Integrated Vehicle-Based Safety Systems Light-Vehicle Field Operational Test Methodology and Results Report

By

James R. Sayer, Mary Lynn Buonarosa, Shan Bao, Scott E. Bogard, David J. LeBlanc, Adam D. Blankespoor, Dillon S. Funkhouser, and Christopher B. Winkler
The University of Michigan Transportation Research Institute
Ann Arbor, Michigan

for

U.S. Department of Transportation
Cooperative Agreement DTNH22-05-H-01232
December 2010

Technical Report Documentation Page

1. Report No. UMTRI-2010-30	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Integrated Vehicle-Based Safety Systems Light-Vehicle Field Operational Test, Methodology and Results Report		5. Report Date December 2010
		6. Performing Organization Code 052004
7. Author(s) James R. Sayer, Mary Lynn Buonarosa, Shan Bao, Scott E. Bogard, David J. LeBlanc, Adam D. Blankespoor, Dillon S. Funkhouser , and Christopher B. Winkler		8. Performing Organization Report No. UMTRI-2010-30
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150		10. Work Unit no. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration ITS Joint Program Office		13. Type of Report and Period Covered
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This document presents the methodology and results from the light-vehicle field operational test conducted as part of the Integrated Vehicle-Based Safety Systems program. These findings are the result of analyses performed by the University of Michigan Transportation Research Institute to examine the effects of a prototype integrated crash warning system on driving behavior and driver acceptance. The light-vehicle platform included four integrated crash-warning subsystems (forward crash, curve speed, lateral drift, and lane-change/merge crash warnings) installed on a fleet of Honda Accords driven by 108 lay-drivers for a period of six weeks each. Each vehicle was instrumented to capture detailed data on the driving environment, driver behavior, warning system activity, and vehicle kinematics. Data on driver acceptance was collected through a post-drive survey, debriefings, and focus groups.

Key findings indicate that use of the integrated crash warning system resulted in improvements in lane-keeping, fewer lane departures, and increased turn signal use. Research also indicated that drivers were slightly more likely to maintain shorter headways with the integrated system. No negative behavioral adaptation effects were observed as a result of drivers' involvement in secondary task behaviors. Drivers generally accepted the integrated system, and 72 percent of the drivers reported they would like to have such a system in their personal vehicles. Drivers also reported that the blind-spot detection component of the lane-change/merge crash warning system was the most useful aspect of the integrated system.

17. Key Words Collision warning, intelligent vehicles, passenger vehicle safety		18. Distribution Statement Unlimited	
19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. of Pages 198	22. Price

Table of Contents

List of Figures

List of Tables

List of Acronyms

AMR	Available maneuvering room
BSD	Blind spot detection
DVI	Driver-vehicle interface
FCW	Forward collision warning
FOT	Field operational test
GPS	Global positioning system
HT	Heavy truck
IVBSS	Integrated Vehicle-Based Safety Systems
LCD	Liquid-crystal display
LCM	Lane change-merge warning
LDW	Lateral drift warning
LED	Light-emitting diode
LH	Line-haul
LV	Light vehicle
P&D	Pick-up and delivery
POV	Primary other vehicle
SV	Subject vehicle
U.S. DOT	United States Department of Transportation
UMTRI	University of Michigan Transportation Research Institute

Executive Summary

Overview

The purpose of the Integrated Vehicle-Based Safety Systems (IVBSS) program is to assess the potential safety benefits and driver acceptance associated with a prototype integrated crash warning system designed to address rear-end, roadway departure, and lane change/merge crashes for light vehicles and heavy commercial trucks. This report presents key findings from the field operational test (FOT) for the light-vehicle platform. The light-vehicle integrated crash warning system incorporates the following functions:

- Forward crash warning (FCW): Warns drivers of the potential for a rear-end crash with another vehicle;
- Lateral drift warning (LDW): Warns drivers that they may be drifting inadvertently from their lane or departing the roadway;
- Lane-change/merge warning (LCM): Warns drivers of possible unsafe lateral maneuvers based on adjacent vehicles, or vehicles approaching in adjacent lanes, and includes full-time side-object-presence indicators. LCM included a blind-spot detection (BSD) component that provided drivers with information about vehicles in their blind spot as well as approaching vehicles; and
- Curve speed warning (CSW): Warns drivers they are traveling at a rate of speed too high to safely negotiate an upcoming curve.

The integrated system also performed warning arbitration in the event that more than one subsystem issued a warning at or very near, the same time. The arbitration process was based upon when the warning was issued and a prioritization scheme for the detected threat. A driver-vehicle interface (DVI) that consisted of auditory and haptic cues, as well as visual feedback was developed. The DVI relied heavily on auditory warnings for threats and situations requiring immediate driver action. The visual elements of the DVI conveyed situational information, such as the presence of a vehicle in an adjacent lane, more so than actual warnings.

The system tested was developed by a team from The University of Michigan Transportation Research Institute (UMTRI), Visteon Corporation, Takata Corporation (TK Holdings), and Honda R&D Americas, Inc. The LDW subsystem was designed by Takata; the remaining subsystems were designed and integrated by Visteon. UMTRI provided expertise and direction for the DVI design. Honda provided expertise and assistance implementing the DVI and completing system integration.

Laypersons with a valid driver’s license were recruited to drive passenger cars equipped with the integrated system and data collection hardware installed on-board. The vehicles were instrumented to capture information on the driving environment, driver behavior, integrated warning system activity, and vehicle kinematics data. Subjective data on driver acceptance was collected using a post-drive survey, driver debriefing and a series of focus groups.

Field operational tests differ from designed experiments to the extent that they are naturalistic and lack direct manipulation of most test conditions and independent variables. Thus, experimental control lies in the commonality of the test vehicles driven and the ability to sample driving data from the data set on a “within-subjects” basis. The within-subjects experimental design approach, in which drivers serve as their own control, is powerful in that it allows direct comparisons to be made by individual drivers on how the vehicles were used and how drivers behaved with and without the integrated crash warning system.

FOT Data Collection

Drivers were recruited with the assistance of the Office of the Secretary of State, the driver licensing authority in Michigan. One hundred and eight randomly sampled passenger car drivers took part in the field operational test (FOT), with the sample stratified by age and gender. The age groups examined were 20 to 30 (younger), 40 to 50 (middle-aged), and 60 to 70 years old (older). Sixteen late-model Honda Accords were used as research vehicles, and were driven by the field test participants. Consenting drivers used the test vehicles in an unsupervised manner, pursuing their normal trip-taking behavior over a 40-day period, using the test vehicles as their own personal vehicles. The first 12 days of vehicle use was the baseline driving period, during which no warnings were presented to the drivers, but all on-board data was collected. On the 13th day, the treatment period began. During this time, the system was enabled, warnings were presented to the drivers, when appropriate, and on-board data collection continued. The treatment period lasted for 28 days, after which time the participants returned the research vehicle to UMTRI. Use of the vehicles by anyone other than designated participants was prohibited, unless it was considered an emergency.

The data set collected represents 213,309 miles, 22657 trips, and 6164 hours of driving. The rates of warnings heard by drivers in the treatment condition were 0.4 per 100 miles for FCW, 7.0 per 100 miles for LDW, 0.63 per 100 miles for LCM, and 0.42 per 100 miles for CSW. The rate of invalid warnings across all drivers was 0.22 per 100 miles for FCW, 0.43 per 100 miles for LDW, 0.02 for LCM, and 0.17 per 100 miles for CSW.

More detailed information on the vehicle instrumentation and experimental design can be found in the Integrated Vehicle-Based Safety Systems – Field Operational Test Plan (Sayer et al., 2008).

Key Findings

The analyses performed were based upon research questions that emphasize the effect that the integrated warning system has on driver behavior and driver acceptance (also see the IVBSS Light Vehicle Platform Field Operational Test Data Analysis Plan [Sayer et al., 2009]). This section presents a summary of the key findings and discusses their implications.

Warnings Arbitration and Comprehensive System Results

Driver Behavior Results

- There was no effect of the integrated system on driver involvement in secondary tasks. Drivers were no more likely to engage in secondary tasks (eating, drinking, talking on a cellular phone) in the treatment condition than had been observed during baseline driving.
- Multiple-threat scenarios are quite rare. Based on data collected during the FOT, it does not appear that secondary warnings may be necessary in multiple-threat scenarios. However, there remains the need for arbitration to prevent the presentation of multiple warnings.

Driver Acceptance Results

- A majority of drivers reported that their driving behavior changed as a result of driving with the integrated system. The most frequently mentioned change was an increase in turn-signal use, which was the result of receiving lane departure warnings triggered when drivers made unsignaled lane changes.
- Drivers accepted the integrated system and rated it favorably for usefulness and satisfaction.
- While 25 percent of the younger drivers were not interested, 72 percent of all drivers said they would like to have the integrated system in their personal vehicles.
- Drivers found the integrated system's warnings to be helpful and further believed that the integrated system would increase their driving safety. In addition, they seemed to accept the integrated system, even though it did not always perform as expected.
- Eight drivers reported that the integrated system prevented them from having a crash.
- The majority of drivers reported that they would be willing to purchase the integrated system; however, most drivers were not willing to spend more than $750 for this advanced safety feature.
- Drivers were more willing to purchase the lateral warning subsystems (LDW and LCM) than the longitudinal warning subsystems (CSW and FCW).

Lateral Control and Warnings Results

Driver Behavior Results

- The integrated system had a statistically significant effect on the frequency of lane departures, decreasing the rate from 14.6 departures per 100 miles during the baseline condition, to 7.6 departures per 100 miles during treatment. When the integrated system began warning drivers during the third week of exposure, the departure rate dropped by more than half from the previous week.
- The integrated crash warning system had a statistically significant effect on the duration of lane departures. The mean duration of a lane departure dropped from 1.98 seconds in the baseline condition to 1.66 seconds in the treatment condition.

- The results show a statistically significant effect of the integrated system on turn-signal use during lane changes. Drivers were less likely to make unsignaled lane changes in the treatment condition than during baseline driving.
- There was a statistically significant reduction in lateral offset[1] associated with the integrated system, but the magnitude of the difference was quite small from a practical perspective.
- There was a statistically significant increase (12.6%) in lane changes associated with use of the integrated crash warning system.

Driver Acceptance Results

- Drivers rated the lateral subsystems (LCM with blind-spot detection [BSD] and LDW) more favorably than the longitudinal subsystems (FCW and CSW).
- Drivers reported getting the most satisfaction out of the BSD component of the LCM subsystem.
- Drivers found the integrated system to be useful, particularly when changing lanes and merging into traffic.

Longitudinal Control and Warnings Results

Driver Behavior Results

- There was a statistically significant effect of the integrated crash warning system on the time spent at short headways. Slightly more time was spent at time headways of one second or less with the integrated system in the treatment condition (24%) than in the baseline condition (21%).
- There was no effect of the integrated system on forward conflict levels when approaching preceding vehicles. Nor was there any effect on the frequency of hard-braking maneuvers.
- The integrated crash warning system had no effect on drivers' curve-taking behavior, or when approaching curves.

Driver Acceptance Results

- Drivers rated the usefulness and satisfaction of FCW and CSW lowest among the subsystems. Overall, drivers rated them neutral with regard to satisfaction, but recognized that they had some utility.
- The brake pulse accompanying FCWs was the single system attribute that drivers disliked most.

---

[1] Lateral offset is the distance between the centerline of the vehicle and the centerline of the lane (see Figure 39).

Summary

Overall, the light-vehicle FOT was successful in that the integrated crash warning system was fielded as planned, and the data necessary to perform the analyses was collected. The system operated reliably during the 12 months of field testing, with no significant downtime. Other than damage sustained as a result of one major and several minor crashes, few repairs or adjustments were necessary.

The average rate of invalid warnings for all warning types across all drivers was 0.83 per 100 miles. While this rate was well below the performance criteria established early in the program, it still may have been too high to meet some of the drivers' expectations. Nevertheless, drivers generally accepted the integrated crash warning system and some benefits in terms of positive driver behavioral changes were observed. Actionable outcomes and implications for deployment to come out of the field test include:

- The FCW subsystem had a higher invalid alert rate, which increased the driver's annoyance level with these alerts. In general, reducing invalid alert rates would benefit all subsystems.
- Multiple-threat scenarios are very rare, and when they occurred in the FOT, drivers responded appropriately to the initial warnings. Yet, there remains the need for arbitration to prevent the presentation of multiple warnings.
- Drivers reported that they did not rely on the integrated system and the results of examining their involvement in secondary behaviors support this claim. However, drivers were observed driving at shorter headways with the integrated system than without it.
- For the FCW subsystem, additional development of location-based filtering to reduce the number of invalid warnings due to fixed roadside objects should be considered.
- Generally speaking, driver behavior improved as a result of using the integrated crash warning system during the field test; notwithstanding this result, the slightly shorter time headways observed may warrant further investigation in order to determine whether some form of interaction with a wider range of variables took place.
- The lateral warning subsystems (LCM and LDW) were the most liked by drivers and provided the most benefit overall. This was supported by drivers' preferences and the positive changes in driver behavior observed. However, there were several crashes that may have been avoided as a result of the FCW subsystem.
- A potential approach for reducing invalid warnings, particularly for fixed objects outside the vehicle's path, would be the development of location-based filtering that could modify threat assessments in response to repeated warnings to which drivers do not respond.

1. Introduction

1.1 Program Overview

The IVBSS program is a cooperative agreement between the United States Department of Transportation and a team led by the University of Michigan Transportation Research Institute. The objective of the program is to develop a prototype integrated, vehicle-based, crash warning system that addresses rear-end, lateral drift, and lane-change/merge crashes for light vehicles (passenger cars) and heavy trucks (Class 8 commercial trucks), and to assess the safety benefits and driver acceptance of these systems through field operational testing. Crash reduction benefits specific to an integrated system can be achieved through a coordinated exchange of sensor data to determine the existence of crash threats. In addition, the arbitration of warnings based on threat severity is used to provide drivers with only the information that is most critical to avoiding crashes.

Three crash-warning subsystems were integrated into both light vehicles and heavy trucks in the IVBSS program: forward crash warning, lateral drift warning, and lane-change/merge crash warning. The light vehicle platform also included a curve speed warnings system.

- Forward crash warning (FCW): Warns drivers of the potential for a rear-end crash with another vehicle;
- Lateral drift warning (LDW): Warns drivers that they may be drifting inadvertently from their lane or departing the roadway; and
- Lane-change/merge warning (LCM): Warns drivers of possible unsafe lateral maneuvers based on adjacent vehicles, or vehicles approaching in adjacent lanes, and includes full-time side-object-presence indicators. LCM included a blind-spot detection (BSD) component that provided drivers with information about vehicles in their blind spot as well as approaching vehicles
- Curve speed warning (CSW): Warns drivers when they are traveling at a rate of speed too high to safely negotiate an upcoming curve.

Preliminary analyses by the DOT indicate that 61.6 percent (3,541,000) of police-reported, light-vehicle crashes and 58.7 percent (424,000) of police-reported, heavy-truck crashes can be addressed through the widespread deployment of integrated crash warning systems that address rear-end, roadway departure, and lane-change/merge collisions. Furthermore, it is expected that improvements in threat assessment and warning accuracy can be realized through systems integration, when compared with non-integrated systems. Integration should dramatically improve overall warning system performance relative to the non-integrated subsystems by increasing system reliability, increasing the number of threats accurately detected, and reducing invalid or nuisance warnings. In turn, these improvements should translate into reduced crashes and increased safety, in addition to shorter driver reaction times to warnings and improved driver acceptance.

1.1.1 Program Approach

The IVBSS program is a five-year effort divided into two consecutive, non-overlapping phases where the UMTRI-led team was responsible for the design, build, and field-testing of a prototype integrated crash warning system. The scope of systems integration on the program included sharing sensor data across multiple subsystems, arbitration of warnings, and development of an integrated driver-vehicle interface. The remainder of this section addresses these efforts for the light-vehicle platform only.

1.1.2 IVBSS Program Team

UMTRI was the lead organization responsible for managing the program, coordinating the development of the integrated crash warning system on both light-vehicle and heavy-truck platforms, developing data acquisition systems, and conducting the field operational tests. Visteon, with support from Takata, served as the lead system developer and systems integrator, while Honda R&D Americas provided engineering assistance. UMTRI supported Visteon in the development of the driver-vehicle interface.

The IVBSS program team included senior technical staff from the National Highway Traffic Safety Administration, the Federal Motor Carrier Safety Administration, the Research and Innovative Technology Administration (Intelligent Transportation Systems Joint Program Office), the National Institute for Standards and Technology, and the Volpe National Transportation Systems Center. RITA’s Intelligent Transportation Systems Joint Program Office was the sponsor, providing funding, oversight, and coordination with other U.S. DOT programs. The cooperative agreement was managed and administered by NHTSA, and the Volpe Center acted as the program independent evaluator.

1.1.3 Phase I Effort

During Phase I of the program (November 2005 to May 2008), several key accomplishments were achieved. The system architecture was developed, the sensor suite was identified, human factors testing in support of the driver-vehicle interface development was conducted (Green et al., 2008), and prototype DVI hardware was constructed to support system evaluation.

Phase I also included the development of functional requirements (LeBlanc et al., 2008) and system performance guidelines (LeBlanc et al., 2008), which were shared with industry stakeholders for comment. A verification test plan was developed in collaboration with the U.S. DOT (Husain et al., 2008) and the verification tests were conducted on test tracks and public roads (Harrington et al., 2008). Prototype vehicles were then built and evaluated.

Program outreach included two public meetings, numerous presentations, demonstrations and displays at industry venues. Lastly, preparation for the field operational test began, including the design and development of a prototype data acquisition system. Vehicles for the FOTs were ordered, and a field operational test plan submitted (Sayer et al., 2008). Further details regarding the efforts accomplished during Phase I of the program are provided in the IVBSS Phase I Interim Report (UMTRI, 2008).

1.1.4 Phase II Effort

Phase II (June 2008 to November 2010) consisted of continued system refinement, construction of a fleet of 18 vehicles equipped with the integrated system, extended pilot testing, conduct of the FOT, and analysis of the field test data. Refinements to the system hardware and software continued, with the majority of changes aimed at increasing system performance and reliability. Specific improvements were made to reduce instances of invalid warnings. In the process of installing the integrated crash warning system, each vehicle underwent major modifications. All of the sensors necessary for the operation of the integrated system, as well as those necessary to collect data for conducting analyses, needed to be installed so that they would survive continuous, naturalistic use. UMTRI designed, fabricated, and installed data acquisition systems to support objective data collection during the field tests. The data acquisition system served both as a data-processing device and as a permanent recorder of the objective and video data collected.

An extended pilot test was conducted (LeBlanc et al., 2009) from November 25, 2008, through March 3, 2009. The results of this test were used to make specific modifications to system performance and functionality prior to conducting the field operational tests; this proved to be a valuable undertaking by improving the systems being fielded. The pilot test also provided evidence of sufficient system performance and driver acceptance to warrant moving forward to conduct the field test. The FOT was launched in April 2009 and completed in May 2010, after approximately 13 months of continuous data collection.

2. Methodology

2.1 Drivers

Nearly 120 lay-drivers were recruited for this FOT. Of the 117 drivers who participated in the FOT, 108 drivers had their data included in the analyses described in this report. The data from these drivers represent the highest quality data collected. The drivers were divided into equally balanced age by gender cells. The three age groups that were run were 20-30 years, 40-50 years, and 60-70 years. Table 1 provides average age data for the driver groups.

Table 1: Descriptive driver age statistics

	Range (years)	**Mean age (years)**
Younger	21-30	25.1
Middle-aged	42-50	46.1
Older	61-69	64.4

2.2 Vehicles and Instrumentation

The passenger cars which were equipped with the integrated system are a mix of model year 2006 and 2007 Honda Accord EXs (4 2006 and 12 2007 models). These vehicles are four-door sedans with V6 engines. Eighteen vehicles were equipped, sixteen served as research vehicles were loaned to participants, one ’06 model served as a spare in the event a vehicle in the field needed to be replaced, and one ’06 model served as a development vehicle on which trouble shooting was performed. All 18 vehicles were gold-toned with leather interiors, ABS, vehicle stability assist, six-CD stereo systems, and conventional cruise control. The vehicles did not have navigation systems installed.

2.2.1 The Light-Vehicle Integrated System and Driver-Vehicle Interface

The primary crash warning information is delivered to the driver through haptic cues and/or audible tones. A visual text message appears in the OEM center-mounted stack display shortly after each warning is issued as confirmation of the warning type (see Figure 1: Visible physical elements of the light-vehicle driver interface

[a]). The driver-vehicle interface also includes a temporary mute button and audio volume control and a blind-spot detection icon in the side-view mirror as shown in Figure 1 (b) and (c), respectively. There are four warning types and one driver information feature, as shown in Table 2. For lateral maneuvers, Table 2 shows that drifting without a turn signal applied into a lane or onto a shoulder that is unoccupied is signaled by a haptic seat cue. Drifting into an occupied lane or shoulder is treated with an audible tone meant to be more salient to the driver; an intentional lane change or merging maneuver (i.e., with turn signal applied) into an occupied lane is treated with the same audible tone and visual text display, as shown in Table 2. The same audible tone and text are used because the crash threat is similar and the likely driver responses will likely be similar.

Table 2 also shows that the two longitudinal crash threats (rear-end and curve-speed) are addressed using similar but not identical warnings to the driver. The FCW functionality provides an audible tone and a brake pulse. The CSW provides the same audible tone as FCW, without the brake pulse. The visual text to confirm the meaning of the warnings to the driver is different for these two, as indicated in the table.

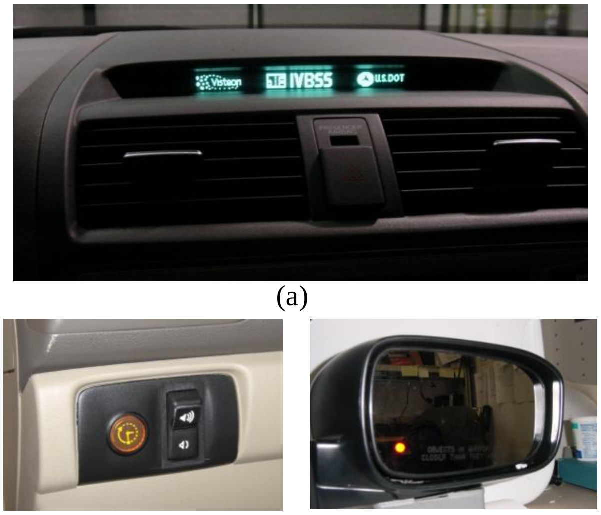


Figure 1: Visible physical elements of the light-vehicle driver interface

Table 2: Crash warning and blind spot detection cues to the driver

Displayed text	Primary cues to driver	Functionality	Crash type addressed
"Hazard ahead"	Audible tone #1, Brake pulse	FCW	Rear-end crash
"Sharp curve"	Audible tone #1	CSW	Curve-overspeed crash
"Left Drift" or "Right Drift"	Seat vibration (directional)	LDW-Cautionary	Lane- or road-departure into an unoccupied lane or shoulder
"Left Hazard" or "Right Hazard"	Audible tone #2 (directional)	LDW-Imminent or LCM	Lane- or road-departure into an occupied lane or shoulder. Lane-change or merging crashes due to changing lanes into an occupied lane.
(None)	LED illuminated in side view mirror	Blind Spot Detection (BSD)	Lane-change or merging crashes.

The integrated system had driver-adjustable volume control for the audible components of warnings that was managed with a three-position rocker switch mounted near the left knee bolster. The integrated system did not allow the driver to turn off the system or to adjust the timing of warnings. A slight exception to this statement was a button near the driver's knee bolster that allowed drivers to temporarily suspend, or "mute", all warnings and information for up to six minutes. This functionality allowed drivers some relief in the unusual case of travel through an environment that may lead to a series of false warnings. An example is traveling through a freeway construction zone in which a lane shift has been made without full eradication of painted lane markers.

2.2.2 Objective Data Collection

This section covers both numeric and video data that constitute the IVBSS. These data are objective in the sense that they are undistorted by emotion or personal bias and are based on observable evidence.

2.2.2.1 The Objective Dataset

The primary goal of the FOT was to determine whether an integrated safety system will bring about objectively measurable changes in driver performance parameters that are likely to affect heavy truck crash rates. The bulk of the data necessary to answer this question was provided by a purpose-built data acquisition system that was virtually transparent to the drivers and had minimal impact on Con-way operations in general. In addition to data collected by the DAS, supplemental objective data was taken from a variety of sources including existing road attribute databases, Con-way's logistical archive, and the National Weather Service (for examples of the data collected from the fleet, see Section 5.9.5). There was also extensive subjective data collected using driver questionnaires and driver interviews. This section characterizes the objective data that was collected and stored in a relational database structure.

The DAS on-board collected hundreds of signals of data along with substantial video of the scene around the vehicle and within the driver cabin environment. On a broad level, these measures are characterized in Appendix C. Although this is not an exhaustive channel data list, it covers the general categories of data retrieval and shows within each category the type of data that was collected to characterize and archive how the system performed, the activities of the driver, and the environment and state of the vehicle. In addition to collecting these measures, a substantive quality control process was used to ensure data channel accuracy.

2.2.2.2 Data Types

Data were separated into general data categories as a function of four classifications, a complete list of the data channels collected can be found in Appendix C.

Source: Most data collected by the DAS were from a dedicated Controller Area Network (CAN) bus (or set of CAN buses) implemented, programmed, and structured specifically for this project. However, other data came from the original equipment vehicle bus (J1939). UMTRI also installed its own set of sensors. These sensors provide researchers at UMTRI with additional measures of vehicle and driver performance, which are independent of the warning system. Finally, a category classified as "other" includes objective data that were linked to the onboard

DAS data but were culled from external data sources such as the National Weather Service, the Highway Performance Monitoring System, and Con-way’s logistical databases.

DAS Format: The data were collected through five general methods:

- **Custom:** Specifically this category applies to the radar and video cameras. For all radar units, the DAS recorded all radar targets and their associated data with the exception of the forward radar. In this case the signals for the primary forward target were recorded at 10 Hz while the signals for up to six secondary targets were recorded at 2 Hz. Video on both platforms was recorded at the highest frequency possible given the storage and compression considerations for the DAS. All video measures were also triggered at least 10 Hz with a pre- and post-event window to capture and save the visual content of the scene surrounding a warning.
- **10 Hz Series:** Most objective data from the vehicle were saved in a time-history format with a 10 Hz resolution.
- **Triggered Event:** Many objective data signals were event-logged by the DAS. That is, when a signal transitioned beyond a threshold or there was a warning, the start and end times of that event were saved along with other relevant signals. These triggered events are the building blocks of more complex analysis methodologies that are used to address specific questions related to how the system and vehicle performed and, more critically, how the driver might have changed their driving behavior. Also, since these summaries are relatively small in size, they could be downloaded to UMTRI after each trip and used to monitor the health of the system and the experience of the driver.
- **Transitional:** Logged events contained the same content as time history events, but required less space and were often easier to summarize in large datasets.
- **Aggregated:** This general classification nearly always involved performing some type of operation on a specific signal and resulted in a number or set of numbers that reflect an overall summary of the measure. Examples include distance traveled, which is the integration of the speed signal over the time resolution of that signal, and the count of brake applications by the driver. Another important aggregation is histograms or the categorization of a signal into predefined bins to produce a time-weighted distribution of a signal. In some cases, two-dimensional histograms were created showing the relationship between two signals such as road type and speed.

Platform: Gives an indication of the differences between the objective data archive of each of the platforms as well as, more importantly, their similarities.

To Monitor: Gave a general breakdown of what the objective data measure will be used for. In many cases, the individual measures served in multiple analysis approaches to better understand the driver, environment, warning system, or vehicle performance.

2.2.2.3 Light-Vehicle Dedicated Instrumentation

In addition to the measures from the warning system and the vehicle CAN, UMTRI instrumented each tractor with a complementary set of sensors that supported and provided additional signals for the analysis phase of the project. These instruments were not part of the system and were installed to provide an independent measure of critical metrics both for the analysis and confirmation of system and vehicle performance. The additional sensors included the following:

- **DGPS**: UMTRI's own differentially corrected GPS module and associated antenna. Measures from this device included latitude, longitude, heading, speed, time and week, number of satellites, and Pdop (percent dilution of position, which is measure of the geometrical strength of the GPS satellite configuration).
- **Yaw Rate**: A stand-alone yaw rate sensor to measure angular velocity. The sensor was ruggedized for transportation applications and had a -60 to 60 deg/s resolution. A routine in the DAS software zeroed the transducer each time the vehicle stopped for at least 60 seconds.
- **Accelerations**: A tri-axial high-precision accelerometer was used to measure longitudinal and lateral accelerations. The unit was mounted near the lateral and longitudinal vehicle mid-point. UMTRI positioned the unit on a rigid cross-member of the frame rail.
- **Steer Angle**: Steer angle was measured by mounting a calibrated string pot to the steering shaft connecting the hand-wheel and steering gear. The string of this analog transducer would wrap or un-wrap around the shaft as the hand-wheel was turned providing a reference voltage to the DAS that was then calibrated to produce an estimate of the actual hand-wheel angle.

2.2.3 Camera Positioning for Video Collection

All FOT vehicles were instrumented with five cameras to capture images of the driving scene and driver activity. UMTRI captured the following; (a) the driver's face; and (b) the driver's hands via a cabin-mounted camera directed over the driver's right shoulder; (c) the forward scene; (d) rearward directed left- and right-side scenes. Sample snapshots of these views are shown in Figure 2 through Figure 4.

Figure 2: Sample driver face and cabin camera images

Figure 3: Sample forward image

Figure 4: Sample left-side rear-looking image

The major reasons for capturing the video data were to:

- Understand circumstances associated with individual episodes, including the forward scene roadway, environment, and traffic, as well as the driver's general direction of gaze;
- Provide samples of roadway type, environment, traffic, and driver behavior at periodic intervals; and
- Aid in determining certain "truth" variables through calculations based on manually assisted extracting of data from images.

All cameras were black-and-white CCD imagers with an analog output (RS170), with the exception of the forward camera, which was shared with the LDW system. For each of the cameras, the images captured by the DAS involved sub-sampling the original image.

2.2.3.1 Video Data Compression and Sampling Rates

The video data from the FOT consumed a large amount of memory, comprising 58 percent of the data collected by the DAS. For this FOT, all video data were compressed both spatially and temporally using H.264 (MPEG-4) video compression.

Video data were collected using frame rates that varied between two discrete frame rate values. Images from the face and forward camera were collected continuously at 5 Hz while images from the left, right and cabin camera were collected continuously at 2 Hz.

2.2.4 Audio Data Collection

Audio data was collected using triggers that included those used for video. Also, audio data were collected using circular buffers, as were video data. Data were being saved continuously but was only stored when a warning occurred. Audio data were saved in a time stamped binary format at 64K bits/second starting 4 seconds before each alert and ending 8 seconds after each alert in both baseline and treatment. The purpose is to hear any audio tones or drivers' verbal responses to the warnings.

2.2.5 Data Acquisition System

UMTRI designed and fabricated a data acquisition system for each vehicle in the FOT. They were installed in each vehicle as a complement to the system and functioned as both a data-processing device as well as permanent recorder of the objective and video data collected during the field tests. The sections below describe the design and operation of the DAS.

2.2.5.1 DAS Main Module

DAS packages were designed and constructed to meet the test requirements of the FOT and the physical configuration of the FOT vehicles. Figure 5 shows an unfolded DAS. The package consists of four subsystems comprising a main computer, video computer, power controller, and cellular communications unit.

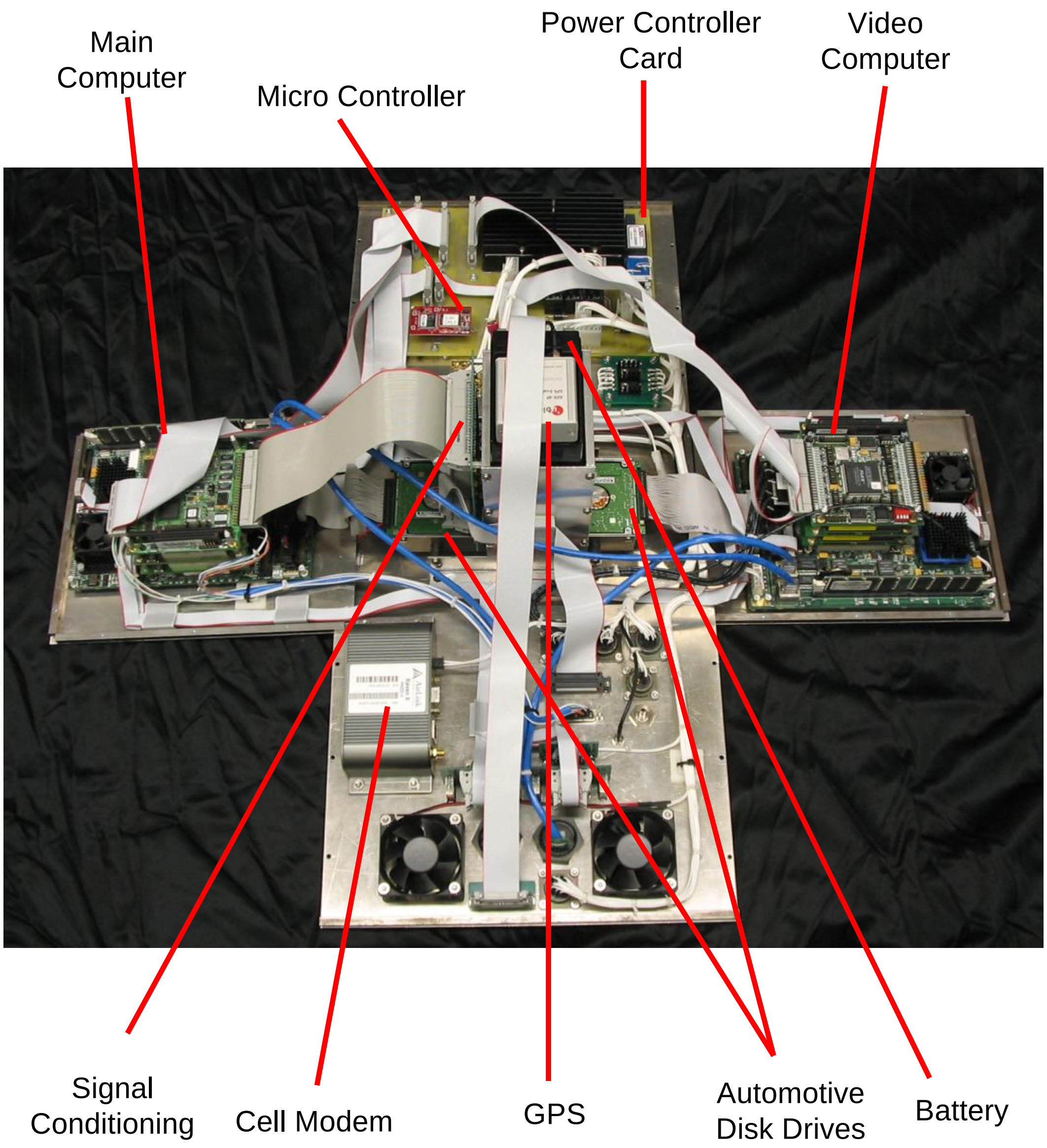


Figure 5: Major DAS components

The main computer consisted of an EBX form-factor single-board computer (including display, and Ethernet controllers), two PC104-plus CAN cards, a PC104 analog and digital interface card, and an automotive hard disk. All of these components operated over a –30C to +85C temperature range.

The video computer ran on an EBX form-factor single-board computer (including display, audio, and Ethernet controllers), two PC104-plus Mpeg4 encoder cards, a digital interface card, and an automotive hard disk. The temperature range of this system also operated from –30C to +85C.

The computers were configured to permit headless operation while a subject has the vehicle and hot-pluggable keyboard, mouse, and video operation for maintenance and troubleshooting activities. Figure 6 shows the location of the connectors for use in data upload and maintenance. The two computers are normally connected to each other via a crossover cable between the two network connectors. During upload this cable was removed and the two computers were plugged into a building Ethernet switch. A battery charger, on-off switch, and mode select switch plug into the mode connector.

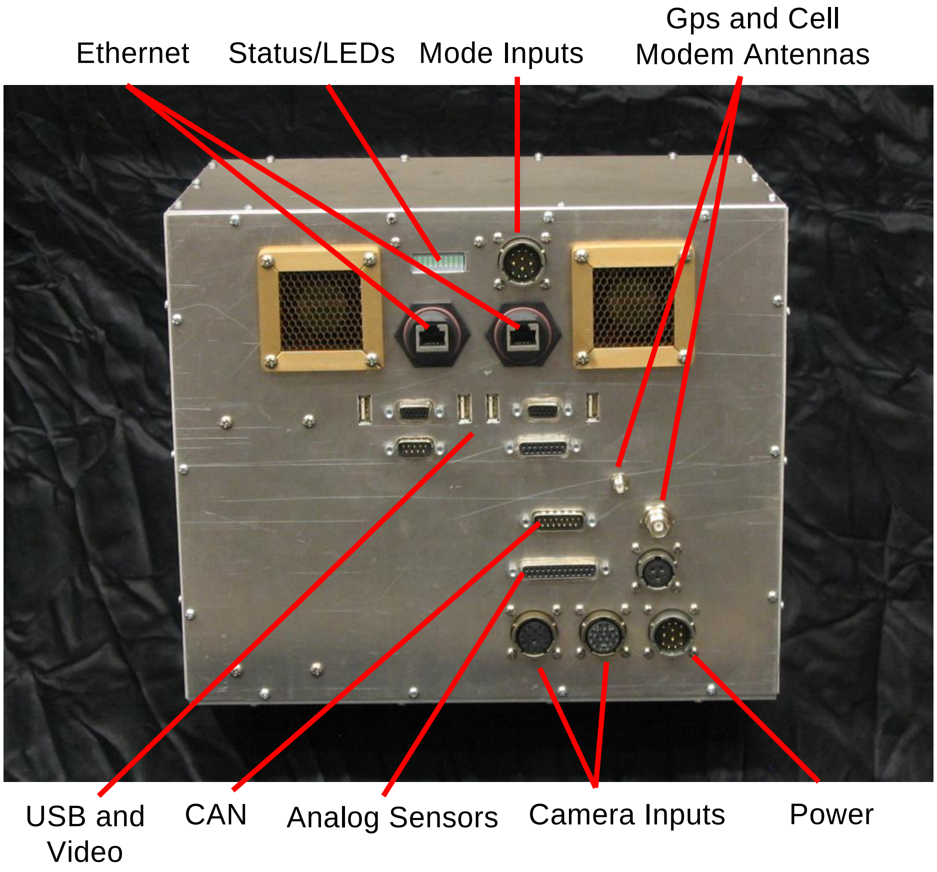


Figure 6: DAS, vehicle, and user interface

2.2.5.2 Modes of System Operation

The system could operate in one of eight modes: FOT, Characterization, Demo, GUI, Maintenance, Upload, No CPU, and Toggle. Figure 7 shows the mode control box that was used to switch between modes. It consisted of a rotary mode switch and a toggle power switch. These switches, along with a battery charger, were connected to the DAS via the mode connector. If nothing was plugged into the mode connector (normal FOT operation) or if the mode control box was plugged in and the rotary switch is in the "FOT" position, the ignition signal controlled the power sequencing and the system ran in the unattended FOT mode. Otherwise the toggle switch powered the computers (the rest of the vehicle remained off), and the computers ran the appropriate programs. The DAS mode box also had a shroud (which is not obvious in Figure 7) to prevent accidental movement of the toggle switch. The following sections describe the operational modes of the DAS.

Figure 7: DAS mode control box

2.2.5.3 FOT DAS Mode

The FOT software was configured to organize all of the gathered data by trip. The main system decoded the CAN messages and extracted the appropriate signals, and scaled and converted the data as necessary. Derived channels were then calculated and selected information was logged to a time-history file. The system was capable of logging raw CAN messages to a separate file for debugging purposes. Slowly changing or intermittent channels were logged transitionally. That is, a transition log was created, capturing transition events by their channel identification, timestamp, and data values.

An episode-processing task monitored the incoming primary and calculated channels for the occurrence of significant episodes (e.g., collision warnings, lane departures, etc.). When an episode was detected, the main system logged details of the alert in a triggered-summary file, and sent a message via Ethernet to the video system. The video system then captured a retrospective clip of audio data extending some time period back from the moment of the episode transition.

Transition counts, histograms, errors, and other trip summary information were recorded to a trip log at the end of each trip. When a trip ended, the main system activated the cellular system to transfer data via modem to UMTRI. Once the transfer was complete, all systems were turned off. The audio/video system continuously digitized, encoded, and buffered the output of five video cameras and one microphone. When an episode trigger was received from the main system, the audio was saved to disk (video is saved continuously).

2.2.5.4 Upload Mode
When the mode switch was in the “Upload” position, both computers automatically transferred the files (of the returning driver) to their respective servers. The main computer maintained a catalog (in an Access database) of all data files generated for each trip. The upload program replicated the catalog to an SQL Server database, copied the files to a specific folder on the data server, and initiated the loading of data from files into tables in the database. The video computer logged onto the video server, uploaded the video catalog, and transferred the video files.

2.2.5.5 GUI DAS Mode
This mode was an enhanced version of the FOT DAS that included real-time display capability for any of the data channels defined in the project. This mode was used for DAS validation, on-track testing, and system troubleshooting. LCD panels (powered by their own DC-DC converters) were plugged into the VGA connectors on the interface panel. Almost all the data on the CAN bus was parsed, scaled, and available for display. The video system showed the images from both cameras on the screen enabling real-time feedback for camera adjustments.

2.3 System Maintenance and Reliability

2.3.1 Scheduled Maintenance and Monitoring
Due to modifications and installation of sensors and other specialized equipment on the vehicles used in the field test, UMTRI staff performed all scheduled maintenance and the majority of repairs throughout the test period. The intent was that the test vehicles would only be repaired by team members familiar with the modified vehicles unless on-road emergencies required other arrangements.

2.3.2 System Performance Monitoring
The task of monitoring system performance is critical in an FOT. Even though thorough testing of all vehicle systems and subsystems was conducted prior to the start of the field test, problems can occur with the fleet once deployed in the field. It was UMTRI’s responsibility to detect these problems and coordinate with the partners to resolve them as quickly as possible when they occurred. The majority of the issues that arose were not ones the drivers would notice, and would not easily present themselves without close scrutiny and analysis of system data. As such, monitoring of the data from the vehicles was performed almost daily throughout the field test. In a fleet setting, sensors would need to be checked when an error message was displayed, there was a known strike to a sensor, or a change in system performance that was detected by the driver.

During the field test, the system performance data was monitored using files that UMTRI received via the cellular phone at the end of each ignition cycle. These files included histograms, counts, averages, first and last values, and diagnostic codes. UMTRI built routines to automatically scan the server for these files, and load them into the database for immediate processing by data validation routines. These routines, which also ran automatically, queried the data to generate summary reports that were broadcast by a Web-based server for viewing over the Internet. To the extent possible, these data provided validation that the integrated crash warning system was working as intended. When abnormal system behavior such as a significantly higher warning rate was observed, the team would look further into intermediate system performance signals in the data to identify the potential root cause and work with UMTRI and the lay driver to schedule an on-site diagnosis and repair if necessary. If an onsite repair was not a possibility, the driver was provided with another IVBSS-equipped Honda Accord.

2.3.3 Scheduled Maintenance

The only scheduled maintenance on the vehicles was the retrieval of data from the data acquisition systems. This was done each time a driver completed his participation in the FOT.

2.4 System Repairs

There were seven instances during the FOT where crashes required repairs or adjustments to the sensors of the integrated crash warning system. With the exception of one rear-end crash that took place on a limited access roadway during the baseline period, most of the other crashes were minor. The rear-end crash required considerable system and body repairs to the research vehicle, including the replacement of the long-range radar used by the FCW subsystem. More minor crashes, such as backing into another vehicle or a post, generally did not require repairs to the sensor suite but sensors had to be aligned after these incidences.

2.4.1 System Repairs and Adjustments

During the course of the FOT, there were two adjustments that were needed to the integrated system. Prior to the beginning of the FOT, the auto calibration function for the LDW subsystem camera was turned off. While researchers were reviewing the data, it was discovered that the camera’s field of view gradually drifted downward resulting in poor lane tracking. Auto calibration was turned back on for each of the research vehicle’s cameras, thus correcting this problem.

A second problem with the LDW subsystem resulted in zero availability for that subsystem. At times during auto calibration, the system would reset to the default settings which did not allow for lane tracking. Whenever this condition existed, researchers reprogrammed the LDW module. At times this meant that researchers visited deployed vehicles in the field to recalibrate the modules.

2.5 Procedure

2.5.1 Participant Recruitment

Participants were recruited with the assistance of the Michigan Secretary of State (the State’s driver licensing bureau). As in other FOTs that UMTRI has conducted, a random sample of a several thousand driving records were drawn from the Michigan Secretary of State’s database for the population of licensed drivers from eight counties surrounding Ann Arbor (all within a 1.5-

hour drive of UMTRI). These individuals received a postcard informing them that they qualified to participate in a study of new automotive technologies being conducted by UMTRI, and to call an 800 number if interested in learning more about participating. This sampling strategy help to ensure that a wide geographical area that includes urban (where lane change conflicts are likely to be greater), suburban, and rural (where single-vehicle road departures are concentrated) driving conditions. Prospective participants having any felony motor vehicle convictions, such as driving while intoxicated or under the influence of alcohol, within 36 months of recruitment were excluded from the extend pilot test. Additionally, drivers had to meet a minimum annual mileage requirement. The qualifying criterion was to report mileage not less than 25 percent below the National Personal Transportation Survey reported average for an age and gender category. All information obtained through State records is treated with strict confidentiality.

For this FOT, 108 drivers were selected, thirty-six drivers from each of three age groups: 20 to 30, 40 to 50, and 60 to 70 years old. An equal number of male and female participants were selected for each age group.

2.5.2 Participant Orientation and Instruction

Participant orientation and training began with an introduction to the research vehicle and the integrated system as provided in an instructional video developed by UMTRI. A briefing and opportunity to ask questions of a researcher followed. The video covered two principle areas: the location of standard controls and displays on the research vehicles including use of the vehicle’s safety equipment (airbag, seatbelt, ABS, etc.) and all usability aspects of the integrated system, including video examples of circumstances in which participants could expect to receive the integrated system’s warnings.

Participants also received hands-on instruction with the research vehicle and the integrated system. The experimental apparatus was identified and their purposes explained. Participants observed each warning/state in a static demonstration. Then, while accompanied by a researcher, each participant experienced the integrated system in operation as a driver during an orientation drive. This drive lasted approximately 20 minutes on local roadways in normal traffic. The researcher who provided the orientation served the primary point of contact for the participant in the event any questions or concerns arose.

Once participants completed the orientation and were comfortable with their understanding of the research vehicle, they will be free to leave with the vehicle. The glove compartment of each vehicle contained the following informational material: the scheduled vehicle return date, the researcher’s contact information including a 24-hour pager number, a copy of the instructional videotape, the owner’s manual, and proof of insurance.

2.5.3 Conduct of the Field Operational Test

2.5.4 Post-Drive Debriefs

At the conclusion of six weeks of driving, drivers were expected to complete the post-drive questionnaire (Appendix D) and participate in a discussion with an UMTRI researcher regarding their responses. Also at this time, drivers were shown 12 warnings that they received over the course of their driving and were asked to rate the usefulness of these particular warnings.

