FCW System (in Green) in the Right Image

The visual alert was based on existing CWI design principles (Table 1; Campbell et al., 2007) as well as the SAE International J2400 standard, *Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements* (2003 and revised), that indicates a red background should be used for an imminent warning icon. The physical dimensions of the visual alert are 47.625 mm by 47.625 mm (1 and 7/8 inches) with a visual angle of 100.5 arc minutes as measured using a male driver approximately 1.85 m (6 ft) in height. Figure 6 shows the alert.

Table 1. HV-CWI Visual Alert Characteristics

Category	Criteria	Guideline
Type	Icon with text	6-2
Class	Symbolic and verbal	6-2
Background Color	Red	6-6
Symbol Color	Black	6-6
Text Color	White	6-6
Complexity	Lines of text	5-4

Figure 6. Visual Alert (Image to Scale)

The auditory alert was played through external speakers located overhead. The alert and volume were based on existing CWI design principles (Table 2; Campbell et al., 2007) and replicated Crash Avoidance Metric Partnership sound 8 (Kiefer et al., 1999). The loudness of the alert also falls within the recommendations of the Integrated Vehicle-Based Safety Systems study (Green et al., 2008). The auditory alert was played at a level of 87 dB which is 15 dB greater than ambient and background music levels. The duration of the auditory alert was 1.10 s.

Table 2. HV-CWI Auditory Alert Characteristics

Category	Criteria	Guideline
Type	Simple tones	7-2
Urgency	Faster pulses, high frequency	7-4
Loudness	15 dB above ambient, less than 90 dB	7-8
Distinctiveness	Unique sound	7-10

The triggering of the ICW alert was experimentally controlled via the DAS and associated instrumentation in relation to the lead vehicle. The FCW alert was activated at a 3-second TTC, chosen due to safety concerns of FCW testing in a large truck driven by naïve drivers while using a real passenger vehicle with a human driver as the lead vehicle.

Experimental Conditions

Test Bed

All testing occurred on the Virginia Smart Road test bed (Figure 7), a section of two-lane highway about 3.5-kilometer long (2.2. miles) that meets Federal and State DOT standards. Only the test vehicle and relevant confederate vehicles were present on the test track at the time of testing.

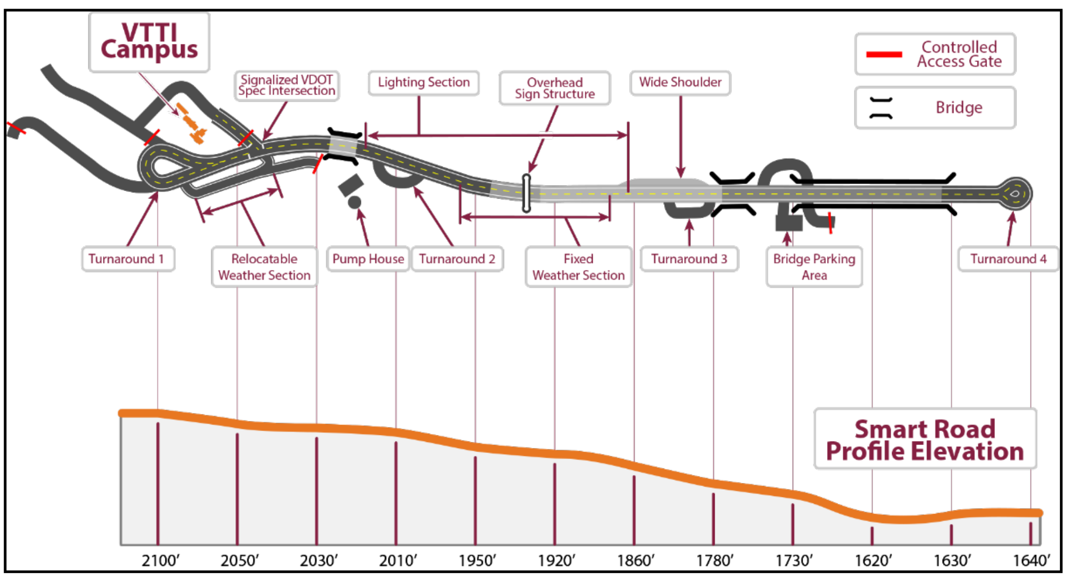

Figure 7. Virginia Smart Road Test Bed

Test Conditions

Four test conditions were examined, with two conditions each in Experiment 4 and Experiment 5. Experiment 4 evaluated the FCW alert in a nighttime setting. A baseline condition (i.e., no alert) was also evaluated. Experiment 5 evaluated the FCW in both a daytime and nighttime setting; however, in this experiment, the visual alert component was delayed by 1 second from activation of the FCW auditory alert. The data from the Experiment 3 FCW alert daytime condition (no visual delay) and the data from the Experiment 3 baseline daytime condition data were also included in the analyses of this testing. To remain consistent with the previous testing, music again provided the secondary cabin sounds for the experiment. Based on the results of prior research examining the effects of different music on driving performance (Brodsky, 2002), a song with a medium-paced tempo was selected (*Café Amore* by Spyro Gyra, 1980[4]). The same song was played across all conditions for all drivers.

Sound level readings were taken to ensure the FCW alert fell within current guidelines and remained consistent throughout testing. These readings were taken with the truck in the test area at test speed (72 km/h; 45 mph) in the gear that drivers were asked to use (8th gear). When the vehicle reached a steady state (i.e., no additional gas pedal manipulations were required to maintain the truck speed in the test area), maximum-value (using the maximum hold setting) sound pressure readings were obtained by holding the measurement wand of a Sper Scientific detachable probe sound meter (Model 840012)[5] in the area directly adjacent to the driver's right ear. These measurements are summarized in Table 3. The auditory alert was played at a level 15 dB greater than ambient and background music levels. The duration of the auditory alert was 1.10 seconds.

Table 3. Sound Pressure Readings from Test Vehicle

Measurement Point	Sound Pressure Level (dB)
Ambient Noise Level	69
Music	72
Music and Alert	87

Experimental Design

The experimental design was a between-subjects design with a single-exposure surprise event. All drivers experienced six test trials. These test trials were the same across all test conditions and were always conducted in the same order. Each test trial was one full length of the test track (2.2 miles). The only test trial of interest for this study was Test Trial 6 (i.e., a near-crash rear-end event). Table 4 describes the six test trials.

Table 4. Description of Experiment 1 Test Trials

Test Trial	Subject Vehicle	Lead Vehicle	Side Vehicle	Test Trial Description
1	Yes	No	No	No secondary task or music. Orientation drive.
2	Yes	Yes	No	No secondary task or music. Orientation drive.
3	Yes	Yes	Yes	Adjusting the radio task. Music playing.
4	Yes	Yes	Yes	Map reading task. Music playing.
5	Yes	Yes	Yes	Paperwork task. Music playing.
6	Yes	Yes	Yes	Reaching for an object task (test trial of interest). Music playing.

[4] Released by MCA Records in association with Amherst Records, produced by Jay Beckenstein and Richard Calandra of Cross Eyed Bear Productions for Amherst Records.
[5] Sper Scientific Direct, Scottsdale, Arizona.

All in-vehicle secondary tasks were based on the results of naturalistic examinations of CMV operator distraction (Olson et al., 2009). The same six test trials were used in all three experiments within this study. The surprise event occurred only in the sixth test trial and consisted of a 0.60-g braking maneuver by the lead vehicle while the driver was performing a task that required eyes off the road. The lead-vehicle braking event resulted in FCW activation at a 3.0-second TTC.

The no-alert condition (baseline) was conducted by having the driver perform the same secondary tasks in each test trial as drivers in the other test conditions, only with no ICW presented during the sixth test trial. As a safety precaution, the lead vehicle experimenter in the Cadillac was instructed to perform a rapid acceleration and lane exit into the adjacent lane at 1.25-seconds TTC in case a driver failed to respond to the ICW alert or during the no-alert condition (baseline).

The purpose of the side vehicle Mercedes R-Class minivan was to replicate real-world driving conditions by having a vehicle in the left adjacent lane, thereby preventing the driver from changing lanes to avoid the lead vehicle during the braking event. Figure 8 shows the lead and side vehicle placement during the test trials.

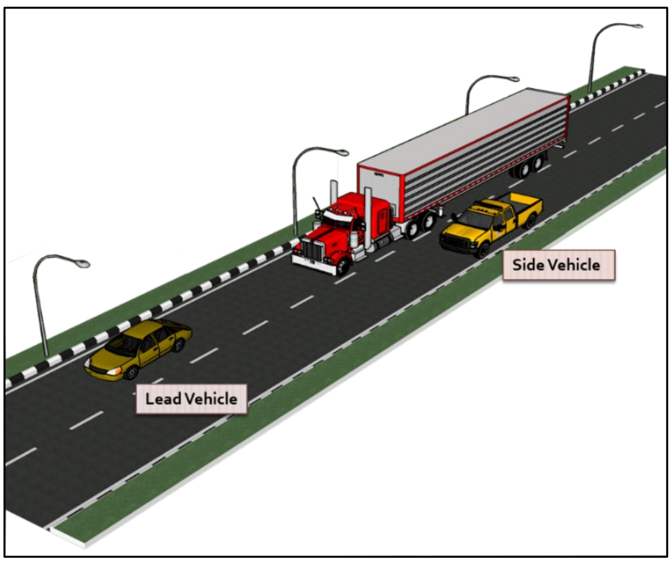

Figure 8. Vehicle Placement During Test Trials

Dependent Variables

Two objective measures provided dependent variables (DVs) for this experiment. The operational definitions are listed below.

- DV #1 – First Response: defined as the driver's first response when the FCW alert is presented
- DV #2 – Reaction Time: defined as the time (as measured in seconds) that elapsed between the presentation of the FCW alert and two separate driver actions (gas pedal release and brake response)

DV #1 (first response) consisted of three driver first-response options: (1) look to the forward roadway, (2) look to the visual alert, and (3) gas pedal release. This dependent variable was analyzed through video reduction. DV #1 was recorded as numerical counts (e.g., number of drivers who looked to the forward roadway first, etc.) and presented as percentages in the results.

DV #2 (reaction time) consisted of two different reaction times. The first reaction time (RT #1 – Throttle Release) was calculated from the time of the FCW alert presentation to gas pedal release. The second reaction time (RT #2 – Brake Response) was calculated from the time of the FCW alert presentation to brake pedal application. This DV was analyzed through a combination of vehicle data and video reduction. The two reaction times recorded for DV #2 were measured in seconds.

The DV objective data were placed into one of two categories: (1) valid alert (reacted to the alert) or (2) invalid alert (reacted before the alert). The operational definitions are listed below.

- Valid Alert (reacted to the alert): defined as the driver having eyes off the road and/or was unaware of the lead vehicle braking and having not yet lifted a foot from the gas pedal prior to FCW alert presentation
- Invalid Alert (reacted before the alert): defined as the driver reacting to the lead vehicle braking prior to the FCW alert presentation

In the case of invalid alerts, one of two responses occurred: (1) drivers glanced back to the forward roadway, saw the lead vehicle braking, and began braking prior to reaching a 3-second TTC and therefore no FCW alert was triggered; or (2) drivers glanced back to the forward roadway, saw the lead vehicle braking, and began lifting their foot from the gas pedal but the FCW alert triggered as the vehicle reached and dropped below a 3-second TTC before they began braking. Both invalid-alert scenarios could be classified as nuisance alerts.

For purposes of this study, DV objective data were only analyzed for drivers with valid test trials.

Subjective

Drivers' subjective feedback on their own performance and the FCW alert was assessed via questionnaire. Participants provided ratings using a 7-point Likert-type scale. Several questions also gathered "yes/no" responses. Responses to open-ended questions about the auditory and visual components of the FCW alert were also collected (Appendix A).

Analysis Methods

The number of drivers evaluated in this study was set by an a priori power analysis with a power of 0.8. This power analysis indicated a power of 0.8 would detect a small to moderate effect while a larger effect would indicate a higher power was attained.

The distribution of response data collected in this study showed non-normality. To assess significant differences between alert conditions, two types of non-parametric tests were used: the Mann-Whitney-Wilcoxon test and the Kruskal-Wallis test. These tests compare independent samples for differences in their distributions to assess whether the samples are significantly different from each other.

The Mann-Whitney-Wilcoxon test is a non-parametric test used with two independent samples. To conduct the test, observations from both sample treatment groups (N) are ordered from smallest to largest, regardless of treatment group. The observations are then assigned a rank value based on their order in the data set (e.g., the first and smallest observation is given rank = 1 and the largest observation receives rank = N). Observations of the same value are given a rank value equal to the average rank of the ordered observations (e.g., two equal observations in rank order 4 and 5 would be given an average rank value of 4.5 each). The following statistics are calculated for each of the two treatment groups:

$$\boldsymbol{U_A = n_A n_B + \frac{n_A(n_A + 1)}{2} - R_A}$$

$$\boldsymbol{U}_{\mathrm{B}} = \boldsymbol{n_A n_B} + \frac{\boldsymbol{n_B}(\boldsymbol{n}_{\mathrm{B}} + \mathbf{1})}{\mathbf{2}} - \boldsymbol{R}_{\mathrm{B}}$$

where n_A is the number of observations in treatment group A, n_B is the number of observations in treatment group B, R_A is the sum of ranks for observations from treatment group A, and R_B is the sum of ranks for observations from treatment group B. The test statistic, U, is determined by taking the smaller of the two calculations and is compared to a critical value of the statistic to determine significance. If the test statistic is significant, we conclude the two treatment groups do not have equal distributions.

The Kruskal-Wallis test is a non-parametric test used to evaluate samples from two or more treatments. This test is an extension of the Mann-Whitney-Wilcoxon test, which is limited to two treatment groups. To perform the test, all observations from all treatments are ordered from smallest ($i = 1$) to largest ($i = N$), without considering treatment group and with each observation receiving a rank equal to its place in the order (so the smallest observation receives a rank value equal to 1). Observations of the same value are given a rank value using the same method described for the Mann-Whitney-Wilcoxon test. The Kruskal-Wallis test statistic is calculated as:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{{R_i}^2}{n_i} - 3(N+1)$$

where N is the total number of observations, n_i is the number of observations in treatment i, R_i is the sum of ranks for sample i, and k is the total number of samples. The Kruskal-Wallis test statistic is compared to a critical value of the statistic to determine statistical significance. If the test is significant, at least one treatment group has a significantly larger mean rank, and the conclusion is the treatments resulted in significantly different observation values.

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Results

Human Performance Testing

As mentioned, drivers completed six test trials during their participation, with the sixth test trial being the trial of interest. Participant drivers arrived under the ruse that researchers were evaluating different types of distracting tasks that CMV operators routinely perform while driving. During the sixth test trial, the driver reached for a red pen located in a cup holder mounted to the floor near the right rear corner of the driver's seat. This location was chosen as naturalistic data from previous research has shown it is common for a CMV operator to reach this location and even behind the seat. Quite often CMV operators place their coolers in this location, and over-the-road trucks typically have refrigerators mounted in the sleeper cabs directly behind the driver's seats. Note that while there were a variety of different color pens in the cup holder, there was no red pen. This was done to keep the driver engaged in the task for as long as possible to allow the unintended surprise braking event to unfold unnoticed. Figure 9 shows the location of the cup holder used in test trial 6.

Figure 9. Cup Holder Location for Test Trial 6

It is important to reiterate that no driver knew an FCW system was installed in the vehicle, and they received no prior training on the visual alert or auditory alert. This was to ensure that no driver would expect that the lead vehicle would perform a hard-braking maneuver. Also, this is representative of fleets randomly assigning drivers to fleet vehicles without informing them that the vehicles had active safety systems or giving drivers any training on active safety systems.

The first measure of interest was DV #1 (first response). The first response to the ICW alert was categorized in one of three ways: (1) look to the forward roadway, (2) look to the visual alert, or (3) lift foot from the gas pedal.

The second measure of interest was DV #2 (reaction time). Data collected from three different points in time were used during the analyses. The first point in time recorded was when the ICW alert was triggered. Note that drivers in the no-alert condition (baseline) did not receive the ICW alert. Therefore, the first point in time recorded coincided with a 3.0-second TTC. The second point in time recorded was when the driver first lifted the foot off the gas pedal (throttle release). The third time recorded was when the driver depressed the brake pedal (brake response).

Two reaction times were obtained from these three recorded times:

- RT #1 – Throttle Release: The time from when the ICW alert was triggered to when the driver first lifted the foot from the gas pedal (i.e., the point of initial deceleration).
- RT #2 – Brake Response: The time from when the ICW alert was triggered to when the driver first depressed the brake pedal.

Figure 10 shows the three recorded points in time and the two reaction times measured.