The post-drive questionnaire contained a combination of open-ended and Likert-scale type questions covering all aspects of the system. Questions asked specifically about the functionality of the system, the consistency of the warnings, the modalities in which the warnings were presented to the driver and the design of the driver-vehicle interface.

During the video review portion of the debrief, drivers were asked to watch videos of warnings they received and to comment on the situation. Twelve warnings for each driver were selected in advance of the debrief by the researcher. Based on the overall frequency of the warnings an ideal set of 12 warning video clips would contain 3 FCWs, 3 LCMs, and 3 LDWs (2 cautionary, 2 imminent) and 3 CSWs. Included in the set of 12 warnings, each driver was shown at least one warning deemed by the researcher to be invalid.

Drivers were asked the same questions about each warning. First, they were asked whether they felt the warning was useful, and if they said “yes”, they were asked to rate the usefulness on a 5 point scale. Also, drivers were asked for their opinion on the timing of the warning, and asked if they had any suggestions for improving the warning.

At the completion of the driver debrief, the driver was paid $200 in cash.

2.6 Light-vehicle Data Retrieval

2.6.1 Procedures for Downloading Data from the Light-vehicle Fleet

Data from each research vehicle were downloaded when they were returned to UMTRI either at the end of a driver’s participation in the FOT or when vehicles were swapped during a driver’s participation. At UMTRI, each returned vehicle was connected to the UMTRI network and data were transferred from the DAS to an IVBSS-dedicated server at UMTRI. The data were then loaded into databases.

2.6.2 Ensuring System Functionality and Integrity of Retrieved Data for Light Vehicles

Diagnostic tools were incorporated into the DAS software and the processing that occurred after receipt of data onto the FOT servers at UMTRI. This form of monitoring ensured (within feasible limits) proper system operation, so that UMTRI could readily detect (via the cellular modem trip summaries) any problems or limitations that arose with a vehicle in the field. This maintenance feature depended upon monitoring the data transmitted to UMTRI via cellular phone while vehicles were in the field. UMTRI also monitored DAS hard drive capacity remotely via the cellular phone and performed operating system level tasks, such as file deletion remotely through cellular phone activities.

UMTRI screened and validated all FOT data as it was uploaded into the phone and FOT databases. As part of this process, trips found to have problems were flagged and assigned a validity code describing the general nature of the data problem. Any data quality issues that were discovered while implementing the analysis and processing methodologies were flagged and documented. The details of the data quality and tracking methods were shared with the independent evaluator and FOT partners with the transfer of newly collected data, and also after the FOT concluded.

Hardware items were inspected and adjusted as necessary. Additional checks were performed by automatic data scan routines at pre-specified intervals during the FOT. These included consistency queries to check that:

- The vehicle's odometer reading agrees with the accumulated distance recorded by the DAS;
- The data file's duration agreed with the known (logged) test duration;
- Start and end times of the recorded data corresponded to the vehicle's launch and retrieve times; and
- The data collection in any trip did not terminate prematurely (e.g., that data files did not end with velocity > 0).

2.6.3 DAS Remote Monitoring

To monitor the functionality of the DAS and warning system, UMTRI customized the DAS software to compute and report summary statistics that helped flag and identify problems and failures with the system and the DAS itself. For example, specialized routines computed the distance between the last and first GPS coordinates from sequential trips in order to determine if mileage (and therefore DAS trips) was missing from the data archive. Additionally, UMTRI downloaded and scrutinized the event logs from the DAS to look for unexpected operating system events from the main and video CPU modules in each DAS. The approach was to provide current summary and diagnostic information for engineers to remotely monitor the fleet on a continuous basis throughout the entire FOT.

2.6.4 Data Validation

There were many layers of data processing in the FOT, beginning onboard the field test vehicles while they were being driven by the subjects in the FOT. In addition to storing time history and transitional and video data, the DAS calculated derived measures, such as time-to-impact and headway-time margin. Some of these derived variables were logged continuously or transitionally, while other measures were just resident in temporary memory to serve as thresholds or triggers for events and processes within the DAS.

The task of data validation was critical to the FOT. Even though thorough testing of all the systems and subsystems of the tractors occurred before the launch of the test, it was expected that problems would occur with the test fleet and it was primarily UMTRI's responsibility to detect these problems and coordinate with the partners to resolve them as quickly as possible.

In many situations the problems were obvious and could be identified by both UMTRI personnel and the subject drivers involved in the FOT. Examples include the illumination of dash lights or the failure of a critical function. However, there were problems that did not easily present themselves without close scrutiny and reconciliation of the data collected by the DAS. These validation tasks occurred on a daily basis throughout the FOT.

During the field test the data validation began with the files that UMTRI received via the cellular phone at the end of each ignition cycle by the driver. These files included histograms, counts, averages, first and last values, and diagnostic codes. UMTRI built routines to automatically scan the UMTRI server for these files and load them into the database for immediate processing by the data validation routines. These routines, which ran automatically, queried these data and generated summary reports. To the extent possible, these data provided validation that the warning system was working as intended. Following is a list of validation checks that occurred with the summary files sent to UMTRI via the cell phone:

- **Small Multiples**: Histograms of most measured variables were displayed in a condensed form that showed the shape of the distribution. Because the human eye is adept at seeing patterns, these distributions could be reviewed quickly by scanning. This was a quick way to visually review a lot of data in a time-efficient way.
- **Histogram Statistics**: Counts, means, most-likely values, and standard deviations of histograms were calculated and tabulated for visual review. By using columns of data that are similar in nature one can quickly scan for values that deviate from an acceptable range.
- **Numerical Summary:** Like histogram counts, there were summary reports and values that characterized each trip. These values included initial and final GPS location, test time, and velocity. From these data it was easy to see if there is continuity in the data on a trip-by-trip basis. For example, the ending GPS location should have agreed closely with the starting GPS location of the subsequent trip. Failure to agree would indicate that a trip or multiple trips were somehow not recorded by the DAS. Similarly, nonzero initial and final speeds may indicate that data were missed during a trip or that the DAS unexpectedly quit during a trip.
- **Mileage Values:** The summary file also contained a final distance traveled for each trip. These values will be aggregated and compared to the odometer values logged from each vehicle at the start and end of each subject's use of the vehicle. This also served as a method of validating that the warning system and DAS were working correctly and all vehicle use was recorded.

- **Diagnostic Codes:** A summary report by trip for all the diagnostic codes was generated and reviewed as the data became available over the cellular lines. This enabled UMTRI to monitor the vehicles continuously throughout the testing period.

Incorporated into the UMTRI data system was documentation of the data authenticity. As data was reviewed and processed, a record of anomalous, false, or compromised data was kept in a form that could be easily linked in queries when processing and analyzing warning system data. These records were shared with the project partners and independent evaluator to aid in their processing and understanding of the data archive. This documentation also served as a record of what has been changed or corrected in the database. This archive can be a very important resource if the database ever needs to be regenerated from the raw binary files generated by the DAS.

2.6.5 Creation of Databases

The IVBSS program had a core set of five different database categories for collecting, maintaining, and analyzing the data generated by the FOT vehicles and gathered through other data sources. A brief description of each category follows:

- **Project Database:** A highly structured database that evolved continuously and contains the project metadata. At its inception, the project database defined all the channels and associated properties being collected by the DAS onboard each FOT vehicle. This core description served as a common reference for exploring and understanding each data element within a project. During and after the FOT, the project database evolved to include the new data elements that are calculated from existing data signals or appended to the database from outside sources. The core elements that define a data channel include: name, version, description, value, rule, units, style, source, gate, and arguments. These elements, along with associated data channel history, served as the data dictionary used to locate, use, and understand the contents of a given project's entire data archive.
- **FOT Database:** A read-only database that contained all the data elements collected by the DAS onboard each FOT vehicle. It was a record of what was collected during the FOT and will not change now that the FOT is finished.
- **Phone Database:** A diagnostic and summary database used during the FOT to monitor the health of all the warning system and DAS components. It also showed summary driver activity and events that allowed UMTRI staff and partners to monitor individual tractors as well as aggregated statistics for the FOT as a whole. UMTRI researchers used these data as a snapshot into the health and progress of the FOT and also to make preliminary decisions related to the post-FOT interviews in which drivers were shown videos of their driving experience and asked to reflect on the their experience with the system and its meaningfulness in terms of a variety of factors such as safety, convenience, and usefulness.
- **Analyst Database:** A personalized database created for each of the primary researchers in a project. It contained tables and procedures that were developed and populated with

data drawn from the project, FOT, and other databases and typically served as an archive for work that is done by a particular researcher. Generally, these data were available to other researchers but were considered preliminary and shared through close consultation to ensure appropriate interpretation and use of these data. Generally, when data were processed, refined, and trusted by an individual researcher, they were published in a common database that served as a container for verified secondary data related to the FOT or other projects.

- **Published Database:** A general database that contained data derived from the FOT and individual analysts' databases. This database served as a common source for measures and results that had been verified. The published database also contained links to an enhanced project database for quick reference to the definition of the data archive and its elements as a whole.

Finally, among the software tools that UMTRI developed was a specialized program that could link to the metadata of a project and efficiently parse and read into a database the binary files that were generated by the UMTRI DAS. Since the structure and content of the binary files are explicitly described by the metadata, any changes to the metadata were automatically reflected in the program that loaded the database. This program could also generate new tables automatically if the structure of the core data system had changed. Also, subjective results resided in database tables to allow statistical analysis of these results and to join them with the objective data for meaningful query generation and analysis. All tables were indexed for efficient data sampling and to expedite the so-called "join" properties that are such an important element of relational database programming.

2.6.6 Distribution of FOT data

This project generated a tremendous amount of data that was to be shared with the program partners and independent evaluator. Roughly 1.8 Tb of data was transferred to Volpe. The collection rate for the video data was 163 MB per hour and for the objective data was 117 MB per hour for a total collection rate of 280 MB per hour. UMTRI performed the following processes before delivery of the data:

- Parsing the agreed set of raw CAN messages into individual variables;
- Scaling into engineering units;
- Removing any known biases or scale factors;
- Making simple transformations of information that do not impute any information loss;
- Making quality checks;
- Compiling histogram calculations (these may always be recomputed by NHTSA since the constituent input variables will always be part of the retained record);
- Loading data into database tables; and
- Correcting any known errors.

UMTRI did not deliver to NHTSA the results of any analyzed data, such as smoothed signals, queried or processed data streams, and so on, except in the context of the UMTRI FOT reports.

To physically transfer the data UMTRI copied project database files to a suitable medium, which were then shipped to the partners and independent evaluator. The entire export and import process for these transfers was defined as jobs to be executed by the SQL Server Agent. Text files were used for data transfer in light of their portability between various database management systems and the ease with which they can be created and imported using SQL Server.

Project data was be bundled by tractor and trip. Each transfer of data included all relevant data for some specific time period in the case of tractors. This made it simple to track which data had been sent. Data was sent roughly every two to four weeks depending on the rate of data generation relative to the size of the portable hard drive and the evaluator’s need to stay current.

2.6.7 Tools for Data Analysis

A variety of tools were used to create, load, and analyze the data archive. Some of these tools were coded in Visual Basic and C^{++} programs created by UMTRI, while others were supplied by software companies like Microsoft. One example of an off-the-shelf program that was very efficient when transferring data from a more traditional relational database to a data warehouse was Data Transformation Services (DTS). This tool was part of the Microsoft SQL Server software package and allowed easily importing and exporting data between a data warehouse and more traditional relational databases. UMTRI used a variety of tools to export and import data in both the data warehouse and FOT databases. These included:

- **WaveMetrics IGOR**: A powerful plotting and analysis program customized for viewing, manipulating, and processing time-history formatted data. IGOR has a built-in scripting language and UMTRI took advantage of this feature to customize and automate the presentation of time-history data in report-quality plots and graphics.
- **Microsoft Access**: This client-based relational database program could easily be linked to the RDCW tables residing in SQL Server. Then using the developed query interface, the exact SQL scripts could be developed either for querying from Access or to be input into Views or stored procedures within the SQL Server.
- **Mathworks MATLAB**: UMTRI used the processing power of MATLAB for a variety of data processing tasks ranging from simulation to Kalman filtering.
- **Microsoft SQL Query Server Analyzer**: This client-based program allowed engineers to develop and decode SQL statements using an interactive/command line interface. This was particularly useful to develop data analysis procedures that ran automatically on the data server since often they involved large datasets and could take many minutes (or hours) to execute. By using the Query Server Analyzer, engineers could test segments of their procedures before implementing the entire procedure, thus reducing the time to develop and debug large procedures that acted on the entire dataset.

- **UMTRI Tools**: UMTRI developed a variety of tools for viewing and exchanging data with a data warehouse or traditional database. These included a TripMapper, VideoViewer, DataExplorer, and a host of other programs that automated the process of summarizing data by generating histograms and event tables. More specifically, a viewer program was developed for the IVBSS program along with the DAS to allow researchers to view multiple aspects of the data simultaneously, at real time or faster. The viewer is shown in Figure 8 and included the following windows:
    - **Video**: A separate video window could be displayed (at normal, half, or double size) for each camera in the vehicle. The video window could be overlaid with dashboard information, including speed, brake, and turn signal. Cameras could be added or have their parameters altered without requiring a change in the viewer program.
    - **Data Tracking:** Allowed the researcher to plot up to four fields from the database over the course of an event.
    - **Audio:** Audio recorded during a trip/event could be identified and played back in sync (approximately) with the other windows.
    - **Map**: Used Microsoft MapPoint to plot the course of the trip and the vehicle's position.
    - **Control Window:** Was used to select a trip and navigate through it, with start/pause, step, replay, reverse, and other controls available to review trips.
    - **Query Window:** Allowed researchers to use SQL queries to identify and quickly view events without having to load complete trips.

Driver 245
Trip 925
Start 782
End 457720
Go To Time 12000
Data Resolution (Hz) 10
☐ Use Timer
☐ Make Screenshot JPG's

Cruise Control
OFF
Not Engaged
Set Speed: -

Enter event query (required: driver, trip, starttime, end

select top 50 * from ldwwarningevents where value>0

driver	Trip	StartTime	EndTime
240	45	30090	30180
240	45	36160	36250
240	45	43750	43810
240	45	68490	68560
240	45	69090	69150
240	45	89840	89970
240	48	61590	61650
240	48	83120	83190
240	48	89670	89740
240	48	89930	90020
240	49	49470	49500
240	49	51160	51280
240	49	51700	51990
240	49	134110	134130

Prestart (s) 0
Postend (s) 0

Figure 8: The UMTRI data viewer

3. Results

This section presents key findings related to overall system performance and the warning arbitration process, including key descriptive data regarding the frequency of warning arbitration, and characterization of the scenarios when arbitration was performed.

3.1 Vehicle Exposure

This section characterizes the range of driving conditions encountered by the passenger vehicles equipped with the integrated crash warning system. Driving conditions include descriptions of where and how the vehicles were driven, including types of roadway and environmental conditions, and the relationship between warnings and driving conditions.

The LV FOT began on April 16, 2009, and ended some thirteen months later on May 13, 2010. Table 3 reviews the various categories of mileage accumulated during that period. The 117 participants drove the research vehicles a total of 234,397 miles during the FOT. The DAS system collected data for 98.7 percent of this distance; much of the 1.3 percent of the lost data was associated with distance covered during system start-up at the beginning of a trip.

Table 3: Project distances for 108 FOT drivers

Distance Category	Miles	Percentage of source
Total odometer distance	234,397	
Total recorded distance	231,420	98.7% of total odometer distance
FOT odometer distance	222,508	94.9% of total odometer distance
Total FOT recorded distance	219,650	98.7% of FOT odometer distance
Valid trip distance	213,309	97.2% of FOT recorded distance
Baseline period	68,870	32.3% of valid trip distance
Treatment period	144,439	67.7% of valid trip distance

Of the total of 117 drivers who participated, 108 were selected as subjects for the analyses. The 108 drivers were distributed equally among six age by gender groups. Those drivers with the highest quality data were included in the analysis. These 108 FOT drivers drove 222,508 miles, and, again, the DAS recorded data for 98.7 percent of that distance. The 108 FOT drivers took a total of 24,989 “trips,” a trip being defined by an ignition cycle. That is, from the time the ignition is turned on until it is turned off defines one trip. Of the 24,989 trips, 2105 had a recorded a distance of less than 100 meters and were dropped from the analyses. Another 136 trips were dropped due to a fault in either the DAS or the integrated crash warning system. This resulted in a set of 22,657 *valid trips* with a total recorded distance of 213,309 miles representing 6164 hours of driving. It is these trips and the related data that form the basis of the analyses to be presented. As shown in Table 3, approximately one third of the valid distance was accumulated with the vehicles in the baseline state and approximately two thirds was accumulated in the treatment period.

Figure 9 shows the chronology of the accumulation of valid trip distance over the course of the FOT. It illustrates that 42,571 miles, or approximately 21 percent of the valid distance, was driven at night and that 14,831 miles (7%) was accumulated with the wipers on. Approximately 15 percent of driving was done in freezing temperature conditions as the FOT was conducted over almost 13 contiguous months, included a full winter in Michigan.

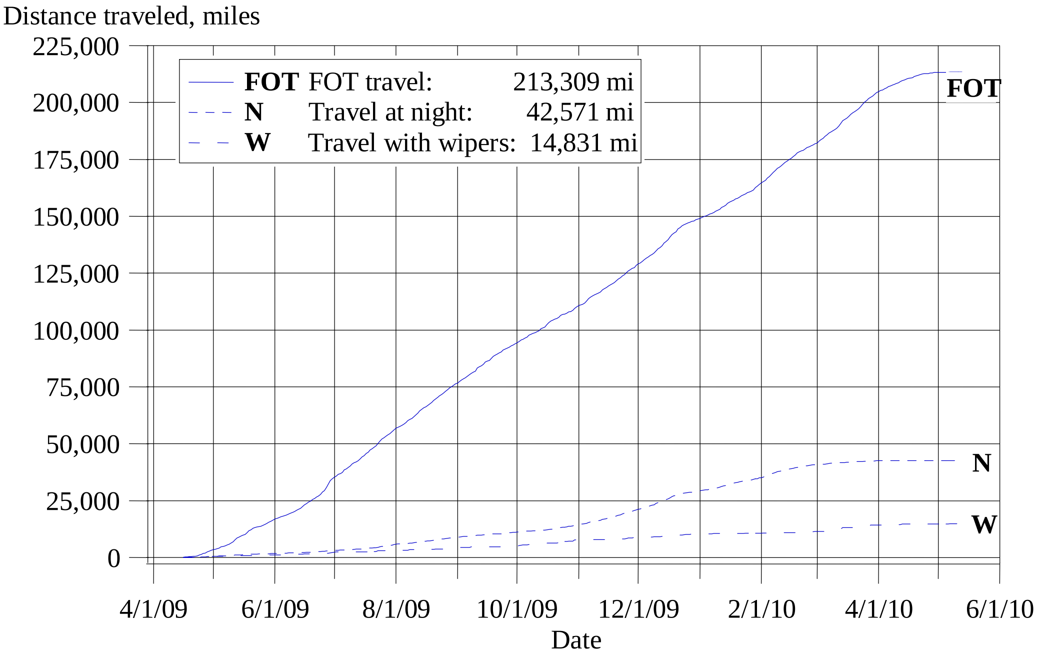


Figure 9: Chronology of the accumulation of valid travel distances

Table 4: Distance accumulations by driver age group

Condition	Age 20 - 30		Age 40 - 50		Age 60 - 70		All Drivers	
	Miles	Percent	Miles	Percent	Miles	Percent	Miles	Percent
Baseline	22181	10	27023	13	19666	9	68870	32
Treatment	46688	22	54706	26	43045	20	144439	68
Total	68869	32	81729	39	62711	29	213309	100

3.1.1 Travel Patterns

Figure 10 shows the geographical range of LV FOT travel. The majority of travel was within the lower peninsula of Michigan, with the greatest concentration in the metropolitan areas of Detroit and Ann Arbor, Michigan. Travel ranged as far north as the upper peninsula of Michigan, west to south central Missouri and east to eastern Pennsylvania, Washington, D.C. and eastern North Carolina. The boundary between the central and eastern time zones is shown with the heavy dashed line.

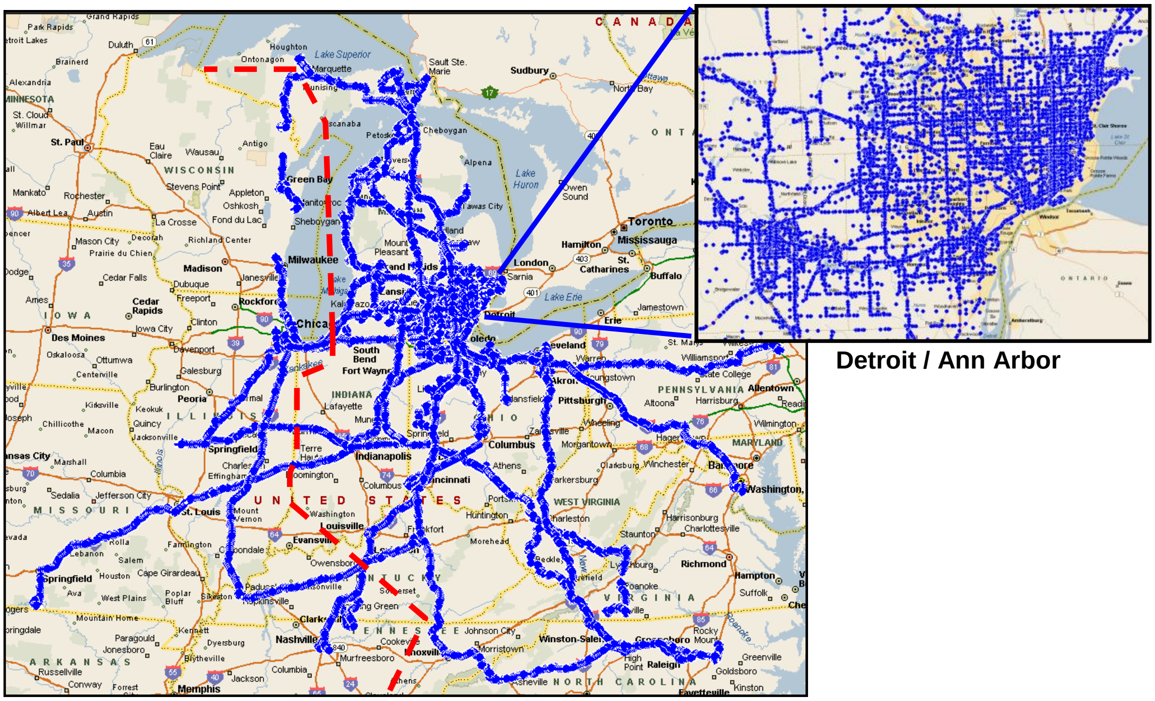


Figure 10: Geographical range of travel by the FOT drivers

3.1.2 Trips and Travel Segments

For the purposes of this field test, a trip is defined as the data-gathering period associated with an ignition cycle. That is, a trip begins when the vehicle ignition key is switched on and the integrated crash warning system and data acquisition system both boot up. A trip ends when the ignition switch is turned off, the integrated crash warning system shuts down, and the data acquisition system halts data collection. Most trips were rather short (18.5% of trips were less than 1 mile and 89.5% less than 22.5 miles). Figure 11 demonstrates that most of the valid distance was accumulated in longer trips (50% of distance in trips longer than 22.5 miles).

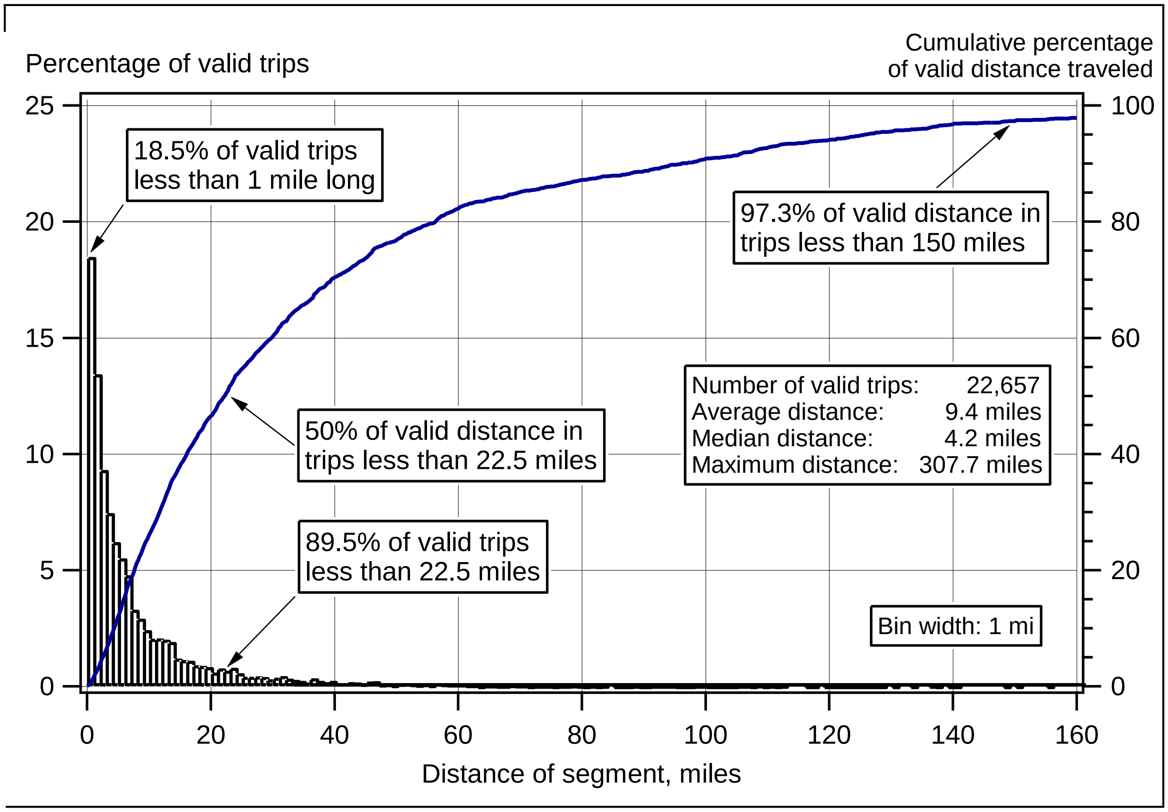


Figure 11: Histogram of trip distance and cumulative histogram of distance traveled

3.1.3 Roadway Variables

Certain analyses that follow will distinguish between travel on surface streets and roads, limited access highways, and highway ramps. The database distinguishes between limited access highways ramps, major and minor surface highways, and local roads. Figure 12 shows the distributions of valid travel distance and time in motion according to these five road types and travel on unknown surfaces (largely parking lots and private roads). Table 5 presents average, median and most likely speeds by road type and also the percent of time the vehicles were in motion while on each road type.

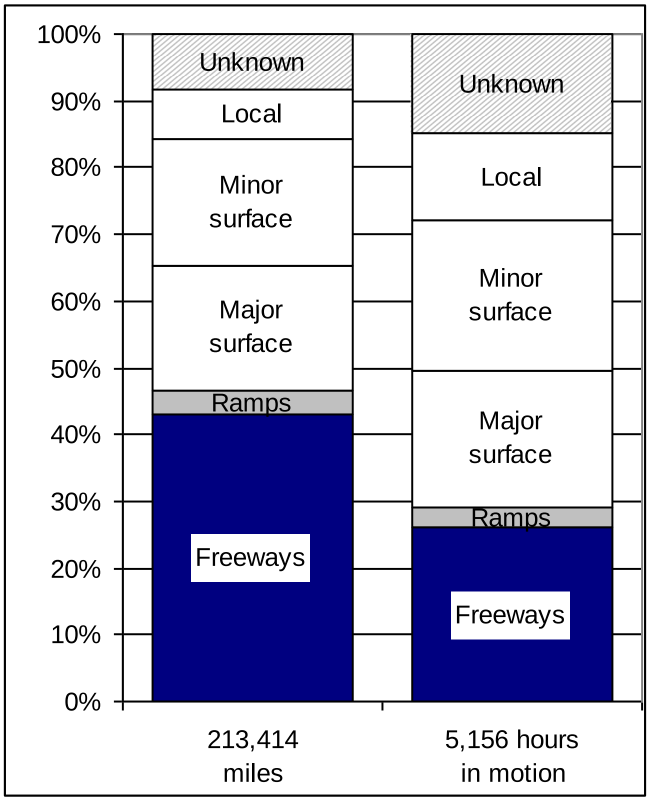


Figure 12: Distribution of travel by road type

Table 5: Average, median and most likely travel speeds by road type

		Freeways	**Ramps**	**Major surface**	**Minor surface**	**Local**	**Unknown**	**All travel**
Speed, mph	Average	68.2	46.4	38.1	34.7	24.0	23.1	41.4
	Median	66.0	60.0	40.8	37.5	16.3	14.2	38.9
	Most likely (±0.5)	70	55	43	40	23	1	70
Percentage of time-in-motion		99.8	93.2	89.2	87.1	76.6	61.1	83.7

3.1.4 Environmental Factors

Figure 13 shows that approximately 78 percent of both travel time and distance took place in daytime lighting conditions, and 14,831 miles (7%) was accumulated with the wipers on. Daytime is defined as the period from morning civil twilight through evening civil twilight, i.e., the period when solar altitude angle is equal or greater than -6 degrees. Average travel temperature is provided in Figure 14. Approximately 15% of driving was done in freezing temperature conditions.

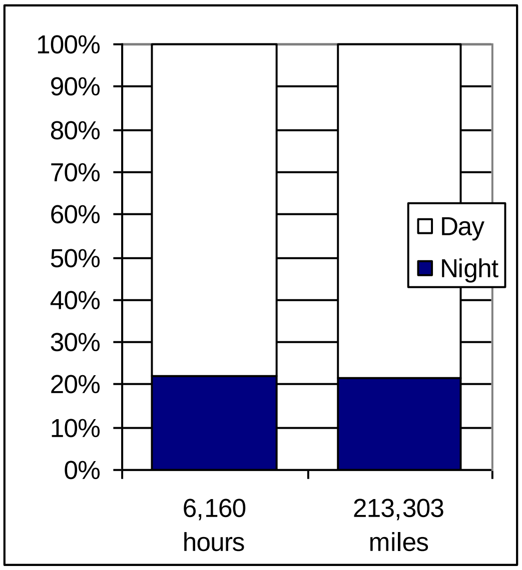


Figure 13: Portions of travel in daylight and nighttime

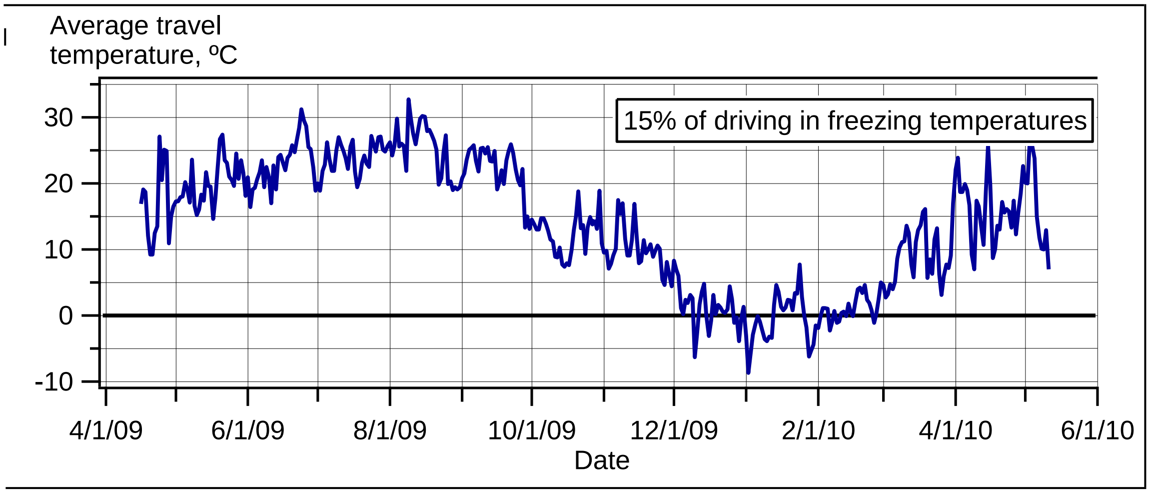


Figure 14: Average travel temperature

3.2 Overall Warning Activity

Overall, there were 22,828 crash warnings issued during the field test. Of these, 46.5 percent were recorded in the treatment condition and 53.5 percent were recorded in the baseline condition. Figure 15 displays the warning rates for the baseline and treatment conditions. The drop in warnings per 100 miles from baseline to treatment is largely driven by a decrease in the frequency of cautionary lane departure warnings that are associated with increased turn signal use in the treatment period when changing lanes (Section 3.5).

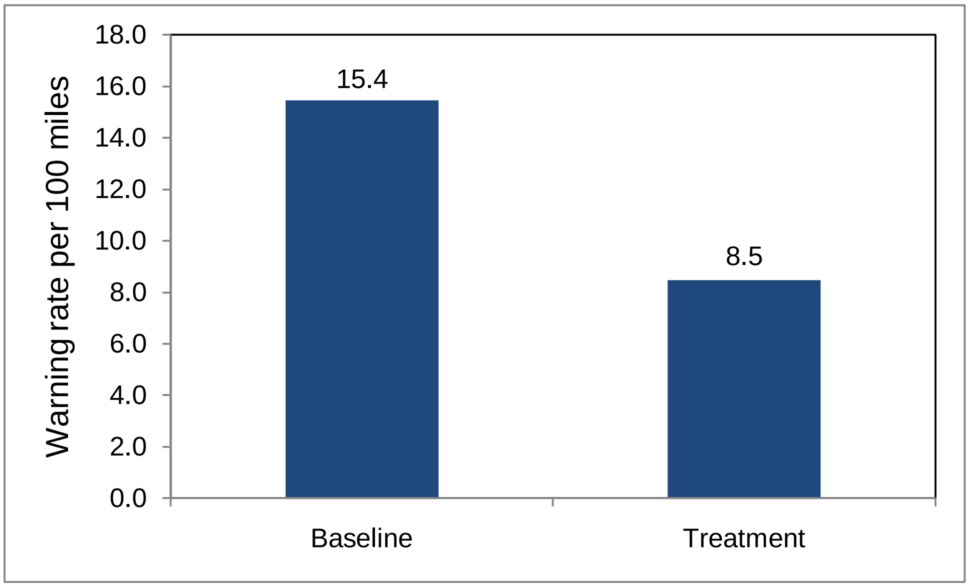


Figure 15: Overall warning rates for baseline and treatment conditions

3.3 Driver Behavior Research Questions

3.3.1 Secondary Behaviors

QC1: When driving with the integrated crash warning system in the treatment condition, will drivers engage in more secondary tasks than in the baseline condition?

Method: Equal numbers of five-second video clips from each of the 108 drivers were taken for both the baseline and treatment condition. Out of a possible 79,861 video clips, 2,160 clips were chosen (20 from each driver, 10 under both baseline and treatment conditions).

For the baseline sample, video clips were chosen randomly for each driver without regard for the presence of the independent variables (ambient light, wipers, etc.). For the treatment-condition sample, video clips were also selected randomly, but with the constraint that the independent variables' frequency must be matched to the baseline sample. For example, if a driver's baseline sample contained five video clips with windshield wiper use, five of the video clips for that driver from the treatment condition would also contain windshield wiper use.

A total of 2,160 five-second video clips were visually coded for the presence of secondary tasks. These video clips were chosen with the following criteria:

The minimum speed for the five-second duration was above 11.18 m/s (25 mph).
The road type was either a surface street or a highway (video clips occurring on unknown or ramp road types were not included).
No warning was given within five seconds before or after the video clip.
Video clips were at least five minutes apart from one another.

Results: A list of potential secondary tasks and the coded frequencies from the 2,160 video clips is displayed below in Table 6. A total of 111 video clips from the sample contained multiple secondary tasks; each individual task is uniquely represented in Table 6. Fifty-nine percent of the time, drivers were not engaged in any secondary task. The most frequently observed secondary task was engaging in conversation with a passenger (17.2%). Drivers were observed talking on a cell phone in just over seven percent of the clips (6.1% hand-held; 1.0% hands-free). Texting was observed in 0.3 percent of the clips.

After wireless communication devices, grooming was found to be the next most common secondary task (4.9%). In this analysis, eating, drinking, grooming, and smoking are broken into two categories: low involvement and high involvement. The two levels are primarily distinguished by the hand position of the driver. Tasks requiring two hands (opening food or drink packaging, removing cigarette, etc.) were scored as high involvement. Tasks involving one hand were scored as low involvement smoking (for example, a driver simply holding a cigarette and any one-handed grooming such as touching the face, head, or hair).

Table 6: Frequency of secondary tasks among the 2,160 five-second video clips

Secondary Task	Number of Video Clips With Task
None	1,265
Dialing phone	4
Text messaging	7
Talking on/listening to hand-held phone	132
Talking on/listening (headset or hands-free)	21
Singing/whistling	47
Talking to/listening to passengers	372
Adjusting stereo controls	40
Adjusting HVAC controls	8
Adjusting other controls on dash	3
Adjusting satellite radio	0
Adjusting navigation system	0
Adjusting other mounted aftermarket device	1
Holding device	34
Looking at device	13
Manipulating device	33
Eating: High involvement	5
Eating: Low involvement	26
Drinking: High involvement	4
Drinking: Low involvement	48
Grooming: High involvement	6
Grooming: Low involvement	99
Smoking: High involvement	2
Smoking: Low involvement	40
Reading	1
Writing	1
Searching interior	21
Reaching for object in vehicle	15
Other	26

Table 7 provides descriptive statistics for secondary task involvement by several different variables. There is a slight (1%) increase in overall secondary task involvement between baseline and treatment conditions. Drivers appeared to be slightly more likely to engage in secondary tasks when driving on surface streets as compared to highways. Younger and middle-aged drivers were more likely than older drivers to engage in a secondary task while driving. On a percentage basis, drivers were much more likely to engage in secondary tasks while driving at night. Weather does not appear to have any effect on secondary task engagement, though it should be noted that there were only 24 exposure clips that had wiper activity.

Statistical analysis using a general linear model was performed to determine whether the integrated system, or any other factors (age, gender, road type, time of day, weather), affected the frequency of drivers performing secondary tasks. Driving with the integrated system did not have a statistically significant effect on the frequency of secondary tasks. The analysis showed that young and middle-aged drivers were more frequently observed engaging in secondary tasks while driving than older drivers (p=0.0011). Furthermore, drivers were more willing to engage in secondary tasks while driving at night as compared to driving during the day (p=0.0034).

Table 7: Descriptive statistics for secondary tasks by multiple variables

Independent Variable	Level	Secondary Task	No Secondary Task	Secondary Task percent
Condition	Baseline	442	638	40.9
	Treatment	454	626	42.0
Age group	Younger	351	369	48.8
	Middle-aged	315	405	43.8
	Older	230	490	31.9
Road Type	Limited Access	369	546	40.3
	Surface	527	718	42.3
Time of Day	Day	680	1052	39.3
	Night	216	212	50.4
Weather	Wipers on	10	14	41.7
	Wipers off	886	1250	41.5

Interpretation: Drivers were no more likely to engage in secondary tasks while driving with the integrated system than without it. That is to say, there was no evidence that drivers over relied on the integrated system—at least to the degree that it was observable through the frequently drivers were willing to engage in secondary tasks. Not surprisingly, younger and middle-aged drivers engaged in secondary tasks more frequently than did older drivers. This may be a result of older drivers compensating for increasing reaction times that accompany aging, less familiarity with wireless communication devices, or a combination of these and other factors. Drivers were much more likely to engage in secondary tasks at night, in comparison to the daytime. This might be associated with lower levels of traffic density during the night; the specific relationship has not been examined.

QC2: Does a driver engaging in a secondary task increase the frequency of crash warnings from the integrated system?

Method: An equal number of video clips from each of 102 drivers were visually coded from the treatment condition. Six drivers were excluded from this analysis for lack of a sufficient number of valid warnings. A total of 2,040 five-second video clips were selected. For each driver, 20 video clips were selected, 10 preceding a warning and 10 not preceding a warning. Where possible, the following number and types of warnings were selected for each driver: 1 CSW, 1 FCW, 1 LDW imminent, 2 LCM, 5 LDW departures.

This mix of warnings roughly corresponded to the overall percentages of each warning type in the FOT, but not necessarily for each particular driver. Only valid warnings were included. If a driver did not have any valid warnings of a particular type, then where possible, longitudinal warnings were substituted for missing longitudinal warnings (e.g., an FCW for a missing CSW) and lateral warnings were substituted for missing lateral warnings. Additionally, LDW departures were selected from those in which the driver drifted in the lane and made a correction. The numerous LDW warnings that were elicited as a result of unsignaled lane changes were not included.

Only video clips that met the following criteria were included in the 2,040 video clip set:

- The minimum speed for the 5-second duration was above 11.18 m/s (25 mph).
- The road type was either a surface street or a limited access highway (video clips occurring on unknown or ramp road types were not included).
- No warning was given within 5 seconds before and after the video clip for the no-warn condition.
- A warning immediately followed the 5-second clip for the warning condition.
- Video clips were at least 5 minutes apart.

Results: Table 8 lists the potential secondary tasks along with the coded frequencies from the 2,040 video clips.

Statistical analyses using a general linear model were performed to determine whether performing a secondary task or other factors (age, gender) affected the frequency of warnings. No factors were found to have a statistically significant effect.

Video clips associated with warnings were more than six times more likely to show text messaging than those clips not associated with warnings. However, drivers were observed holding/looking at/manipulating devices (e.g., cell phones) 1.5 times more frequently in video clips not associated with warnings than those associated with warnings. Video clips not associated with warnings were more likely to show drivers talking to passengers. In general, video clips preceding warnings were slightly less likely to show involvement in secondary tasks (41.7%) than those when there was no warning (43.0%).

Table 8: Frequency of secondary tasks among 2,040 five-second video clips

Task	Not Associated with Warnings	Preceding Warnings
No secondary task	581	595
Dialing phone	3	3
Text messaging	3	19
Talking/listening on hand-held phone	58	59
Talking/listening on headset or hands-free phone	8	4
Singing/whistling	23	25
Talking to/looking at passengers	167	132
Adjusting stereo controls	15	17
Adjusting HVAC controls	1	2
Adjusting other controls on dash	1	4
Adjusting satellite radio	0	0
Adjusting navigation system	0	0
Adjusting other mounted aftermarket device	0	1
Holding device	16	19
Looking at device	5	8
Manipulating device	23	8
Eating: High involvement	2	1
Eating: Low involvement	8	9
Drinking: High involvement	0	0
Drinking: Low involvement	19	17
Grooming: High involvement	1	0
Grooming: Low involvement	44	46
Smoking: High involvement	1	0
Smoking: Low involvement	17	26
Reading	1	6
Writing	1	0
Searching interior	5	2
Reaching for object in vehicle	6	12
Unknown	7	5

Interpretation: Warnings from the integrated system were no more likely to occur when drivers were engaged in a secondary task. This result also suggests that drivers did not become overly reliant on the integrated system.

QC3: When the system arbitrates between multiple threats, which does the driver respond to first?

Method: For purposes of this analysis, multiple warnings are those warnings that occur as a result of different threats within three seconds of each other.

Results: In the FOT, only 23 multiple warning events occurred. Of those, only six occurred during the treatment period. Three of the six events involved an LDW followed by a CSW. In these cases although temporally associated, the drift warning was unrelated to the CSW. The three remaining events and the driver's response are as follows:

1. CSW followed by an LCM: The driver was on an exit ramp when he decided not to exit, but received a CSW. While changing lanes from the exit ramp into the adjacent lane to his left, he then received an LCM as a vehicle passed him on the left. He remained in his lane and did not brake nor steer.

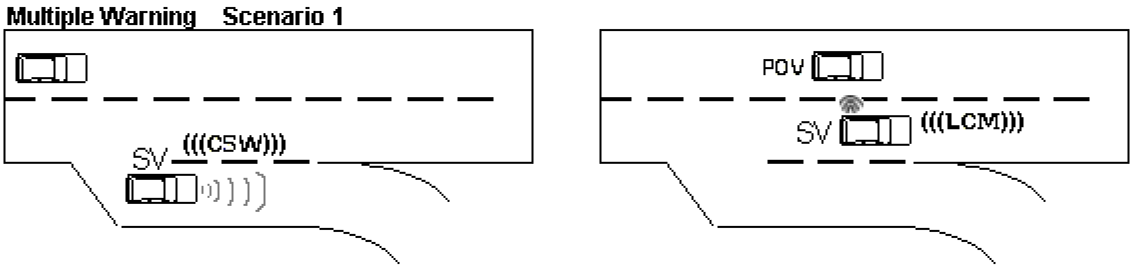


Figure 16: Multiple warning scenario 1

2. FCW followed by an LDW: A large truck was departing the driver's lane. The driver was closing on the truck and received an FCW as the truck was departing the travel lane. The driver moved to the left of the travel lane, not intending to change lanes, in order to provide the truck some additional room as she passed. In the process the driver also received an LDW, as there was an approaching vehicle in the lane adjacent to her on the left but she did not have her turn signal on since she did not intend to leave the lane. The driver did not brake in response to the FCW, and she was already steering to move around the truck at the time of the warning. After receiving the LDW, she steered so that her vehicle moves back into the center of her lane.

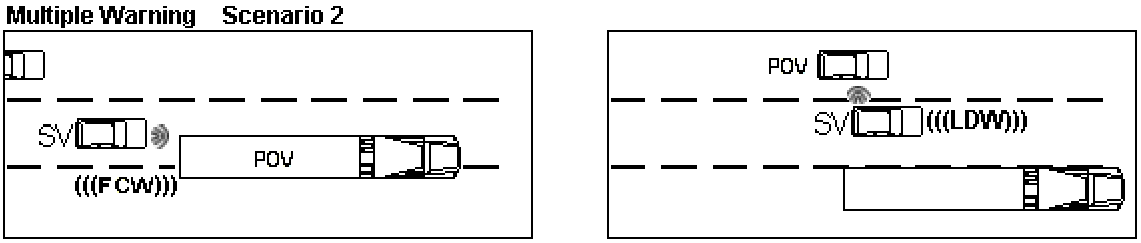


Figure 17: Multiple warning scenario 2

3. LDW followed by an FCW: The driver moved into a passing lane on a one-lane road to pass a stopped, turning vehicle on its right. He received an LDW as he crossed a dashed line without his turn signal then an FCW as he moved to pass the stopped vehicle-due to passing at a close range. He was already steering to initiate a pass when he received the FCW.

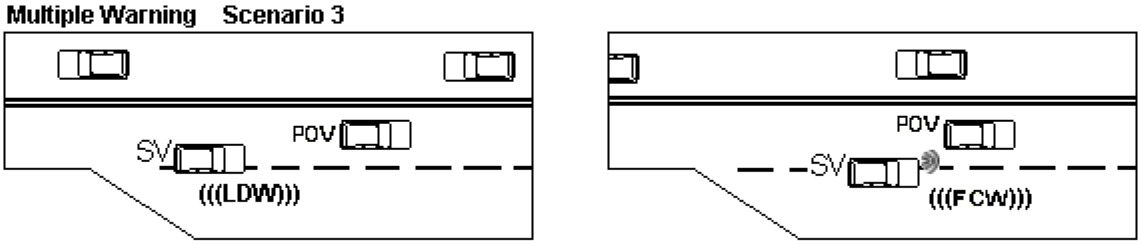


Figure 18: Multiple warning scenario 3

Interpretation: Multiple warning events are rare. At least for this group of drivers, they were rarely in situations where they had to respond to two different threats within a three-second window. Because only three valid cases of multiple warnings were observed in the FOT, no patterns could be observed about which warning drivers responded to if at all.

3.3.2 Driver Acceptance Research Questions

This section discusses key findings on driver acceptance of the overall integrated system. Results are predominantly based on results from the post-drive survey regarding the integrated crash warning system overall. The majority of the questions employed a 7-point rating scale. Higher numbers correspond to positive attributes. Additionally, there were some open-ended questions. Finally, five of the questions made use of the van der Laan scale. The van der Laan scale represents one way to broadly capture drivers' subjective assessments of usefulness and satisfaction with a new automotive technology. The van der Laan Scale of Acceptance uses a five-point scale to assess nine different attributes of a given technology. Each item on the van der Laan scale is anchored by two polar adjectives, such as "good" and "bad", and the driver is asked to rate their perception of the technology by marking a box along a continuum between these two poles. Each participant assessed the system for nine pairs of adjectives, and the responses were then grouped into two categories, "usefulness" and "satisfaction." Scale scores range from -2 to +2, with positive numbers indicating positive feelings about a technology. For each question, overall means and standard deviations as well as means and standard deviation for each age group are presented in Appendix E.

QC4: Do drivers report changes in their driving behavior as a result of the integrated crash warning system?

Results: When drivers were asked if their driving behavior changed as a result of the integrated system, 28 percent of drivers replied that their driving behavior did not change. There was no effect of age. Nearly 25 percent of drivers said they increased their use of turn signals with the integrated system. Drifting less often, generally driving more carefully, and increased awareness (Figure 19) were each mentioned by about 20 percent of the drivers. An increased knowledge of vehicles in the blind spot, which aided in changing lanes, was mentioned by 13 percent of the drivers. Because drivers could report multiple changes in behavior, the sum of the above is greater than 100 percent.

When asked if they relied on the integrated system, more than 60 percent of drivers stated that they did not. Of those drivers who reported relying on the integrated system, 75 percent of them said that they relied on BSD when changing lanes.

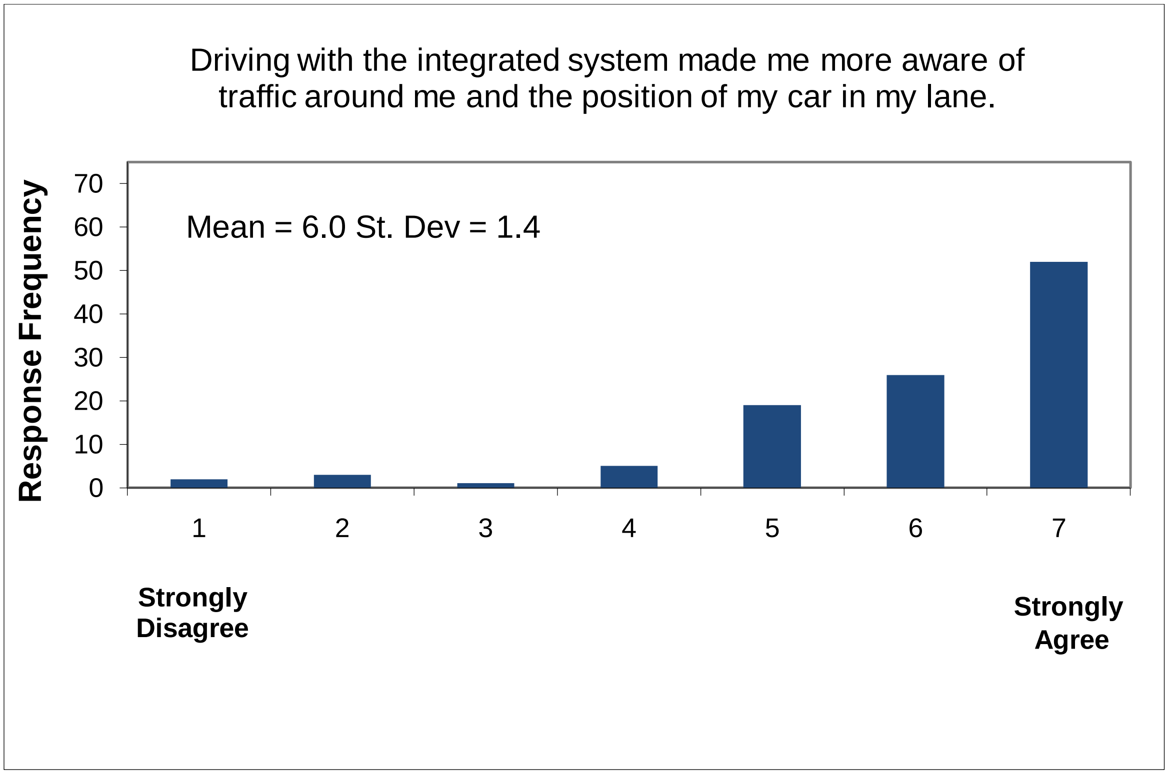


Figure 19: Responses to post-drive questionnaire Q7. "Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane”

Interpretation: The majority of drivers reported that their driving behavior changed as a result of driving with the integrated system. All of the behavioral changes reported would be considered positive changes, resulting in increased safety benefit, with the possible exception being some level of reliance on BSD when changing lanes. The most frequently mentioned change in behavior was an increase in turn-signal use, which was the result of receiving LDW warnings provoked by failing to use turn signals when changing lanes.

QC5: Are drivers accepting the integrated system (i.e. do drivers want the system on their vehicles)?

Results: Generally speaking, drivers are accepting of the integrated system and are willing to make allowances for some of its shortcomings (e.g., invalid warnings). Van der Laan scores were calculated to investigate how useful drivers perceived the system to be and how satisfied they were with the integrated system. The mean usefulness score was 1.4 while the mean satisfaction score was 0.8. Both scores indicate positive feelings about the crash warning system. On a subsystem basis:

- Drivers were largely indifferent towards the CSW and FCW functions, and rated them neutral with regards to satisfaction while recognizing they had some utility.
- Both LDW and LCM were rated well for both usefulness and satisfaction and were commensurate with the rating of the overall integrated system.
- BSD was rated very highly for both usefulness and satisfaction, above the overall integrated system.

Overall, drivers rated the integrated system favorably (Mean = 5.7). While still satisfied with the integrated system, younger drivers were less satisfied than middle-aged and older drivers (Figure 20). Whether or not drivers would like to have the integrated system on their personal vehicles is a measure of how accepting they are of the integrated system. The majority of drivers (72%) indicated that they "probably would" or "definitely would" like to have the integrated system on their personal vehicle, with younger drivers being less likely to want the integrated system on their vehicles than older and middle-aged drivers. Twenty-five percent of the younger drivers reported that they "definitely (would) not" or "probably (would) not" want the integrated system on their personal vehicle (Figure 21).

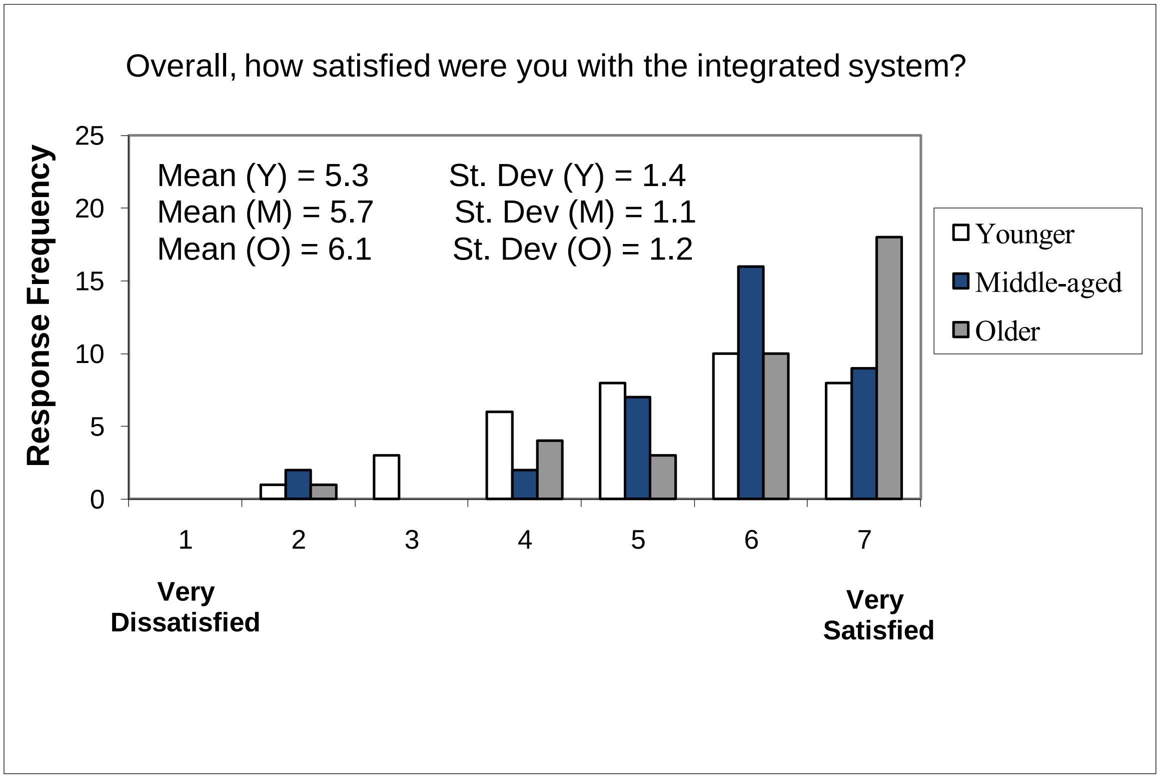


Figure 20: Overall driver satisfaction with the integrated system

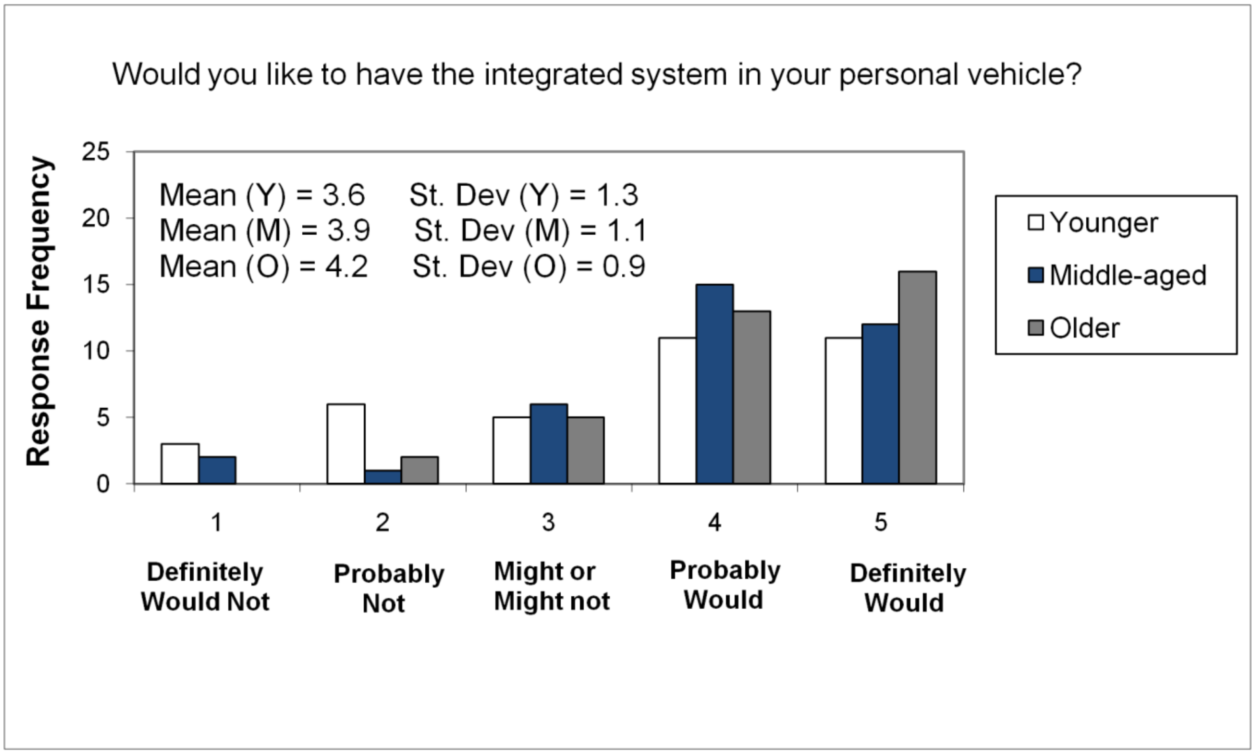


Figure 21: Drivers' willingness to have the integrated system in their personal vehicle

Interpretation: Drivers were accepting of the integrated system and rated it well in terms of both usefulness and satisfaction. Van der Laan scores enable comparisons between different automotive technologies. Drivers who drove with the integrated system were more satisfied and found the system to be more useful than drivers who experienced the curve speed warning and lane departure warning system fielded in the RDCW FOT (LeBlanc, et al, 2007). While twenty-five percent of the younger drivers were unwilling, 72 percent of all drivers would like to have the integrated system in their personal vehicle.

QC6: Are the modalities used to convey warnings to driver salient?

Results: Drivers reported that the all of the warning types were attention-getting. Table 9 provides mean ratings for the attention-getting properties and ratings of annoyance for the various warning modalities. The most attention-getting of the warnings was the seat vibrations. Drivers found this modality to be unique and interesting. While all of the warning modalities were attention-getting, drivers agreed with the statement, "I was not distracted by the warnings" (mean = 5.3) (Figure 22). Additionally, when drivers were asked if they were annoyed by the warnings, they reported that they were generally not annoyed by the warnings, and reported being least annoyed by the yellow lights for BSD in the exterior mirrors. This may be explained by the fact that drivers only received information about vehicles in their blind spot when they looked directly to the exterior mirrors. While salient, several drivers in debriefing sessions mentioned that they were “startled” or “alarmed” when they experienced a brake pulse, particularly if the FCW that they received was invalid.

Table 9. Warning modalities and mean ratings of attention-getting properties and annoyance

Warning Modality	“The warnings got my attention”	“The warnings were not annoying”
Auditory	6.4	5.3
Seat Vibration	6.6	6.0
Brake pulse	6.1	4.8
BSD yellow lights	6.2	6.8

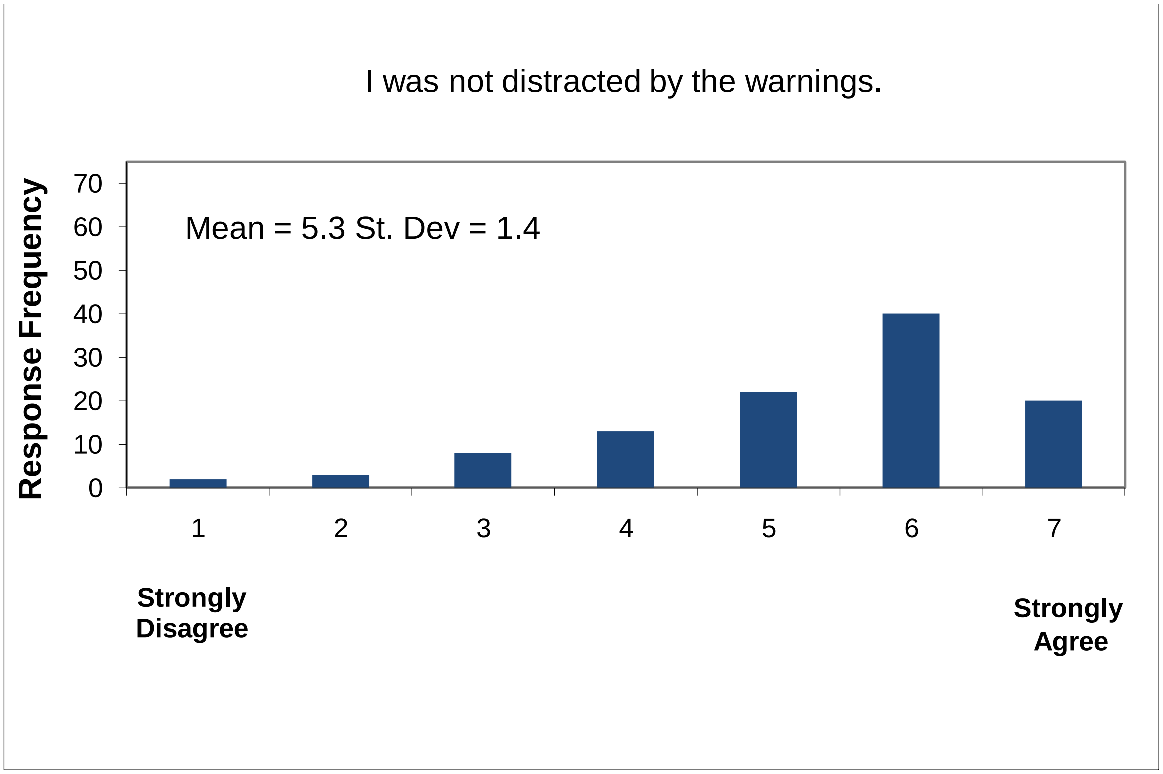


Figure 22: Drivers’ perception of the warnings level of distraction

Interpretation: The warnings presented by the integrated system were attention-getting but at the same time not distracting. From a human factors perspective, this is the ideal balance.

QC7: Do drivers perceive a safety benefit from the integrated system?

Results: Overall, drivers perceived a safety benefit from the integrated system. They reported believing that the integrated system was going to increase their driving safety (Mean = 5.5), and that this effect appears to increase with increasing driver age (Figure 23). Further, drivers reported that the integrated system heightened their awareness (Mean = 6.0). When asked how helpful the integrated system's warnings were, drivers' mean rating was 5.5, with older drivers rating the system to be more helpful than younger or middle-aged drivers (Figure 24). Nearly half of the older drivers rated the integrated system as "very helpful". Drivers found the integrated system to be most helpful in providing information when another vehicle was in their blind spot and when they were departing the lane. Eight of twenty-eight focus group attendees stated that the integrated system prevented them from crashing.

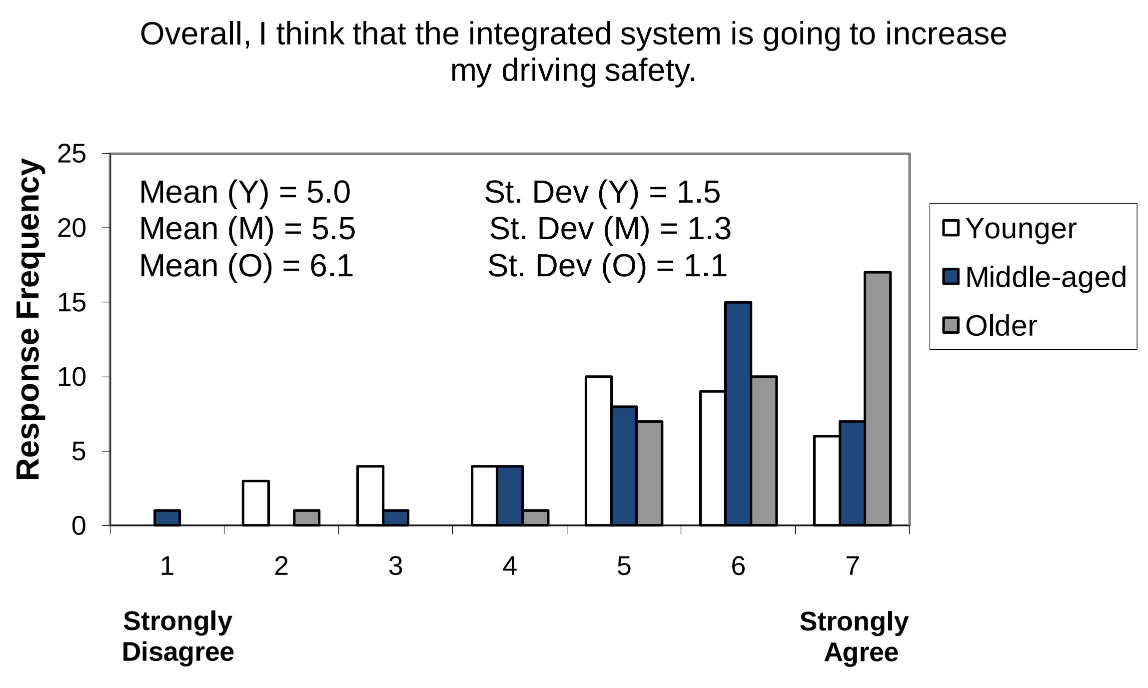


Figure 23: The integrated system's effect on safety

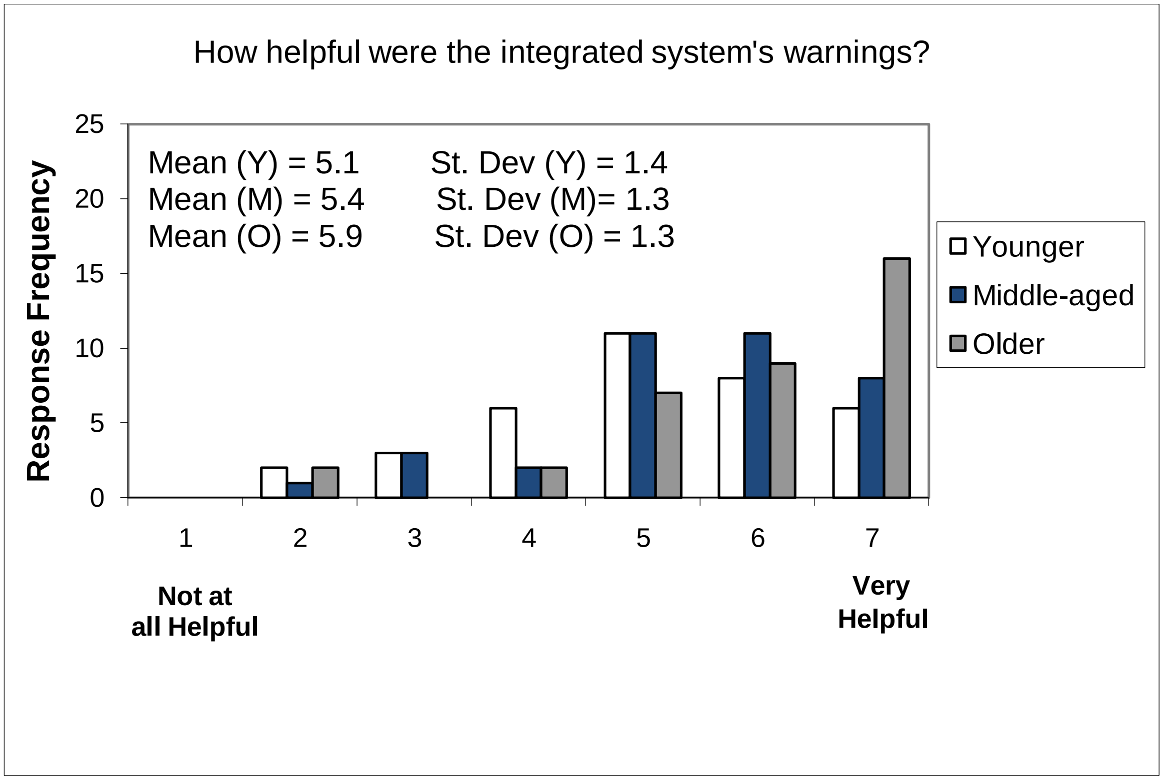


Figure 24: Drivers' perception of the integrated system's warnings helpfulness

Interpretation: Drivers found the integrated system's warnings to be helpful and further believed that the integrated system would increase their driving safety. Both of these effects increase with increasing driver age. These responses indicate that drivers received benefit from the system beyond the more abstract benefits such as "increased awareness." If drivers believe that the presence of the integrated system specifically prevented a crash, they are very likely to accept the integrated system—even if all aspects of it did not perform as they may have expected.

QC8: Do drivers find the integrated system convenient to use?

Results: Overall, drivers found the integrated system to be more predictable and consistent, than not (Figure 25). Those drivers who did not agree that the system was predictable and consistent generally reported that invalid warnings (e.g., receiving a warning when there was not an actual threat) affected their rating. There was no noticeable impact of age in response to this question.

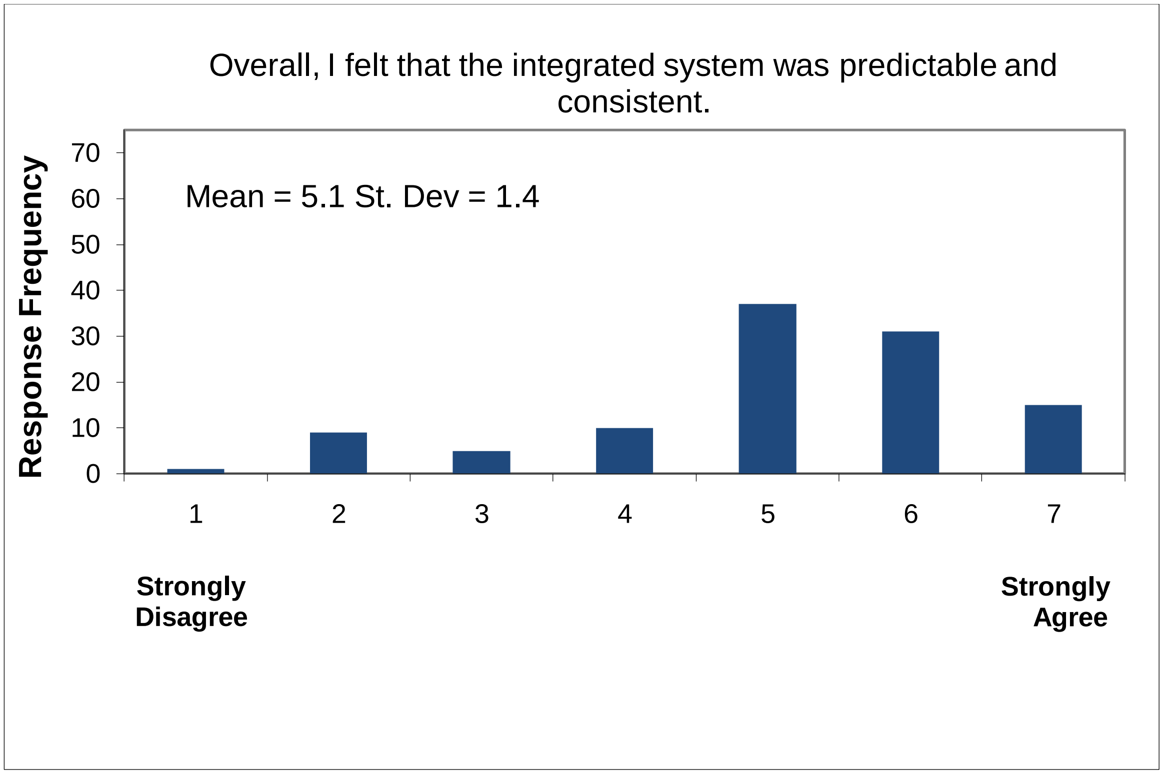


Figure 25: Ratings of the integrated system's predictability and consistency

Interpretation: In general, drivers rated the integrated system fairly well in terms of predictability and consistency. Reducing the invalid warning rate would enable future drivers of these systems to develop a more accurate mental model of the system, and likely result in improved ratings of predictability and consistency. Enabling drivers to construct an accurate mental model of a warning system will allow them to develop confidence that the integrated system will provide them with warnings to safety critical events.

QC9: Do drivers report a prevalence of false warnings that correspond with the objective false warning rate?

Results: In the questionnaire, the word, "nuisance" is used which encompasses invalid warnings as well as those warnings which were valid, but the driver did not find the warning to be helpful or useful.

The questionnaire addressed nuisance warnings for the entire system as well as individually for each subsystem. While the integrated system provided warnings when drivers did not need them, participants did not feel that these warnings were provided too frequently (Figure 26 and Figure 27). Older drivers stated that they received nuisance warnings with the lowest frequency of the age groups, however middle-aged drivers agreed with the statement, "The integrated system gave me warnings when I did not need them" more strongly than the other age cohorts. This effect is supported by data presented in Table 10. As a group, middle-aged drivers received more invalid warnings than the other age groups; however, younger drivers had the highest invalid warning rate per 100 miles of the age groups.

For the individual subsystems, based on the means to questions regarding receiving nuisance warnings, drivers appeared to get fewer nuisance warnings from the CSW and FCW subsystems than they did from the lateral subsystems (Figure 28). In fact, drivers received the most invalid LDW cautionary warnings followed by FCWs per 100 miles**.** It is quite possible that drivers are responding to the absolute number of nuisance warnings that they received rather than a nuisance-warning rate in response to this particular question. With the exception of left and right hazards, the subjective ratings of nuisance warnings from the subsystems increase with increasing numbers of nuisance warnings. That is to say, drivers were generally able to perceive differences among the number of nuisance warnings provided by the subsystems.

This relationship between the number of nuisance warnings received by drivers and their subjective ratings does not hold for left and right hazards which were received for the LCM imminent warnings. Drivers received the fewest invalid warnings from these subsystems yet subjectively provided the highest rating to the statement, “The subsystem gave me warnings when I did not need them.” Perhaps the nature of and the conditions under which drivers received nuisance LCMs was more concerning (e.g., making a lane change after a POV has clearly passed the SV and receiving an LCM nevertheless).

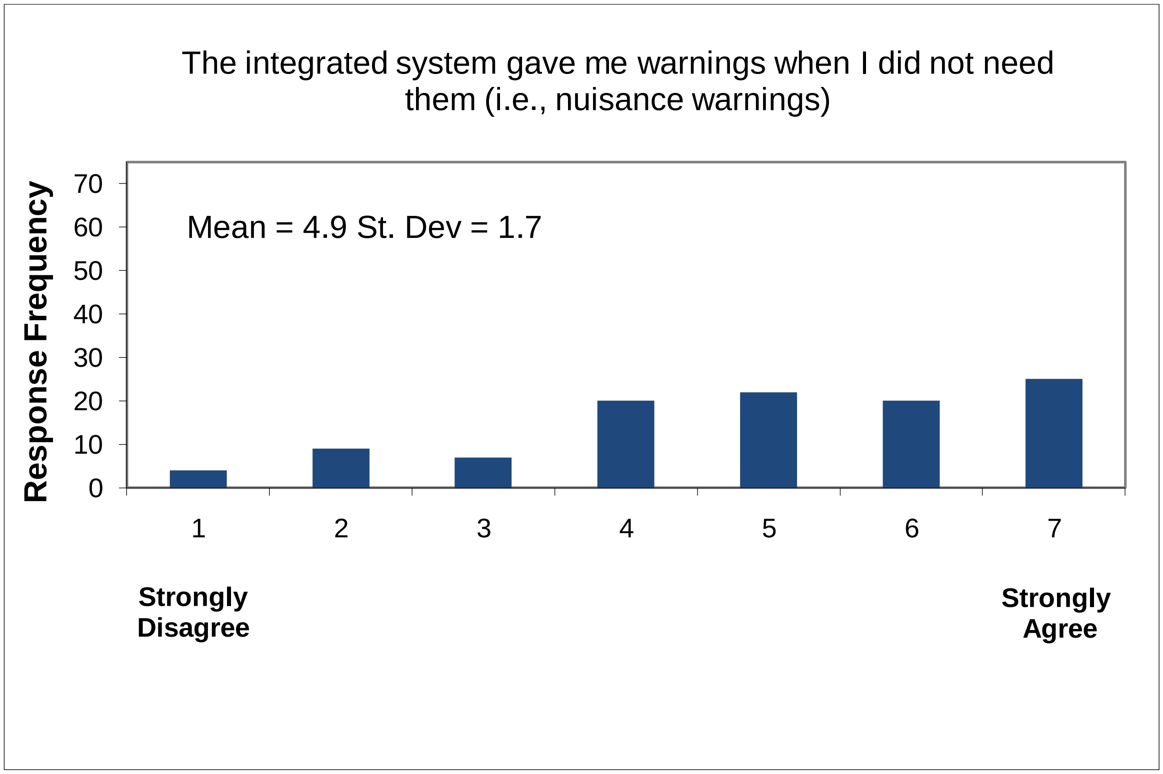


Figure 26: Drivers’ perception of nuisance warnings

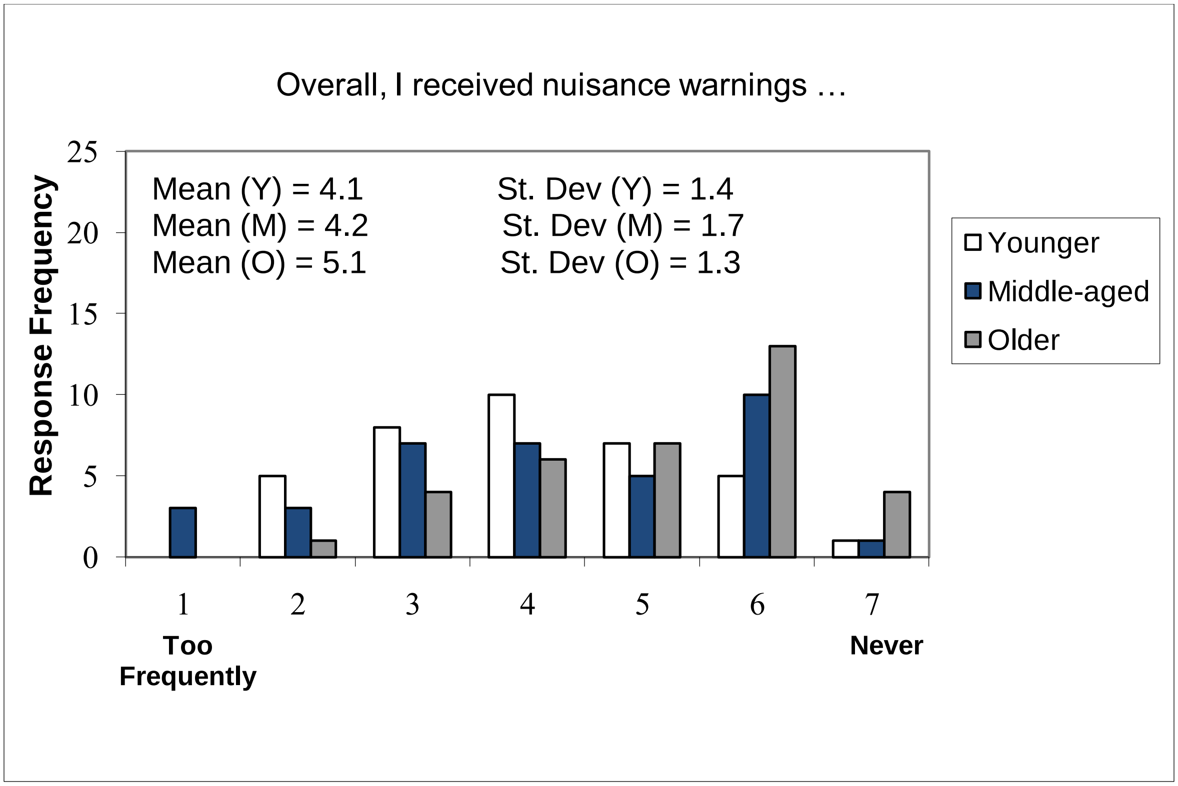


Figure 27: Frequency of nuisance warnings.

Table 10: By age group, count of invalid warnings and invalid warning rates

Age group	Invalid Warnings (count)	Percent Invalid Warnings	Invalid Warnings/100 miles
Younger	400	11%	.86
Middle-aged	412	9%	.75
Older	306	8%	.71

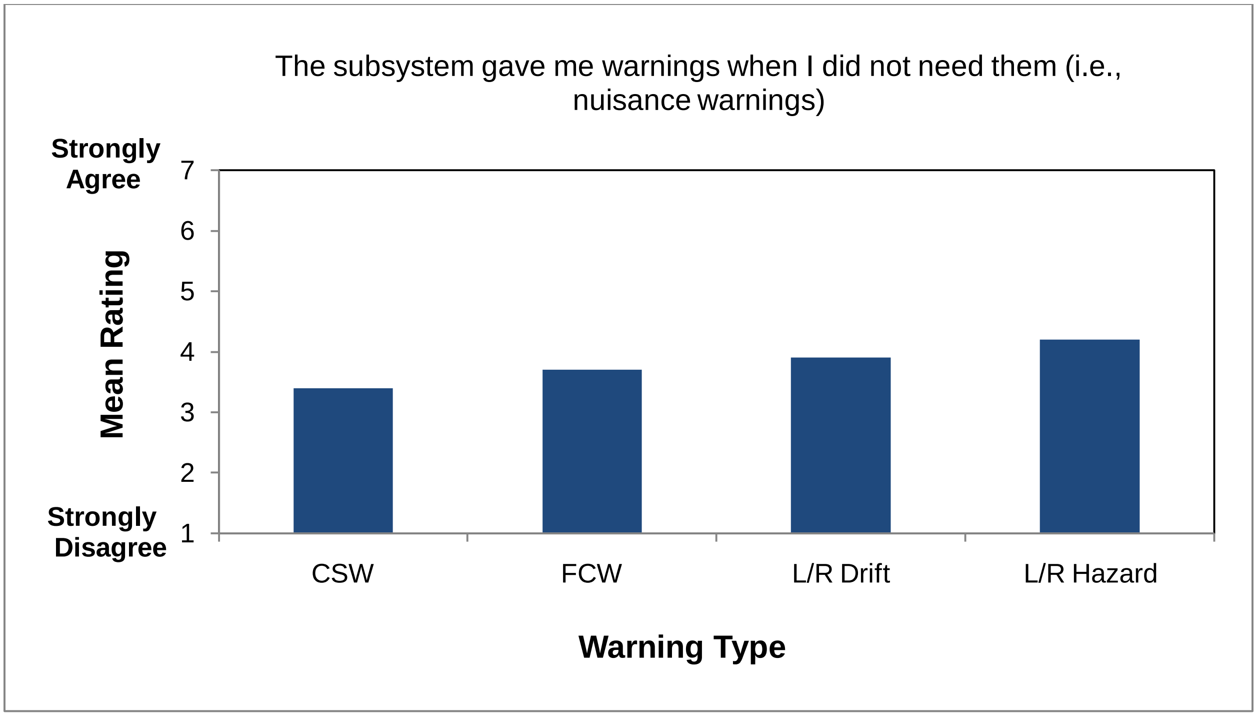


Figure 28: Mean ratings for each subsystem's nuisance warnings

Table 11: , Total and invalid warning counts, percentages, and invalid warning rates for each warning type

Warning Type	Total Warnings	Invalid Warnings	Percentage of Invalid Warnings	Invalid Warnings per 100 miles
CSW	601	152	26%	.11
FCW	579	307	53%	.21
LDW	8,505	489	6%	.43
LCM	2,508	31	1%	.02

Interpretation: While drivers received nuisance warnings from the integrated system, they did not feel that they received them too frequently. There appears to be an age effect with middle-aged drivers receiving the most nuisance warnings and younger drivers having the highest nuisance warning rate (nuisance warnings/100 miles).

Drivers received nearly ten times more warnings from the lateral subsystems than they did from the longitudinal subsystems, while receiving only 15 percent more nuisance warnings per 100 miles from the lateral subsystems. However, the percentage of invalid warnings for the longitudinal subsystems was much higher than for the lateral systems, particularly since the alert overall alert rate of those systems were low. In general, reducing invalid alert rates would benefit all subsystems.

QC10: Do drivers find the integrated system to be easy to use?

Results: Drivers found the integrated system easy to use. With the exception of the mute button and volume control, there were no driver inputs to the integrated system. When they integrated system provided a warning, drivers generally knew how to respond as displayed in Figure 29.

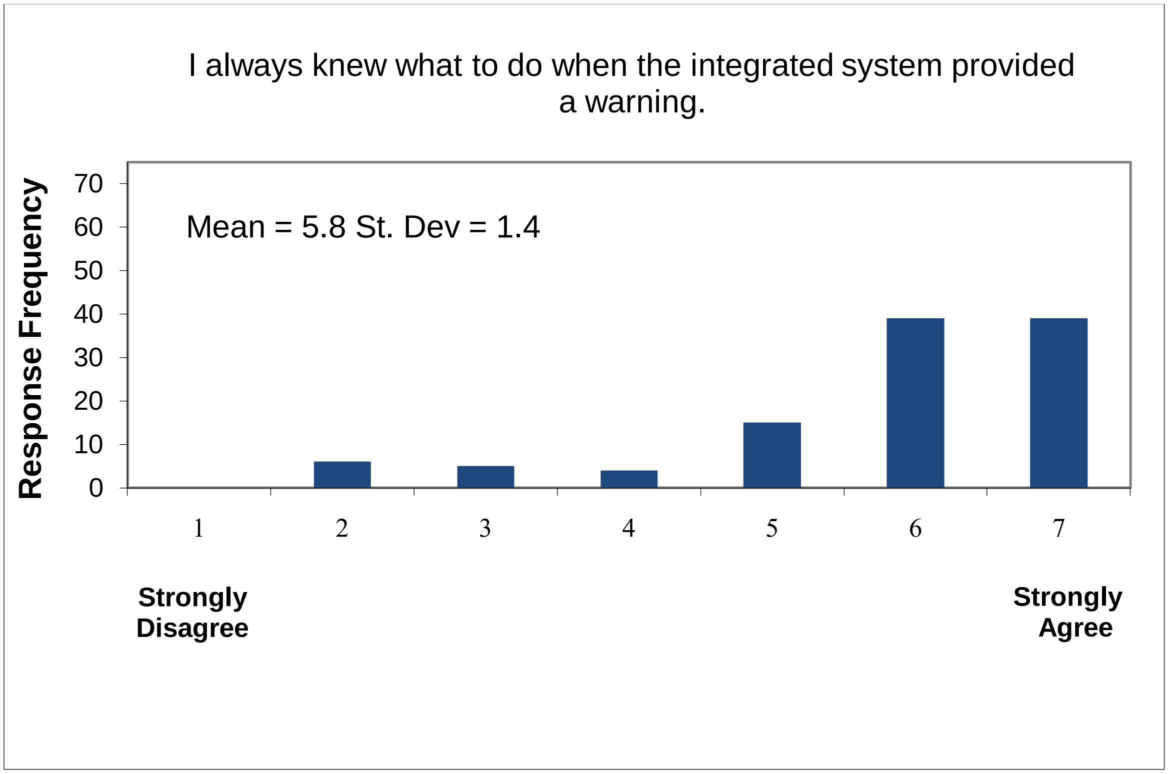


Figure 29: Drivers' understanding about how to respond to warnings

Interpretation: Generally speaking, drivers found the integrated system easy to use. When presented with warnings, they knew how to respond. Designing integrated systems that are intuitive and easy to use is vital to the success of these and similar systems.

QC11: Do drivers find the integrated system to be easy to understand?

Results: Even though drivers were told that they might receive invalid warnings, they did not always understand why the integrated system provided them with a warning. In spite of receiving some invalid warnings, drivers generally understood why the system provided them with a warning (Figure 30) and very much understood what to do (e.g., brake in response to an

FCW) when the integrated system provided a warning (Figure 29). There was no effect of driver age on understanding of the integrated system.

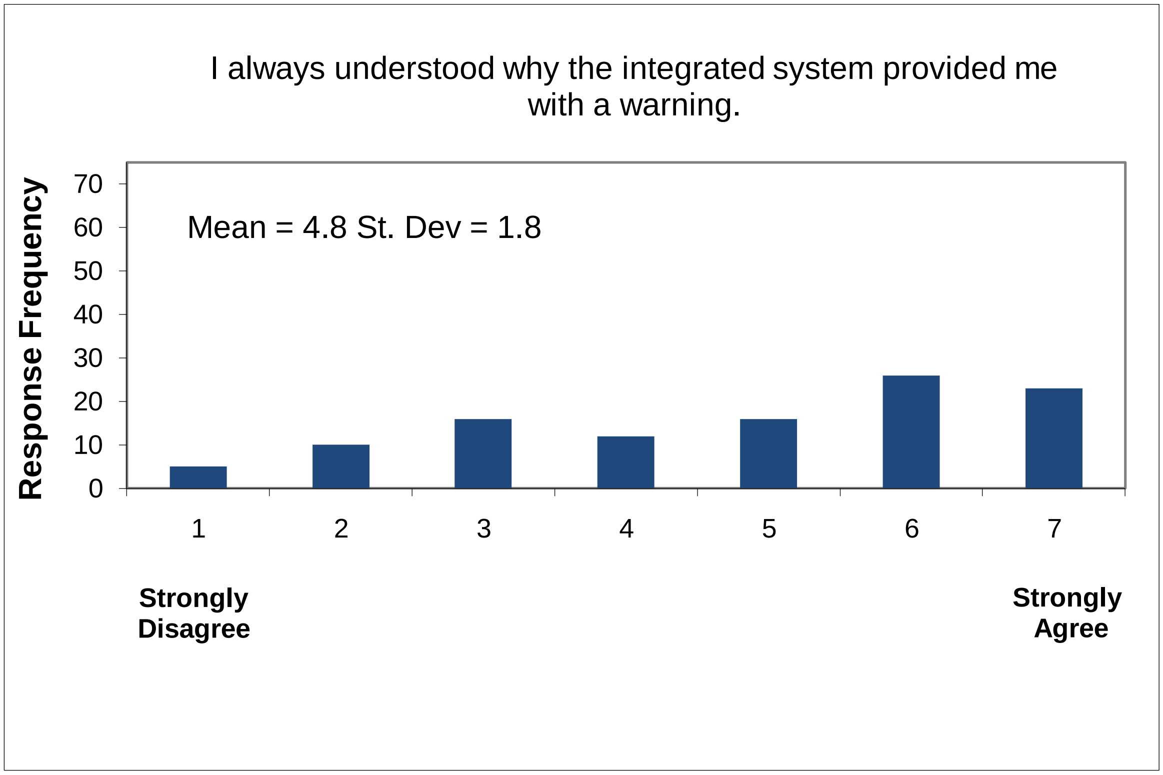


Figure 30: Drivers' level of understanding of the integrated system

Further examination of drivers' understanding of the different warning modalities reveals that they mostly understood why the integrated system provided them with yellow lights in the mirrors indicating that a vehicle was in or approaching their blind spot and least understood why the system provided them with brake pulse warnings (Table 12). This result is not surprising given the percentage of FCW warnings that were invalid, even if the overall warning rate for FCW was lower than other subsystems.

Table 12: Drivers' understanding of the different warning modalities

Warning Modality	Understood why the system provided a warning (mean rating)
Auditory	5.6
Seat vibration	6.0
Brake pulse	4.5
BSD yellow lights	6.6

Interpretation: Drivers understood the integrated system's warnings and how to respond when they received warnings; however, they generally reported not liking the brake pulse. Reducing the invalid warning rate particularly for FCWs, may increase drivers' understanding of why the integrated system provides those warnings.