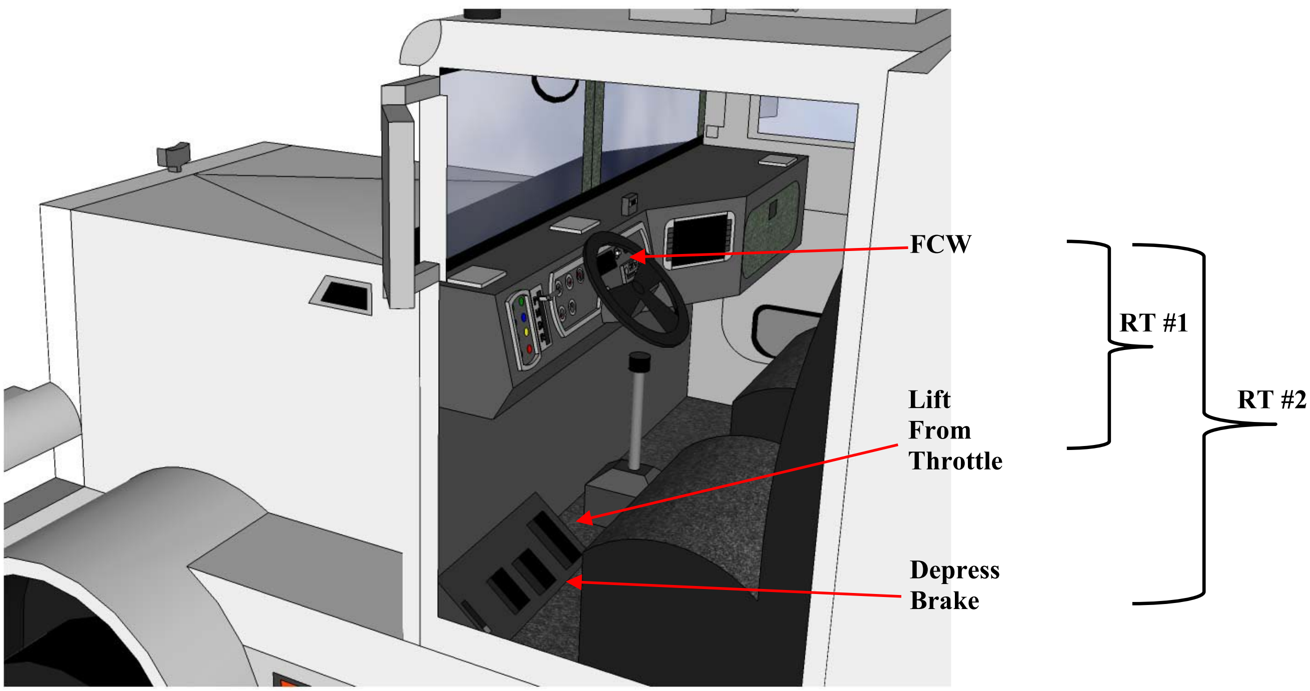

Figure 10. Three Recorded Points in Time and the Two Reaction Times Measured

Participant Demographics

Demographics were collected and compiled for all drivers. However, only demographics of those drivers with valid test trials (i.e., drivers who reacted to the alert) are presented in the tables below. Fifty-nine drivers completed the study with valid test trials. Their mean age was 46.5 years (standard deviation [SD] = 13.1 years). Fifty-six drivers were male, while three were female. All drivers had valid CDLs (58 from the Virginia and one from Indiana), valid State DOT medical card (medical examiner's certificate), and no DOT-reportable crashes within the past year. Table 5 shows driver demographics per test condition.

Table 5. Participant Demographics per Test Condition

Condition	*n*	Male	Female	Mean Age (years)	SD Age (years)	Minimum Age (years)	Maximum Age (years)
FCW Day – No Visual Delay	10	10	0	46.3	15.0	21	62
FCW Night – No Visual Delay	10	9	1	48.6	11.9	32	75
FCW Day – Delayed Visual	10	10	0	41.6	12.6	22	59
FCW Night – Delayed Visual	9	7	2	46.1	10.8	28	61
Baseline – Day	10	10	0	48.8	13.1	29	67
Baseline - Night	10	10	0	47.5	15.0	21	67

Additional demographic data captured included years of experience operating CMVs and the distance classification of their employment. According to the U.S. Census Bureau's Vehicle Inventory and Use Survey (2004), distance classifications are divided into the five categories shown in Table 6.

Table 6. Distance Classifications

Distance Classification	Definition
Local	Trips 50 miles or less
Short Range	Trips between 51 and 100 miles
Short Range–Medium	Trips between 101 and 200 miles
Long Range–Medium	Trips between 201 and 500 miles
Long Range	Trips 501 miles or greater

Motor carriers typically have many routes comprising different distances; thus, short range, short range–medium, and long range–medium are collectively referred to as "short haul." For the purposes of this report, distance classifications are reported as local (trips 50 miles or less), short haul (trips between 51 and 500 miles), and long haul (trips 501 miles or greater). Table 7 shows the drivers' years of experience operating CMVs. Table 8 shows the number of drivers per distance classification within each test condition.

Table 7. Participant Years of Experience

Condition	*n*	Mean Experience (years)	SD Experience (years)
FCW Day – No Visual Delay	10	22.5	12.1
FCW Night – No Visual Delay	10	19.3	16.8
FCW Day – Delayed Visual	10	12.0	11.9
FCW Night – Delayed Visual	9	14.3	9.6
Baseline – Day	10	23.8	17.4
Baseline – Night	10	25.0	14.8

Table 8. Number of Participants per Distance Classification

Condition	*n*	Long Haul	Short Haul	Local
FCW Day – No Visual Delay	10	4	3	3
FCW Night – No Visual Delay	10	2	6	1
FCW Day – Delayed Visual	10	1	4	5
FCW Night – Delayed Visual	9	3	4	2
Baseline – Day	10	5	4	1
Baseline – Night	10	3	3	4

*One driver in the FCW Night – No Visual Delay condition did not respond to this question.

First Response to FCW Alert

Video reduction assessed each driver's responses to the FCW alert. Note that both the daytime and nighttime baseline conditions were not included in this video reduction as those drivers did not receive the FCW alert. Only the first three potential responses were included in the analysis. Lifting the foot from the gas pedal is the first action to begin mitigating a potential rear-end conflict and must occur before depressing the brake; therefore, depressing the brake (a fourth potential response) was omitted from these results. Also, note that the response of looking to the visual alert may not sum to 100 percent of the drivers because some drivers did not look at the visual alert component.

The majority (90%) of the drivers looked to the forward roadway as their first response after the FCW was activated. However, there were some differences between the first responses of drivers in the condition with a delayed visual alert component and those in the condition that did not delay it. Figures 11 to 14 show the breakdown of driver responses between test conditions.