QC12: Do drivers find the overall frequency with which they received warnings to be acceptable?

Results: Overall, drivers found the frequency with which they received warnings to be acceptable. This result is displayed in Figure 31. Of the drivers who reported receiving warnings too infrequently, 70 percent of them reported they should have received more CSWs and FCWs. About one-third of the drivers reported receiving warnings too frequently. A number of these drivers reported that they received too many LDWs, and the LDW subsystem did produce both the highest number of warnings in addition to the highest warning rate. There was no effect of driver age on the response to this question.

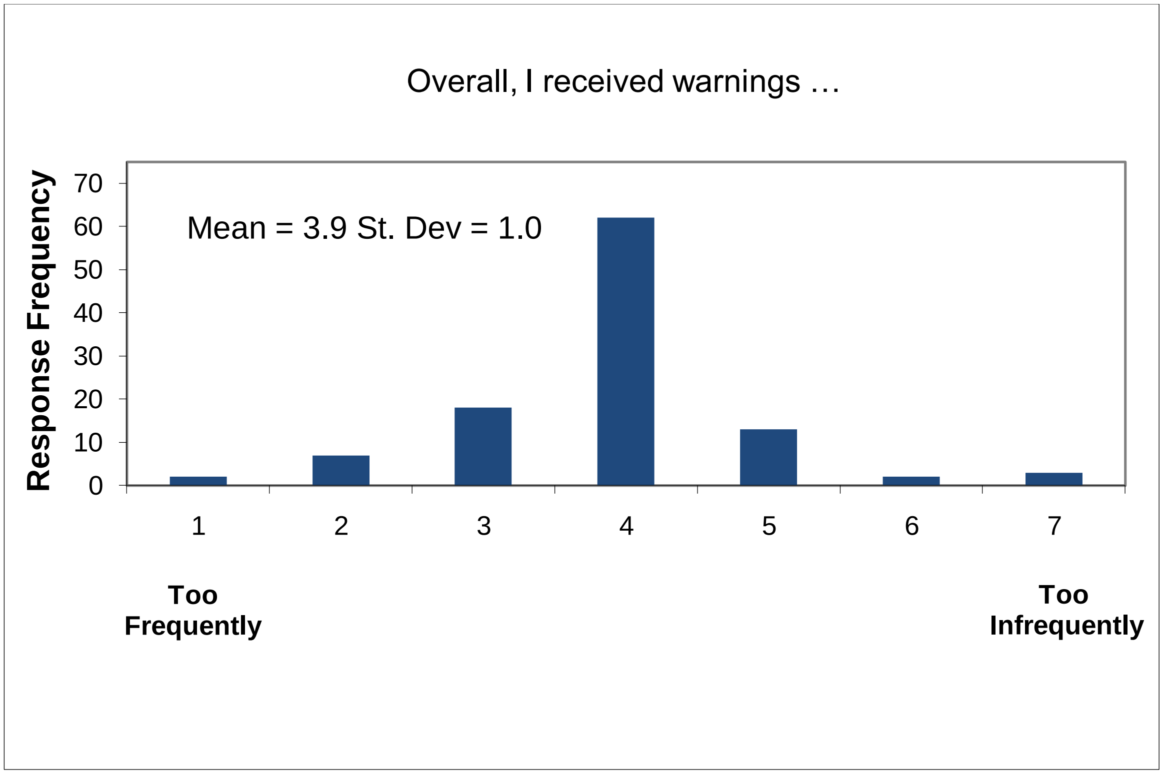


Figure 31: Ratings of frequency with which drivers received warnings

Interpretation: Overall, drivers reported receiving warnings with about the right frequency. For the drivers who wanted to have received more warnings than they did, they suggested that they should have received more FCWs and CSWs. If future rates of these warning types are increased, care should be taken to keep the invalid warning rate low. In debriefing sessions, some drivers complained about receiving lane departure warnings when they failed to use their turn signals even if they were making lane changes in the absence of other vehicles.

QC13: Do drivers find then nuisance warnings to be bothersome?

Results: In general, while drivers did not like receiving nuisance warnings, they were not overly annoyed by them. As seen in Figure 32, more than half of the younger drivers (56%) found the nuisance warnings to be annoying, more so than the other age cohorts. Older drivers' mean rating of the annoyance of nuisance warnings was nearly two points higher than that of younger drivers (5.5 versus 3.6). Older drivers appeared not to be annoyed by nuisance warnings. In debriefing sessions, several drivers stated that they were willing to tolerate some nuisance warnings for the safety benefit of being warned in the event of a serious crash

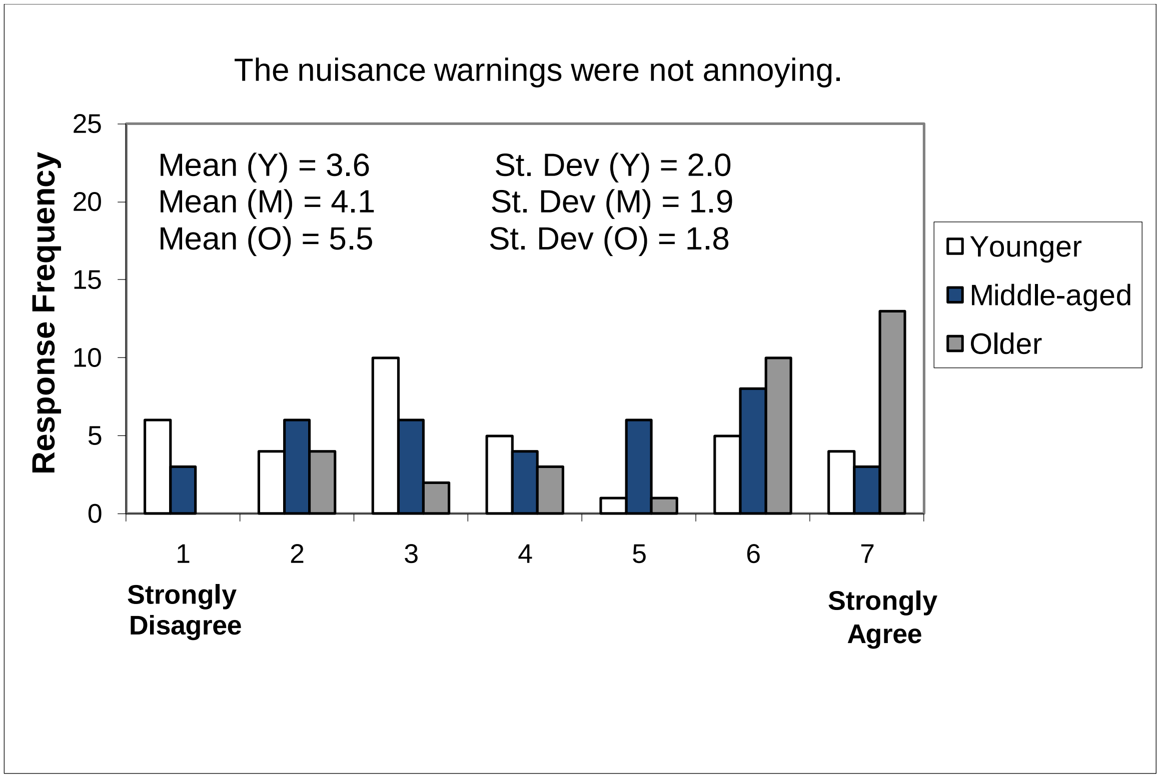


Figure 32: Drivers' perception of nuisance warnings' annoyance

Interpretation: Even though more than half of the younger drivers were annoyed by nuisance warnings, in general drivers were not overly annoyed by them. This may in part be explained by the fact that they did not think that they received nuisance warnings too frequently (See QC9). Additionally, drivers in focus groups, and in debriefing sessions, stated that they were willing to overlook some of the shortcomings of new technologies to reap the safety benefit.

QC14: Are drivers willing to purchase the integrated system or its individual subsystems, and if so, how much are they willing to spend?

Results: Drivers are willing to purchase both the integrated system as well as well as the individual subsystems. Figure 33 shows that about half of the drivers reported being willing to spend between $250 and $750 for the integrated system. Of the group of drivers who said that they would not pay for the integrated system, several reported that they felt that the integrated system should come as standard safety equipment on all vehicles and as such, they were not willing to pay extra for it.

Drivers appear to be more willing to purchase the lateral subsystems (LCM and LDW) than the longitudinal systems (FCW and CSW). Examining the mode (i.e., the most frequently occurring response) for the maximum amount that drivers are willing to pay for each of the subsystems reveals that drivers are unwilling to pay for an FCW subsystem; they are willing to pay between

$100 and $200 for the CSW subsystem and LDW subsystem; and pay between $200 and $300 for an LCM subsystem or BSD subsystem (Figure 34).

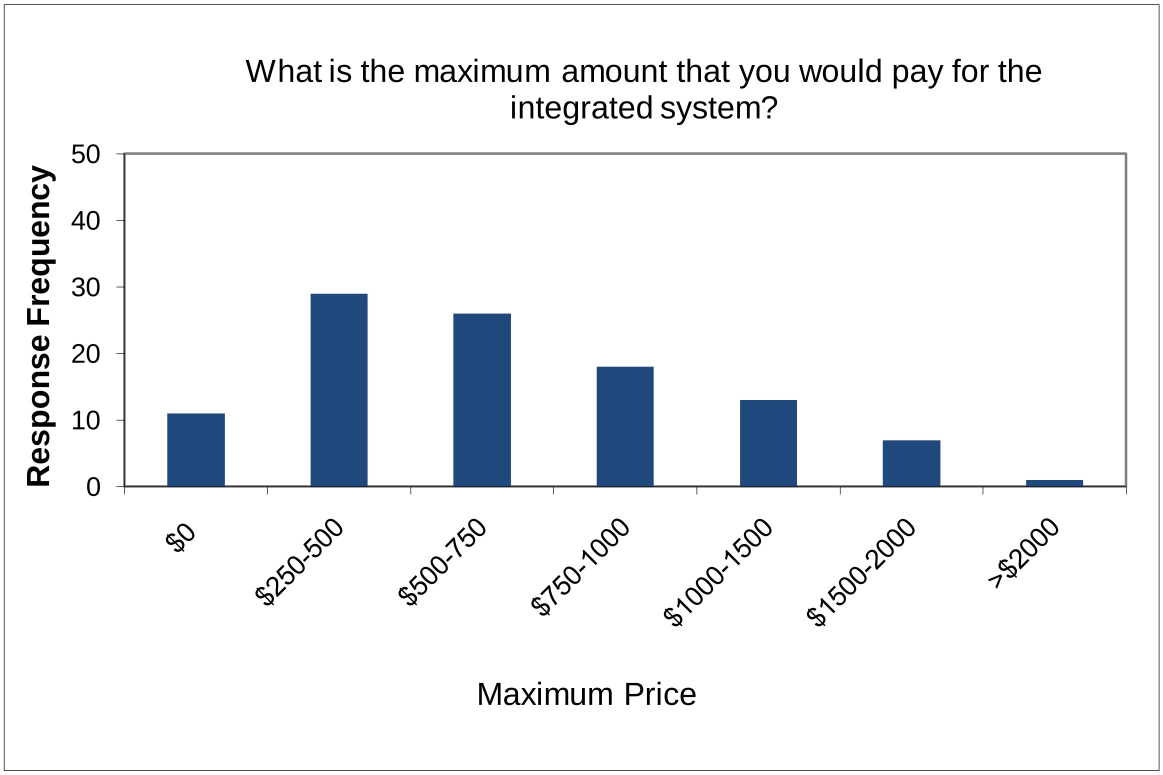


Figure 33: Maximum price that drivers would pay for the integrated system

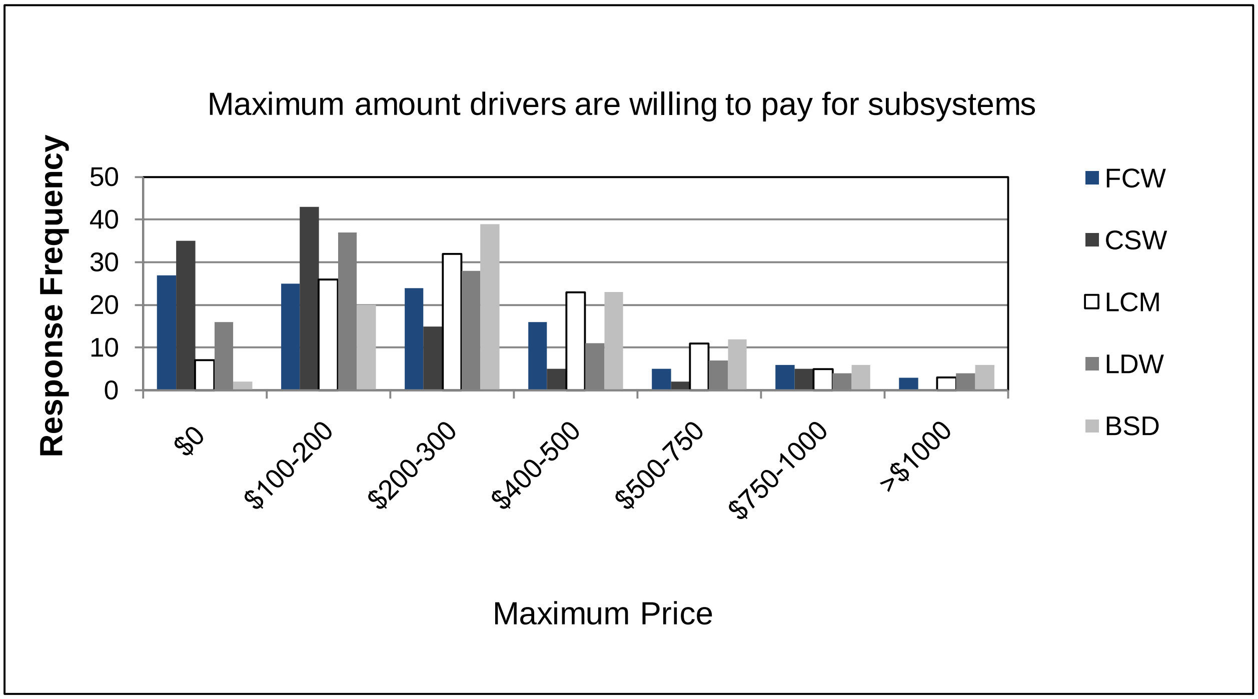


Figure 34: Maximum price that drivers would pay for each of the subsystems

Interpretation: The majority of drivers reported that they were willing to purchase the integrated system. Most drivers are not willing to spend more than $750, however. Drivers were more willing to purchase lateral subsystems such as LDW and LCM, and pay up to $300 for these subsystems, whereas they are only willing to spend up to $200 for CSW.

Given the complexity of the integrated system, and what drivers are willing to spend for such a system, it seems prudent to bundle two or three subsystems together for a first generation introduction. Discussions held in focus groups support the bundling together of the lateral systems (i.e., LDW, LCM, and BSD).

3.4 Lateral Control and Warnings Results

This section analyzes the performance of the lateral drift and lane change/merge crash warning subsystems. This includes key descriptive data, results regarding the frequency of lateral warnings, and changes in warning rates both with and without the integrated system.

3.4.1 Vehicle Exposure and Warning Activity

This section describes the frequency of lateral drift and lane change/merge warnings in both baseline and treatment conditions. Key descriptive statistics are provided as a function of road class, route type, and exposure over time, along with brief descriptions of warning scenarios.

During the FOT 21,037 lateral warnings (LCM and LDW cautionary and imminent) were recorded. The overall warning rate across all drivers, speeds, and other conditions was 14.6 lateral warnings per 100 miles of travel in the baseline period and 7.6 lateral warnings per 100 miles of travel in the treatment condition. A summary of the overall lateral warning activity as a function of condition and road type is given in Table 13. The highest overall rate was consistently on exit ramps. The lowest rate was on unknown road types, which include parking lots and other typically low speed areas.

Table 13: Overall lateral warning activity by condition and road type

Condition	Road type	Count	Percent	Rate per 100 miles
Baseline	Limited access	4,792	47.8	15.9
	Surface	4,285	42.8	13.7
	Ramps	362	3.6	16.4
	Unknown	580	5.8	11.1
Treatment	Limited access	4,398	39.9	7.1
	Surface	5,457	49.5	8.4
	Ramps	443	4.0	9.2
	Unknown	720	6.5	5.9

3.4.2 Lateral Warning Classification and Validity

The analysis in the previous section considered all lateral warnings and gave an overall summary of the warning rate regardless of type of warning or its validity and relevance. In this section, each lateral warning type will be considered separately in terms of both the assessed effectiveness of the warning and the driver's intention and reaction to the warning. The goal of this classification is to group all warnings into two categories that are defined as:

- **Valid**—warnings are helpful to the driver since they bring additional awareness to the driving task and can mitigate ignorance of an unrecognized conflict in the current driving situation. Warnings that are predictable and probable are also defined as valid. After a valid warning, the driver becomes more vigilant and makes an assessment of urgency. A valid warning may not be helpful in the immediate sense, but can be informative in that typically the driver is assuming normal driving behavior and actions will resolve the situation.
- **Invalid**—warnings are characterized by an incorrect or inaccurate assessment of the current or future driving circumstances (e.g., no vehicle present in the forward path, or a driver does not traverse the road branch with the curve), or very complex environments (e.g., roadway construction zones). Invalid warnings are not helpful to the driver since there is no additional knowledge provided about the driving environment, and there is no threat in the current driving situation—and one does not develop. While the system may be operating in accordance with the specific design intent, to the driver the warning is likely to appear to be spurious without any clearly identifiable reason and are therefore

not predictable by the driver. Some invalid warnings will be unavoidable as it is not possible to predict the future actions of vehicles in all situations.

The logic for sorting all LDW events was based on an analysis of driver intent and reaction to the warning explained below. However, note that the sorting and classification of LDW imminent events also depends on the state of the zones adjacent to the vehicle.

- **Valid**—there was a lateral drift sufficient for a warning followed by a measurable reaction by the driver to return to the original lane within a 5-second time window. For example, the driver is involved in a secondary task and inadvertently drifts into an adjacent lane, but upon hearing the warning, the driver actively corrects back toward the center of the original lane.
- **Valid and not corrected**—there was a lateral drift sufficient for a warning but no immediate correction in lateral offset by the driver occurred within a 5-second time window.
- **Valid and intentional**—the warning occurs when a driver makes an un-signalized (or late turn signal) lane change or intentionally moves outside of the lane due to road construction or a stopped vehicle on a shoulder. In these events, the driver drifts far enough outside of the lane that the center of the vehicle crosses the common boundary between lanes, triggering the lane change flag.
- **Invalid**—the warning was issued during a period of poor boundary-tracking confidence or around transitions in boundary-tracking confidence.
- **Invalid (imminent only)** - the adjacent lane was mistakenly classified as occupied and the maximum lateral offset was not within a standard deviation of the average distance to lane edge at the time of cautionary LDW events.

The following categories were used to classify the LCM warnings:

- **Valid but with poor boundary conditions**—the space adjacent to the vehicle was occupied but reliable lateral position information was not available. In this situation, initiating the turn signal shows intent to move into an occupied space and hence a LCM warning is issued.
- **Valid and immediate lane change**—the space adjacent to the vehicle was occupied, there is valid lateral position information and the driver times the lane change such that the POV clears the adjacent space as the SV occupies the adjacent space. For example, on a three lane road with one lane unoccupied, both the SV and POV move laterally in a synchronous fashion, both changing lanes at the same time. Another common example is when the SV changes lanes behind a faster moving POV just as the POV clears the adjacent lane but is still in the field of view of the forward lateral-facing proximity radar.
- **Valid and delayed lane change**—the space adjacent to the vehicle was occupied and there is valid lateral position information but the driver is waiting for the space to become

available and during that time exceeds the lateral position or velocity warning criteria resulting in an LCM.

- **Invalid**—the space adjacent to the vehicle was misclassified as occupied so no LCM should have been given when the driver signaled and moved laterally into the adjacent lane.

3.4.3 Lateral Warning Summary

In this section, the lateral warning exposure is presented using terms defining lateral warning type and validity. Figure 35 shows the overall lateral warning rate per 100 miles for valid and invalid warnings. Drivers had an overall valid lateral warning rate of 7.6 per 100 miles. Drivers had an invalid lateral warning rate of 0.45 per 100 miles. The invalid warnings, six percent of all lateral warnings, are characterized by an incorrect or inaccurate assessment of the driving environment by the warning system.

Figure 36 shows the overall warning rate as a function of each warning type. Notable in this figure are the relatively low levels of invalid warnings for each of the lateral warning types. Low boundary confidence was the leading contributor to the LDW cautionary invalid warning rate.

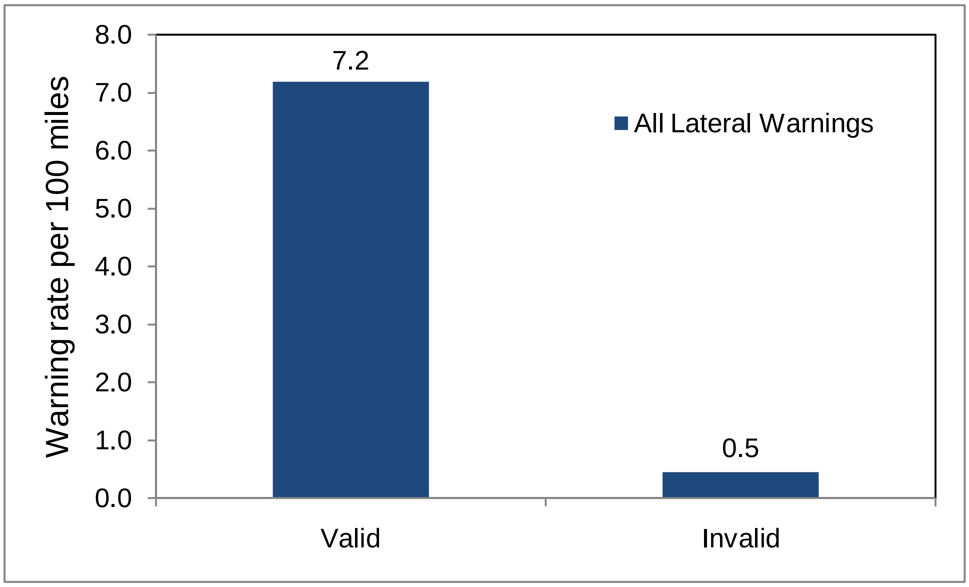


Figure 35: Overall lateral warning rate per 100 miles in the treatment period.

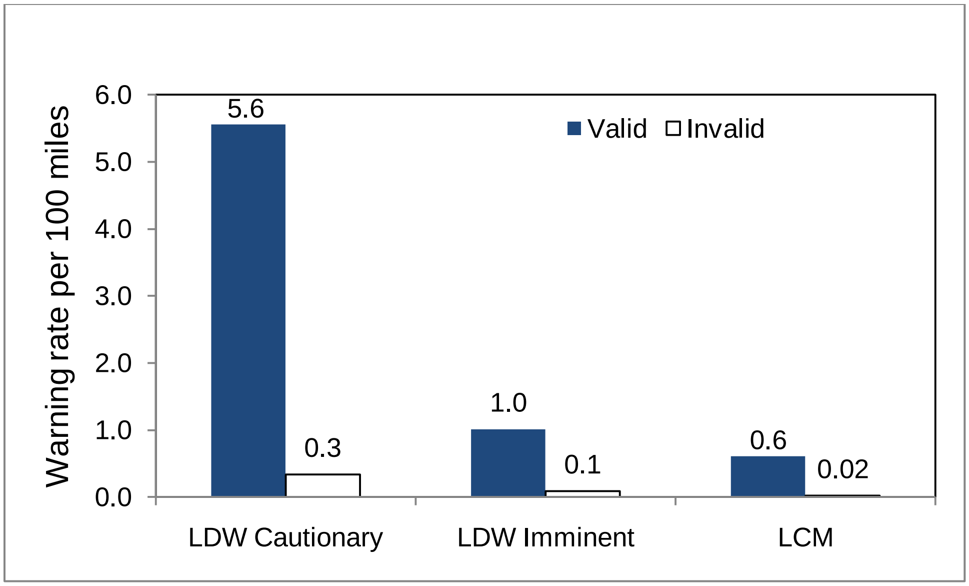


Figure 36: Treatment period overall lateral warning rate per 100 miles for each warning type.

Figure 37 and Figure 38 show the lateral warning rate per 100 miles as a function of warning type and side of the vehicle (from the driver's perspective). These figures show that the rate of warning is higher on the left side of the SV as compared to the right in all categories. Of all LDW imminent warnings and LCMs, 69 percent and 61 percent, respectively, were to the left side of the SV. A left side bias for LDW cautionary warnings also occurred. For this type of warning, 68 percent resulted from drifting to the left as opposed to the right.

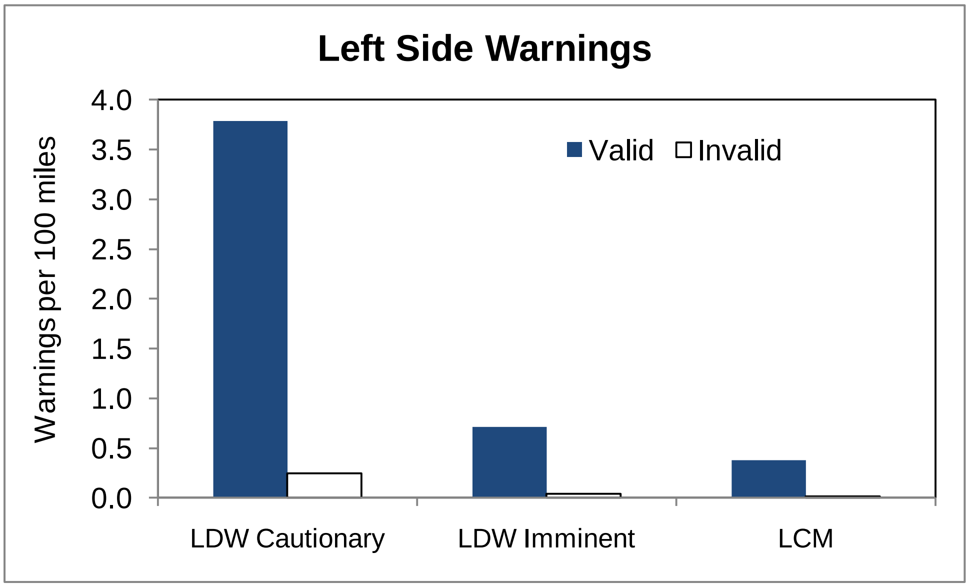


Figure 37: Overall lateral warning rate per 100 miles as a function of type on the left side.

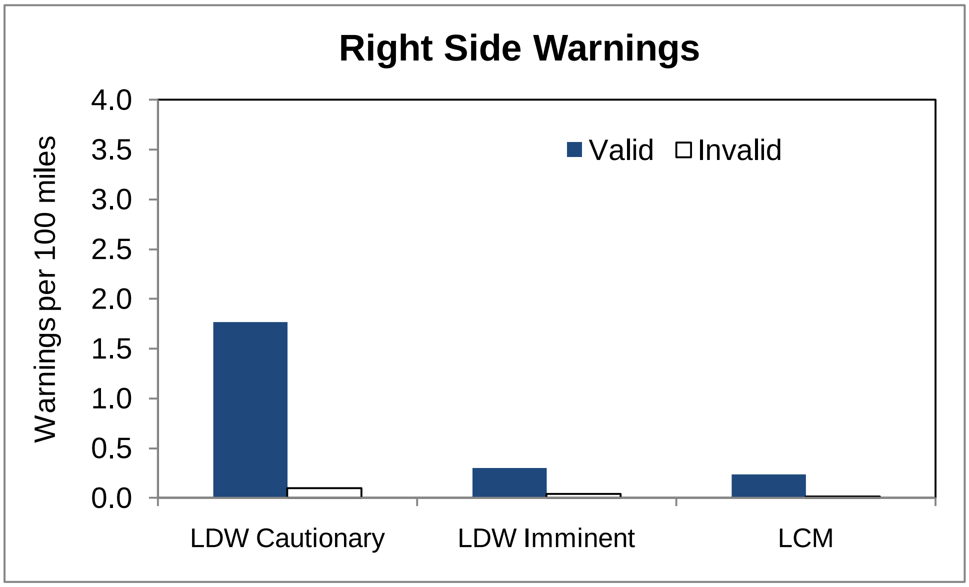


Figure 38: Overall lateral warning rate per 100 miles as a function of type on the right side

Table 14: Lateral warning rate by classification for the treatment period

Condition	**Warning type**	**Classification**	**Count**	**Percent**	**Rate per 100 miles**
Treatment	LDW Cautionary	Valid	8,016	72.8	5.56
		Invalid	489	4.4	0.34
	LDW Imminent	Valid	1,462	13.3	1.01
		Invalid	131	1.2	0.09
	LCM	Valid	884	8.0	0.61
		Invalid	31	0.3	0.02

3.4.4 Driver Behavior Research Questions

QL1: Does lateral offset vary between baseline and treatment conditions?

Research Hypothesis: There will be no difference in lateral offset between the baseline and treatment conditions.

Importance: It is important to understand the overall effect of the integrated system on driver behavior, not just in the event of a warning. Previous FOTs have reported overall improvements in lane keeping by drivers because of a crash warning system, and this question investigates possible changes in the lane position of the FOT participants.

Method: The lateral offset is defined as the distance between the center line of the vehicle and the center line of the lane as shown in Figure 39. If the vehicle is perfectly centered in the lane, lateral offset is zero.

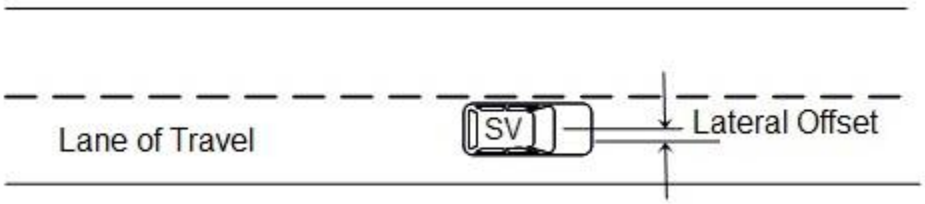


Figure 39: Conceptual drawing of lateral offset

This investigation is based on a subset of steady-state lane keeping events where the primary driving task is defined as maintaining a proper lateral offset. Intentional driving maneuvers such as lane changes and braking events were removed. When such a maneuver was performed, a buffer time of 5 seconds before and after was also removed to allow the driver to return to the lane-keeping task. Each lane-keeping event was required to last longer than 20 seconds to ensure that the driver settled into the driving task and eliminated short periods of driving where the driver was likely preparing for the next maneuver. Additional criteria required the lane tracking system to have known boundaries on both sides and the lane tracking status enabled to ensure that good estimates of the lateral offset were used. A list of the constraints used in this analysis can be seen in Table 15.

Table 15: QL1 analysis constraints

Constraints
Boundary types known and real (virtual boundaries not included)
Lateral offset confidence 100 percent
Lane tracker enabled
No braking, lane changes or turn-signal use
Buffer time of 5 seconds before and after any intentional maneuver
Steady-state duration longer than 20 seconds (plus buffer)
Speed above 11.2 m/s (25 mph)
Valid trip and driver

Using the constraints listed 128,626 events consisting of 794 hours (21% of driving when speeds greater than 25 mph) and 53,560 miles (27% of driving when speeds greater than 25 mph) of driving. For each event the mean lateral offset was calculated from the raw FOT data and was used as the dependent variable.

This analysis used a Linear Mixed Model with the driver as a random effect to determine the significant factors in predicting the lateral offset. The non-significant independent variables were removed from the analysis one at a time and the model was rerun until only the significant factors remained. The predictions generated by the model were also verified against the raw FOT data.

Results: The only independent variables that had a statistically significant effect on the lateral offset were the ambient light ($F(1,96) = 136.86$; $p < 0.0001$) and the average speed ($F(1,93) = 5.67$; $p = 0.0193$). These variable also showed a two way interaction ($F(1,93) = 108.00$; $p < 0.0001$). The integrated crash warning system did not show an effect on lateral offset. Figure 40 illustrates the lateral offset as a function of average speed for both day and night conditions. It should be noted that a negative offset means the vehicle is left of the center of their travel lane. Figure 41 shows the least square means for the ambient light interaction on lateral offset.

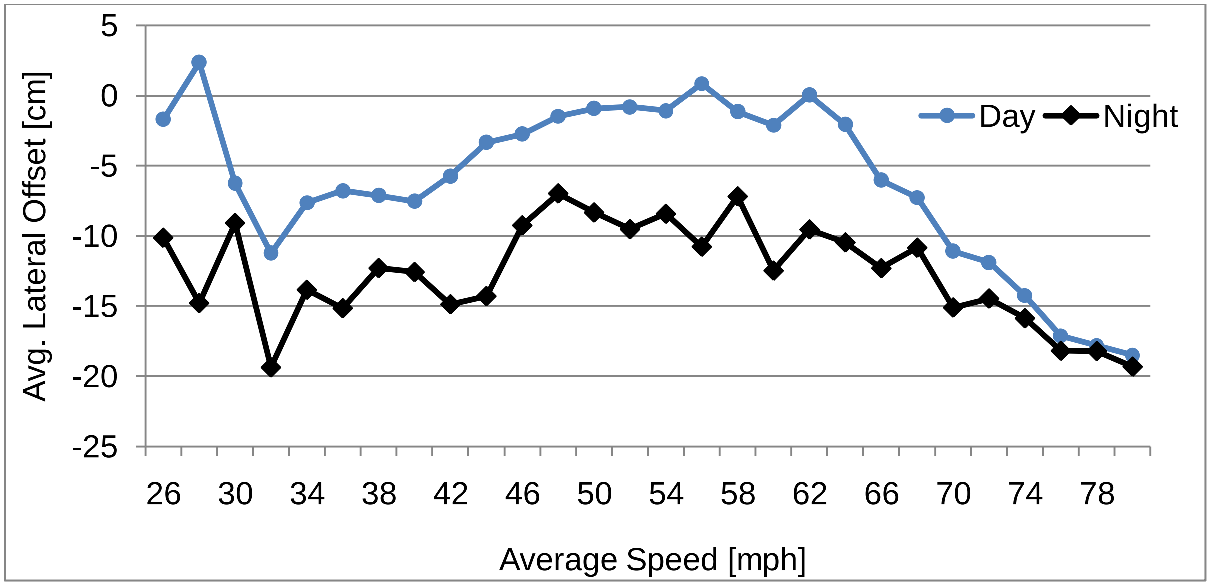


Figure 40: Average lateral offset for day and night conditions versus average speed during steady-state lane keeping

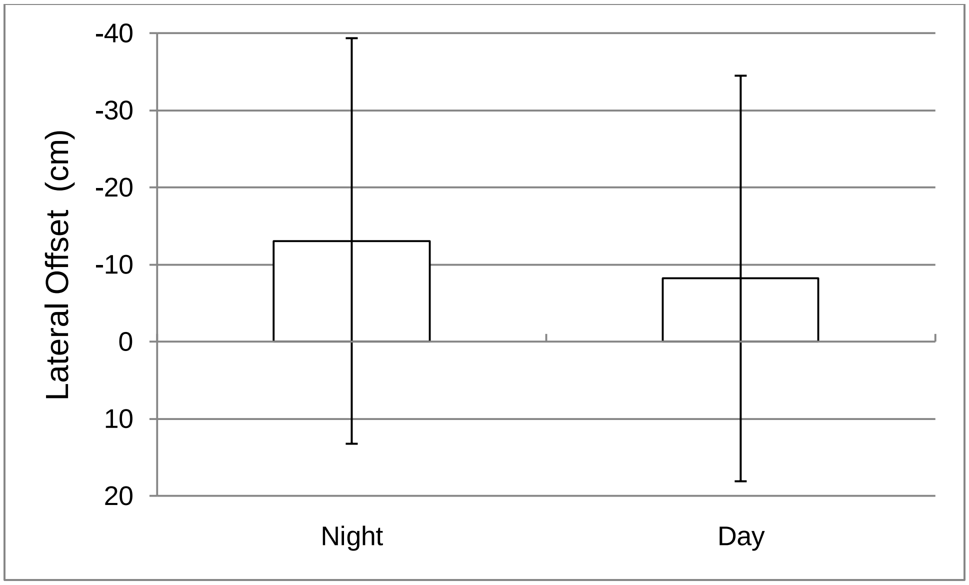


Figure 41: Lateral offset for day and night during steady-state lane keeping.

Descriptive Statistics: A slight change in lateral offset can be seen from the FOT data shown in Figure 42. The figure shows the percentage of travel time spent at various lateral-offset locations, and shows a slight shift from the left of the lane center to a more central lane position. The average lateral offset was –9.96 cm for the baseline period and -9.05 cm for the treatment period.

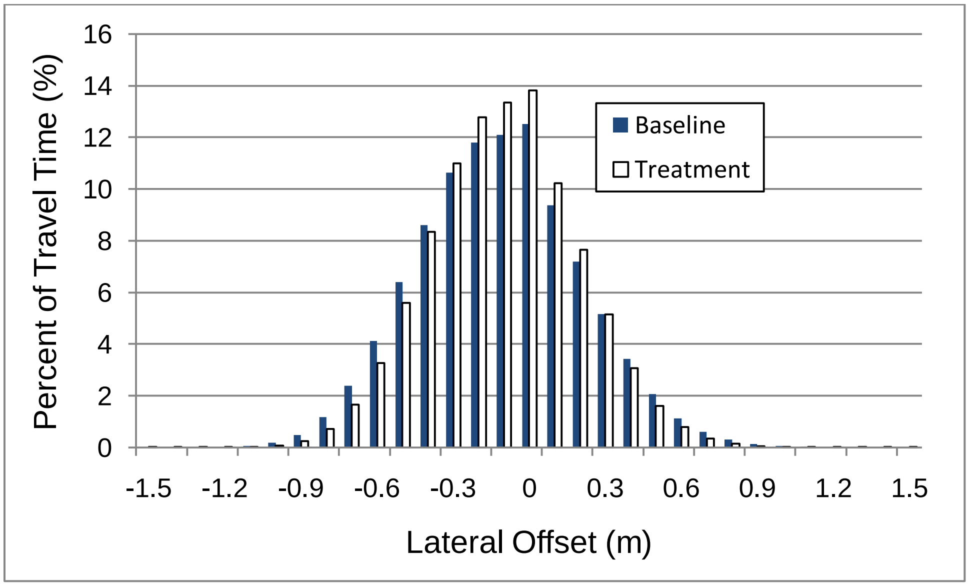


Figure 42: Percentage of driving time spent at a given lateral offset location for all drivers in both treatment conditions.

Interpretation: The integrated crash warning system did not have a statistically significant effect on lateral offset. Drivers on average positioned the vehicle about 9 cm to the left of the center of their lane. The average lateral offset moved about one centimeter towards the center of the lane under the treatment condition, but the change was not found to be a statistically significant change.

QL2: Does lane departure frequency vary between baseline and treatment condition

Research Hypothesis: There will be no difference in lane departure frequency between the baseline and treatment conditions.

Importance: One major goal of the FOT is to determine whether an integrated system has an impact on lane departures that might ultimately lead to a road departure and a crash. This research question examines the frequency of lane departures with and without the integrated crash warning system.

Method*:* The lane departures used in this analysis were pulled from periods of steady-state lane keeping and excluded active maneuvers such as changing lanes or braking. A lane departure does not always elicit a lane departure warning due to the sophisticated warning algorithms based on numerous vehicle measurements. This analysis focused on all departures beyond the lane boundary without isolating the departures selected by the integrated system as a safety threat. A lane departure is defined as an incursion of either side of the vehicle into an adjacent lane as measured by the lane tracker. The event must include both the exit from the lane and the return back to the original lane.

The previous research question (QL1) focused on periods of driving when maintaining the proper lane position was the primary task, and includes the unintentional lane departures of interest for this research question. Table 16 shows the constraints used to find the lane departures for this research question. A constraint on the maximum duration of the lane departure was implemented after video review determined that all of the eleven events over 20 seconds were not valid departure events, due to poor lane tracking or intentional maneuvers near construction or roadway hazards.

Table 16: QL2 analysis constraints

Constraints
Outer edge of vehicle beyond the estimated lane boundary
Boundary types known and real (virtual boundaries not included)
Lateral offset confidence 100 percent
Lane tracker enabled
No braking, lane changes or turn-signal use
Buffer time of 5 seconds before and after any intentional maneuver
Vehicle returns to lane in less than 20 seconds
Speed above 11.2 m/s (25 mph)
Valid trip and driver

During the steady-state driving, there were 12,760 lane departure events which were used for this analysis. These events were grouped into each unique scenario. The number of lane departures was then normalized by the number of 100 miles driven in that scenario to determine the lane departure frequency (departure per 100 miles). The normalized departures where then used for modeling the significant interactions.

This analysis used a General Linear Mixed Model with the driver as a random effect to determine the significant factors in predicting the lane departure frequency. The non-significant independent variables were removed from the model one at a time until only the significant independent variables remained.

Results: The presence of the integrated crash warning system had a statistically significant effect on the frequency of lane departures (p = 0.0044). Figure 43 provides the least square means of the departure rates for the baseline and treatment conditions. The figure shows a decrease in the frequency of lane departures per 100 miles. Specifically, a reduction of 5.9 departures per 100 miles was seen in the FOT data.

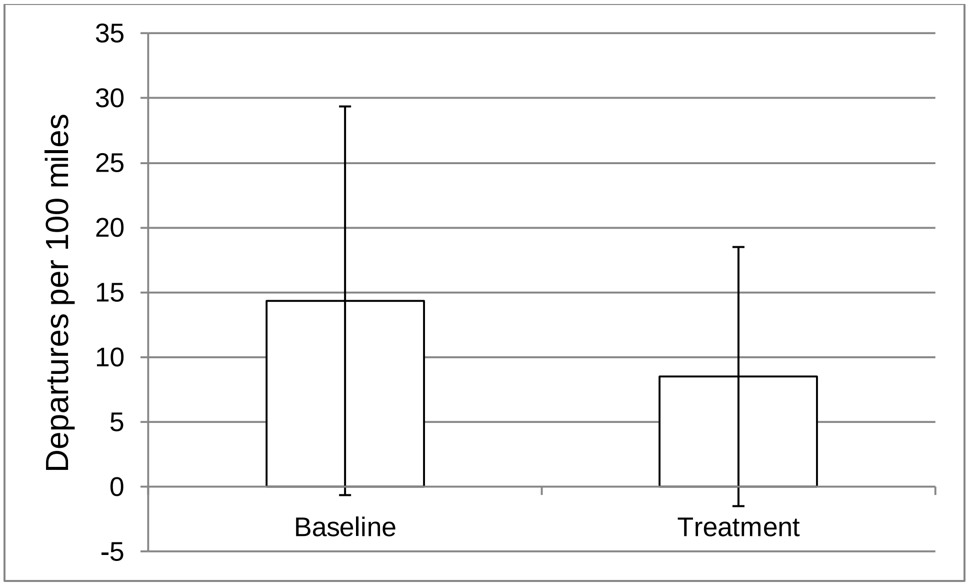


Figure 43: Means of departure rates for experimental condition

The direction of the departure, either to the left or right, had a statistically significant effect on the departure frequency (*p* = 0.0002). Figure 44 shows that the departure rate over the left boundary is much higher for both the model and FOT data. In both data sources, the departure rate to the left is over three times that to the right.

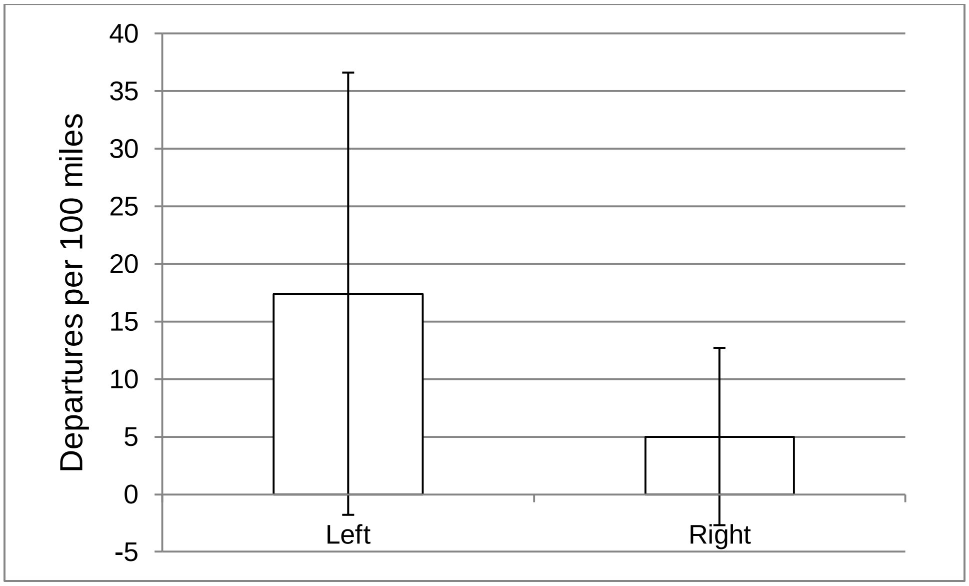


Figure 44: Means of departure rates by direction during steady-state lane keeping

Descriptive Statistics: As stated above, this analysis was based on the 12,760 lane departure events that occurred during the steady-state lane keeping. The frequency of lane departures shows a change over the course of the FOT, see Figure 45. The independent variable for week did not show a statistically significant interaction with the departure frequency, but there is a definite change in behavior from week to week. There is the largest change in driver behavior between week two and three, when the integrated warning system was activated, followed by a slight increase during the remaining weeks of the FOT.

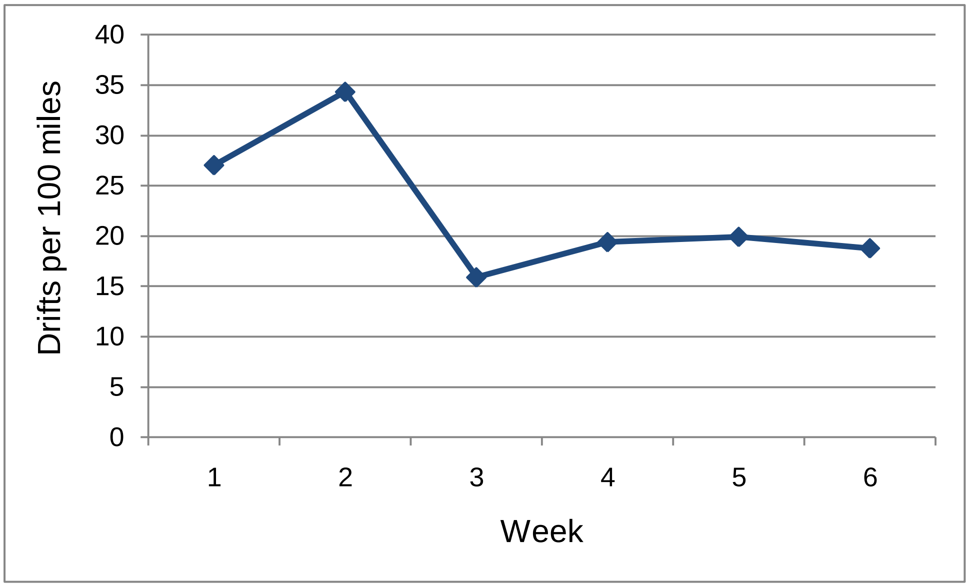


Figure 45: Average departure frequency by week during steady-state lane-keeping

Interpretation: The integrated system had a statistically significant effect on the frequency of lane departures, decreasing the rate from 14.4 departures per 100 miles under the baseline condition to 8.5 departures per 100 miles under the treatment condition. Additionally, the average departure frequency for all of the drivers shows changes from week to week. When the system began warning the drivers during the third week and the departure rate was cut by more than half from the previous week.