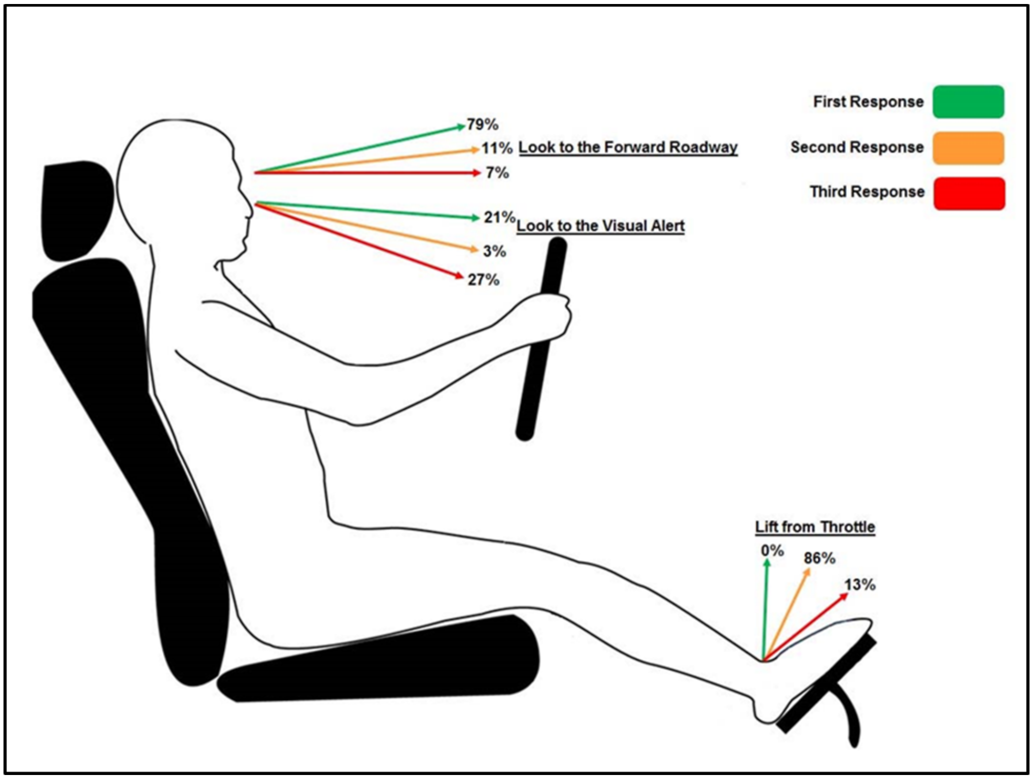

Figure 11. Participant Responses to FCW Day – Not Delayed

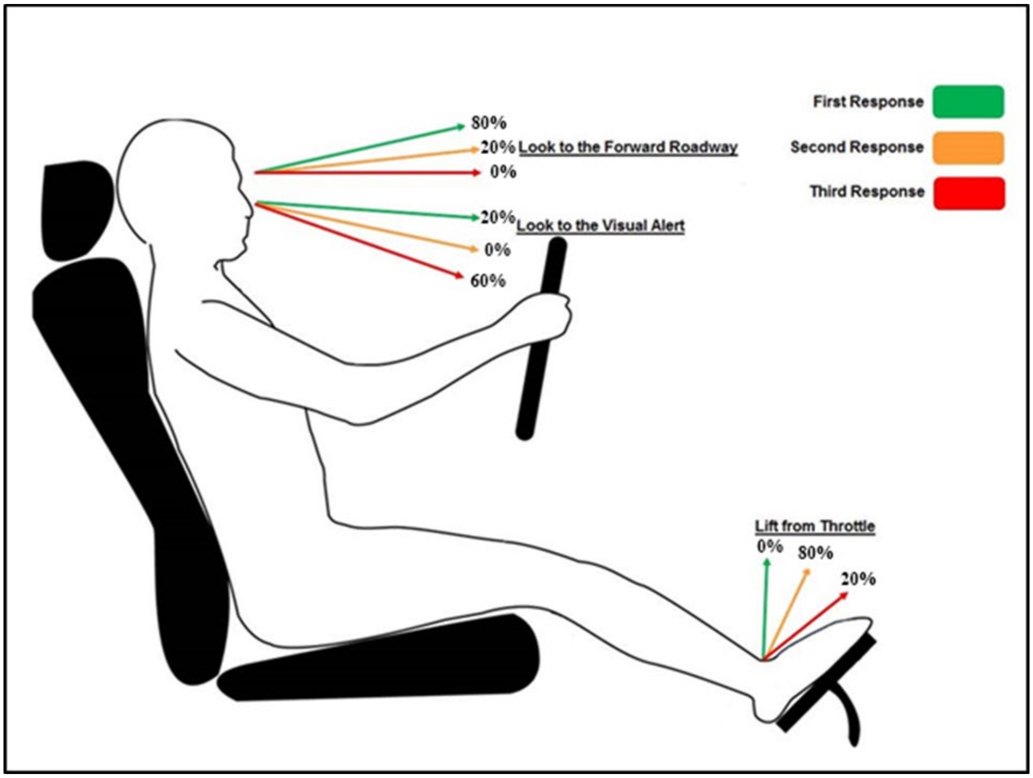

Figure 12. Participant Responses to FCW Night – Not Delayed

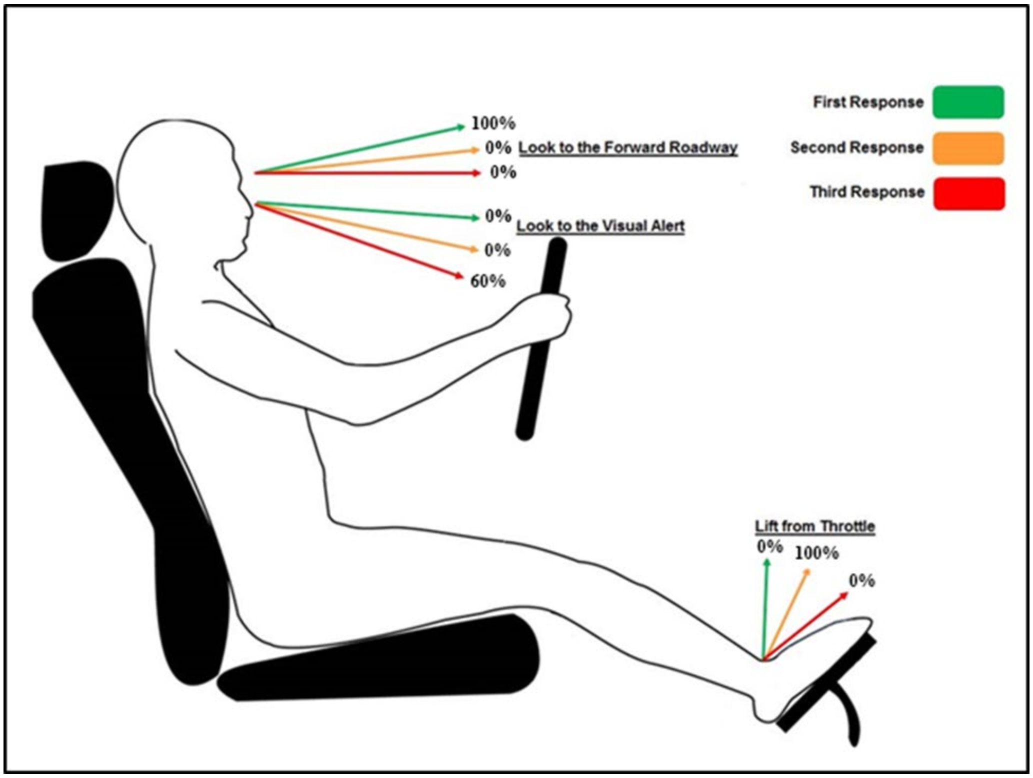

Figure 13. Participant Responses to FCW Day – Delayed Visual

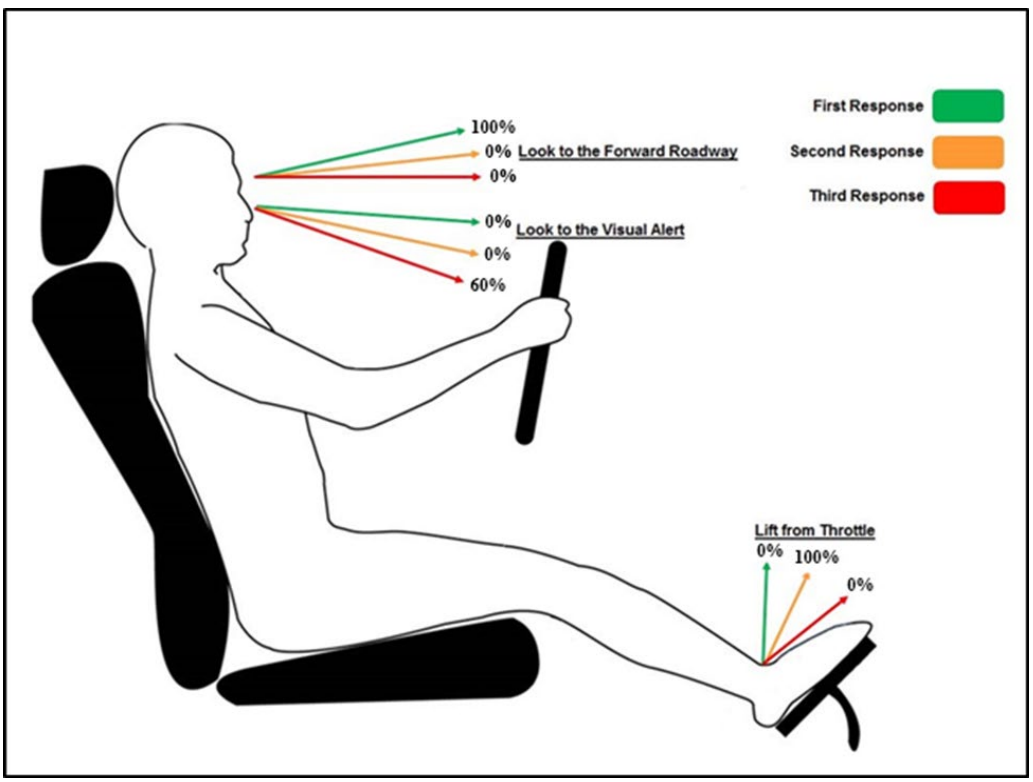

Figure 14. Participant Responses to FCW Night – Delayed Visual

As seen in the previous four figures, delaying the visual component of the alert generated the intended effect of 100 percent of the drivers looking to the forward roadway as their first response to FCW. Not delaying the visual component of the alert resulted in the finding that approximately 20 percent of drivers' first response was looking at the visual alert located in the instrument panel. It is important to note that nearly two-thirds of drivers did glance to the visual component of the alert at some point during the surprise braking event once the FCW activated.

Reaction Times

Delaying Visual Alert Versus Not Delaying Visual Alert

Two analyses were performed on the reaction time data. As reaction times tend to not follow a normal distribution and outlier values are common and greatly influence the mean of each data set, we conducted non-parametric statistical tests in these analyses as this method accounts for the median rather than the mean. See Table 9 and Figure 15 for the descriptive results.

We applied the Mann-Whitney-Wilcoxon non-parametric test to the combined daytime and nighttime data set to evaluate any differences between delaying the visual alert and not delaying the visual alert. This test was conducted on both the gas pedal release reaction time and brake response reaction time data. See Table 10 for the results of these analyses.

Table 9. Descriptive Results

Test Condition	Throttle Release (s)	Brake Response (s)
FCW Alert – Delayed Visual	Mean = 0.64; Med = 0.54; SD = 0.36	Mean = 1.14; Med =1.02; SD = 0.40
FCW Alert – No Delay	Mean = 0.44; Med = 0.39; SD = 0.37	Mean = 1.11; Med = 0.91; SD = 0.66

Med = median

Table 10. Mann-Whitney-Wilcoxon Test Results

Reaction Time	Significance Test
Throttle Release	$W = 303.0$; $p = .050$
Brake Response	$W = 338.0$, $p = .350$