QL3: When the vehicles depart the lane, does the vehicle trajectory, including the lane incursion and duration, change between the baseline and treatment conditions?

Research Hypothesis: There will be no difference in the distance or duration of the lane departures between the baseline and treatment conditions.

Importance: It is important to understand not only if the frequency of lane departures is reduced with the integrated system (QC2), but also the magnitude of a departure should it occur. In particular whether the integrated system prompts drivers to deviate less and return sooner to their lane—whereby potentially reducing crash risk.

Method: The same 12,760 lane departures used in research question QL2 were used in this analysis. The lane departures were pulled from the steady-state, lane keeping events and excluded active maneuvers. For each lane departure, the time from when the edge of the vehicle first crosses the lane boundary to when the entire vehicle is again in its lane was determined. In addition, the maximum lane incursion distance into the adjacent lane was recorded for each event.

All of the departure events in this analysis require the subject vehicle to return to its original lane in less than 20 seconds (see research question QL2). Table 16 in section QL2 summarizes the constraints used for this question.

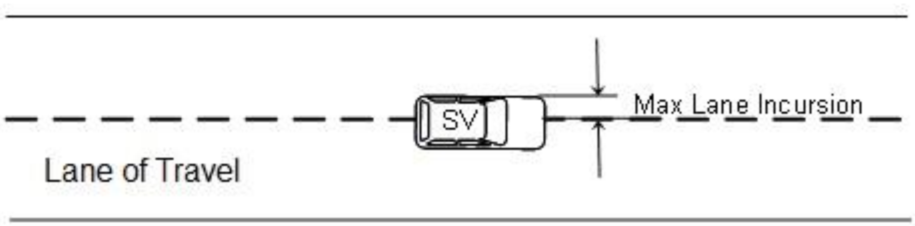


Figure 46: Illustration of lane incursion

Results: Departure Duration

The experimental condition had a statistically significant effect on the duration of the lane departures (*F*(1,98) = 44.42; $p < 0.0001$). However, the difference between the baseline and treatment durations was very small from a practical perspective, from 1.98 to 1.66 seconds (Figure 47).

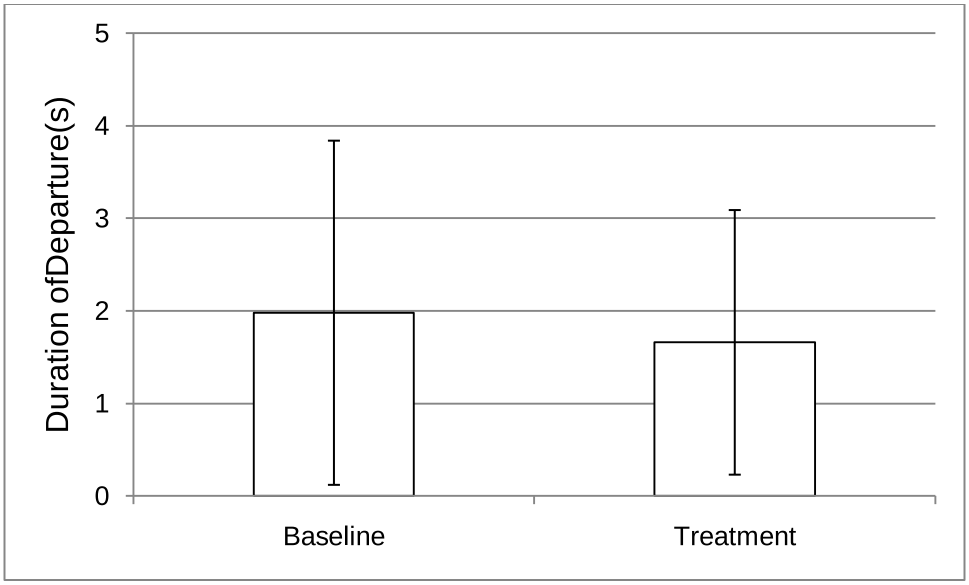


Figure 47: Duration least square means for experimental condition

The presence of a vehicle in the adjacent lane (Figure 48), the principal other vehicle (POV), also had a statistically significant effect on departure duration (*F*(1,42) = 13.64; *p* = 0.0006). The FOT data demonstrated longer departure durations, away from the POV, when there was an adjacent POV (Figure 49). The average duration of departure for no POV was 1.80 seconds compared to 2.28 seconds with a POV. Only 128 of the 11855 departures had an adjacent POV present, so the result here may be an effect of a small amount outlying data.

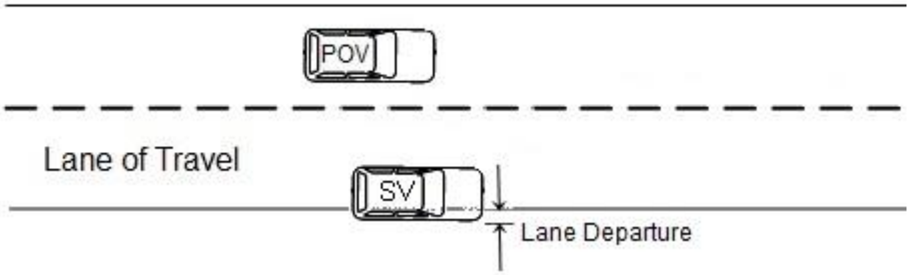


Figure 48: Illustration of lane departure with another vehicle present in the adjacent lane

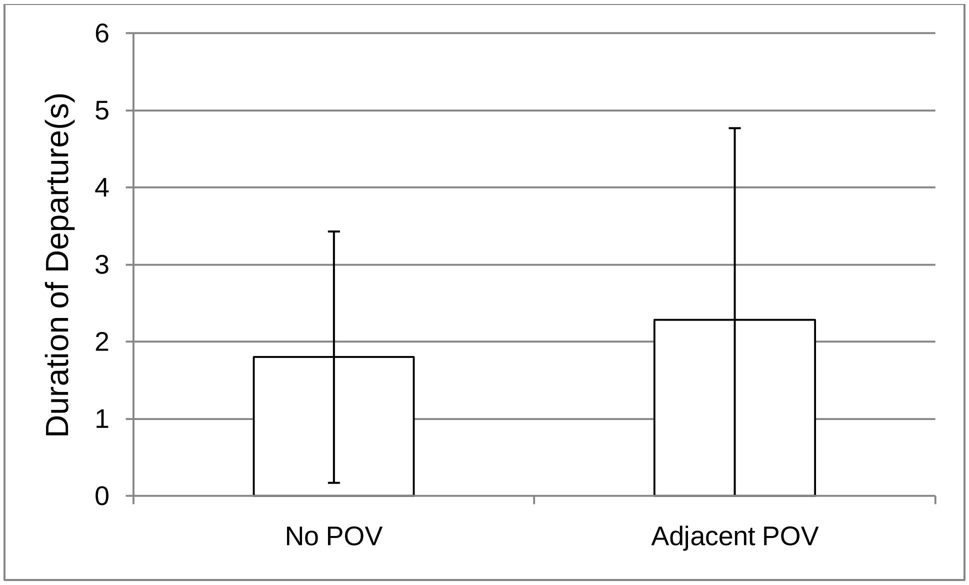


Figure 49: Duration least square means for POV in adjacent lane during

Results: Maximum Incursion Distance

The maximum incursion distance of the departures was statistically significantly affected by the experimental condition (*F*(1,98) = 30.15; $p < 0.0001$), however the practical significance may be fairly small. On average, the distance of a lane departure decreased by 1.2 cm in the treatment condition. Figure 50 shows the average maximum incursion measured during the FOT.

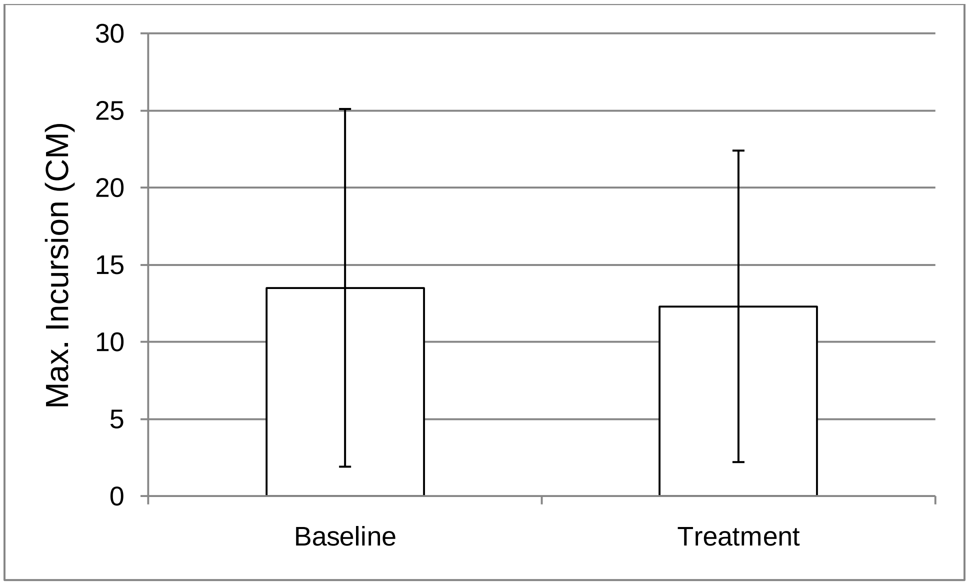


Figure 50: Maximum incursion distance least square means for experimental condition during steady-state lane keeping

Finally, the presence of a POV also had a statistically significant effect on the lane incursion distance ($F(1,42) = 11.9$; $p = 0.0013$). The FOT data show an increase in maximum incursion distance of 3.5 cm with an adjacent POV (Figure 51). This increase is similar to the increase in duration discussed above, see Figure 49.

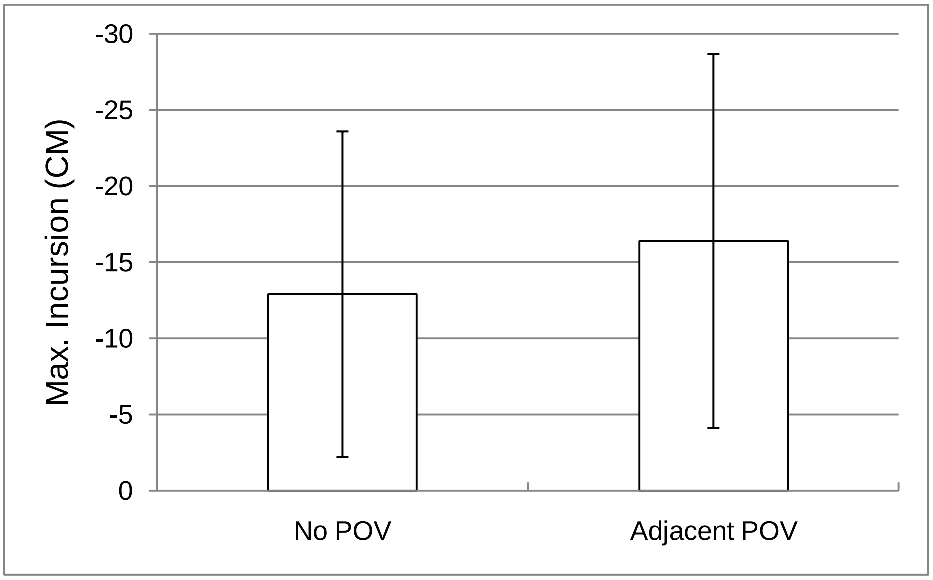


Figure 51: Maximum incursion distance least square means for departures with POV in adjacent lane

Although the week was not found to have a significant effect on either the duration or incursion distance, they did show a change during the FOT. Figure 52 shows the average drift duration for each week. The figure shows a decrease in the average drift duration after the treatment started in the third week with a slight increase during weeks five and six. Figure 53 shows the average of the maximum incursion distance for each week. Both plots show a minimum at the fourth week followed by increases.

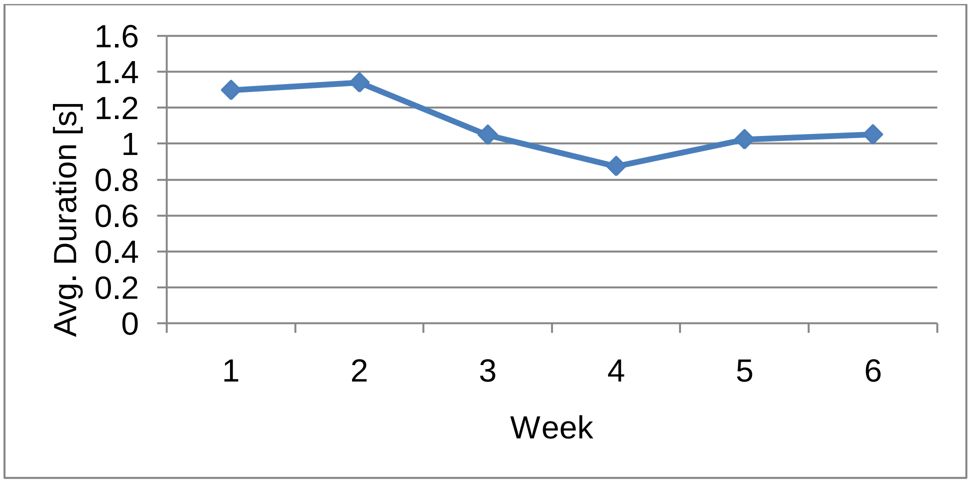


Figure 52: Average drift duration by week during steady-state driving

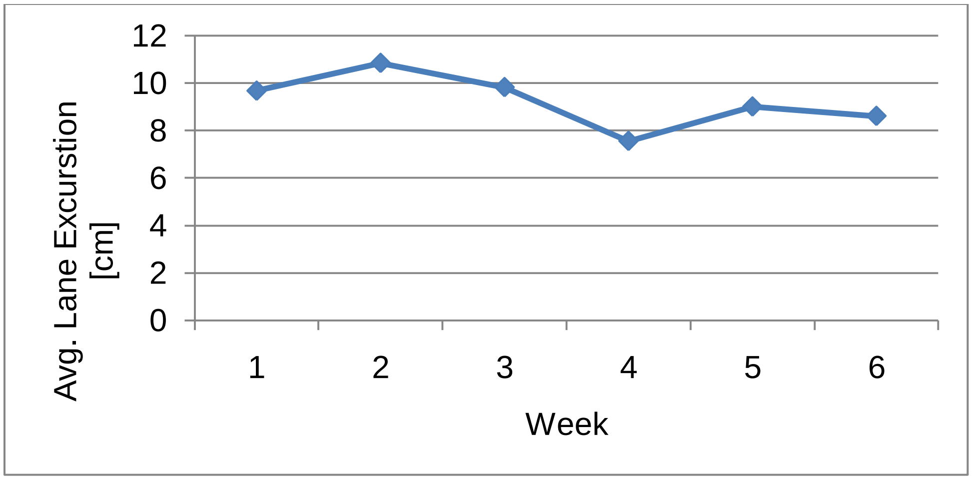


Figure 53: Average maximum incursion distance by week during steady-state driving

Descriptive Statistics: Figure 54 and Figure 55 show histograms for the departure duration and maximum incursion for the steady-state lane keeping departure events. The figures include all lane departures and the departures that resulted in a lane departure warning. As noted previously, the LDW system uses a variety of variables and algorithms to determine when a warning should be sent to the driver in order to reduce nuisance warnings and account for the variety of situations encountered by drivers.

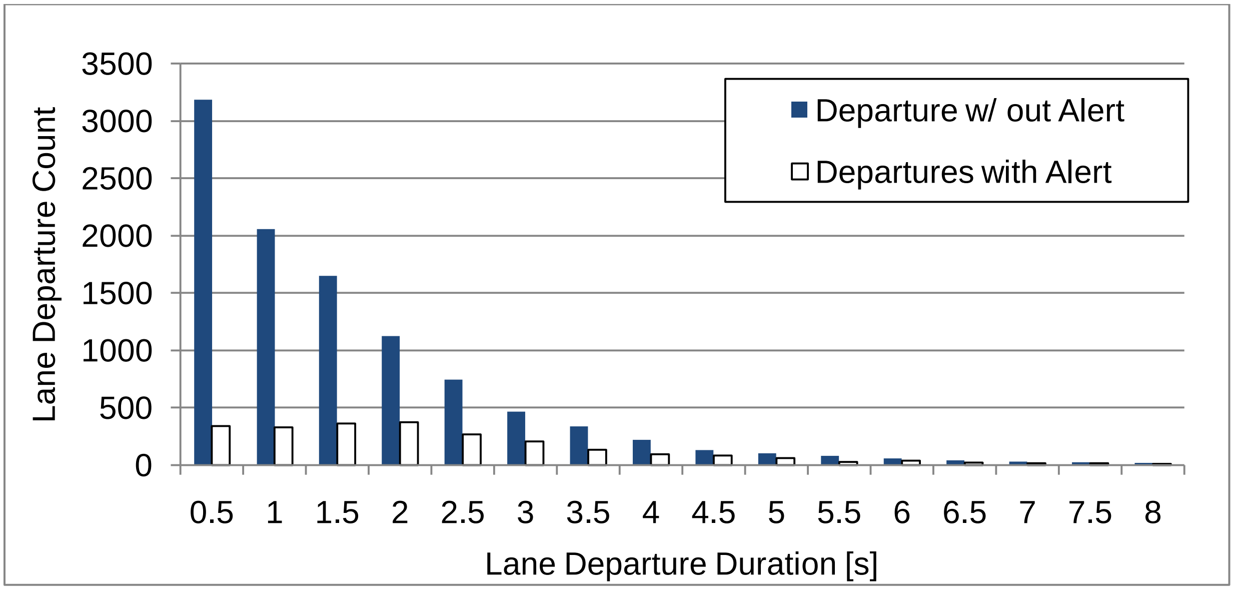


Figure 54: Histogram of departure durations

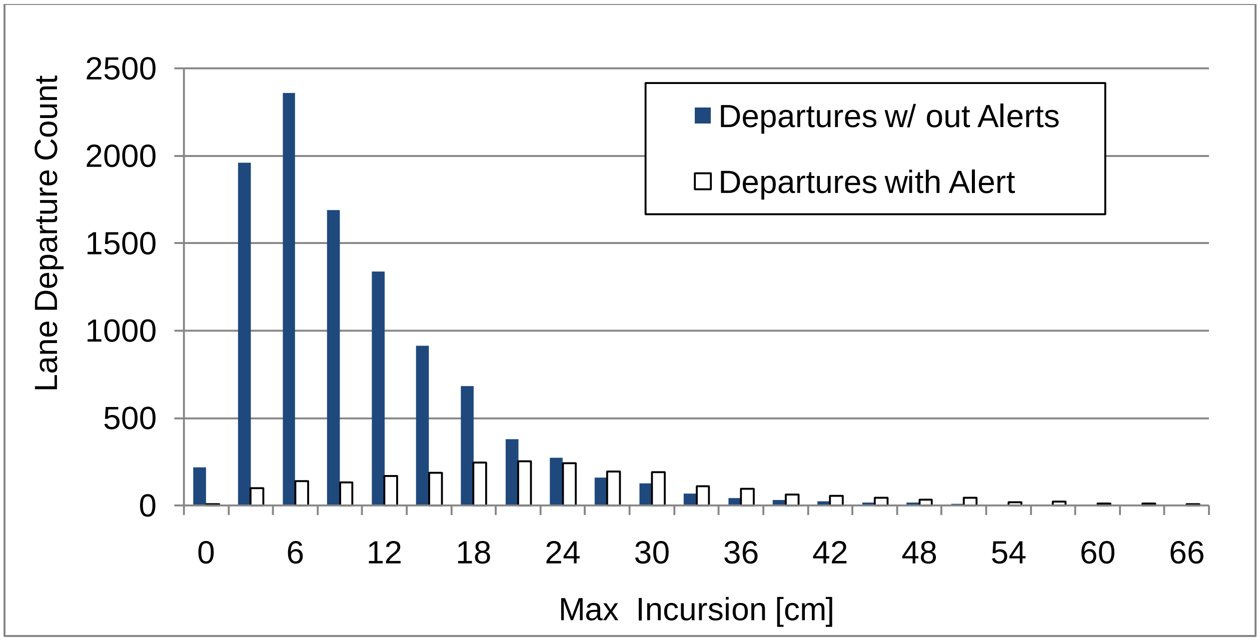


Figure 55: Histogram of maximum incursion during steady-state lane keeping events

A Linear Mixed Model was used to determine if the trajectory of lane departures varies with the independent variables for both the duration and incursion distance. Only the variables with a statistically significant effect on the trajectory were left in the model. The results for the duration of the departure events will be discussed first, followed by the incursion distance.

Interpretation: The integrated crash warning system had a statistically significant effect on the distance and the duration of lane departures. The mean duration of a departure dropped from 1.98 sec in the baseline condition to 1.66 sec in the treatment condition, and the distance decreased by 1.2 cm. The presence of an adjacent POV and boundary type also had statistically significant effects on duration of a lane departure.

QL4: Does turn signal usage during lane changes differ between the baseline and treatment conditions?

Research Hypothesis*:* There will be no difference in the use of the turn signal for lane changes with the integrated system.

Importance: It is important to understand the overall affect of the integrated system on driver behavior, not just in the event of a warning. Previous FOTs have reported overall improvements in turn signal use by drivers because of a crash warning system, and it is believed that the same could be true in the IVBSS FOT.

Method: A sub-set of 56,647 of left and right lane-change events was used to examine turn-signal use. The analysis addressed changes in the frequency of turn-signal use during lane changes. A lane change was defined as the lateral movement of the SV relative to the roadway in which the SV begins in the center of a defined traffic lane with boundary demarcations, and ends in the center of an adjacent traffic lane that also has defined boundary demarcations. A lane change is defined as the instant in time when the SV centerline crosses the shared boundary between the two adjacent traffic lanes.

The principal findings of this analysis are based on the results of a mixed linear model that examined turn-signal usage. The findings are based on a sample size of 106 drivers. Two drivers were excluded from the analysis since they did not have any un-signaled lane-changes under the baseline condition. The following turn signal use data is presented below in Figure 56.

Results: The presence of the integrated system had a statistically significant effect on turn-signal use during lane changes ($F(1,106) = 77.76$; $p < 0.0001$). Drivers in the FOT under the baseline condition failed to use the turn signal in 18.6 percent of lane changes, while drivers under the treatment conditions only failed to use the turn signal in 6 percent of lane changes.

Also found to be statistically significant was the effect of road type ($F(1,106) = 112.44$; $p < 0.0001$) on turn-signal usage. Drivers in the FOT on limited access highways failed to use the turn signal in 8.9 percent of lane changes, while drivers on surface streets failed to use the turn signal in 12.9 percent of lane changes.

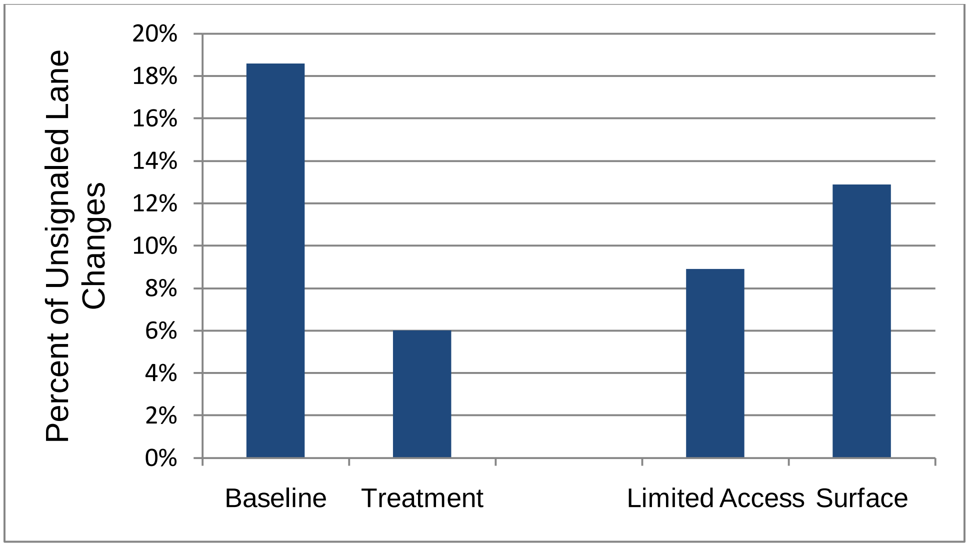


Figure 56: Percent of unsignaled lane changes over two significant independent variables

As shown in Figure 57, a statistically significant two-way interaction ($F(1,106) = 30.01$; $p<.0001$) exists between road type and treatment condition. Drivers under the baseline condition and on surface streets were the least likely to use the turn signal when making a lane change, failing to use the turn signal in 20.6 percent of these lane changes. However, lane changes under this specific scenario were relatively rare, with only 8.7 percent of all lane changes occurring on surface streets under the baseline condition.

The most common scenario in which lane changes occurred was on highways under the treatment condition encompassing 47.8 percent of all lane changes. This was also the scenario with the highest turn signal usage, with drivers only omitting turn signal use in 4.5 percent of these lane changes.

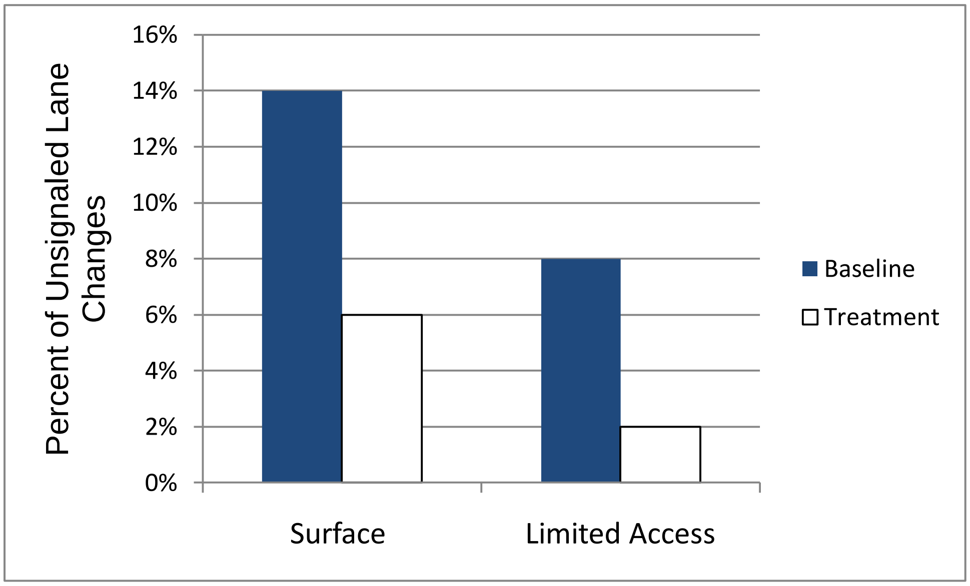


Figure 57: Interaction between condition and road type

Interpretation: The results show a statistically significant effect of the integrated system on turn-signal use during lane changes. Drivers were 3 times less likely to forget to use a turn signal when making a lane change in the treatment condition as compared to the baseline condition. Also statistically significant was the effect of road type where drivers were more likely to fail to use a turn signal during a lane change on surface streets than on limited-access highways.

QL5: Do drivers change their position within the lane when another vehicle occupies an adjacent lane?

Research Hypothesis: When adjacent same-direction traffic is present on only one side of the host vehicle, drivers will not alter their lane position to increase the separation between the host and the vehicle in the adjacent travel lane.

Importance: It is important to understand the overall affect of the integrated system on driver behavior, not just in the event of a warning. If drivers are receiving too many LCM warnings, they may attempt to reduce the frequency of these warnings my maintaining a larger distance from adjacent vehicles. However, in maintaining a larger distance, drivers might also be increasing the risks of a warning, or crash, on the opposite side of the vehicle.

Method: A set of 99,680 randomly sampled events, 5 seconds in duration, was identified in the data set. For every event, a lateral-offset position that characterizes the lateral position of the vehicle within the lane, with respect to the lane boundary markers was calculated. Then an analysis was performed for each side of the SV. In the analysis comparing lane position with or without the presence of a POV on the left side of the SV, the AMR on the right side was always unoccupied and conversely in the analysis for the right side of the SV, the AMR on the left was always unoccupied. Figure 58 shows the conditions for the analysis on the left side of the SV. Additional constraints were: straight sections of road with good boundary markings, no intentional lateral maneuvers temporally near the sampled period by the driver, and a speed of 11.2 m/s (25 mph) or higher.

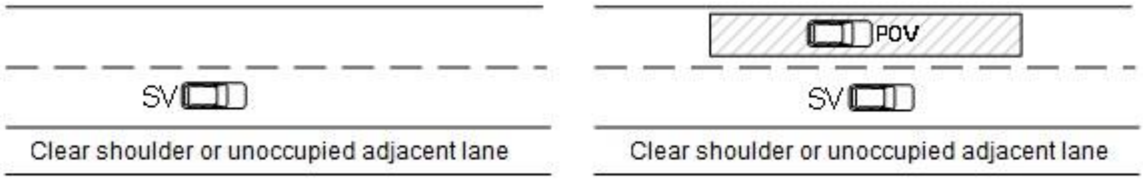


Figure 58: Lateral offset change away from an occupied space

Results: The principal findings of this analysis are based on the results of a mixed linear model conducted for an adjacent lane on each side of the SV.

On average, drivers had a lateral offset bias of 11.5 cm to the left of lane center. The independent measures found to have a statistically significant effect on lateral lane position were the integrated system, ambient light, and the presence of a vehicle in an adjacent lane. In the treatment condition there was a statistically significant, but practically small, shift by drivers 1.3 cm toward the center of the lane (*F*(1,107)=7.99; *p*=0.0056) as compared to baseline condition (Figure 59).

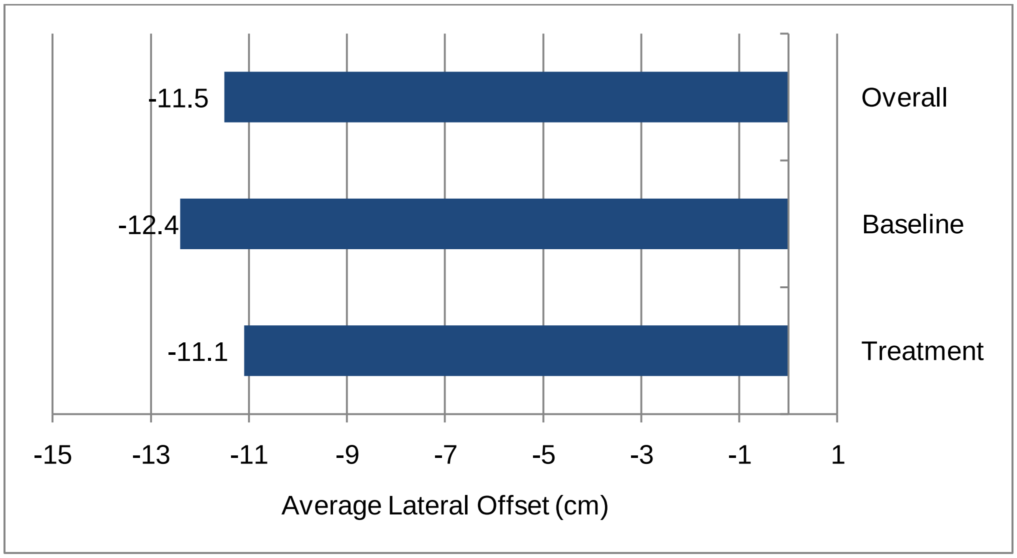


Figure 59: Lateral offset with an adjacent vehicle by condition

When and adjacent lane was occupied, ambient light was also found to have a statistically significant affect on the lateral offset ($F(1,102)=24.52$; $p<0.0001$) with drivers having on average a lateral offset bias of 15.5 cm to the left of lane center at night and 10.4 cm to the left of the center of the lane during the day. Average lateral offsets as a function of the adjacent lane state are displayed in Figure 60 below.

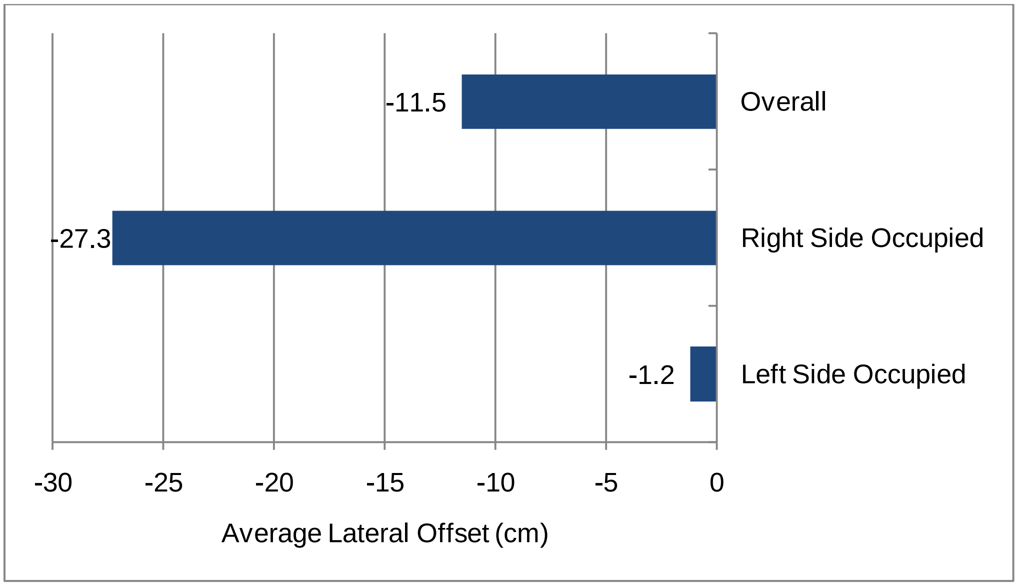


Figure 60: Lateral offset as a function of adjacent lane state

When the right lane was occupied, drivers moved to the left an extra 16.4 cm compared to when the right lane was unoccupied ($F(1,107)=280.5$; $p<0.0001$). This put the average driver over 27 cm to the left of the center of the lane when a vehicle was directly adjacent on the right side

If the left lane was occupied, drivers moved to the right (back towards the center of the lane) 10.7 cm compared to when the left lane was unoccupied ($F(1,105)=147.6$; $p<0.0001$). Even with a vehicle adjacent to the subject vehicle on the left side, on average drivers still stayed slightly to the left of center in their lane.

Interpretation: Generally, drivers have a lateral offset of approximately 11.5 cm to the left of lane center and although there was a statistically reliable reduction in lateral offset associated with the integrated system, the magnitude of the difference was small. A larger effect was found when the space adjacent to the host vehicle was occupied. Drivers adjusted their lane position away from a vehicle in an adjacent lane regardless of which side of the adjacent vehicle is on. This suggests that drivers' awareness regarding the presence of other vehicles adjacent to them is rather high. This information may be beneficial for designers of crash warning systems in terms of understanding how best to establish thresholds for warnings when there are vehicles in the adjacent lane.

QL6: What is the location of all adjacent vehicles relative to the subject vehicle for valid LCM warnings?

Research Hypothesis: Valid LCM warnings will be evenly distributed along the side of the tractor and trailer unit.

Importance: It is important to understand where vehicles are located when they result in LCM warnings in order to understand how future systems can be improved and contribute to drivers' perception of the systems utility.

Method: First, the region adjacent to each side of the subject vehicle was divided into three zones as shown in Figure 61. Next, LCM warnings for conditions in which the space adjacent to the subject vehicle is occupied by a same-direction vehicle were identified. For this analysis, the data set excluded cases in which the space was occupied by a fixed roadside object such as a guardrail or barrier. For each LCM event, the zones on the corresponding side of the vehicle were characterized as being occupied or not. For those targets in the rear-looking radar the range and range-rate from the radar to the closest vehicle in that zone was identified.

The analysis was performed using the constraints shown in Table 17. These rules helped establish a steady-state condition for the subject vehicle and dictate how long the turn signal and targets had to have persisted for the event to be considered a candidate for this analysis. Warning validity was determined by reviewing video associated with the events. Shown in Table 18 are the dependent variables for the analysis and a list of independent variables that were included in the analysis.

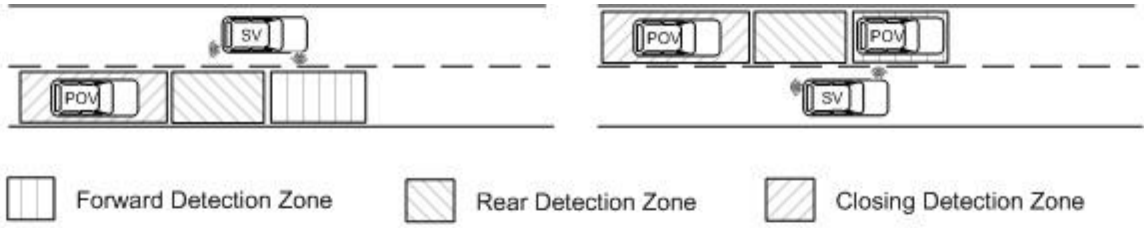


Figure 61: Location of zones for adjacent vehicles for valid LCM warnings

Table 17: QL6 analysis constraints

Constraints
Boundary types known and lateral offset confidence 100 percent
Dashed boundary between the equipped vehicle and POV(s)
Turn signal active for at least 1 second before LCM warning is issued
Speed above 11.2 m/s (25 mph)
Target duration greater than 2 seconds
No intentional lateral maneuvers by the equipped vehicle driver in a 5-second window prior to the LCM (i.e., the vehicle is in a steady-state condition within its lane)

Table 18: QL6 dependent and independent variables

Dependent Variables
Count and distribution of valid LCM warnings for the six zones around the vehicle
Independent Variables
Condition (baseline, treatment)
Wiper state (on, off)
Side (left, right)
Ambient light (day, night)
Road type (limited access, surface)
Gender (male, female)
Age group (younger, middle-aged, older)

Results: The principal findings of this analysis are based on the results of a chi-square test. The statistical significance was determined based on an alpha level of 0.05.

In this analysis, data from the three side radars on each side of the SV is combined, and used to classify each LCM based on the presence or absence of a vehicle in each of the three radars' zones. Depending on which radars detected adjacent vehicles, a different "zone code" was assigned to each unique combination of target locations. The eight possible zones codes and their definitions are presented below in Table 19.

Table 19: Adjacent zone code definitions

Front-side Radar	Rear-side Radar	Closing-zone Radar	Zone Code	Percent of LCMs
Yes	No	No	1	1%
Yes	Yes	No	2	21%
No	Yes	No	3	38%
No	Yes	Yes	4	7%
Yes	No	Yes	5	7%
No	No	Yes	6	23%
Yes	Yes	Yes	7	2%
No	No	No	8	1%

Because of the extremely small proportion of LCMs resulting from zone codes one, seven and eight, these zones could not be used in the statistical analysis.

For the analysis, 1270 valid LCM warnings (772 to the left and 498 to the right) were examined and five zone categories (zones 2, 3, 4, 5, 6) were considered. Figure 62 shows the count of warnings occurring as a function of zone. The most active zone was the area covered by the rear-side radar (from the B-pillar to about 3 m behind the SV) which was occupied in 40 percent of the warnings occurred. The second most active zone was the closing-zone radar which covers the rear approach area adjacent to the SV. This zone was occupied in 24 percent of these LCMs.

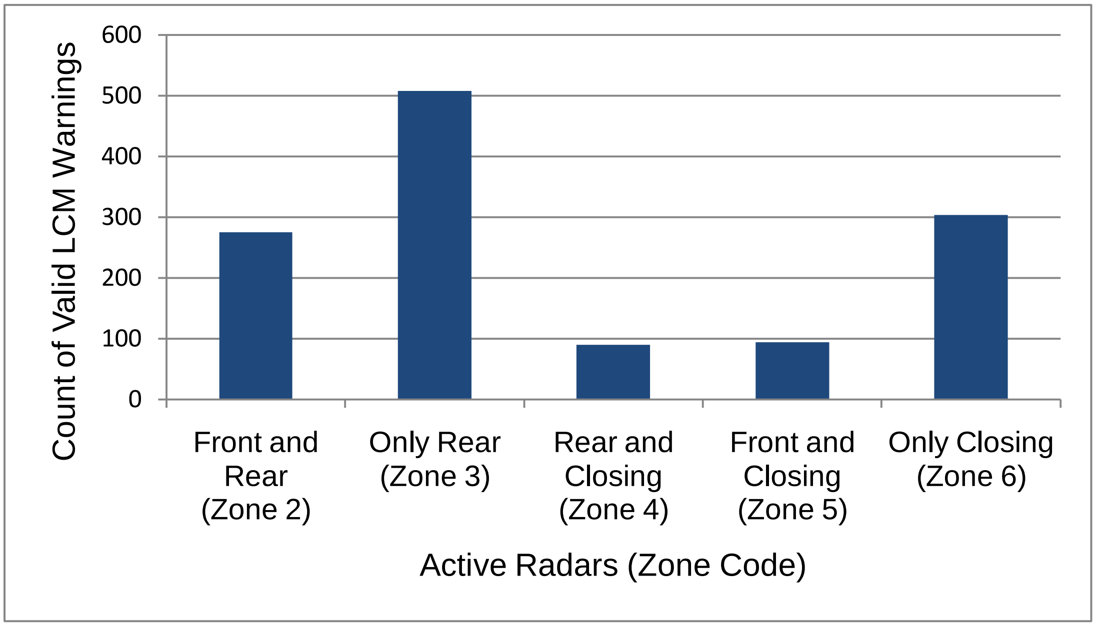


Figure 62: Summary of the distribution of LCM warnings by adjacent zone.

The effect of condition was not found to be statistically significant (X^2 (4, N = 1270) = 4.86, *p* = 0.3021) for the location of LCM warnings.

Figure 63 shows the percentage distribution of LCM warnings for the baseline and treatment periods. For baseline there were 398 LCM warnings, for treatment 872. When exposure is considered, the warning rate is marginally higher (4 percent) for treatment condition (A total of 68,870 and 144,439 miles were used in the normalization for baseline and treatment, respectively).

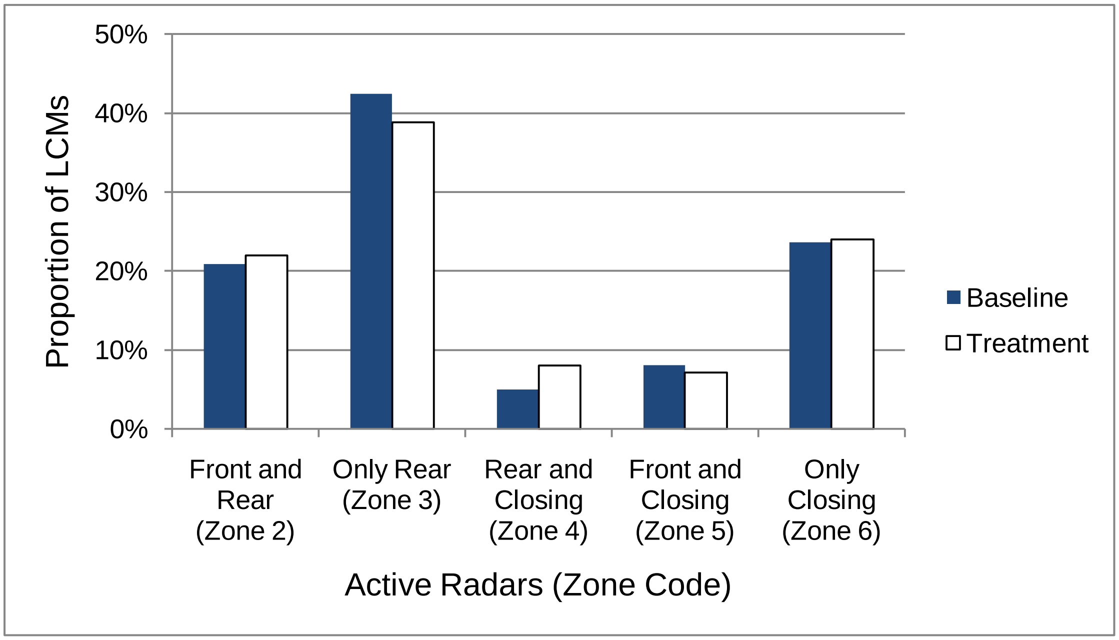


Figure 63: Summary of the distribution of LCM warnings as function of condition.

Several dependent variables were found to be statistically significant. These results are summarized in Table 20.

Table 20: Significant findings using the chi-square test for variance

Main Effect	**N**	**df**	X^2	***p***
Side	1270	4	30.7954	<.0001
Road type	1270	4	15.5973	0.0036
Age Group	1270	8	19.9393	0.0106

The results for POV side are shown in Figure 64. Of the 1270 LCM warnings, 772 (61 percent) resulted from a POV on the left side of the SV. For LCM warnings to the right of the SV, almost half (49%) were issued with a vehicle in the rear “blind spot” zone. From an exposure perspective, a LCM in the left closing zone is more likely to occur then the right closing zone. This is probably a result of lane selection of the POV for passing the SV.

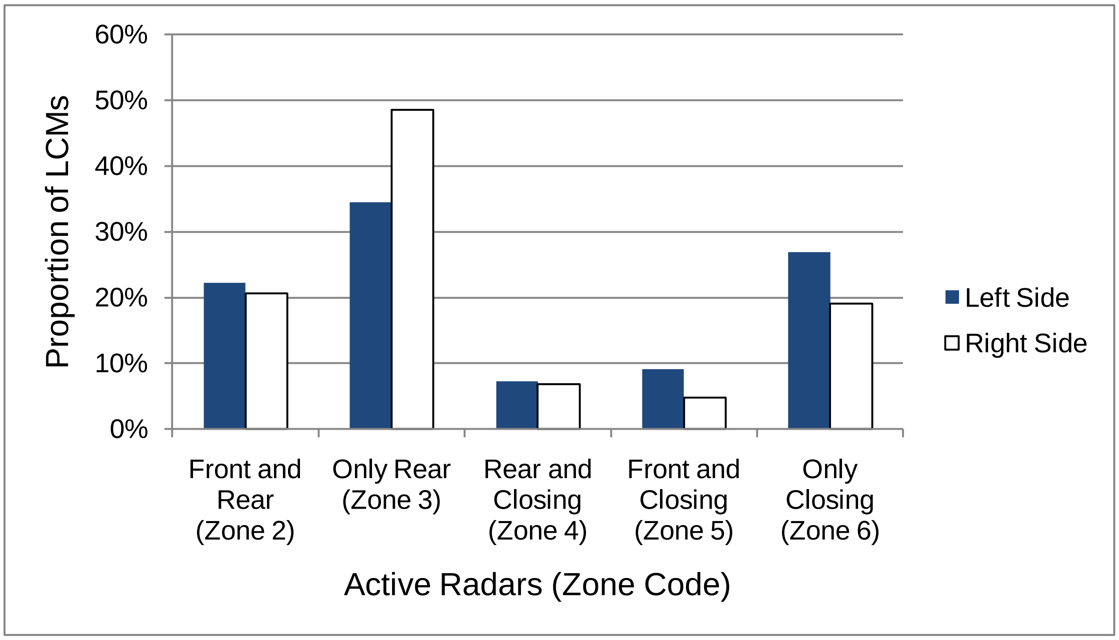


Figure 64: Main effect of side on POV location during LCM warnings

The main effect of road type is shown in Figure 65. A total of 828 LCM warnings (65 percent) were on limited access and 342 on surface roads. Adjusted for exposure (based on 92,092 miles on limited access and 96,656 miles on surface roads) and assuming the distribution of this set is representative of all LCM warnings, LCM warnings were 2.5 times more likely to occur on limited access as compared to surface roads.

Regarding the zone distribution for the two road types in this analysis, the most likely location of the POV for an LCM warning on both road types is adjacent to the SV in the rear-side radar zone. On surface streets, LCMs were more likely to be elicited from the front and rear radars together (26.9% on surface and 22.1% on highways), while on highways, LCMs were more likely to be elicited from targets only in the closing zone (22.5% on surface and 27.3% on highways).

The main effect of age group is shown in Figure 66. A total of 531LCM warnings (42 percent) were produced by younger drivers, 457 (36 percent) middle aged, and 282 for older drivers. Adjusted for exposure, LCM warnings are 38 percent more likely with younger drivers then middle aged and 71 percent more likely with younger drivers than older drivers. For all age groups the rear zone accounts for the majority of warnings (exposure ratio is based on 68,868, 81,730, and 62,710 miles for younger, middle-aged, and older drivers, respectively).

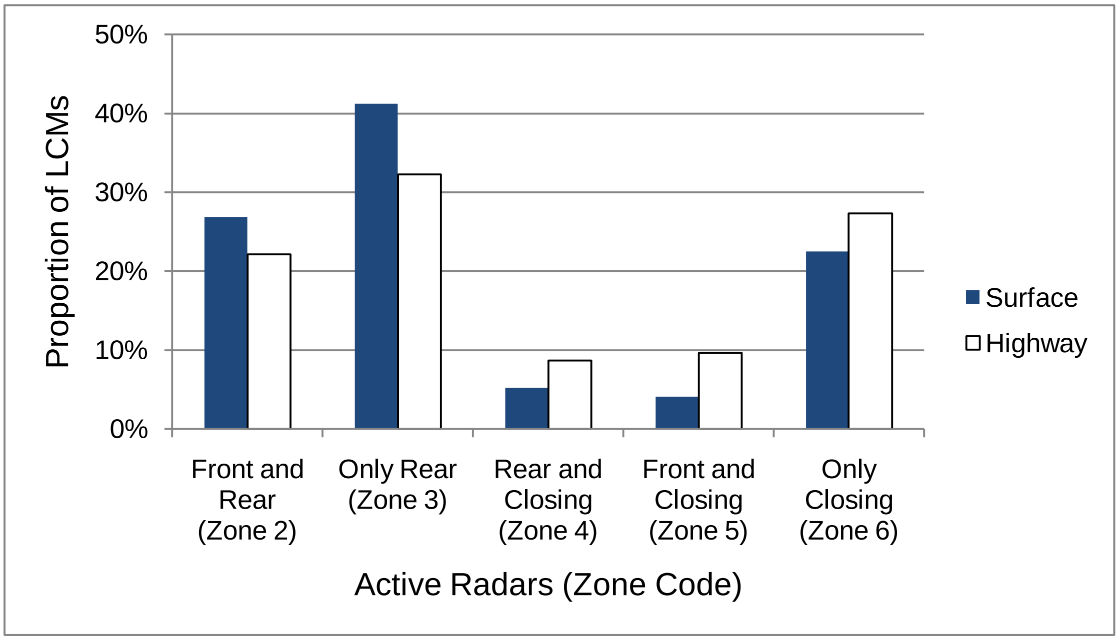


Figure 65: Main effect of road type on POV location during LCM warnings

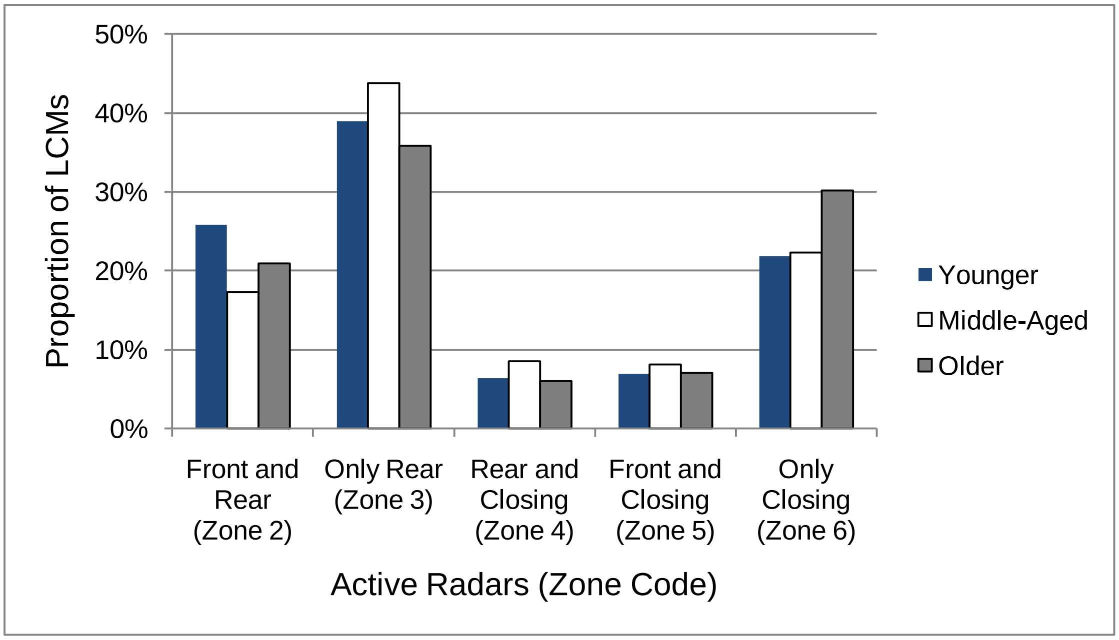


Figure 66: Main effect of age group on POV location during LCM warnings

Interpretation: The integrated crash warning system did not have a statistically significant effect on the location of LCM warnings. However, there was a statistically significant effect associated with which side of the vehicle the warning occurred. Of the 1270 LCM warnings, 772 (61 percent) resulted from a POV on the left side of the SV. Regarding zone, all effects show the rear zone occupied the most for valid LCM warnings.

Most interestingly, it was found that for LCMs on the left side, the POV was much more likely to be in the rear-side zone than for LCMs on the right. This is probably a result of lane changes to the left where a vehicle encroaching into the blind spot would be more likely than the case where the SV has passed a car in the left lane and receives an LCM as it returns to the right lane.

Not surprisingly, on highways a larger proportion of closing zone LCMs were recorded than on surface streets. This seems reasonable as the passing-speed differentials on highways are likely greater than on surface streets. The closing zone radar only becomes active when another vehicle is quickly moving up into the blind spot from longer distances behind the SV, and these scenarios would be more common on highways.

QL7: Will drivers change lanes less frequently in the treatment period, once the integrated system is enabled?

Research Hypothesis: The frequency of lane changes is independent of condition.

Importance: It is important to understand the overall effect of the integrated system on driver behavior, not just in the event of a warning. Previous FOTs have reported reductions in lane changes by drivers because of a crash warning system, and it is believed that the same could be true in the IVBSS FOT.

Method: The investigation into possible changes in lane-change rate during the FOT is based on a sub-set of 39,553 lane-change events. For the purpose of this report a lane-change is defined as the lateral movement of the SV relative to the roadway in which the SV starts in the center of a defined traffic lane with boundary demarcations and ends in the center of an adjacent traffic lane that also has defined boundary demarcations. The explicit instant in time of the lane-change is defined as the moment when the SV lateral centerline crosses the shared boundary between the two adjacent traffic lanes.

Lane-changes are comparatively complex events that involve both infrastructure information, primarily lane boundary demarcation, as well as lateral performance information from the sensors onboard the vehicle. The set of lane changes used in this analysis was constrained using the rules stated in Table 21. These constraints ensure that the set of lane changes analyzed does not contain events that were not intended to be lane changes by the SV driver. For example, a driver may intentionally occupy part of an adjacent traffic lane while maneuvering away from a stationary vehicle on the shoulder, or may inadvertently drift laterally into an adjacent lane before returning to the center of the original lane, especially at night and in low traffic situations.

Table 21: QL7 analysis constraints

Constraints
Boundary types known and lateral offset confidence 100%
Lane change is across a dashed boundary type
Lane change is performed on a straight segment of roadway
Turn signal active for at least 1 second before the lane change
Speed above 11.2 m/s (25 mph)
No intentional lateral maneuvers in a 5-second window prior to the lane-change (i.e., the equipped vehicle is in a steady-state condition within its lane)

Shown in Table 22 is the dependent variable for the analysis and a list of independent variables that were included to investigate the relationship between lane-change frequency and other aspects of the vehicle environment, during lane changes.

Table 22: QL7 dependent and independent variables

Dependent Variables
Lane changes performed
Independent Variables
Condition (baseline, treatment)
Wiper state (on, off)
Ambient light (day, night)
Road type (limited access, surface)
Gender (male, female)
Age group (younger, middle-aged, older)
Traffic (sparse, moderate, dense)
Exposure (units week)

The principal findings of this analysis are based on the results of a mixed linear model. The principal main effects found to be statistically significant where condition, wiper state, ambient light, road type and traffic.

Results: The integrated crash warning system had a statistically significant effect on the number of lane changes ($F(1,105)=32.66$; $p<0.0001$). There was a 12.6 percent increase in the rate of lane changes from the baseline to treatment condition. There were also a statistically significant increases in the rates of lane changes associated with the wipers being on (17% increase, $F(1,25)=18.1$; $p=0.0003$) and driving at night (9% increase, $F(1,25)=12.39$; $p=0.0017$).

The lane change rate also increased by 21 percent when comparing limited access to surface roads (*F*(1,106)=38.97; *p*<.0001). For the surrogate measure of traffic density (*F*(2,168)=46.17; *p*<.0001), the results showed an increase of 23 percent when comparing sparse to moderate traffic and an increase of 27 percent when comparing moderate to dense traffic. Drivers increased their rate of lane changes by 56 percent (1.5 times) when comparing the sparse to dense traffic condition. The estimated lane change rates (per 100 miles) for the main effects are shown in Figure 67.

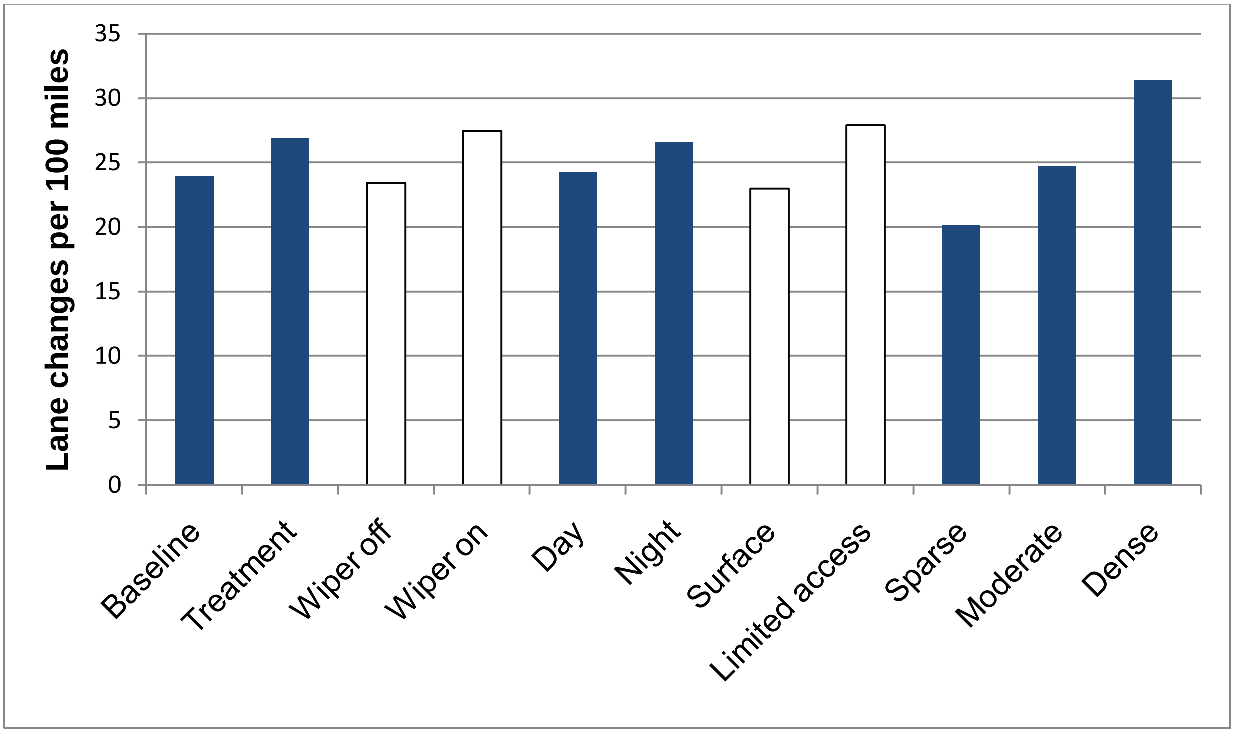


Figure 67: Main effects of condition, wiper state, ambient light, road type, and traffic on lane change frequency

Interpretation: There was a statistically significant increase in lane change rate with the integrated crash warning system (12.6%). It is not readily apparent why drivers would increase their lane change behavior, but it is potentially related to an increased sense of confidence that they can do so given the presence of the crash warning system. The most pronounced effect of on lane change rate can be found with changing traffic conditions.

QL8: Is the gap between the subject vehicle (SV) and other leading vehicles influenced by the integrated system when the SV changes lanes behind a principal other vehicle (POV) traveling in an adjacent lane?

Research Hypothesis: The size of the forward gap when changing lanes between the SV and other leading vehicles will not be influenced by the integrated system.

Importance: Gap size is important to understand because it is directly related to the time a driver has available to respond should a lead vehicle brake suddenly. Ideally, use of the integrated system would make drivers more aware of unsafe following distances, and therefore they would allow more distance between themselves and lead vehicles.

Method: This analysis identified instances in which the SV approaches a lead vehicle in the same lane and makes a lane change behind a passing POV1 in an adjacent lane on the left (Figure 68). The range and range-rate to POV1 and POV2 were determined at the instant when the SV's left front tire crossed the boundary. It is assumed that lane changes to the right under similar circumstances are far less frequent, and therefore only lane changes to the left are considered. The constraints in Table 23 were used to ensure that the events are reliable and consistent with the scenario definition. Shown in Table 24 are the dependent variables for the analysis and a list of independent variables that were included in the analysis to investigate the relationship between the vehicles and other aspects of the environment and performance criteria.

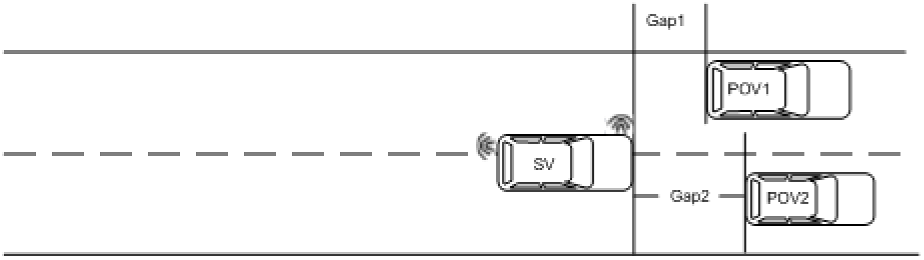


Figure 68: Location of adjacent and forward vehicles relative to the subject vehicle during lane-changes

Table 23: QL8 analysis constraints

Constraints
Boundary types known and lateral offset confidence 100%
Lane change across a dashed boundary type
Lane change performed on a straight segment of roadway
Turn signal active for at least 1 second before lane change
Speed greater than 11.2 m/s (25 mph)
No intentional lateral maneuvers by the driver in 5-second window prior to lane change (i.e., equipped vehicle is in steady-state condition within its lane)

Table 24: QL8 dependent and independent variables

Dependent Variables
Range between the SV, POV1, and POV2 during lane changes and range-rate between SV and POV2
Independent Variables
Condition (baseline, treatment)
Wiper state (on, off)
Ambient light (day, night)
Road type (limited access, surface)
Gender (male, female)
Age group (younger, middle-aged, older)
Speed (units, m/s)
Exposure (units week)

Results: The results are based on 7,346 lane changes to the left. The principal findings are based on the results of a mixed linear model for the three dependent variables shown below. Analyses for each of the dependent variables were run independently.

- POV2 Range (range between the SV and the POV before the lane change)
- POV1 Range (range between the SV and the POV after the lane change)
- POV2 Range-rate (range-rate between SV and POV before the lane change)

Each analyses were run initially with all of the independent variables and based on this non-significant factors were removed from the model one at a time and the model was rerun in an iterative process until only significant factors remained. Even when the presence of the integrated crash warning system was found to be not statistically significant, it was left in the model until the last step. Once the model contained only statistically significant main effects, two-way interactions were included; and the model was rerun in the same fashion as described above until only significant factors remained.

POV2 Range: A statistically significant effect of the integrated crash warning system was observed for the range to POV2 ($F(1,101)=7.22$; $p = 0.0085$) where a marginal decrease in the range to POV2 of 1.3 m was observed under the treatment condition when compared to the baseline condition. Overall conditions, as speed increased, so did the predicted gap between the SV and the initial lead POV ($F(1,75)=88.99$; $p < .0001$). The effect of speed is the least pronounced on surface streets during the day where the difference in gap from 17 mph to 80 mph is predicted to be only 0.4 meters. The effect of speed is stronger at night on surface streets where the gap increased 12.4 meters from 17 mph to 80 mph.

On highways speed has an especially large effect on the gap between the SV and the initial lead POV ($F(1,97)=96$; $p < .0001$). This is likely because when a driver is on the highway at very low speeds (under 50 mph), it is almost exclusively because of heavy traffic and/or construction. In these situations lane changes would occur with very small gaps. For the ambient light condition the model predicts that at speeds under 50 mph, drivers will change lanes with smaller gaps at night ($F(1,81)=6.19$; $p = 0.0149$), while at speeds over 50 mph, drivers will change lanes with smaller gaps during the day.

Finally, for age group, younger and middle age drivers on average got closer to POV2 before the lane change ($F(2,102)=8.59$; $p = 0.0004$) by 6.3 and 3.2 m, respectively as compared to older drivers.

POV1 Range: There was no statistically significant effect of the integrated crash warning system on the range to POV1. Statistically significant effects for range to POV1 were for when the when it was raining ($F(1,78)=6.27$; $p = 0.0144$), at night ($F(1,82)=18.16$; $p <0.0001$), and vehicle speed ($F(1,103)=113.19$; $p <0.0001$). When the windshield wipers were on, the average range between the SV and POV1 just after the lane change is 4.1 meters greater than when the windshield wipers were off. Drivers are also predicted to increase the gap between themselves and POV1 at night by 5.8 meters. Both of these would seem to indicate drivers make more conservative lane change decisions at night and in inclement weather.

Relative to the effect of speed, drivers increased the distance to POV1 by 1.94 m for every 5 mph increase in speed. Again, this shows drivers in more dangerous situations tend to behave more conservatively when deciding how close they are willing to get to the POV1 after the lane change.

POV2 Range Rate: There was no statistically significant effect of the integrated crash warning system on the range rate to POV2. Statistically significant effects for POV2 range rate included road type ($F(1,97)=33.34$; $p < 0.0001$), vehicle speed ($F(1,89)=11.12$; $p = 0.0012$), and age group ($F(2,102)=10.73$; $p <0.0001$).

The finding related to the effect of speed was that the range rate to POV2 is linearly related to speed. On highways, as speed increases, the range rate between the SV and POV2 decreases. As range rate is positive here, more speed causes the gap to open more slowly between the SV and POV2. On surface streets, as speed increases, the range rate between the SV and POV2 increases. For younger and middle-aged drivers this functionally reduces the closing speed to POV2. For older drivers, this functionally increases the widening gap been the SV and POV2.

Interpretation: The results show that the only statistically significant effect of the integrated crash warning system on gap size was an average decrease of 1.3 m between the SV and the POV before the lane change in the treatment condition. Other independent measures such as road type, ambient light level, vehicle speed, and age group had a larger effect on driver performance when conducting these maneuvers.

3.4.5 Driver Acceptance Research Questions

This section reports key findings on driver acceptance of the lane departure and lane change/merge crash warning subsystems. Post-drive survey results include data on driver comfort, perceived utility, and perceived convenience associated with the integrated crash warning system.

QL9: Are drivers accepting of the LDW sub-system (i.e. do drivers want LDW on their vehicles?)

Results: The lateral subsystems provided both auditory and haptic warnings. Auditory warnings were presented whenever a driver drifted in the lane and there was an adjacent threat (e.g., another vehicle, a guardrail) which was the LCM component, while haptic warnings were presented whenever the driver drifted in the lane without an adjacent threat or changed lanes without using a turn signal (the LDW component). Figure 69 displays the van der Laan scores for the integrated system as well as the individual subsystems. BSD was part of the LCM subsystem whereby yellow lights in the exterior mirrors were illuminated whenever another vehicle was in or approaching the driver's blind spot indicating that it was unsafe to make a lane change. Drivers rated BSD the highest for usefulness and satisfaction. In terms of usefulness, drivers rated the lateral subsystems on par with the integrated system as a whole, but somewhat less useful than BSD. The same can be said of their rating of satisfaction with the lateral subsystems. Further, the lateral subsystems outperformed both of the longitudinal subsystems.

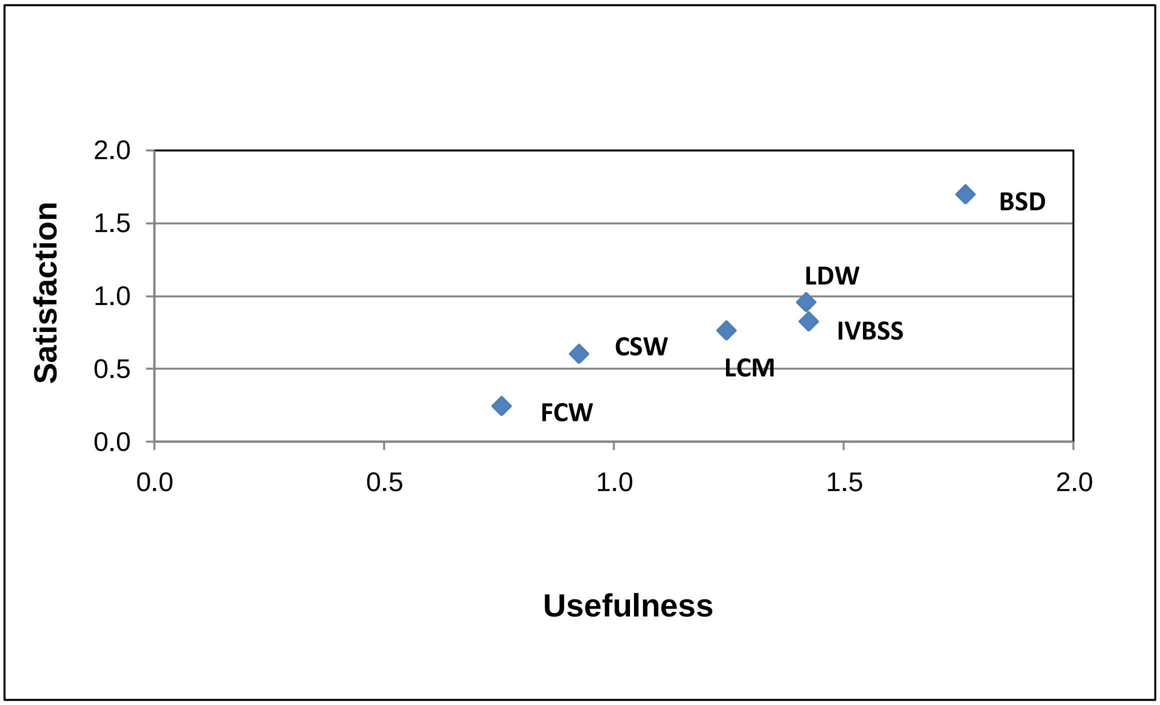


Figure 69: Van der Laan scores for the integrated system and subsystems

In the post-drive questionnaire, drivers were asked if they received lateral warnings when they did not need them. While Figure 70 and Figure 71 demonstrate that, on average, drivers were mostly neutral in their ratings of lateral nuisance warnings, Figure 72 displays that younger drivers reported that they received more nuisance left/right hazard warnings than the other age cohorts.

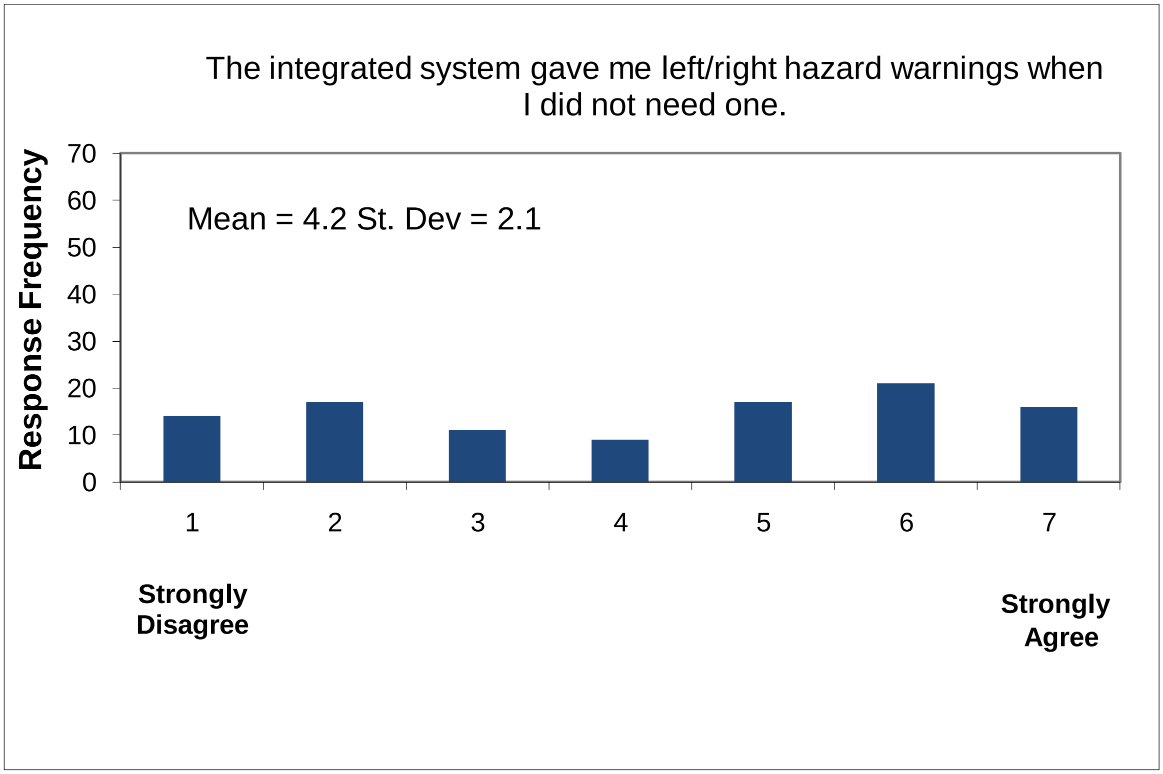


Figure 70: Drivers' perceptions regarding LCM nuisance warnings

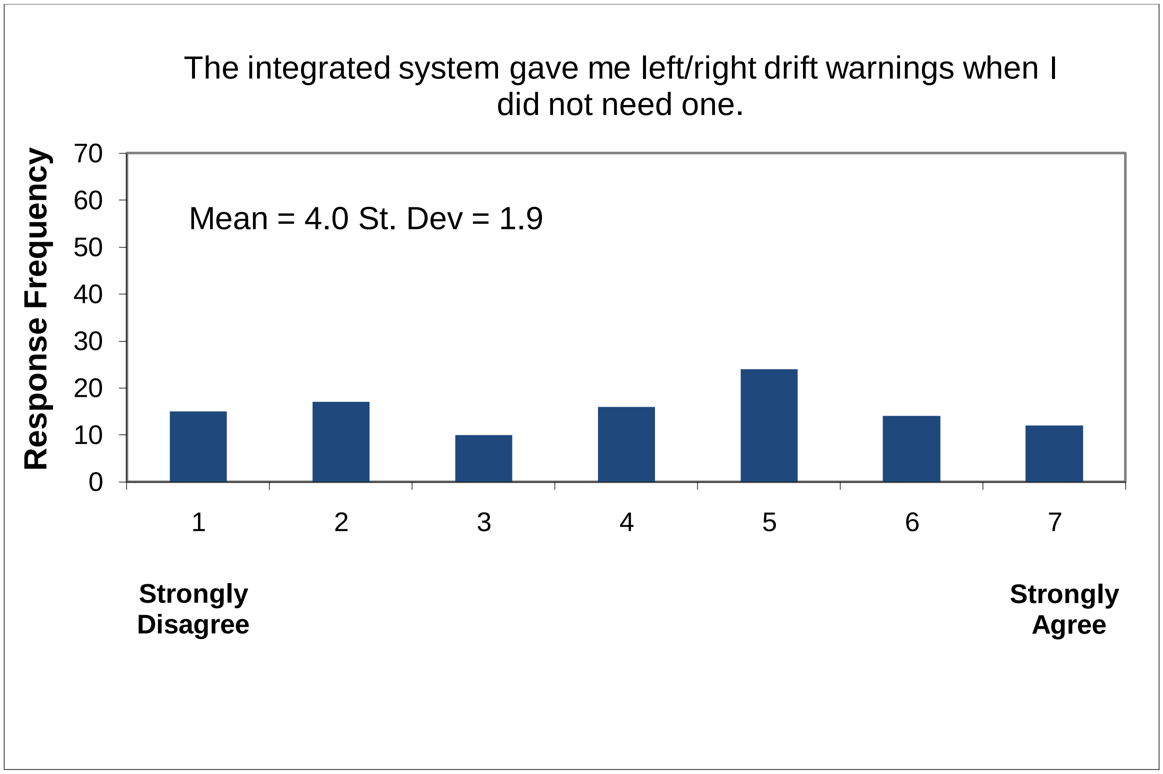


Figure 71: Drivers' perceptions regarding LDW nuisance warnings

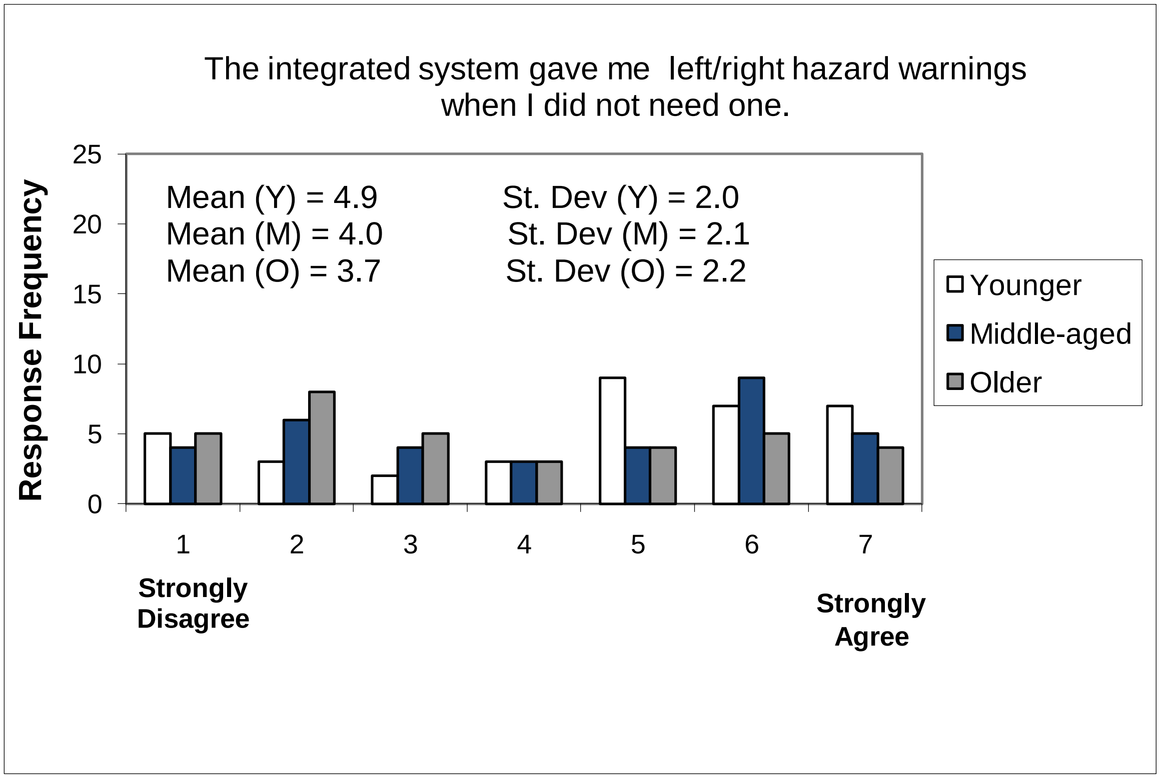


Figure 72: Drivers' perceptions regarding LCM nuisance warnings by age group

Interpretation: While drivers rated all of the subsystems and the integrated system positively in terms of satisfaction and usefulness, they rated the lateral subsystems (LCM with BSD and LDW) more favorably than the longitudinal subsystems. Overall, they were most satisfied with the BSD component of the LCM subsystem. Drivers' mean subjective rating as to whether the integrated system provided them with nuisance warnings was generally neutral, although younger drivers felt that they received more lateral nuisance warnings than the other age groups.

QL10: Do drivers find the integrated system to be useful; in which scenarios was the integrated system most and least helpful?

Results: As Figure 69 demonstrates, the mean rating of usefulness for the integrated system was 1.4 (recall that the van der Laan scale ranges from -2 to +2), therefore drivers found the integrated system to be useful. When asked to provide situations in which the integrated system was helpful, drivers overwhelmingly mentioned that the BSD component of the LCM subsystem aided them in making decisions about changing lanes or merging into traffic. The second most mentioned situation was drifting and that the LDW subsystem provided a heightened awareness to distraction and general lane-keeping behavior.

When drivers were asked what they like least about the integrated system, they provided the following top three responses:

1. Invalid warnings (approximately 40% of all drivers raised this issue)
2. Brake pulse which accompanied FCW
3. Auditory tones: some drivers described them as too startling; others didn't like having tones and would have preferred a voice

Interpretation: Generally speaking, drivers found the integrated system to be useful, particularly when changing lanes and merging into traffic. Additionally, the system provided a heightened awareness if the driver was distracted. Reducing the invalid warning rate will undoubtedly increase the usefulness of the integrated system.

3.5 Longitudinal Control and Warnings Results

This section analyzes the performance of the forward crash warning subsystem. This includes key descriptive data, results regarding the frequency of FCW and CSW warnings, and changes in warning rate both with and without the integrated system.

3.5.1 Vehicle Exposure and Warning Activity

Over the course of the 12-month FOT, a total of 858 forward crash and 919 curve speed warnings were recorded. This total includes all longitudinal warning scenarios. The overall warning rate across drivers, speeds, and all other conditions was 0.9 longitudinal crash warnings per 100 miles of travel. This rate was approximately the same for both the baseline and treatment conditions. A summary of the overall forward crash and curve speed warning activity as function of condition and road type are given in Table 25 and Table 26. In general, the highest overall rate of warnings for the FCW subsystem was on unknown roads, followed by surface streets. For the CSW subsystem, the highest overall rate was on highway ramps

Table 25: Overall FCW activity by condition and road type

Condition	Road type	Count	Percent	Rate per 100 miles
Baseline	Limited access	33	11.9	0.1
	Surface	196	70.5	0.6
	Ramps	8	2.9	0.4
	Unknown	41	14.7	0.8
Treatment	Limited access	82	14.2	0.1
	Surface	397	68.7	0.6
	Ramps	17	2.9	0.4
	Unknown	82	14.2	0.7

Table 26: Overall CSW activity by condition and road type

Condition	Road type	Count	Percent	Rate per 100 miles
Baseline	Limited access	16	5.2	0.1
	Surface	102	33.0	0.3
	Ramps	191	61.8	8.7
Treatment	Limited access	38	6.2	0.1
	Surface	178	29.2	0.3
	Ramps	394	64.6	8.2

3.5.2 Longitudinal Classification and Warning Summary

The analysis in the previous section considered all FCW and CSW warnings, and gave an overall summary of the warning rate regardless of type of warning scenario or its validity and relevance. In this section, each type of warning will be considered separately in terms of both the assessed effectiveness of the warning and the driver's intention and reaction to the warning. The validity of longitudinal warnings was determined by whether or not there was a vehicle in the actual or intended forward path of the subject vehicle at the time of the warning for FCW, and whether or not there was a curve in the actual or intended path of the subject vehicle that was traversed for CSW. For both FCW and CSW the warning was evaluated based on the driver's actual or intended path. UMTRI researchers examined a total 579 FCW and 610 CSW events from the treatment period by reviewing the forward video for each. The goal of this classification is to group warnings into two categories that are defined as:

- **Valid**—warnings are helpful to the driver since they bring additional knowledge and awareness to the driving task and can mitigate ignorance of an unrecognized conflict in the current driving situation. Warnings that are predictable and probable are also defined as valid. After a valid warning, the SV driver becomes vigilant to the driving task and makes an assessment of urgency in the current driving situation. A valid warning may not be helpful in the immediate sense, but can be informative in that typically the driver is assuming normal driving behavior and actions will resolve the situation.
- **Invalid**—warnings are not helpful to the driver since there is no additional knowledge provided about the driving environment, and there is no threat in the current driving situation—and one does not develop. Invalid warnings are characterized by an incorrect or inaccurate assessment of the current or future driving circumstances (e.g., no vehicle present in the forward path, or a driver does not traverse the road branch with the curve), or very complex environments (e.g., roadway construction zones). While the system may be operating in accordance with the specific design intent, to the driver the warning is likely to appear to be spurious without any clearly identifiable reason and are therefore not predictable by the driver. Some invalid warnings will be unavoidable as it is not possible to predict the future actions of vehicles in all situations.

The following categories were used to classify the FCW and CSW events. The sorting logic was based on an analysis of the drivers' actual and intended actions as explained below.

- **Valid** – For FCW this includes warnings resulting from stationary objects, including stopped vehicles that are in the vehicle's path, or in response to a high rate of closure between two vehicles. For CSW this includes going too fast for a curve that is traversed, or about to be traversed, given the curve's geometry.
- **Invalid but necessary** – The system responded to design intent, but the warning provided little, or no, utility to the driver. In the case of FCW, this could happen with momentarily changes in heading toward a stopped object. The FCW system detects an apparent threat, not knowing that the threat is only momentary and that the driver will steer away from the object to complete their intended maneuver. For CSW, this could occur whenever a driver has a turn signal on, suggesting that the vehicle is about to take an exit ramp, but is actually only performing a lane change near, and in the direction toward, an exit.
- **Invalid** – The system presents a warning that is not consistent with the design intent. For FCW, identifying a manhole cover as an in-path object is considered invalid. For CSW, warning where no curve was present is considered invalid.

There were two FCW scenarios to consider:

- **Stopped Objects**—Stationary objects, including stopped vehicles (i.e., valid FCW events) and stationary roadside objects (i.e., invalid FCW events).
- **Moving objects**—Lead vehicle decelerating or the SV accelerating. The distance between the lead vehicle and SV is decreasing.

Figure 73 shows the FCW warning rate per 100 miles for valid and invalid warnings. Drivers had a valid FCW rate of 0.19 per 100 miles and an invalid FCW rate of 0.21 per 100 miles. The invalid FCW events were most frequently associated with fixed roadside objects in a curve (44.2%) and vehicles or objects in adjacent lanes (32.3%). In addition, invalid warnings occurred in construction zones or other challenging settings (10.6%), and in response to drivers' abrupt, but momentary, changes in heading that cause the FCW subsystem to think roadside objects are in the lane of travel (4.3%). Twenty-one drivers received 50 FCW invalid warnings (16.5% of all FCW alerts) that occurred more than once at the same geographic location.

Figure 74 shows the overall warning rate as a function of each warning scenario. Notable in this figure are the relatively high levels of invalid warnings for stopped objects, such as fixed roadside objects.

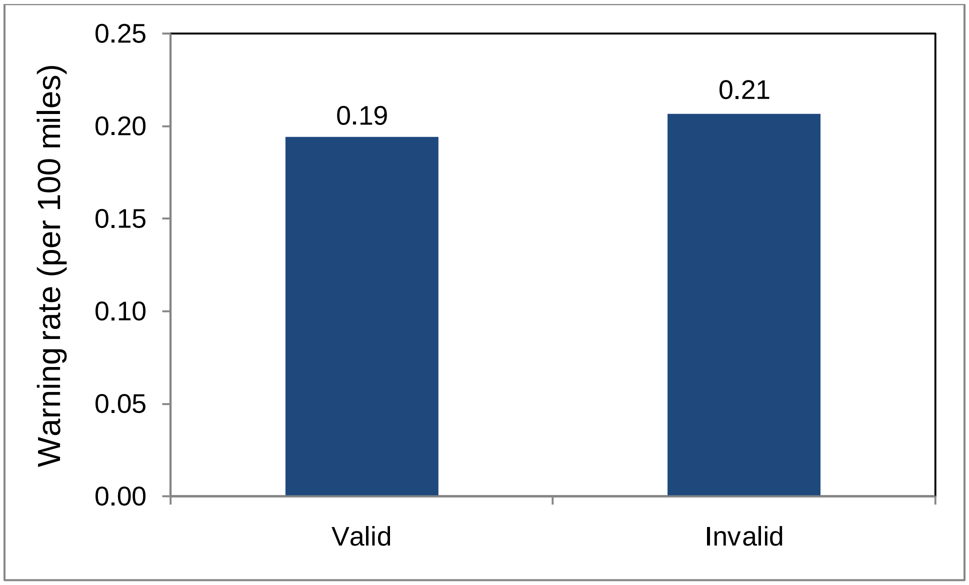


Figure 73: FCW warning rate per 100 miles in treatment period

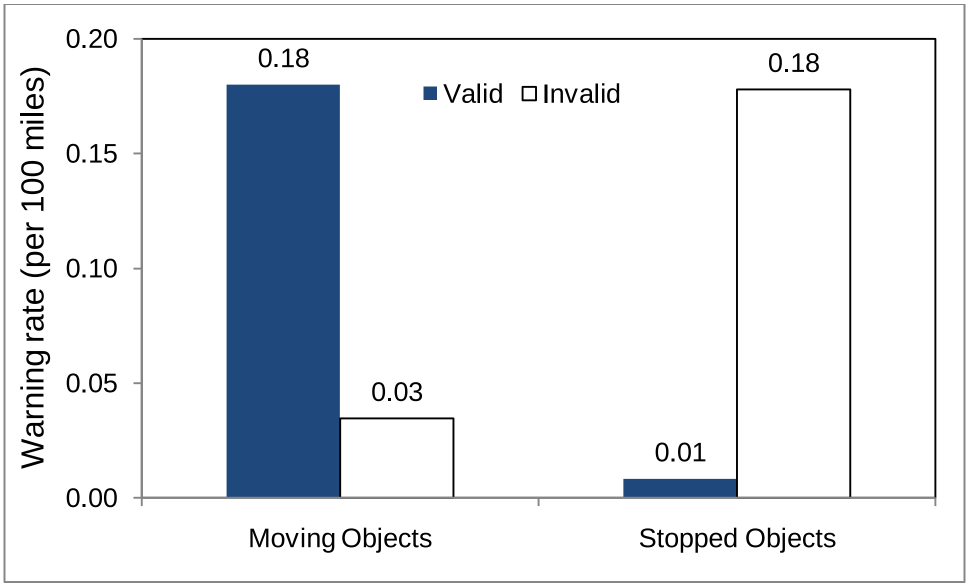


Figure 74: Treatment period FCW warning rate per 100 miles for each warning type

In terms of the broader exposure variable of treatment condition, Table 27 shows the number of FCW warnings, percentage, and rate as a function of warning scenario and classification. Generally, *stopped object* warnings have a higher invalid rate than valid rate, while *moving object* warnings have a higher valid rate than invalid rate.

Table 27: FCW warning rate by classification for the treatment period

Warning type	**Classification**	**Count**	**Percent**	**Rate per 100 miles**
Moving objects	Invalid	50	8.63	0.03
	Valid	260	44.9	0.18
Stopped objects	Invalid	257	44.4	0.18
	Valid	12	2.07	0.01

Figure 75 below presents the rate for valid and invalid curve speed warnings received per 100 miles. Drivers had an invalid CSW rate of 0.12 per 100 miles, and a valid CSW rate of 0.31 per 100 miles. The majority of invalid CSWs (59%) were associated with driving in the vicinity of exit ramps on limited access freeways. These scenarios include, but are not limited to, lane changes near and in the direction of an exit ramp.

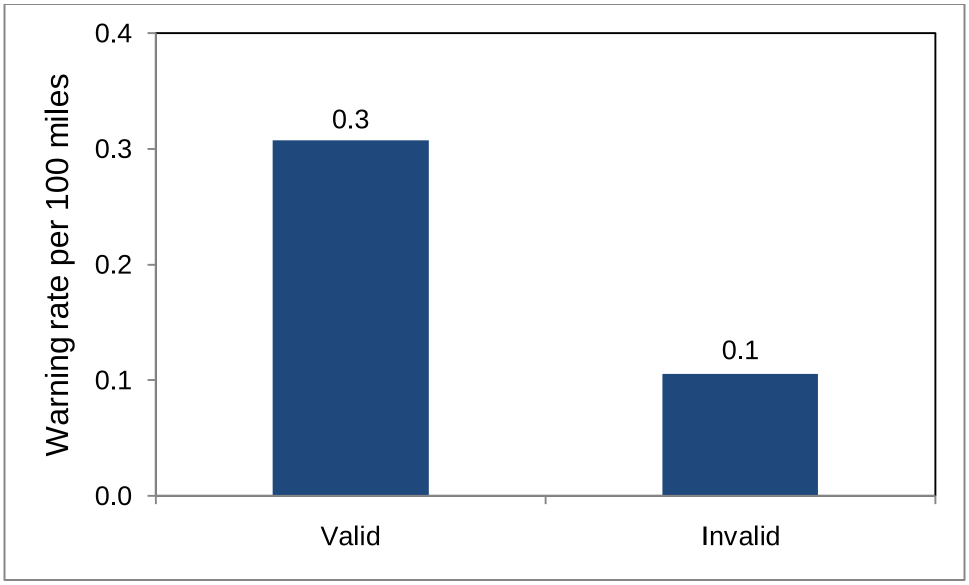


Figure 75: CSW warning rate per 100 miles

3.5.3 Driver Behavior Research Questions

In this section, important changes related to the longitudinal control of vehicles, both during safety-relevant scenarios (e.g., abrupt braking in response to lead vehicles) and in longer-term behavioral metrics (e.g., headway keeping) are reported, and their implications are discussed.