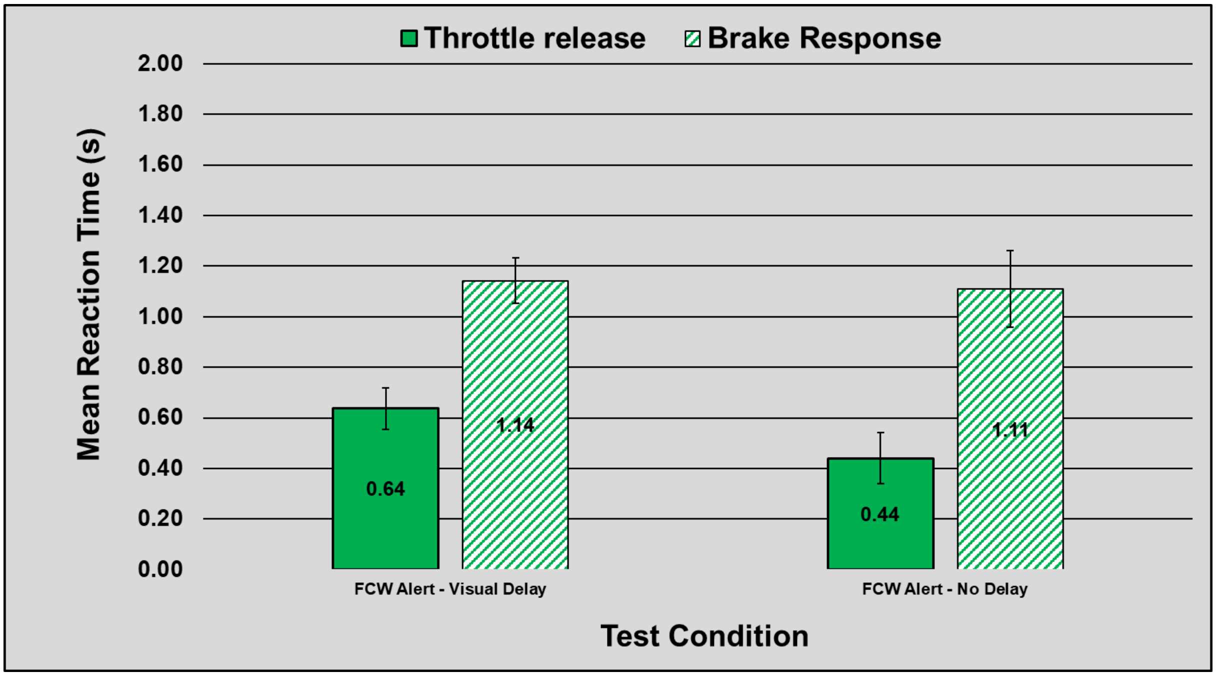

Figure 15. Mean Reaction Times for Delayed Visual Alert and No Delay

While these findings indicate that the gas pedal release reaction was 0.20 seconds quicker when not delaying the visual alert than when the visual alert was delayed, this difference was not statistically significant. Brake response was nearly identical between the two conditions.

Following the combined data evaluation, we applied the Kruskal-Wallis non-parametric test across all four test conditions for both gas pedal release and brake response reaction times. See Table 11 for the descriptive results and Table 12 for the results of these analyses.

Table 11. Descriptive Results

Test Condition	**Throttle Release (s)**	**Brake Response (s)**
FCW Day – No Delay	Mean = 0.45; Med = 0.37; SD = 0.39	Mean = 1.41; Med =1.02; SD = 0.71
FCW Night – No Delay	Mean = 0.43; Med = 0.39; SD = 0.37	Mean = 0.78; Med = 0.79; SD = 0.43
FCW Day – Delayed Visual	Mean = 0.74; Med = 0.56; SD = 0.43	Mean = 1.22; Med = 1.08; SD = 0.44
FCW Night – Delayed Visual	Mean = 0.53; Med = 0.51; SD = 0.24	Mean = 1.05; Med = 0.96; SD = 0.35

Table 12. Kruskal-Wallis Test Results

Reaction Time	**Significance Test**
Throttle Release	$H(3) = 4.60$; $p = .204$
Brake Response	$H(3) = 7.11$, $p = .068$

Figure 16 shows the mean reaction times with standard error between the four FCW alert configurations.

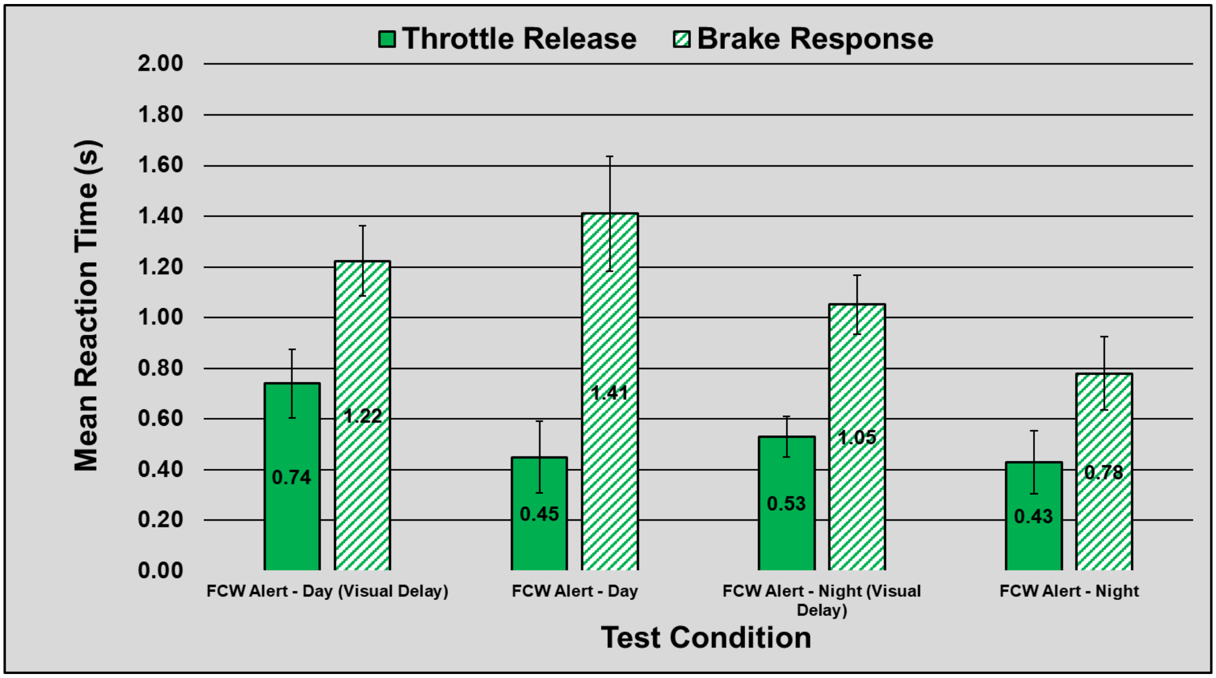

Figure 16. Mean Reaction Times Between Test Conditions

These findings indicate no significant difference in reaction time for gas pedal release or brake response when evaluating between each of the test conditions.

FCW Alert Versus No Alert

We compared two analyses of reaction times between the FCW alert conditions and no alert. The initial analysis compared the combined data from all FCW alert conditions to the data from the baseline conditions. The second analysis compared the data of all four test conditions and the two baseline conditions. Similar to the previous analyses, non-parametric test methods were used.

A Mann-Whitney-Wilcoxon non-parametric test was applied to the combined data set to evaluate any differences between the FCW alert and no-alert conditions on both the gas pedal release reaction time and brake response reaction time data. See Table 13 for the descriptive results and Table 14 for the results of these analyses.

Table 13. *Descriptive Results*

Test Condition	Throttle Release (s)	Brake Response (s)
FCW Alert	Mean = 0.54; Med = 0.49; SD = 0.37	Mean = 1.13; Med =0.96; SD = 0.54
Baseline (No Alert)	Mean = 0.87; Med = 0.75; SD = 0.54	Mean = 1.47; Med = 1.32; SD = 0.78

Table 14. Mann-Whitney-Wilcoxon Test Results

Reaction Time	Significance Test
Throttle Release	$W = 743.0$; $p = .013$*
Brake Response	$W = 711.0$, $p = .049$*

* Indicates significance

Figure 17 shows the mean reaction times with standard error for the overall alert and baseline conditions.

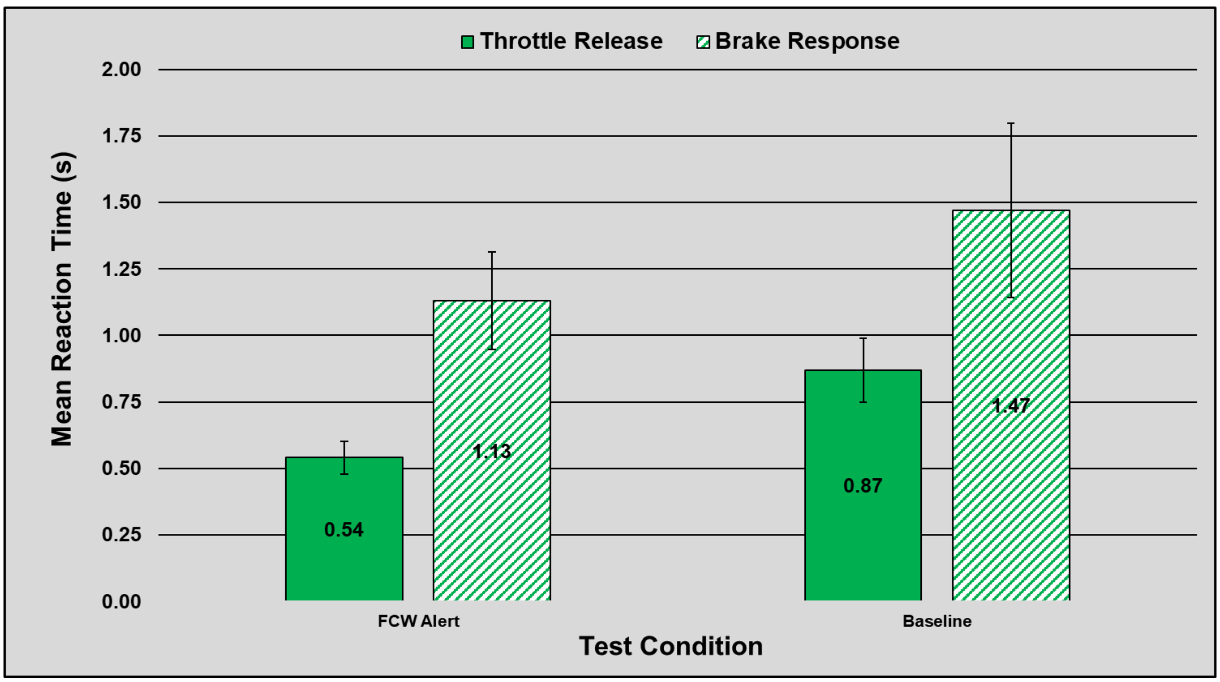

Figure 17. Mean Reaction Times Between Test Conditions

These findings indicate that under conditions with the FCW alert, both gas pedal release and brake response reaction times were significantly quicker than under baseline conditions. Overall, drivers who received an alert released the gas pedal 0.33 seconds quicker and depressed the brake pedal 0.34 seconds quicker than drivers not receiving an alert.