QF1: Does the use of the integrated system affect the following distances maintained by the passenger-car drivers?

Research Hypothesis: The integrated system will not affect drivers' following distance

Importance: Following distance is important to understand because it is directly related to the time a driver has available to respond should a lead vehicle brake suddenly. Ideally, use of the integrated system would make drivers more aware of unsafe following distances, and therefore they would allow more distance between themselves and lead vehicles.

Method: The analysis addresses periods of steady state following, and evaluates whether the fraction of following time spent at short headways is affected by the integrated system. Steady-state following is defined as:

- Traveling at 11.2 to 35.8 m/sec (25 to 80 mph);
- Traveling with a time headway less than 3.5 sec; and
- Following with a relative closing speed between -2.2 and +2.2 m/sec (-5 to +5 mph).

The dependent variable for this study is the percentage of steady-state following time where the headway time is less than 1 sec. This value was selected since analyses in (Ervin et al., 2005) showed that it was this range of short headways that were most affected by a forward crash warning system. Also, headways less than 1 sec are usually considered to be following too close for safety.

The method of analysis was a mixed linear model. The data are the 10 Hz samples of headway time within periods of steady state following. There were 76,555 such periods that in total represent 1,059 hours of steady-state following.

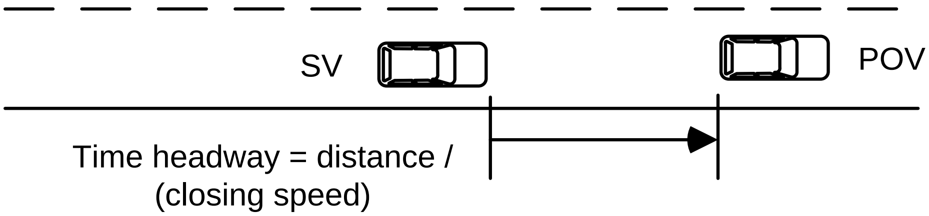


Figure 76: Steady-state following

Table 28: QF1 analysis constraints

Constraints
Speed is between 11.2 and 35.8 m/sec (25 and 80 mph)
Steady-state following is defined for moving POVs, with the magnitude of the relative closing speed less than 2.2 m/sec (5 mph), and the headway time less than 3.5 seconds
The following period must be at least 15 seconds long to be considered
Periods in which cruise control is active are included, as well as cruise control inactive
Valid trips only
Roadway type data must be known for the following period to be considered

Results: The integrated crash warning system did have a statistically significant effect on headway time. Specifically the fraction of following time at 1 sec or less increased from 21 to 24 percent between the baseline to the treatment condition ($F(1,107) = 4.35$, $p = 0.0394$).

Several other independent variables were found to have main effects as well, including age group, road type, ambient light, , and wiper state. The direction of these effects is all as what might be hypothesized (see Table 29). The principal findings of this analysis are based on the results of the mixed linear model. There were no statistically significant interactions that resulted from this analysis.

Table 29: Statistically significant main effects for headway time

Variables	Dependent variable: Fraction of following time spent at less than 1 second headway			
	Main effect?	**Statistics results**	**More time at shorter headways observed for:**	**Percent time at short headways**
Treatment condition	Yes	$F(1{,}107) = 4.35$, $p = 0.0394$	Treatment condition	24% vs. 21%
Age group	Yes	$F(2{,}105) = 11.54$, $p < 0.0001$	Young vs. middle-aged drivers; Middle-aged vs. older drivers	31% vs. 22% vs. 14%
Roadway type	Yes	$F(1{,}107) = 55.40$, $p < 0.0001$	Limited access highways vs. surface streets	29% vs. 16%
Ambient light	Yes	$F(1{,}99) = 45.44$, $p < 0.0001$	Daytime	26% vs. 19%
Travel speed	Yes	$F(2{,}213) = 41.56$, $p < 0.0001$	Higher speeds	29% (55 to 80 mph) vs. 27% (40 to 55 mph) vs. 12% (25 to 40 mph)
Wiper state	Yes:	$F(1, 103) = 11.70$, $p = 0.0009$	Wipers not active	25% vs. 20%

Descriptive Statistics: The 76,555 steady-state following events used in this analysis represent 1,059 hours of driving time. This includes 326 hours of time with the SV driver within 1 sec headway of the preceding vehicle. These events include each of the 108 drivers, both for steady-state time and headway times less than 1 sec.

The variation among drivers of the percent of following time at short headways is illustrated on the left side of Figure 77 below. That figure shows the number of drivers who spent different fractions of time with short headways, with the most common being between 20 to 30 percent of steady state following time. Note that since Table 29 showed that there are five other main effects, this figure is illustrative in nature since some drivers spent more time in conditions that apparently encourage short headways, such as higher speeds, freeways, and dry, daylight periods.

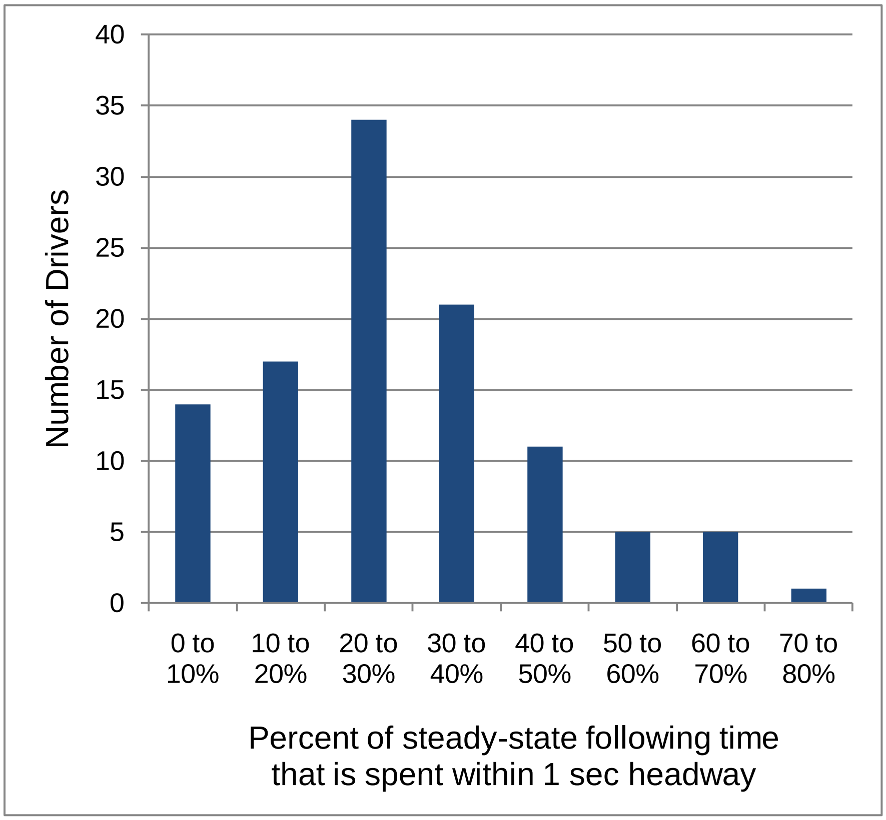


Figure 77: Percent time spent at headways of 1 second or less

Interpretation: There is a statistically significant effect of the integrated crash warning system on the time spent at short headways, such that more time was spent with shorter headways with the integrated system than in the baseline condition. The travel time at headways less than 1 sec increased from 21 percent of steady-state following time to 24 percent. The effect is weaker than the other main effects associated with driving context and driver age, but it is of some practical significance. This result is unexpected, based on previous research with FCW systems. This analysis is similar to one conducted for the Automotive Collision Avoidance System Field Operational Test project (ACAS FOT) (Ervin et. al., 2005). The ACAS FOT analysis compared headways when drivers were not using cruise control, since that experiment involved conventional cruise control in the baseline and adaptive cruise control in the treatment period. That study found that the treatment (ACAS) did not have a main effect, but had two second-order effects with daylight and with freeway road types. Both of those effects were to slightly *reduce* the occurrence of short headways. Thus, the studies appear slightly contradictory in findings.

QF2: Will the magnitude of forward conflicts be reduced between the baseline and treatment conditions?

Research Hypothesis: There will be no difference in the magnitude of forward conflicts with the integrated system.

Importance: In addition to providing alerts to drivers to help avoid or mitigate forward crashes in specific events, the integrated system may also affect how drivers choose to approach preceding vehicles. A reduction in forward conflicts would suggest a positive safety benefit since the drivers would be leaving more margin in potential forward-crash situations.

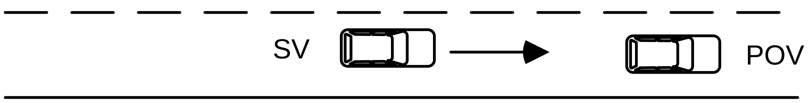
Method*:* The analysis addressed forward conflict in 20,096 events. The measure of forward conflict is the minimum level of required deceleration during the event to avoid a collision. The required deceleration is defined as the constant level of SV braking needed to simultaneously bring range and closing speed to zero, i.e., to just avoid impact. Required deceleration is negative when braking is needed, so that the minimum value is the greatest magnitude of braking required.

The events are identified by searching through the data for episodes in which the constraints in Table 30 apply, and in which either of the following are also true:

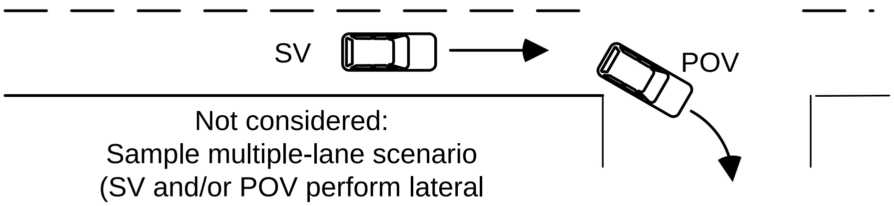
- The time to collision (distance divided by closing speed) falls below 10 seconds and the required deceleration is less than +0.5 m/sec^2, or
- The required deceleration falls below -1 m/sec^2.

These rules were used because the resulting events are ones in which the driver usually slows their vehicle, whether through braking or throttling off. Many subsequent processing steps are needed to ensure that each event is truly a unique encounter of a preceding vehicle. Thus the radar data is filtered to identify and bridge dropouts, target index changes, to recognize when a radar target shift is still associated with the same preceding vehicle, and more.

Additional constraints are used, as shown in Table 30, including limiting the analysis to shared-lane conflicts, in which the two involved vehicles continue to share that lane at least five seconds after the mild conflict ends (and share it five seconds before the bulleted criteria above apply). Only shared-lane scenarios are studied here since drivers in multiple-lane scenarios often allow very high conflicts to develop since they anticipate that a lane change or turn will resolve the conflict (Ervin et al., 2005). Thus it is very difficult to use a simple measure to represent risk in the multiple-lane scenarios.



Considered: Shared-lane scenario
(SV and POV in same lane throughout scenario)



Not considered:
Sample multiple-lane scenario
(SV and/or POV perform lateral
maneuver during the conflict episode)

Figure 78: Forward conflict in shared-lane scenarios

Table 30: QF2 analysis constraints

Constraints
Speed is between 11.2 and 35.8 m/sec (25 and 80 mph)
Conflicts with objects that the radar never observed to be moving were discarded because of the difficulty of identifying which were legitimate rear-end threats
Only valid trip conflicts were considered
Conflicts that occurred when the roadway type was not known were discarded
Only those conflicts that met the minimum level of conflict, as described above, were used
Only conflicts that were shared-lane scenarios were used

Results: The findings of this analysis are based on the results of a mixed linear model. The integrated crash warning system did not affect the level of conflict, which is defined as the mean of the required decelerations. There was a difference in the means, such that the mean of the required deceleration for the conflict set was -0.77 and -0.74 m/sec^2 in the baseline and treatment periods, respectively.

There were main effects associated with driver age group, road type, ambient light, travel speed, and wiper state. There was main effect found with gender, and there were no second-order effects associated with the treatment variable. The direction of the main effect was surprising in one of the five statistically significant variables: older drivers were seen to have higher conflict levels than middle age drivers, and middle-age drivers were found to have higher conflict levels than younger drivers.

Table 31: Main effects for forward conflict magnitude

Independent Variables	Dependent variable: Highest level of deceleration required during conflict			
	Main effect?	**Statistics results**	**Conditions with more conflict**	**Deceleration required (m/sec^2)**
Age group	Yes	$F(2,103) = 6.16$, $p = 0.0030$	Older vs. middle-aged drivers; Middle-aged vs. younger drivers	-0.79 vs. -0.77 vs. -0.71
Roadway type	Yes	$F(1,103) = 38.4$, $p < 0.0001$	Limited access highways	-0.81 vs. -0.70
Ambient light	Yes	$F(1,92) = 14.24$, $p = 0.0003$	Daytime	-0.79 vs. -0.72
Travel speed	Yes	$F(2,202) = 122.77$, $p < 0.0001$	Lower speeds	-0.56 (55 to 80 mph) vs. -0.84 (40 to 55 mph) vs. -0.87 (25 to 40 mph)
Wiper state	Yes:	$F(1,96) = 6.50$, $p = 0.0124$	No wipers active	-0.78 vs. -0.73

Descriptive Statistics: The greatest magnitude of required deceleration associated with each of the 20,096 conflict events is shown in Figure 79 below. The model mean values are -0.74 and -0.77 m/sec2 for the baseline and treatment conditions, respectively, but the difference is not statistically significant ($p = 0.097$). The dip in the curves is due to the use of two criteria for defining a conflict. The rightmost portions of the curves in the figure are associated with benign values of required deceleration, but noteworthy values of time to collision. It is noted that 89 percent of the events studied were associated with driver braking in both the baseline and treatment conditions, supporting the assumption that the isolation of conflict events does capture ones in which drivers are likely to perceive a forward conflict.

A key decision in the analysis was to isolate only the shared-lane cases, which reduces the amount of data with higher deceleration rates. For example, when considering only the shared-lane scenarios, as this analysis does, very few events require more than 3 m/sec^2 deceleration (two in the baseline period, and 11 in the treatment condition).

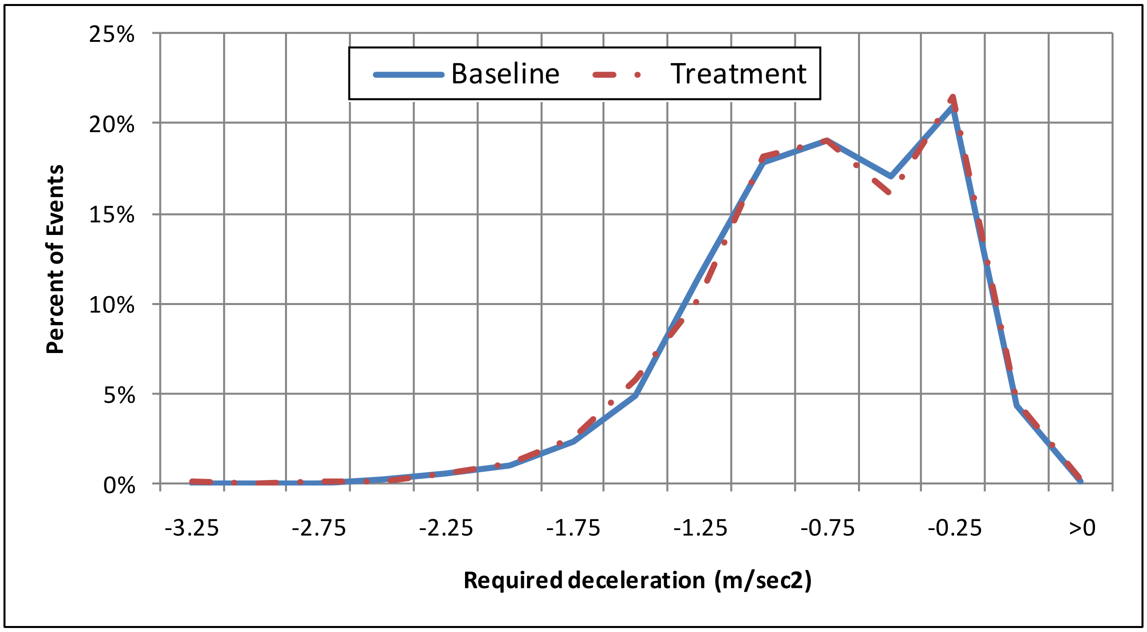


Figure 79: Required deceleration in baseline and treatment conditions

Interpretation: The results showed that there was no statistically significant effect of the integrated system on forward conflict levels during approaches to preceding vehicles. However, it was shown that the conflict measure does depend on several other variables, including road type, travel speed, driver age, wiper state, and ambient light level.

QF3: Does the integrated system affect the frequency of hard-braking maneuvers involving a stopped or slowing POV?

Research Hypothesis: The integrated system will have no effect on either the frequency of hard braking maneuvers involving a stopped or slowing POV.

Importance: One major goal of the FOT is to determine whether an integrated system can reduce the incidences of forward conflicts that might ultimately lead to rear-end crashes. If the FCW subsystem is effective, then one might expect fewer hard-braking maneuvers with the integrated system as a result of increased driver awareness.

Method: The actual braking level is an important concept in driving safety measurement. The consideration here of actual braking levels recognizes that hard braking – whether required or not – may contribute to crash risk. Only those events in which a POV contributed to the driver’s use of the brake are considered in this analysis. For instance, the analysis does not address cases in which the SV is stopping without a lead POV present. The dependent variable is the frequency of hard braking events. The data selected for analysis was constrained by the conditions listed in Table 32. Table 33 provides a list of the variables used in the analysis.

Table 32: QF3 analysis constraints

Constraints
Maximum speed above 11.2 m/s (25 mph) during the braking events
Presence of a lead vehicle
Peak braking level is at least 0.45g

Table 33: QF3 dependent and independent variables

Dependent Variables
Hard braking events per 100 miles
Independent Variables
Condition (baseline, treatment)
Wiper state (on, off)
Ambient light (day, night)
Road type (limited access, surface)
Traffic (sparse, moderate, dense)
Gender (male, female)
Age group (younger, middle-aged, older)

Results: The results are based on a linear mixed model analysis. Pairwise comparisons using the Tukey test were conducted post hoc.

Results of the analysis showed that the integrated crash warning system did not have a statistically significant effect on the frequency of hard braking events. The mean rate of hard braking events per mile under the treatment condition was 5.01/100 miles while the mean rate under baseline condition was 4.45/100 miles. The effect of roadway type was statistically significant (X^2 (1) = 7.09, $p < 0.01$). Drivers executed more hard braking events on surface streets (mean = 5.83 per 100 miles) than on limited-access roadways (mean = 3.83 per 100 miles) as shown in Figure 80.

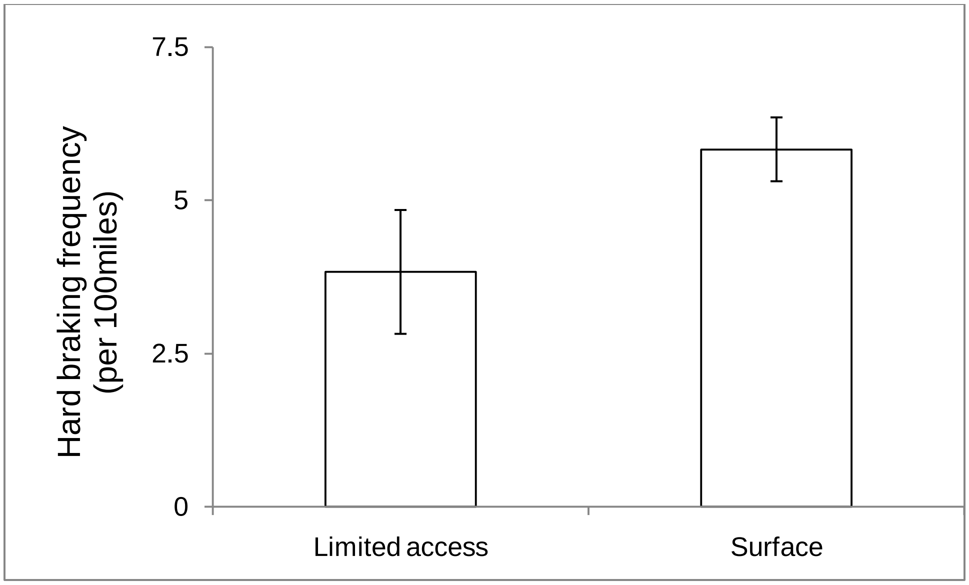


Figure 80: Least squares means of hard braking frequency on different road types, including standard error

Drivers also had a statistically higher hard braking frequency at night than during the daytime X^2 (1) = 5.88, *p* =0.015; mean = 5.59 per 100 miles and mean = 3.99 per 100 miles). This data is presented in Figure 81.

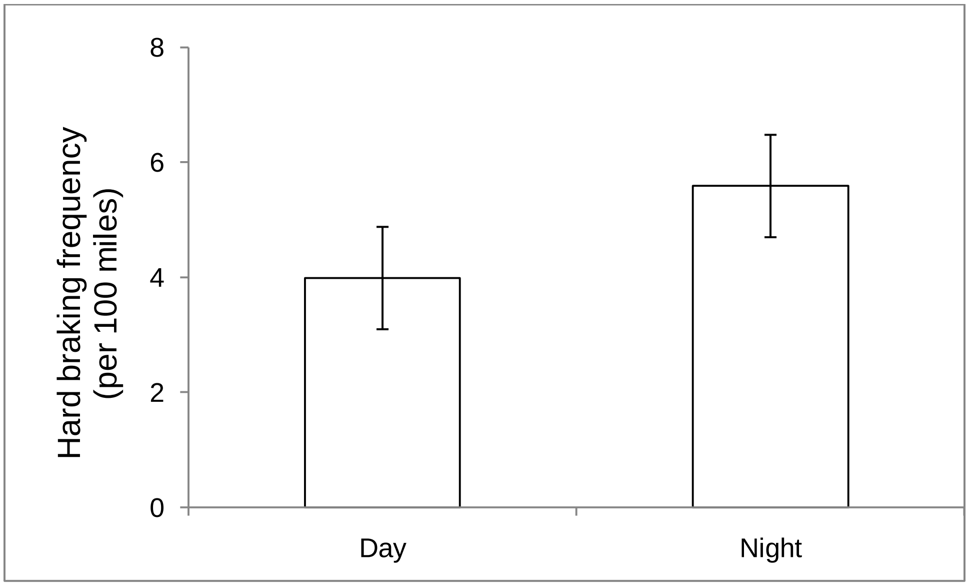


Figure 81: Least squares means of hard braking frequency at day or night, including standard error

Interpretation: The results showed no effect of the integrated crash warning system on hard-braking event frequency. Drivers were found to be more likely to brake harder on surface roads as compared to limited access highways. Given that opportunity for interruptions in traffic flow associated with surface streets, this result might not particularly surprising. However, observing higher incidences of hard braking at night, as compared to daytime, is not as easily interpreted.

QF4: Will the integrated system warnings improve drivers' response to those forward conflicts in which closing-speed warnings occur?

Research Hypothesis: The integrated system will not affect drivers' responses in closing-speed FCW events.

Importance: One major goal of the FOT is to determine whether the integrated system can reduce the incidences of forward conflicts in part by increasing drivers' awareness of lead vehicles and closing rates. If the FCW subsystem is effective then one might expect fewer conflicts with lead vehicles, and the conflicts that do occur should be less severe.

Method: For this analysis, data from two types of closing conflict events were examined: "slowing objects" warnings and "closing half-second" warnings. Warnings due to fixed roadside objects and overhead road structures were excluded from this analysis because over 95 percent of these were invalid warnings (as determined by video review). Two dependent measures regarding drivers' responses to those warning events were calculated and evaluated:

- Brake Response: A binary variable (yes or no) indicating whether the driver pressed the brake pedal during the closing-conflict event
- Braking Reaction Time: The time duration (seconds) between the warning onset and the time at which the driver initiated braking

The constraints shown in Table 34were used to eliminate those invalid FCW warnings (e.g., FCW warnings triggered with no lead vehicle) and exclude events in which drivers responded to new conflicts other than the initial FCW warning. The "5 seconds" constraint was chosen based on video sampling results to ensure that in greater than 95 percent of the events the drivers responded to the current conflict rather than a new conflict (e.g., a different lead vehicle or a lane change was made). The dependent and independent variables used in the analysis are listed in Table 35.

Table 34: QF4 analysis constraints

Constraints
Speed above 11.2 m/s (25 mph)
Presence of a lead vehicle
A closing conflict
Driver's response time within 5 seconds (to consider only responses to the current conflict)
Driving on a limited access highway or surface street

Table 35: QF4 dependent and independent variables

Dependent Variables
Brake response, brake reaction time
Independent Variables
Condition (baseline, treatment)
Wiper state (on, off)
Ambient light (day, night)
Road type (limited access, surface)
Traffic (sparse, moderate, dense)
Gender (male, female)
Age group (younger, middle-aged, older)

Results: A total of 294 closing-conflict FCW events met the above constraints and were used in the following analyses.

Brake Response: The brake response analysis was performed using a logistic regression model approach. The integrated crash warning system did not have a statistically significant effect on brake response, but the likelihood of applying the brake in the treatment condition (mean of 59%) was higher than in the baseline condition (mean of 47%). The likelihood of applying the brake during closing-conflict events on surface streets was statistically significantly higher (mean of 62%) than on the limited access highways (mean of 43%, $\chi^2(1) = 3.88$, $p<0.05$).

Brake Reaction Time: The brake reaction time analysis was performed using a linear mixed model approach. The integrated crash warning system did not have a statistically significant effect on brake reaction time (mean 0.49 s under baseline condition; mean 0.5s under treatment condition). A statistically significant effect of traffic density was observed ($F(2,20) = 4.03$, $p<0.05$). As shown in Figure 82, brake reaction time between the warning and the time at which driver hit the brake pedal decreases with the growing traffic density (least squares mean 0.63s for low traffic, 0.47 for medium traffic, and 0.33 for dense traffic). No other statistically significant differences were observed.

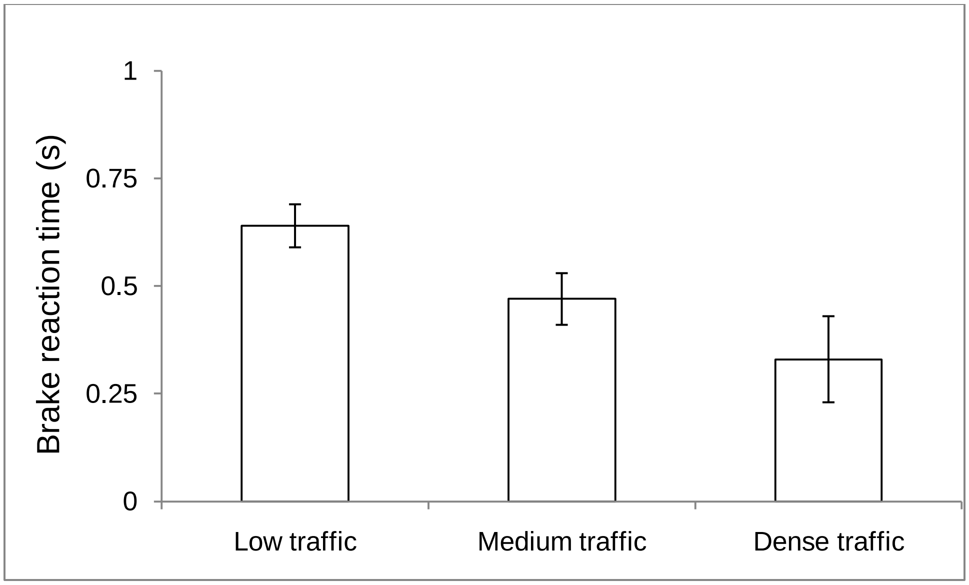


Figure 82: Least squares means of brake reaction time for three traffic density groups, including standard error

Interpretation: There was not a statistically significant effect of the integrated crash warning system on brake reaction time. A statistically significant difference was found between the brake reaction times of drivers to varying traffic densities. As one might anticipate, drivers in higher traffic densities braked faster in response to forward threats than drivers experiencing lower traffic densities (most likely due to the fact that they were of the increased general complexity of driving in dense traffic). The integrated crash warning system did not affect either the braking frequency as a response to valid FCWs, or the braking reaction time to valid FCWs.

3.5.4 Driver Acceptance Research Questions

This section reports key findings on driver acceptance of the forward crash warning and curve speed warning subsystems. Post-drive survey results regarding the FCW and CSW subsystems include aspects of driver comfort, perceived utility, and perceived convenience.

QF5: Are drivers accepting of the FCW subsystem (i.e. do drivers want FCW on their vehicles?)

Results: While the van der Laan usefulness and satisfaction scores for FCW were positive, they were the lowest among the subsystems (Figure 69). Chief among the issues that people did not like about the integrated system was the brake pulse feature of the FCW subsystem, despite drivers somewhat agreeing with the statement, “The brake pulse warnings were not annoying” (Figure 83). Further, in debriefing sessions, many drivers voiced their dislike of the brake pulse warning. Some drivers described it as “startling” while other drivers reported being scared when they first received a brake pulse.

During debriefing sessions, several drivers reported receiving FCWs which prevented a crash. The most dramatic of these FCWs involved a driver with both hands off of the wheel and eyes off of the road. He was texting and completely unaware of the braking vehicle ahead of him. Receiving the FCW returned his attention to the forward scene and provided him with time to brake to avoid a crash. Another driver was distracted while chewing her nails. Her eyes were off of the road when the vehicle ahead of her began to brake. Her gaze returned to the forward scene as she received an FCW. She reported that receiving that timely FCW prevented a crash. Still another driver reported in his debriefing session as well as in a focus group that receiving an FCW while he was engaged in an emotional conversation with a passenger prevented him from crashing into a vehicle braking in his lane.

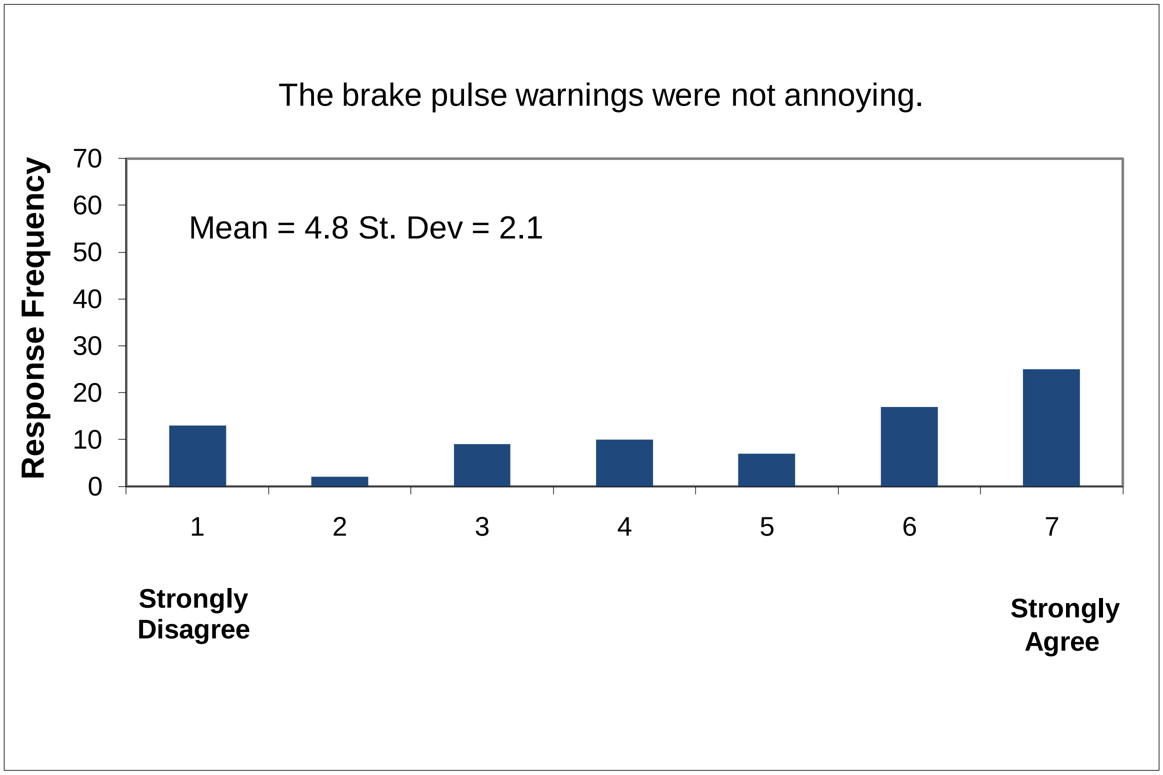


Figure 83: Drivers' perception of annoyance of the brake pulse warning which accompanied hazard ahead warnings

As a group, drivers appear to be split as to whether they received nuisance FCW warnings. Forty percent of the drivers disagreed with the statement, "The integrated system gave me hazard ahead warnings when I did not need one" while thirty-two percent agreed with the statement. There appears to be little effect of age as shown in Figure 84.

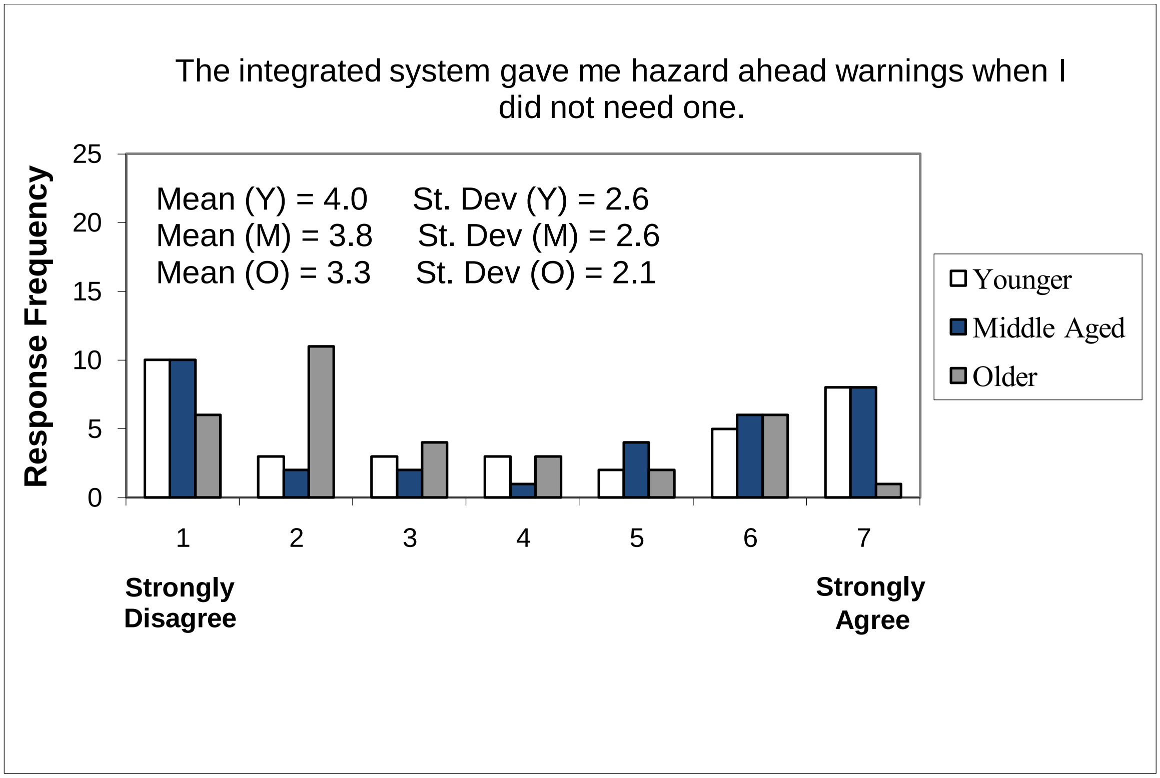


Figure 84. Drivers' perceptions regarding hazard ahead nuisance warnings by age group

Interpretation: Among the subsystems, drivers rated the usefulness of FCW the lowest and were the least satisfied with it among the subsystems. Given the high invalid warning rate for FCW, these results are not surprising.

QF6: Are drivers accepting of the CSW subsystem (i.e., do drivers want CSW on their vehicles?)

Results: Drivers rated the usefulness of the CSW subsystem on par with the FCW subsystem (mean van der Laan scores of 0.9 and 0.8, respectively). They were, however, more satisfied with the CSW subsystem than the FCW system (mean van der Laan scores of 0.6 and 0.2, respectively). On average, drivers did not feel that they received nuisance sharp curve warnings (Figure 85).

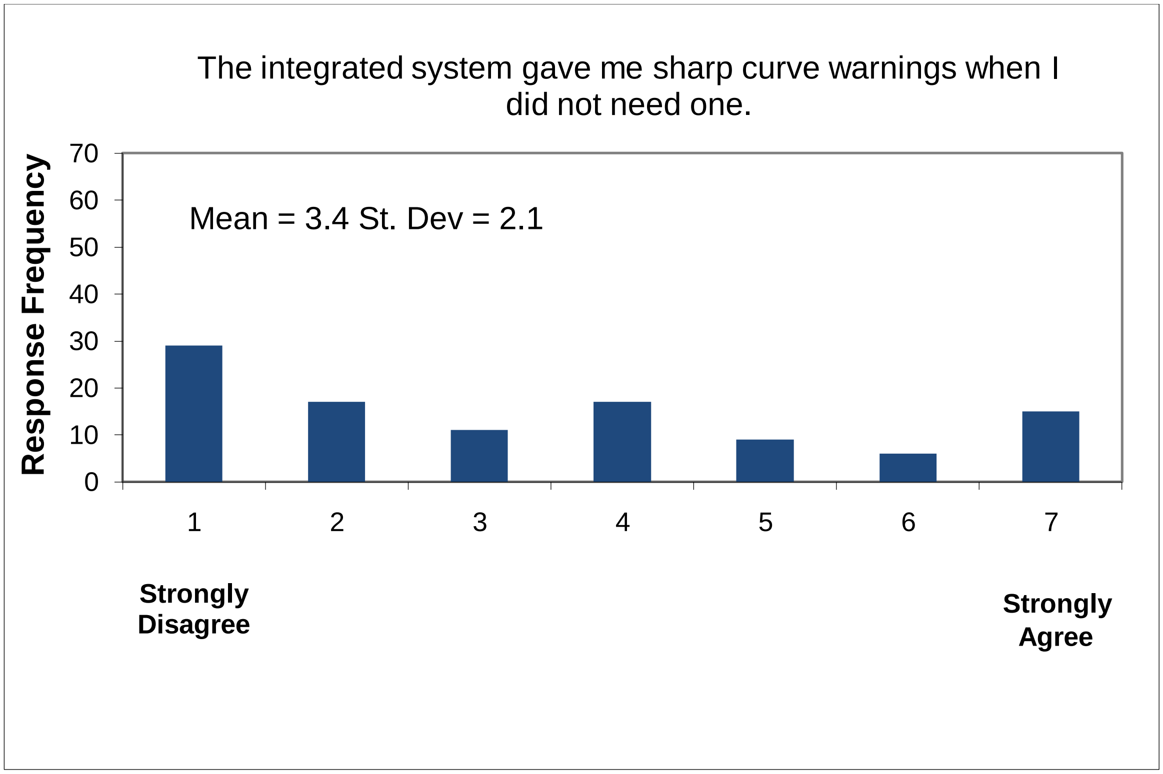


Figure 85. Drivers' perceptions regarding sharp curve nuisance warnings

Interpretation: Of the two longitudinal subsystems, CSW was preferred over FCW in terms of perceived usefulness and satisfaction. On average, drivers were willing to pay between $100 and $200 for the CSW subsystem (See QC14). Given that most of the mileage that was accrued in this FOT was in southeastern Michigan where the roads tend to be straight, it's not too surprising that drivers did not find the CSW subsystem to be more useful. Regular use of CSW over different terrain might produce different results.

QCS1: Will the magnitude of lateral accelerations observed in curves be reduced between the baseline and treatment conditions?

Research Hypothesis: The integrated system will not change the magnitude of lateral accelerations observed in curves.

Importance: One goal of the FOT was to determine whether an integrated system can reduce the number of road-departure crashes caused by drivers entering a curve too fast.

Method: A set of 1,632 curve traversals were identified in the data set. This included data for sixty drivers. For each curve traversal event, two dependent variables were examined: Peak sustained lateral acceleration, and peak sustained combination of lateral acceleration and longitudinal deceleration. Peak sustained lateral acceleration was determined by first calculating the minimum acceleration for 1 second windows throughout each curve event. Then the 90th percentile of these sustained acceleration windows was used as the peak sustained lateral acceleration for each curve event. The peak sustained combination of lateral acceleration and longitudinal acceleration was calculated in a similar manner. For each instant, these accelerations were combined, using the square root of the squares of the two acceleration components. Then the minimum values for each 1 second window was calculated and the 90th percentile combination of accelerations was used as the peak sustained combination of lateral acceleration and longitudinal deceleration.

Table 36 lists the constraints employed in the analysis. The constraints limit the study set to curve-taking events that are at speeds at which the CSW is active and potentially influencing behavior. Furthermore, events are excluded if there other factors can be expected to strongly influence the curve-taking behavior, such as slower traffic ahead or stop signs at the end of the curve (e.g., at the end of exit ramps).

Table 36: QCS1 analysis constraints

Constraints
Speed above 11.2 m/s (25 mph)
Speed is not hindered by a vehicle ahead of the subject vehicle
Speed is not affected by traffic control devices or other similar influences at or near the end of the curve

Results: The principal findings of this analysis are based on the results of a mixed linear model. From Figure 86 below, it can be seen that a few drivers dominate the sample of curve traversals. One driver accounted for 349 out of the 1632 curve traversals (or 21.4%). Removing this driver has only a negligible effect on the model so the driver was left in the sample for analysis. The eight drivers with the most curve traversals included comprised 50 percent of the total sample.

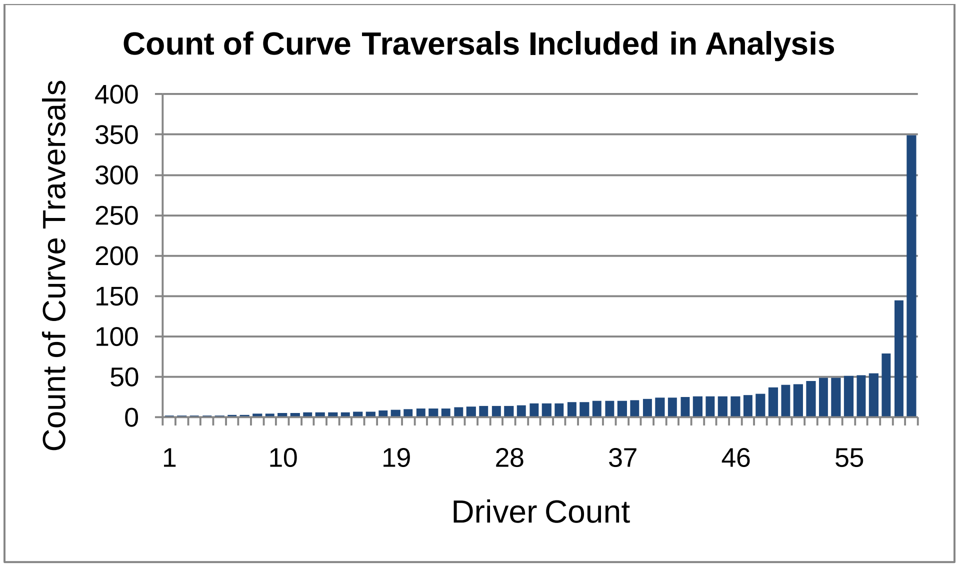


Figure 86: Count of curve traversals included in analysis by driver

Peak Sustained Lateral Acceleration

The integrated crash warning system did not have a statistically significant effect on peak sustain lateral accelerations. The independent measures that were found to have a statistically significant effect on peak sustained lateral acceleration were ambient light and age group. For ambient light ($F(1,41)=10.62$; $p=0.0023$) the data predicts statistically significantly higher peak sustained lateral accelerations during day time. A statistically significant effect of age group was also found ($F(1,56)=4.48$; $p=0.0157$), with younger drivers having the highest peak sustained lateral accelerations and older drivers the lowest.

Peak Sustained Combination Lateral Acceleration and Longitudinal Deceleration

The integrated crash warning system did not have a statistically significant effect on peak sustain lateral accelerations and longitudinal deceleration. The only independent measure found to have a statistically significant effect on peak sustained combined lateral acceleration and longitudinal deceleration was age group. Older drivers experience the lowest combination of peak sustained accelerations while the middle aged drivers had the highest.

Interpretation: The integrated system had no effect on the curve taking behavior of these drivers. The only environmental factor significantly affecting the curve taking behavior, the ambient light level, intuitively indicated that drivers took curves at lower peak sustained lateral accelerations after dark. Also as expected, older drivers took curves at lower peak sustained lateral accelerations than younger drivers. The peak sustained combination lateral acceleration and longitudinal deceleration closely matched the data for the simple peak sustained lateral accelerations. All independent variables affected these two measures similarly. Ultimately, it appears curve-taking behavior is determined by each driver to match the levels of lateral acceleration and longitudinal deceleration that they are comfortable with, and not by the outputs of the integrated system.

QCS2: Will the integrated system’s warnings reduce hard braking upon approaches to curves?

Research Hypothesis: CSW warnings from the integrated system will not change the decelerations observed as drivers approach curves that trigger CSW alerts.

Importance: Drivers who have initially misjudged a curve may decelerate hard as they near the curve. Hard braking may also occur for drivers with more aggressive driving styles. Such braking behavior may introduce crash risk. This research question investigates whether such behavior may be observable and also compares the relative frequency of hard braking near curves between the baseline and treatment conditions.

Method: A set of 851 curve approaches were identified in the data set. This included data for fifty-eight drivers. For each curve approach event, the peak longitudinal deceleration was found.

This analysis complements that in research question QC1, which studied acceleration components within the curve itself. Table 37 presents the analysis constraints.

Table 37: QCS2 analysis constraints

Constraints
Speed above 11.2 m/s (25 mph)
Speed is not hindered by the presence of a lead vehicle
The curve type can be readily identified using data and automatic computations

Results: The principal findings of this analysis are based on the results of a mixed linear model. From Figure 87, it can be seen that a few drivers dominate the sample of curve approaches. One driver accounted for 159 out of the 851 curve approaches (or 18.7%). Removing this driver had only a negligible effect on the model so the driver was left in the sample for analysis. The nine drivers with the most curve approaches included comprised 50 percent of the total sample.