Following the combined data evaluation, we applied the Kruskal-Wallis non-parametric test to all four FCW alert test conditions and both daytime and nighttime baseline conditions. Again, both gas pedal release and brake response reaction times were evaluated. See Table 15 and Figure 18 for the descriptive results and Table 16 for the results of the inferential analysis.

Table 15. Descriptive Results

Test Condition	Throttle Release (s)	Brake Response (s)
FCW Day – No Delay	Mean = 0.45; Med = 0.37; SD = 0.39	Mean = 1.41; Med =1.02; SD = 0.71
FCW Night – No Delay	Mean = 0.43; Med = 0.39; SD = 0.37	Mean = 0.78; Med = 0.79; SD = 0.43
FCW Day – Delayed Visual	Mean = 0.74; Med = 0.56; SD = 0.43	Mean = 1.22; Med = 1.08; SD = 0.44
FCW Night – Delayed Visual	Mean = 0.53; Med = 0.51; SD = 0.24	Mean = 1.05; Med = 0.96; SD = 0.35
Baseline – Day	Mean = 0.87; Med = 0.86; SD = 0.36	Mean = 1.72; Med = 1.53; SD = 0.75
Baseline – Night	Mean = 0.86; Med = 0.69; SD = 0.70	Mean = 1.22; Med = 1.03; SD = 0.75

Table 16. Kruskal-Wallis Test Results

Reaction Time	Significance Test
Throttle Release	$H(5) = 10.73; p = .057$
Brake Response	$H(5) = 12.77, p = .026$*

* Indicates significance

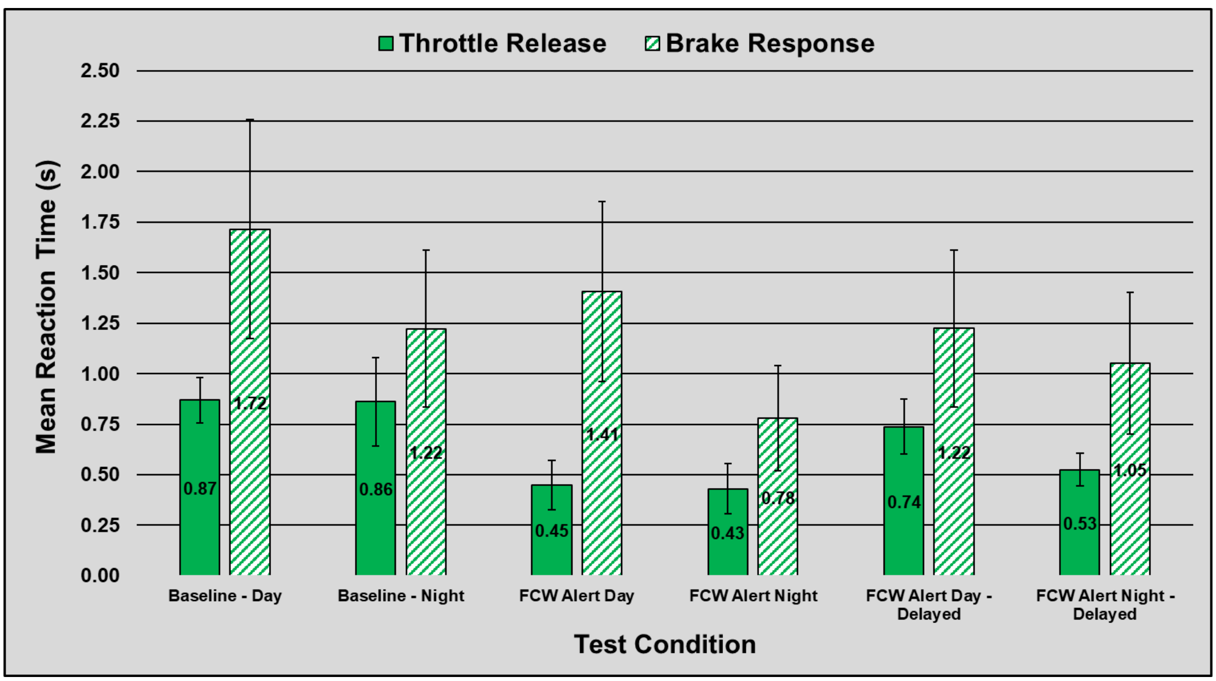

Figure 18. Mean Reaction Times Between FCW Alert Conditions and Baseline Conditions

These findings indicate significant differences among the brake response reaction times. Post hoc analysis indicated the FCW Alert – Night condition was significantly quicker than the Baseline – Day condition. The gas pedal release reaction times, while not significantly different, should not be entirely discounted. More importantly, in terms of driving safety and real-world implications, the FCW alert conditions resulted in gas pedal release and brake response reaction times that were between 0.30 seconds to nearly a half-second quicker than baseline conditions, a difference that could significantly mitigate the potential outcome in a rear-end crash. In this study, drivers are traveling at 45 mph (66 feet per second); therefore, a half-second quicker brake response would begin braking the vehicle 33 feet sooner.

Subjective Results

Immediately after the unanticipated surprise braking event was completed and the truck safely stopped, the drivers completed a secondary consent process due to the use of deception and then filled out the post-drive questionnaire. This questionnaire centered on three main areas:

- Attention-getting qualities of the auditory alert,
- Attention-getting qualities of the visual alert, and
- Appropriateness of the alert timing

Drivers also provided input on the perceived necessity of the visual alert component, on potential glare during the nighttime conditions, and on the individual alert characteristics such as color, size, loudness, type of sound, and duration. Note that drivers in the Baseline - Day or Baseline - Night conditions did not receive these questions as they did not have the opportunity to experience the alert.

Attention-Getting Qualities of the Auditory Alert

This question asked for driver ratings of how well the FCW's auditory alert captured their attention. Each driver provided a rating based on a 7-point Likert-type scale that ranged from "very" attention-getting to "not at all" attention-getting.

An analysis of variance (ANOVA) test did not find any significant differences among the four FCW alert conditions; $F(3,33) = 0.55$, $p = .654$. Most drivers rated the attention-getting qualities of the auditory alert between "moderate" to "very" attention-getting. See Figure 19 for the mean driver ratings of the attention-getting qualities of the auditory alert.

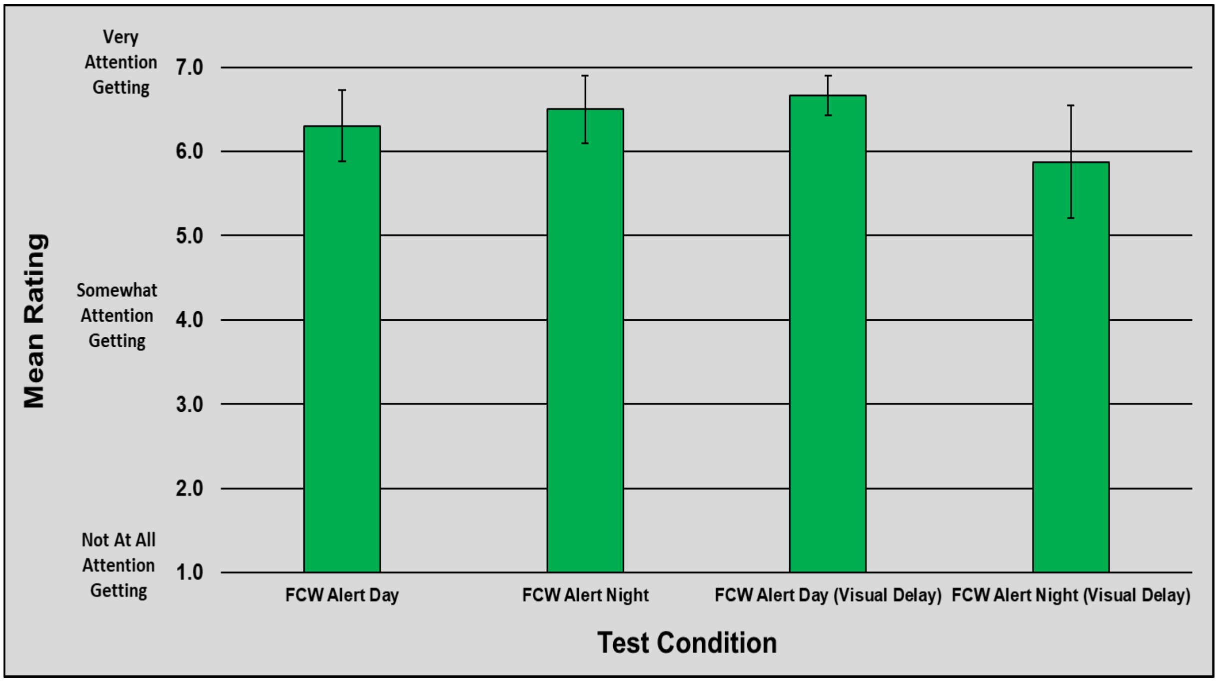

Figure 19. Mean Participant Ratings of the Attention-Getting Qualities of the Auditory Alert

Attention-Getting Qualities of the Visual Alert

Similar to the question about the auditory alert, this question asked drivers how well the visual alert captured their attention. The same 7-point Likert-type scale was used for this question.

The ANOVA test found significant differences among the four FCW alert conditions; $F(3,33) = 4.12$, $p = .014$. Post hoc analysis revealed that the FCW Night – No Delay condition was rated significantly more attention-getting than both FCW daytime conditions. Unsurprisingly, both FCW alert nighttime conditions were rated more attention-getting than either of the FCW alert daytime conditions. This can be explained by the increase in perceived contrast difference of the visual alert in the dark. See Figure 20 for the mean driver ratings of the attention-getting qualities of the visual alert.

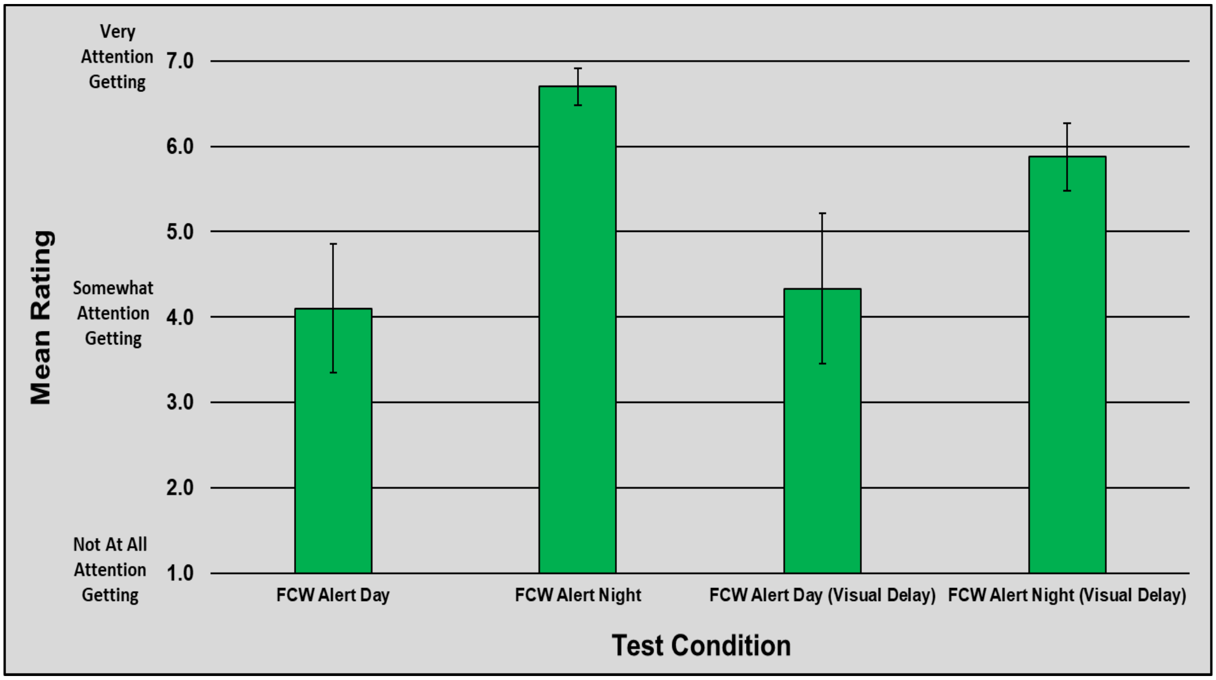

Figure 20. Mean Participant Ratings of the Attention-Getting Qualities of the Visual Alert

Appropriateness of the Alert Timing

This question assessed whether drivers believed that the timing of the FCW alert was appropriate. Participants provided a rating based on a 7-point Likert-type scale with choices ranging from "too early" to "too late."

The ANOVA test found significant differences among the four FCW alert conditions; $F(3) = 2.91$, $p = .050$. Post hoc analysis revealed that the FCW Night – No Delay condition was significantly different from both FCW daytime and nighttime conditions when the visual alert was delayed. Overall, all the ratings for all four FCW alert conditions clustered around appropriate, with the FCW nighttime condition without delaying the visual alert approaching "slightly too late" and both FCW alert conditions with the visual alert delayed approaching "slightly too early." See Figure 21 for the driver mean ratings on the appropriateness of the alert timing.

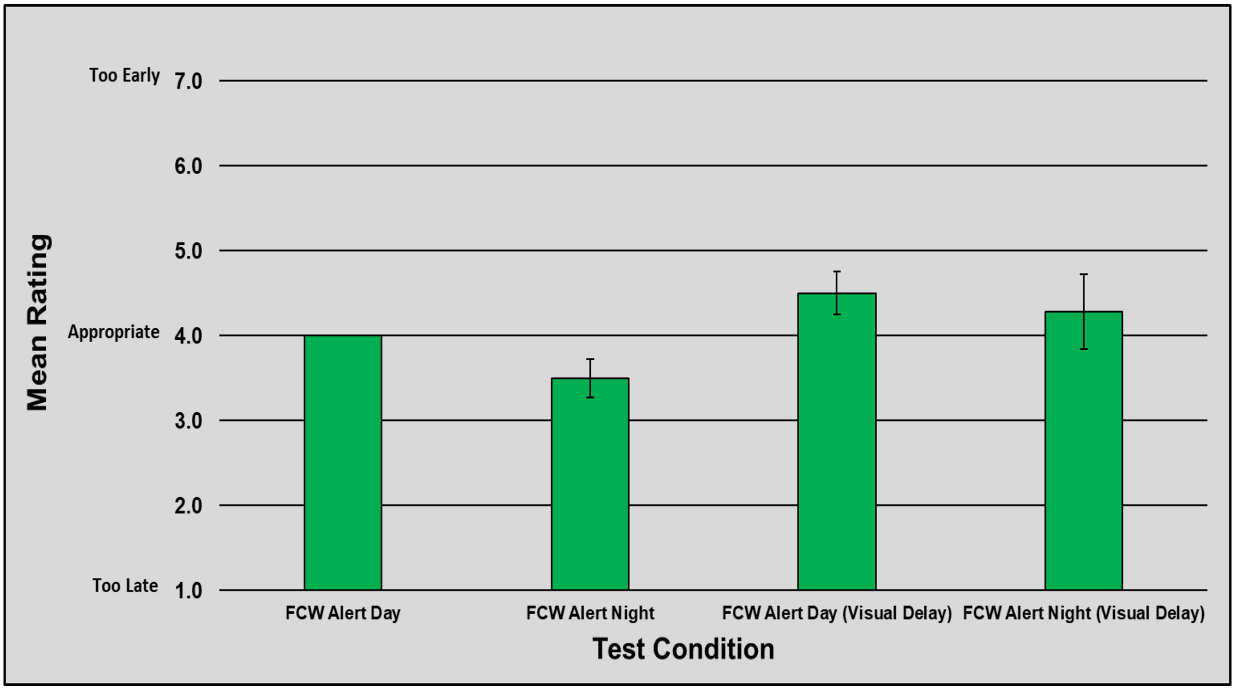

Figure 21. Mean Participant Ratings on the Appropriateness of the FCW Alert Timing

Other FCW Alert Aspects

Participants were also able to provide feedback on nighttime glare from the visual FCW alert component and the need for this component, as well as open-ended comments on the individual alert aspects.

For the nighttime test conditions, 78 percent of drivers reported no glare from the visual alert component. However, the remaining 22 percent of drivers said there was some glare from the visual alert, with 16 percent reporting glare but feeling it was at an appropriate level and 6 percent reporting moderate glare that affected them.

Overall, 76 percent of drivers felt the visual alert component was necessary and stated the need for a visual confirmation of the type of alert being activated. Table 17 shows the breakdown per FCW alert condition.

Table 17. Need for Visual Alert

FCW Alert Condition	Percentage
FCW Day – No Delay	80%
FCW Night – No Delay	80%
FCW Day – Delayed Visual	56%
FCW Night – Delayed Visual	88%

The open-ended feedback on the different aspects of the FCW alert showed overwhelming support for red as the background color (88 percent). The majority of drivers indicated that red means danger or warning and this color would immediately Most drivers also reported that the loudness (88 percent) and duration (82 percent) of the auditory, alert as well as the size (59 percent) of the visual alert, were appropriate.

Conclusions

Research Question #4

Research Question #4 (Experiment 4): Based on a comparison of the previous findings from Experiment 3 (daytime) to those from Experiment 4, are reaction times comparable when assessed during nighttime conditions?

Overall, the reactions times were comparable between the daytime and nighttime conditions. Statistically, no significant differences were found. Without delaying the visual alert, mean gas pedal release was 0.44 seconds, while delaying the visual alert had a mean gas pedal release of 0.64 seconds. Mean brake response time was found to be 1.11 seconds without delaying the visual alert, while delaying the visual alert had a mean brake response of 1.14 seconds. However, despite the lack of significant findings, it is important to compare daytime and nighttime performance in future studies due to the unique workday hours of CMV operators. Future studies may also be able to verify the non-significant but consistently observed trend of FCW alert nighttime conditions (both with and without delaying the visual alert) showing quicker brake response times than either of the daytime conditions.

Research Question #5

Research Question #5 (Experiment 5): Based on a comparison of the previous findings from Experiment 3 and the new findings from Experiment 4 to the findings from Experiment 5, is there a benefit or disbenefit in terms of reaction time when the visual component of the alert is delayed (i.e., upon FCW activation the auditory alert is triggered followed by the visual alert 1 second later)?

Analysis for this research question did not identify any statistically significant differences. When the visual alert component was delayed, the mean gas pedal release reaction times slowed by an average of 0.29 seconds in the daytime and 0.10 seconds at night. When the visual alert component was delayed, the mean brake response reaction time was 0.27 seconds slower for the nighttime conditions. When the visual alert component was delayed in the daytime, the brake response reaction time was an average 0.19 seconds longer than the reaction time with no delayed visual alert component.

Overall Conclusions

Delaying the visual component of the FCW alert increased the percentages of drivers who first responded by looking to the forward roadway from 79 percent in the daytime and 80 percent at night without the delay to 100 percent with the delay. This is important as CMV operators need to see the event unfolding in front of them in order to take the correct action to avoid and/or mitigate the potential safety-critical event. However, brake reaction times showed no significant differences between delaying the visual alert component as compared to not delaying the visual alert component. Under the experimental scenario with a 3-second TTC, the driver made the correct decision to not brake immediately in response to the auditory alert, using the visual scene unfolding on the roadway ahead. Similar reaction times with delaying the visual alert while retaining the 3-second TTC auditory alert suggests that with or without the visual alert, the driver reacts the same. However, the subjective data showed that most drivers indicated the need for the visual alert as a means to confirm what alert was activated. Although this does not explain driver performance, it does shed light on driver understanding of the different alerts and that drivers could be more satisfied with the additional information provided by the visual alert.

The biggest take-away from this study came when examining the comparison of FCW alert versus no alert, the FCW alert produced statistically significant quicker gas pedal release and brake response times. In this study, overall, the FCW alert produced a 38 percent quicker gas pedal release and a 23 percent quicker brake response when compared to not receiving an alert.

Limitations

It is important to point out the limitations in this study. Drivers were naïve to the use of the FCW in the study and did not receive any training. Previous exposure and training on the FCW alert may produce quicker driver reaction times. In this study, 10 out of the 58 drivers had previous exposure to some type of active safety system. Also, this study used a single-exposure design, which may be a limitation in assessing drivers' performance in all sets of conditions. Drivers did not have the opportunity to experience both daytime and nighttime conditions or both FCW alert and baseline conditions. Experiencing more than one condition would give drivers the ability to compare alerts with and without a delay of the visual component; however, the intent of this study was to obtain data from truly naïve drivers. Last, this study did not take into account the effects of false positive alerts and false negatives, which may have biased the drivers' reaction times as well as their feedback and opinions of FCW alert characteristics. This study was conducted on a test track under perfect conditions for reasons of safety. Future studies may require different sampling methods in order to investigate performance and the relationship to various demographic factors. The current study did not recruit a sample balanced for demographic factors of interest and was not able to assess performance differences in factors such as gender.

References

Brodsky, W. (2002). The effects of music tempo on simulated driving performance and vehicle control. *Transportation Research Part F, 4*, 219-241.

Campbell, J. L., Richard, C. M., Brown, J. L., & McCallum, M. (2007). *Crash warning system interfaces: Human factors insights and lessons learned* (Report No. DOT HS 810 697). National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.gov/files/cws_hf_insights_task_5_final_rpt.pdf

Campbell, J. L., Brown. J. L., Graving, J. S., Richard, C. M., Lichty, M. G., Sanquist, T., & Morgan, J. L. (2016, December). *Human factors design guidance for driver-vehicle interfaces* (Report No. DOT HS 812 360). National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/812360_humanfactorsdesignguidance.pdf

Federal Motor Carrier Safety Administration. (2020). *Large truck and bus crash facts 2018*. Federal Motor Carrier Safety Administration.

Green, P., Sullivan, J., Tsimhoni, O., Oberholtzer, J., Buonarosa, M.L., Devonshire, J., Schweitzer, J., Baragar, E., & Sayer, J. (2008). *Integrated vehicle-based safety systems (IVBSS): Human factors and driver-vehicle interface (DVI) summary report* (Report No. DOT HS 810 905). National Highway Traffic Safety Administration. https://rosap.ntl.bts.gov/view/dot/3973

Grove, K., Atwood, J., Hill, P., Fitch, G., Blanco, M., Guo, F., Russell, S., Marchese, M. Bartholomew, P. & Richards, T. (2016, June). *Field study of heavy-vehicle crash avoidance systems* (Report No. DOT HS 812 280). National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.gov/files/812280_fieldstudyheavy-vehiclecas.pdf

Jones, W. D. (2001). *Keeping cars from crashing*. IEEE Spectrum. [Web page]. https://spectrum.ieee.org/keeping-cars-from-crashing

Kiefer, R.J., LeBlanc, D., Palmer, M. Salinger, J., Deering, R. and Shulman, M. (1999). *Development and validation of functional definitions and evaluation procedures for collision warning/avoidance systems* (Report Number DOT HT 808 964). National Highway Traffic Safety Administration. https://rosap.ntl.bts.gov/view/dot/2319

Montgomery, D. C. (2009). *Design and analysis of experiments* (7th ed.). John Wiley & Sons, Inc.

National Private Truck Council. (2017). *Benchmarking survey report 2017*. Author. https://www.nptc.org/wp-content/uploads/2017/07/2017-Benchmarking-Cover.pdf

Olson, R. L, Hanowski, R. J., Hickman, J. S., & Bocanegra, J. (2009). *Driver distraction in commercial vehicle operations* (Report No. FMCSA-RRR-09-042). Federal Motor Carrier Safety Administration. https://www.fmcsa.dot.gov/sites/fmcsa.dot.gov/files/docs/FMCSA-RRR-09-042.pdf

Research and Markets. (2019). *North America life cycle and TCO analysis of class-8 trucks report 2018-2019 & long-term forecast to 2032*. PR Newswire. https://www.prnewswire.com/news-releases/north-america-life-cycle-and-tco-analysis-of-class-8-trucks-report-2018-2019--long-term-forecast-to-2032-300915395.html

Rice, J. A. (2007). *Mathematical statistics and data analysis* (3rd ed.). Thomson Brooks/Cole.

SAE International. (2003, August, and revised). J2400, *Human factors in forward collision warning systems: operating characteristics and user interface requirements.*

Statista. (2019). *Class 8 truck manufacturers' market share in the U.S. as of December 2020*. https://www.statista.com/statistics/274937/market-share-of-truck-manufacturers-in-the-united-states/

Tidwell, S., Blanco, M., Trimble, T., Atwood, J., & Morgan, J. F. (2015, September). *Evaluation of heavy vehicle crash warning interfaces: Final report* (Report Number DOT HS 812 191). National Highway Traffic Safety Administration. https://www.nhtsa.gov/sites/nhtsa.gov/files/812191_evalheavyvehiclecrashwarninterface.pdf

Zhang, F., Rundus, C. R. M., Alshaikh, E., Peek-Asa, C., & Yang, J. (2025, May 1). Vehicle age and driver assistance technologies in fatal crashes involving teen and middle-aged rivers. *JAMA*, 8(5):e258942. https://doi.org/10.1001/jamanetworkopen.2025.8942

Appendix A: Post Questionnaire

Please answer each question by selecting a number on the scale that best reflects your response. Half numbers, such as 4.5, are also acceptable. **(If this is the baseline condition skip questions 1, 2, & 3)**

1. How attention-getting was the sound of the alert?

1		3		5		7
Very			Somewhat			Not at All

2. How attention-getting was the visual display for the alert?

1		3		5		7
Very			Somewhat			Not at All

3. How would you rate the glare from the visual display? (night drivers only)

1		3		5		7
Too Much			Appropriate			Too Little

4. Was there any glare discomfort from the visual alert? (night drivers only)

1		3		5		7
Very			Somewhat			Not at All

5. How appropriate was the timing of the alert?

1		3		5		7
Too Early			Appropriate			Too Late

6. Were you aware of the lead vehicle braking?

Yes / No

7. How quickly did you become aware of what was happening in the event?

1		3		5		7
Very			Somewhat			Not at All

8. Where was the side vehicle when the lead vehicle was braking?

Response:

9. Do you feel the visual alert was needed?

Yes / No

10. Have you previously driven a heavy vehicle equipped with a forward collision warning system?

Yes / No

If yes, please describe the name of system and the type of alert(s) issued:

11. We would like your input on the visual alert icons you may have encountered during the study (Hand driver sheet with alert icons). Please take your time and provide input on the following:

Size:

Background color:

Text color:

Image color:

Additional comments:

12. We would also like your input on the auditory alert you may have encountered during the study (Play the auditory alert). Please take your time and provide input on the following:

Duration of alert:

Loudness of alert:

Sound of alert:

Additional comments:

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