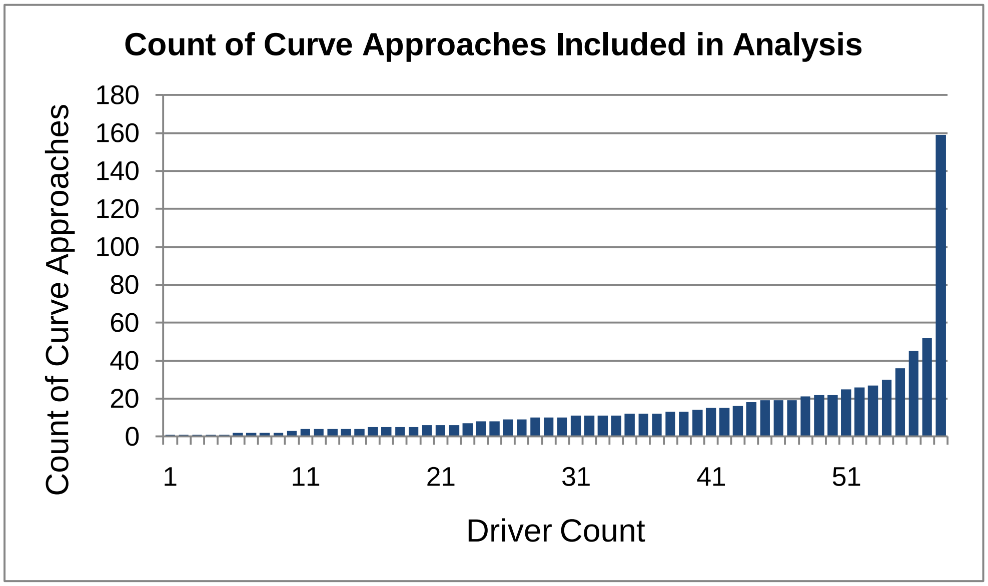


Figure 87: Count of curve approaches included in analysis by driver

The integrated crash warning system did not have a statistically significant effect on peak longitudinal deceleration. The only independent measures found to have a statistically significant effect on peak longitudinal deceleration was ambient light. For ambient light ($F(1,34)=4.8$ $p=0.035$) the higher peak longitudinal decelerations were observed during the daytime.

Interpretation: The integrated system had no effect on driver behavior when approaching a curve. The only environmental factor significantly affecting the curve taking behavior, the ambient light level, intuitively indicated that drivers approached curves at lower speeds were forced into lower peak longitudinal decelerations after dark.

3.6 Driver-Vehicle Interface

This section presents results regarding drivers' perception of and interaction with the integrated system's driver-vehicle interface (DVI). Key results regarding the DVI from the post-drive survey are included.

QD1: Did drivers perceive the driver-vehicle interface for the integrated system easy to understand?

Results: Drivers reported using the integrated system's display to confirm the type of warning that they received. Additionally, they used the display to help in determining what may have triggered an invalid warning. They found the display to be useful (Mean = 5.6, Figure 88), however in focus groups many drivers suggested moving the display to a more central location and having the display messages displayed for a longer period of time.

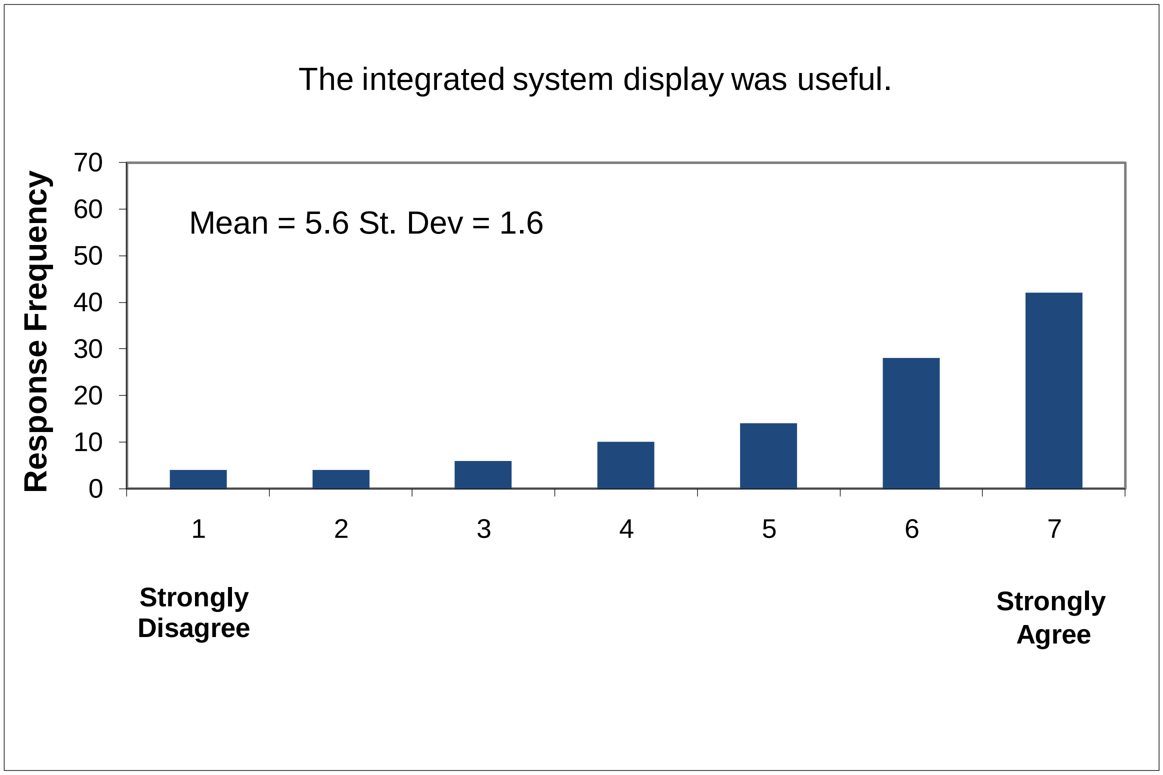


Figure 88: Drivers' ratings of the usefulness of the display

Interpretation: Drivers had a good understanding of both the integrated system and the warnings that the DVI was conveying. This result suggests that, with a modest amount of introduction to the system, drivers were able to learn how the system worked, and that the DVI contained the information necessary to allow drivers to learn how the system operated.

QD2: Do drivers find the volume and mute controls useful, and do they use them?

Results: There were only two features of the integrated system that drivers could adjust. They were able to select from three warning volume levels as well as employ a mute button which would silence warnings for up to six minutes in situations where the driver did not wish to receive warnings (e.g., construction zones with narrowed lanes which could produce invalid warnings).

Only 35 percent of the drivers employed the mute button. Of those drivers, only ten used it five times or more. Drivers were neutral about the mute button's usefulness (Mean = 4.5). The volume adjustment control was used by all of the drivers at least once.

Drivers had the volume control set to medium more frequently than either the low or high settings. Figure 89 demonstrates the number of times drivers employed each volume control setting. It should be noted that when drivers departed UMTRI after their test drive, the volume control switch was set to medium. Drivers rated the volume control adjustment more useful than the mute button (Means of 5.6 and 4.5, respectively (Figure 90 and Figure 91). There was no effect of age on drivers' assessment of the usefulness of the mute button or the volume control.

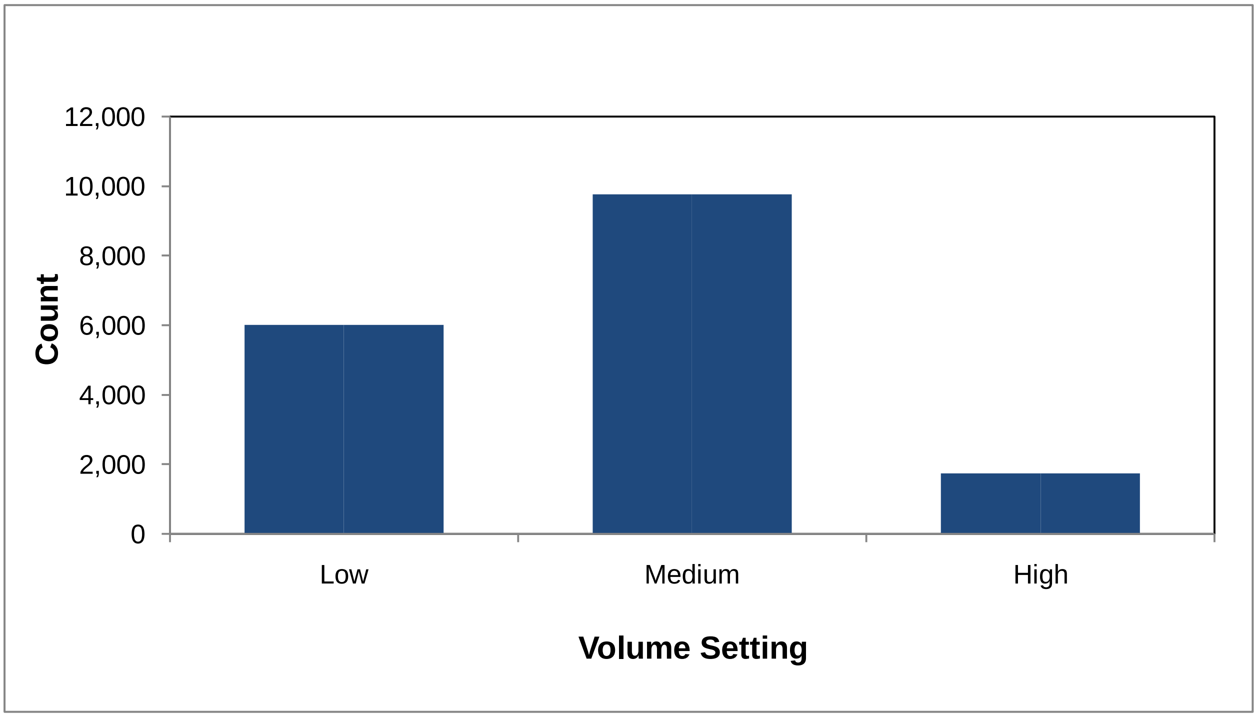


Figure 89: Use of the volume control adjustment

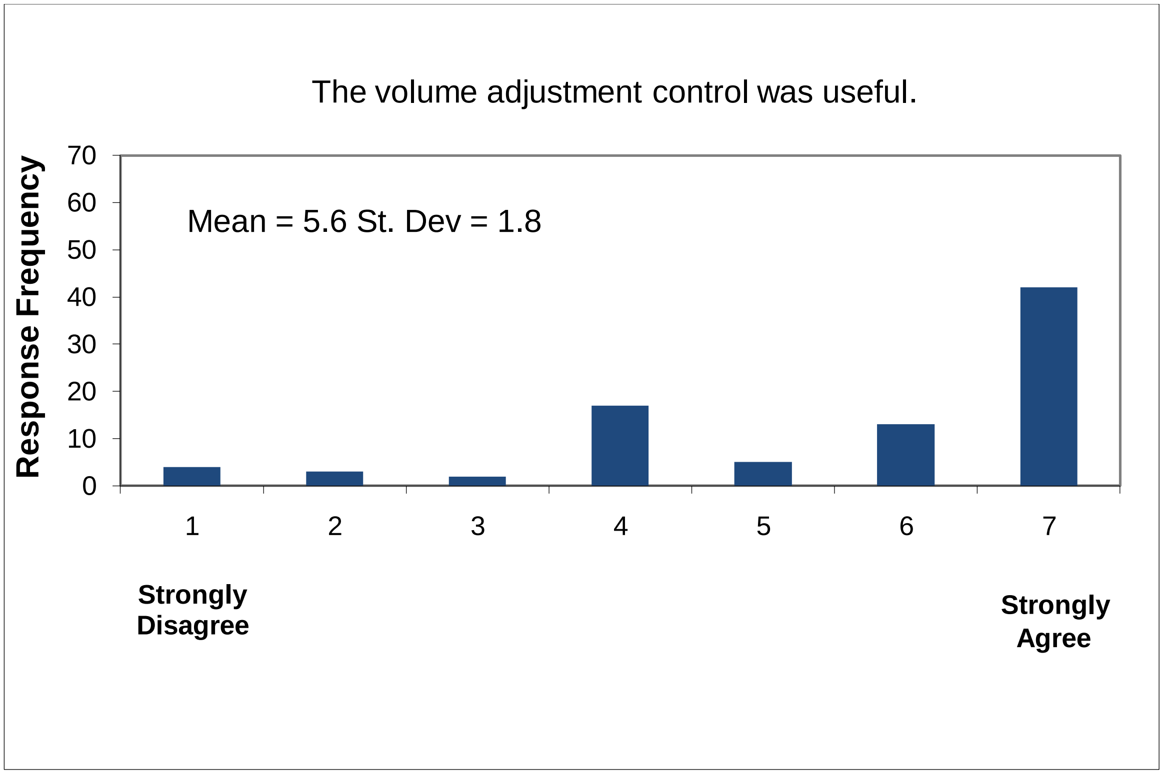


Figure 90: Usefulness of the volume adjustment control

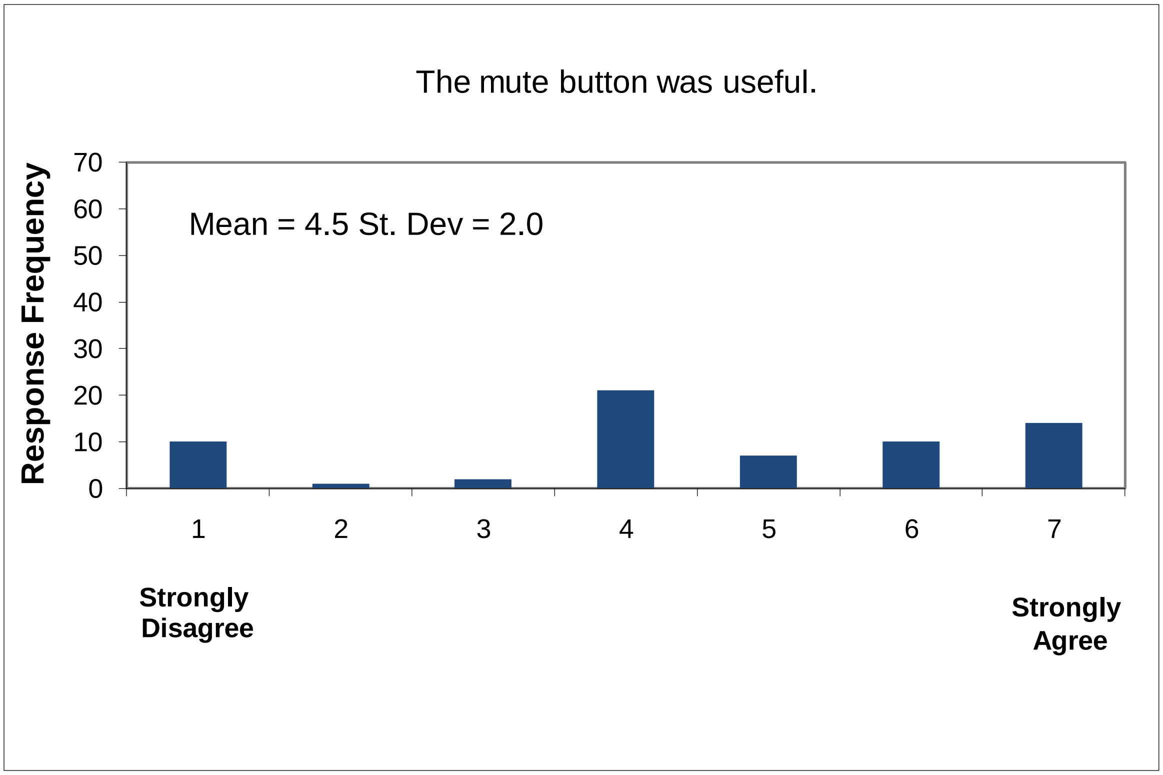


Figure 91: Usefulness of the mute button

Interpretation: The majority of drivers did not utilize the mute function, and drivers were neutral on its usefulness. System designers might consider not including a mute function in future systems. While drivers used the volume control adjustment more extensively than the mute button, the default setting (i.e., medium) was preferred more than 1.5 times than the next selected setting (low) and more than 5.5 times the high setting. System designers may consider using only one volume level in future systems.

3.7 Summary of Focus Groups Sessions

Three focus groups were held as part of the light-vehicle FOT. Each was conducted at UMTRI and lasted about two hours. Twenty-eight of the 108 drivers participated. Drivers were invited to a focus group after they had completed their six weeks of driving one of the research vehicles. Since drivers were free to choose to attend or not, there was no attempt made to balance the focus group attendees for age and gender. In each of the focus groups, the same nineteen questions were asked by a moderator. No other observers were permitted in the conference room where the focus groups were held, however, IVBSS team members were able to observe the focus groups remotely in an adjacent room. The moderator was the person primarily responsible for the recruitment and training of drivers during the FOT.

The nature of focus group data does not lend itself to quantitative analyses rather it is possible to extract qualitative themes about people's experiences with the integrated system. One of the goals of the focus groups was to elicit information and experiences that drivers may have not thought of, or reported, previously in questionnaires or debriefings.

Generally speaking, drivers were familiar with the integrated system after driving with it for only a short time, within a day or two. When drivers received warnings, the vast majority of them surveyed the driving situation, made adjustments to their driving as necessary, and then consulted the display. Several drivers reported looking at the display first to gain information about the type of warning that was being presented.

Drivers were split as to whether they thought that the integrated system was ready for production. Half of them stated that it was not and cited false and nuisance warnings as the main reasons that it was not ready. The other half of the drivers recognized that the system needed some adjustments, but it was otherwise ready for production. When asked about which two or three subsystems that they would buy, all of the drivers reported that they would buy BSD. Further, they were most likely to bundle it with the lateral warning subsystems.

When asked if they received warnings because they were not paying enough attention, fourteen drivers stated that they had. One driver mentioned that he was working split shifts and while driving in the early morning hours had a tendency to fall asleep. The lateral drift warnings helped to wake him and keep him on the roadway. Three drivers reported receiving warnings when they were involved in secondary tasks (e.g., talking on the phone while writing down information). Further, seven drivers reported that an LCM that they received prevented them from crashing during a lane change or merging into traffic. Another driver reported receiving an FCW while he was texting. He stated that the FCW prevented him from having a rear-end crash.

Drivers were asked how false warnings affected their perceptions of the integrated system. Many of the drivers found the false warnings to be tolerable and they accepted them. However, several drivers reported that because they received false warnings they did not trust the system and began to ignore the part of the system that was responsible for providing the false warning. For example, one driver reported ignoring FCWs because the integrated system provided warnings when there was no threat in his lane; while another driver reported ignoring lateral drift warnings on rural roads.

Finally, drivers were asked if they would have turned off the integrated system had they been able to do so. Nine drivers mentioned they would have turned off the system, but only one said that he would have turned off the system permanently. The remaining drivers stated that they would have turned off the integrated system in specific circumstances (e.g., construction zones, etc.).

4. Conclusions

Overall, the IVBSS light-vehicle FOT was successful. The team was able to collect the majority of data that was sought, and the integrated crash warning system operated reliably and consistently with very few system failures. The overall system performance and invalid warning rate showed some improvement over what had been previously observed during extended pilot testing. The average rate of invalid warnings across all drivers for all warning types was 0.84 per 100 miles, which is quite low, but some drivers felt that the rate of invalid alerts was still high enough that it did not meet their expectations.

4.1 Summary of Key Findings

4.1.1 Driver Behavior.

Below are several key findings related to driver behavior:

- In multiple-threat scenarios, the first warning presented to the driver appeared to be sufficient to direct their attention to perform an appropriate corrective maneuver. This finding, in combination with the rarity of multiple-threat scenarios, raises the question of how much emphasis needs to be placed on addressing multiple-threat scenarios through warning arbitration.
- Passenger car drivers in the field test did not appear to become overly reliant on the integrated system, and did not increase the frequency of their involvement in secondary tasks (eating, talking on a cellular telephone, etc.).
- Improvements in lane-keeping and lane-changing behaviors were observed with the integrated system. A change in the rate of lane departures was significantly lower with the integrated system, and lateral offset improved. Furthermore, when drivers did depart the lane, the duration that they remained outside of their lane was shorter. While the frequency of lane changes was significantly higher with the integrated system, turn-signal use when making a lane change increased.
- No substantive changes in driving behavior relative to longitudinal control were observed. The integrated system did not affect forward conflict levels, nor did it change driver behavior in curves. There was a statistically significant observation in that drivers were slightly more likely to maintain shorter headways, i.e., less than one second, with the integrated system than without it.

4.1.2 Driver Acceptance.

Below are several key findings regarding driver acceptance:

- Most drivers reported that their driving behavior changed as a result of driving with the integrated system. The most frequently mentioned change in behavior was an increase in turn-signal use, which was the result of receiving LDWs triggered by failing to use turn signals when changing lanes (which was confirmed by the objective data).

- Drivers accepted the integrated system and rated it favorably for both usefulness and satisfaction, and 72 percent of the drivers said they would like to have the integrated system in their personal vehicle.
- Drivers found the integrated system's warnings to be helpful and said they believed that such a system would increase their driving safety. In focus groups, eight drivers reported that the integrated system prevented them from having a crash.
- Drivers rated the lateral subsystems (LCM with BSD and LDW) more favorably than the longitudinal subsystems (FCW and CSW), and reported getting the most satisfaction out of the BSD component of the LCM subsystem. Drivers found the integrated system to be useful in particular when changing lanes and merging into traffic.
- Drivers reported FCW to be the least useful and satisfying of the subsystems. Numerous drivers commented that they did not like the brake pulse that accompanied the warnings.
- The high percentage of longitudinal warnings (FCW and CSW) that were invalid affected driver confidence, leading to reduced driver acceptance of these subsystems.

4.2 Actionable Outcomes and Implications for Deployment

The following are a series of actionable outcomes, or implications for the development and deployment of integrated crash warning systems that are supported by the IVBSS light-vehicle field operational test findings:

- Despite a very low invalid warning rate for the FCW and CSW subsystems, driver feedback seems to suggest that some drivers would expect the invalid warning rates to be even lower—or perhaps that the percentage of warnings that were invalid affected their confidence in these subsystems or their understanding how they operated. Achieving a lower invalid warning rate may be extremely challenging for system engineers, as might the elimination of certain warning scenarios.
- A potential approach to reducing invalid warnings, particularly to fixed objects outside the vehicle's path, would be the development of location-based filtering that could modify threat assessments in response to repeated warnings to which drivers do not respond.
- Drivers preferred, and obtained the most direct benefit from the lateral subsystems (LDW and LCM). The preference could be due in part to the more subtle nature of the warnings for the lateral systems when a threat is not imminent. Specifically, the presence of LEDs in the side-view mirror (BSD) and the haptic seat (LDW) are less intrusive than are the auditory warnings used for CSW and FCW in response to imminent threats.
- Multiple-threat scenarios are quite rare; because there were so few multiple warning events during the field test, it was not possible to determine patterns identifying which threat drivers responded to first. Drivers generally reacted to whatever warning was presented, and their responses were appropriate for the indicated threat. However,

warning arbitration continues to be necessary in order to preclude the possibility of issuing multiple warnings to drivers.

- There was no direct evidence of driver over-reliance on crash warnings as indicated by an increased involvement in secondary tasks. However, there was a statistically significant observation in that drivers were slightly more likely to maintain a shorter headway, less than one second, with the integrated system than during baseline driving.

References

Ervin, R., Sayer, J., LeBlanc, D., Bogard, S., Mefford, M. L., Hagan, M., Bareket, Z., and Winkler, C. (2005). Automotive Collision Avoidance System (ACAS) Field Operational Test – Methodology and Results. DOT HS 809 901. Washington, DC: National Highway Traffic Safety Administration.

Bogard, S., Tang, Z., Nowak, M., Kovacich, J., Reed, A., Sayer, J. and Sardar, H. (2008). Integrated Vehicle-Based Safety Systems Heavy Truck Verification Test Plan. Report No. UMTRI-2008-15. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Bogard, S., Funkhouser, D., and Sayer, J. (2009). Integrated Vehicle-Based Safety System (IVBSS): Heavy Truck Extended Pilot Test Summary Report. Report No. UMTRI-2009-12. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Brown, J., McCallum, M., Campbell, J. and Richard, C. (2008). Integrated Vehicle-Based Safety System Heavy Truck Driver-Vehicle Interface (DVI) Specifications (Final Version). Report No. UMTRI-2008-27. Ann Arbor, MI: University of Michigan Transportation Research Institute.

General Estimates System (GES) USDOT, Federal Motor Carrier Safety Administration and Trucks Involved in Fatal Accidents (TIFA). Rear-end Large Truck Crashes, Large Trucks in Crashes by Crash Type and Severity 1994-1999 (annual average)

Green, P., Sullivan, J., Tsimhoni, O., Oberholtzer, J., Buonarosa, M.L., Devonshire, J., Schweitzer, J., Baragar, E., and Sayer, J. (2008). Integrated Vehicle-Based Safety Systems (IVBSS): Human-Factors and Driver-Vehicle Interface (DVI) Summary Report. DOT HS 810 905. Washington, DC: National Highway Traffic Safety Administration.

Harrington, R., Lam, A., Nodine, E., Ference, J., & Wassim G. Najm (2008). Integrated Vehicle-Based Safety Systems Heavy-Truck On-Road Test Report. DOT HS 811 021. Washington, DC: National Highway Traffic Safety Administration.

LeBlanc, D., Sardar, H., Nowak, M., Tang, Z., and Pomerleau, D. (2008). Functional Requirements for Integrated Vehicle-Based Safety System (IVBSS) – Heavy Truck Platform. Report No. UMTRI-2008-17. Ann Arbor, MI: University of Michigan Transportation Research Institute.

LeBlanc, D., Nowak, M., Tang, Z., Pomerleau, D., and Sardar, H. (2008). System Performance Guidelines for a Prototype Integrated Vehicle-Based Safety System (IVBSS) – Heavy Truck Platform. Report No. UMTRI-2008-19. Ann Arbor, MI: University of Michigan Transportation Research Institute.

McCallum, M. and Campbell, J. (2008). Integrated Vehicle-Based Safety System Heavy Truck Driver-Vehicle Interface (DVI) Stage 1 Jury Drive Summary. Report No. UMTRI-2008-26. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sayer, J., LeBlanc, D. and Bogard, S., and Blankespoor, A. (2009). Integrated Vehicle-Based Safety Systems (IVBSS) Heavy Truck Platform Field Operational Test Data Analysis Plan.

Report No. UMTRI-2009-31. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Sayer, J., LeBlanc, D., Bogard, S., Hagan, M., Sardar, H., Buonarosa, M, and Barnes, M. (2008) Integrated Vehicle-Based Safety Systems – Field Operational Test (FOT) Plan. DOT HS 811 010. Washington, DC: National Highway Traffic Safety Administration.

Sayer, J.R., Devonshire, J.M., and Flannagan, C.A. (2005). The Effects of Secondary Tasks on Naturalistic Driving Performance. Report No. UMTRI-2005-29. Ann Arbor, MI: University of Michigan Transportation Research Institute.

University of Michigan Transportation Research Institute (2008). Integrated Vehicle-Based Safety Systems (IVBSS) Phase I Interim Report, DOT HS 810 952. Washington, D.C.: National Highway Traffic Safety Administration.

U.S. Department of Transportation, Federal Transit Administration, National Transit Database, available at http://www.ntdprogram.gov/ntdprogram/data.htm as of December 20, 2009

Van Der Laan, J. D., Heino, A., and De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. Transportation Research, 5(1), 1-10.

Appendix A: Research Question Key Findings Summary Table

Question Number	Research Question	Key Findings
QC1	When driving with the integrated crash warning system in the treatment condition, will drivers engage in more secondary tasks than in the baseline condition?	There was no evidence of risk compensation or over reliance on the integrated system—that is, there was no effect of the integrated system on the frequency of secondary tasks.
QC2	Does a driver's engaging in secondary tasks increase the frequency of crash warnings from the integrated system?	Warnings from the integrated crash warning system were no more likely to occur because drivers were engaged in a secondary task.
QC3	When the integrated system arbitrates between multiple-threats, which threat does the driver respond to first?	Based upon the multiple-threat events observed in this field test, the initial warning was generally enough to get the attention of drivers and result in an appropriate correction when necessary. This FOT demonstrated that multiple warning scenarios are rare events. Because of the apparent low utility of a second warning within 3 seconds of the first warning, designers of crash warning systems might consider suppressing the second warning all together.
QC4	Do drivers report changes in their driving behavior as a result of the integrated crash warning system?	The majority of drivers reported that their driving behavior changed as a result of driving with the integrated system. The most frequently mentioned change in behavior was an increase in turn-signal use, which was the result of receiving LDW warnings provoked by failing to use turn signals when changing lanes.

Question Number	Research Question	Key Findings
QC5	Are drivers accepting the integrated system (i.e., do drivers want the system on their vehicles)?	Drivers were accepting of the integrated system and rated it well in terms of both usefulness and satisfaction. Seventy-two percent of all drivers would like to have the integrated system in their personal vehicle.
QC6	Are the modalities used to convey warnings to drivers salient?	The warnings presented by the integrated system were attention-getting but at the same time not distracting.
QC7	Do drivers perceive a safety benefit from the integrated system?	Drivers found the integrated system's warnings to be helpful and believed that the integrated system would increase their driving safety. Both of these effects increase with increasing driver age. Drivers reported benefit from "increased awareness."
QC8	Do drivers find the integrated system convenient to use?	Drivers rated the integrated system fairly well for predictability and consistency. Reducing the invalid warning rate would likely result in improved ratings of predictability and consistency.
QC9	Do drivers report a prevalence of false warnings that correspond with the objective false warning rate?	While drivers received nuisance warnings from the integrated system, they did not feel that they received them too frequently. There appears to be an age effect with middle-aged drivers receiving the most nuisance warnings and younger drivers having the highest nuisance warning rate (nuisance warnings/100 miles).

Question Number	Research Question	Key Findings
QC10	Do drivers find the integrated system to be easy to use?	Drivers found the integrated system easy to use and had a good understanding of what to expect from it.
QC11	Do drivers find the integrated system to be easy to understand?	Drivers understood the integrated system's warnings and how to respond when they received warnings. Reducing the invalid warning rate particularly for FCWs, will most probably increase drivers' understanding of why the integrated system provides those warnings.
QC12	Do drivers find the overall frequency with which they received warnings to be acceptable?	Drivers reported receiving warnings with about the right frequency. Some drivers complained about receiving LDW warnings when they failed to use turn signals while making a lane change.
QC13	Do drivers find then nuisance warnings to be bothersome?	Half of the younger drivers were annoyed by nuisance warnings, but drivers overall were not annoyed by them. Drivers in focus groups, and in debriefing sessions, stated that they were willing to overlook some of the shortcomings of new technologies to reap the safety benefit.
QC14	Are drivers willing to purchase the integrated system or its individual subsystems, and if so, how much are they willing to spend?	The majority of drivers reported that they were willing to purchase the integrated system. Most are not willing to spend more than $750. Drivers were more willing to purchase lateral subsystems, and pay up to $300, whereas they are only willing to spend up to $200 for CSW.
QL1	Does lateral offset vary between baseline and treatment conditions?	The integrated crash warning system did not have a statistically significant effect on lateral offset. The average lateral offset moved about one centimeter towards the center of the lane under the treatment condition.

Question Number	Research Question	Key Findings
QL2	Does the lane departure warning frequency vary between baseline and treatment conditions?	The integrated system had a statistically significant effect on the frequency of lane departures, decreasing the rate from 14.4 departures per 100 miles under the baseline condition to 8.5 departures per 100 miles under the treatment condition.
QL3	When vehicles depart the lane, does the vehicle trajectory, including the lane incursion and duration, change between the baseline and treatment conditions?	The integrated crash warning system had a statistically significant effect on the distance and the duration of lane departures. The mean duration of a departure dropped from 1.98 sec in the baseline condition to 1.66 sec in the treatment condition, and the distance decreased by 1.2 cm.
QL4	Does turn signal use during lane changes differ between the baseline and treatment conditions?	The results show a statistically significant effect of the integrated system on turn-signal use during lane changes. Drivers were 3 times less likely to forget to use a turn signal when making a lane change in the treatment condition as compared to the baseline condition.
QL5	Do drivers change their position within the lane when another vehicle occupies an adjacent lane?	Drivers adjusted their lane position away from a vehicle in an adjacent lane regardless of which side of the adjacent vehicle is on.
QL6	What is the location of all adjacent vehicles relative to the subject vehicle for valid LCM warnings?	The integrated crash warning system did not have a statistically significant effect on the location of LCM warnings. However, there was a statistically significant effect associated with which side of the vehicle the warning occurred.
QL7	Will drivers change lanes less frequently in the treatment period, once the integrated system is enabled?	There was a statistically significant increase in lane change rate with the integrated crash warning system (12.6%).

Question Number	Research Question	Key Findings
QL8	Is the gap between the subject vehicle (SV) and other leading vehicles influenced by integrated system when the SV changes lanes behind a principal other vehicle (POV) traveling in an adjacent lane?	The only statistically significant effect of the integrated crash warning system on gap size was an average decrease of 1.3 m between the SV and the POV before the lane change in the treatment condition.
QL9	Are drivers accepting of the LDW and LCM subsystems (i.e., do drivers want LDW and LCM on their vehicles?)	While drivers rated all of the subsystems and the integrated system positively in terms of satisfaction and usefulness, they rated the lateral subsystems (LCM with BSD and LDW) more favorably than the longitudinal subsystems.
QL10	Do drivers find the integrated system to be useful, what attributes and in which scenarios was the integrated system most and least helpful?	Drivers generally found the integrated system to be useful, particularly when changing lanes and merging into traffic. Additionally, the system provided a heightened awareness if the driver was distracted.
QF1	Does the presence of integrated system affect the following distances maintained by the passenger-car drivers?	There is a statistically significant effect of the integrated crash warning system on the time spent at short headways, such that more time was spent with shorter headways with the integrated system than in the baseline condition. The travel time at headways less than 1 sec increased from 21 percent of steady-state following time to 24 percent.
QF2	Will the frequency and/or magnitude of forward conflicts be reduced between the baseline and treatment conditions?	The results showed no statistically significant effect of the integrated system on forward conflict levels during approaches to preceding vehicles.

Question Number	Research Question	Key Findings
QF3	Does the integrated system affect the frequency of hard-braking maneuvers involving a stopped or slowing POV?	There was no effect of the integrated crash warning system on hard-braking event frequency.
QF4	Will the integrated system warnings improve drivers' responses to those forward conflicts in which closing-speed warnings occur?	There was no effect of the integrated crash warning system on brake reaction time. A statistically significant difference was found between the brake reaction times of drivers to varying traffic densities.
QF5	Are drivers accepting of the FCW subsystem (i.e., do drivers want this system on their vehicles)?	Among the subsystems, drivers rated the usefulness of FCW the lowest and were the least satisfied with it among the subsystems.

Appendix B: Variable Definitions Table

Independent Variable	Units	Levels	Description and Source
Ambient Light	-	Day, Night	Determined by calculating the angle of the sun relative to the horizon (Solar Zenith Angle: an angle < 90 = daytime; between 90 and 96 civil twilight; > 96 nighttime). Time of day is determined via GPS signal.
Available Maneuvering Room	-	Occupied, Unoccupied	Represents the state of the lane adjacent to the vehicle, could be occupied by a vehicle or by a fixed roadside object (such as a Jersey barrier)
Brake Reaction Time	s		Time duration (seconds) between the warning onset and the time at which driver initiated braking.
Brake Response		Yes, No	A binary variable indicating whether the driver pressed the brake pedal during the closing conflict event
Boundary Type	-	Solid, Dashed, Virtual, No marking	Classification of the longitudinal pavement markings, Virtual indicates a boundary's location was inferred based on the location of the boundary on the opposite side of the lane
Condition	-	Baseline, Treatment	State of the integrated crash warning system, where baseline represents that no warnings are being presented to drivers but data is being recorded
Deceleration Required	m/s^2		An estimate of the actual deceleration required to maintain a minimal headway, derived from the forward radars and vehicle state variables
Distance Past Lane Edge	m		A derived measure of how far the front tire of the vehicle has drifted past the lane boundary (calculated for either left or right front wheel)

Independent Variable	Units	Levels	Description and Source
Driver	-		Unique identification number that links each tractor and trip with a subject via manual coding of the face video
Driver Reaction Time	s		Time duration between the warning onset and the time at which driver responded by releasing the accelerator pedal
Incursion Distance			See Distance Past Lane Edge
Lateral offset	m/s		Vehicle offset from lane center from the LDW subsystem
Lane Offset Confidence	%	0-100	Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem

Independent Variable	Units	Levels	Description and Source
Month	-		Months of data collection. Months 1 and 2 are always baseline condition, 3 and above are treatment condition
Road Type	-	Limited Access, Surface, Ramp	Indicates the type of road, derived from HPMS and previous UMTRI FOTs
Route Type	-	P&D, Line-haul	Daytime pick-up and delivery (local roads) and nighttime line-haul delivery between distribution terminals (Each *Driver* is exclusively associated with one of the two route types)
Side	-	Left, Right	Left and right side of the vehicle
Speed	m/s		Estimate of forward speed
Traffic Density	-	Sparse, Moderate, Dense	A count of the number of same-direction vehicles that is smoothed and weighted by the number of thru lanes.
Trailer	-	Single, Doubles	Input from the driver via the DVI and defines the number and length of the trailers attached to the tractor/power unit. Single is single axle 28 and 32 foot trailers and tandem axle 45, 48 and 53 foot trailers. Double is two single axle 28 foot trailers joined by a single axle dolly
Wiper State	-	Wipers on, Wipers off	Wiper switch state from the J1939 CAN bus and relates to the wiper speed and is used as a surrogate for active precipitation

Dependent Variable	Units	Levels	Description and Source
Brake Reaction Time	s		Time duration (seconds) between the warning onset and the time at which driver initiated braking.
Brake Response		Yes, No	A binary variable indicating whether the driver pressed the brake pedal during the closing conflict event
Deceleration Required	m/s2		An estimate of the actual deceleration required to maintain a minimal headway, derived from the forward radars and vehicle state variables
Distance Past Lane Edge	m		A derived measure of how far the front tire of the vehicle has drifted past the lane boundary (calculated for either left or right front wheel)
Driver Reaction Time	s		Time duration between the warning onset and the time at which driver responded by releasing the accelerator pedal
Incursion Distance			See Distance Past Lane Edge
Lane Offset	m/s		Vehicle offset from lane center from the LDW subsystem
Maximum Incursion			The maximum distance past the outer edge of a lane boundary the leading tire travels before returning to the lane in a lane departure
Time-to-collision	s		An instantaneous estimate of the number of seconds until a crash based on range and range-rate from the forward looking radar (TTC = - Range/Range-rate for Range-rate < 0.0)

Other Terms	Units	Levels	Description
Backspotter Radars			Radars mounted on the sides of the tractor facing outwards. These do not measure range, only the presence of an object
Closing Conflict			A situation where the SV is behind a slower moving POV and therefore decreasing the forward range
Drift Event			See Lane Departure
Driver Video	-		Video of the driver's face and over-the-shoulder view that illustrates behavior in the vehicle cabin
Exposure			Refers to the amount of time a driver spent with the system
Following event			An extended period of following behavior, with durations of 5 seconds or longer on the same road type, where the SV follows the same POV. This excludes lane changes and turns by either the SV or lead POV
Hard-braking Event			Speed greater than 25 mph, with a lead POV and a peak braking deceleration greater than .2g
Headway-Time-Margin	s		See Time-gap
Lane Boundaries	-		See Boundary Type
Lane Change	-		A lateral movement of the SV in which the SV starts in the center of a defined traffic lane with boundary demarcations and ends in the center of an adjacent traffic lane that also has defined boundary demarcations. The explicit instant in time of the lane-change is defined as the moment when the SV lateral centerline crosses the shared boundary between the two adjacent traffic lanes.

Other Terms	Units	Levels	Description
Lane departure			An excursion on either side of the vehicle into an adjacent lane as measured by the lane-tracking component of the LDW subsystem. A lane departure was considered to have occurred when the entire lane boundary was covered by the vehicles tire. Must include both and exit from and a return to the original lane.
Lane incursion			See Lane Departure

Other Terms	Units	Levels	Description
Lane Offset Confidence	%		Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem
Lateral Position			See Lane Offset
Lateral Speed	m/s		Vehicle speed lateral to lane direction from the LDW subsystem
Likert-Type Scale Value	-	1 to 7	A number between 1 and 7 indicating general agreement of a driver with a question included in the post-drive survey. Anchor terms are provided at the two ends of the extreme
MACOM Radars			Radars mounted on the side-mirrors facing backwards down the sides of the trailer
Post-Drive Survey	-		A series of Likert-type scaled and open-ended questions completed by drivers upon completion of their study participation
POV Type	-		A video analysis based classification of the vehicle type (passenger or commercial) for vehicles treated as a Principal Other Vehicle (POV)
Range	m		Distance from the SV to the POV
Range-rate	m/s		Rate at which the SV is closing on the POV
Scenario		Shared-lane, Multi-lane	Number of travel lanes in the same direction as the Subject vehicle's motion
Secondary Task			A task performed by the driver not critical to normal driving.
Steady-state Lane Keeping			A period of time on a single road type with no lane changes or braking where the primary driving task is maintaining lane position
Subsystem			Refers to the Forward crash warning system, the Lane departure warning system or the Lane change/Merge warning system

Other Terms	Units	Levels	Description
Time-gap	s		The result of the forward range to a POV divided by the SV's speed. Given an instant in time with a measured range and speed, this is the time (sec) needed to travel the measured range assuming a constant speed.
Time-headway	s		See Time-gap

Other Terms	Units	Levels	Description
Trailer Reflection			A target detected by the MACOM radars that proves to be simply a reflection from the trailer and not an adjacent vehicle or object
Van der Laan Score	-	-2 to 2	One of two possible scores relating driver perceived usefulness or satisfaction with the system being evaluated in the post-drive survey
Warning Type			One of the three possible warnings from the integrated system on the heavy truck platform (FCW, LDW, LCM)

Appendix C: DAS data collection variables

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Radar															
Front		x			x					x	x	x	x	x	
Side		x			x					x	x	x	x	x	
Rear		x			x						x		x	x	
Lane-Departure															
Boundary types		x				x				x	x		x	x	
Lane position		x				x				x	x	x		x	
Lateral speed		x				x				x	x	x		x	
Lane change events		x				x		x		x	x	x		x	
Ambient light		x				x				x	x		x	x	
Future lane offset		x				x				x	x		x	x	
Road shoulder width		x				x				x	x		x	x	
Road curvature		x				x				x	x		x	x	
Alert request		x				x	x			x	x	x	x	x	
Status		x				x		x	x	x	x			x	
Lane-Change/Merge															
Lateral presence		x				x				x	x	x	x	x	
Lateral clearance		x				x				x	x	x	x	x	
Future lateral clearance		x				x				x	x	x		x	
Time to lane crossing		x				x				x	x	x		x	
Object position		x				x				x	x		x	x	

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Object velocity		x				x				x	x		x	x	
Alert request		x				x	x			x	x	x		x	
Status		x				x		x	x	x	x			x	
Forward Collision															
Heading wrt road		x				x				x	x	x		x	
CIPV Range		x				x				x	x	x	x	x	
CIPV Range rate		x				x				x	x	x	x	x	
CIPV Azimuth		x				x				x	x	x	x	x	
CIPV Ax		x				x				x	x	x	x	x	
Target type		x				x				x	x			x	
Lane change flag		x				x				x	x	x		x	
Alert request		x				x	x			x	x	x		x	
Status		x				x		x	x	x	x			x	
Curve Speed Warning															
Map type		x							x		x		x	x	
Mapping quality		x							x		x		x	x	
Availability		x							x		x		x	x	
Maximum desired speed		x							x		x	x		x	
Required acceleration		x							x		x	x		x	
Most likely path		x							x		x			x	
Number of thru lanes		x							x		x		x	x	
Road curvature points (CPOI)		x							x		x		x	x	

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Alert request		x				x	x				x	x		x	
Status		x				x		x	x		x			x	
DVI															
Display state		x				x				x	x	x		x	
System sensitivity		x				x		x	x		x	x		x	
System suppression		x				x		x	x	x	x	x	x	x	
Visual alert		x				x	x			x	x			x	
Audio alert		x				x	x			x	x			x	
Haptic alert		x				x	x				x			x	
Alertness index		x				x					x	x	x	x	
Status		x				x		x	x	x	x			x	
Vehicle Performance															
Transmission speed	x					x				x	x	x			x
Transmission gear	x							x			x	x			x
Fuel Used	x					x					x	x			x
Engine torque	x					x				x		x			x
Retarder torque	x					x				x		x			x
Coolant temp	x					x				x					x
Intake temp	x					x				x					x
Battery voltage	x					x			x	x	x			x	x
Traction control	x						x	x	x		x	x			x
ABS event	x						x	x			x	x			x

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Status	x					x		x	x	x	x				x
Driver Activity and switches															
Wipers	x					x		x		x	x	x		x	
Turn signal	x					x		x		x	x	x		x	
Steer	x		x			x				x	x	x		x	
Accel. pedal	x					x		x		x	x	x			
Brake	x					x		x		x	x	x		x	
Head/parking lamp	x					x		x		x	x	x			
Horn	x							x		x		x			
Cruise control	x					x		x			x	x		x	
Parking brake	x							x		x		x			
Clutch state	x					x		x		x		x			
Vehicle State Measures															
Weight				x				x	x	x					x
Ax			x			x				x	x	x			x
Ay			x			x				x	x	x			x
Yaw rate			x			x				x	x	x		x	x
Speed	x					x				x	x	x		x	x
Roll angle			x			x				x	x	x			x
Roll rate			x			x				x	x	x			x
Lat. and Long.			x			x				x	x		x	x	x
Compass heading			x			x				x	x		x	x	x

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
System State and Diagnostic															
Versions		x						x		x	x			x	
Heartbeats		x				x				x	x			x	
Failure codes		x				x		x		x	x			x	
Histograms		x							x	x	x			x	
Enabled		x							x	x	x			x	
Road Characteristics															
Limited access		x				x					x		x	x	
Ramp		x				x					x		x	x	
Major surface		x				x					x		x	x	
Minor surface		x				x					x		x	x	
Local		x				x					x		x	x	
AADT		x						x		x	x		x		
Number of thru lanes		x						x			x		x		
Urban flag		x						x			x		x	x	
Paved flag		x						x			x		x	x	
Function class		x						x		x	x		x	x	
Time of Day															
Solar zenith angle			x			x				x	x		x	x	
Traffic															
Number of targets		x				x				x	x		x	x	
Location of targets		x				x				x	x		x	x	

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Estimated traffic density		x				x				x	x		x		
Trip Summary Statistics															
Distance traveled				x					x	x	x			x	
Counts of events				x					x	x	x			x	
System availability time				x					x	x	x			x	
Vehicle location				x					x	x	x			x	
Vehicle ID									x	x	x			x	
Weather															
Precipitation				x				x		x	x		x		
Wind speed				x				x		x			x		
Wind direction				x				x		x			x		
Temperature				x		x				x	x		x		
Visibility				x				x		x			x		
Atm pressure				x				x		x			x		
Video															
Forward				x	x		x			x	x		x		
Left side				x	x		x			x	x		x		
Right side				x	x		x			x	x		x		
Cabin				x	x		x			x	x	x	x		
Face				x	x		x			x	x	x	x		
Driver Characteristics															
Age				x					x	x	x			x	

Data Category	Source				DAS Format					Platform		To Monitor			
	Vehicle Bus	System Bus(s)	UMTRI (AtoD)	Other	Custom	10 Hz series	Triggered Event	Transitional	Aggregated	Heavy Truck	Light Vehicle	Driver Activity	Environment	IVBSS	Vehicle
Gender				x					x	x	x			x	

Appendix D: Light-vehicle post-drive questionnaire

IVBSS LV FOT Questionnaire and Evaluation

Please answer the following questions about the Integrated Vehicle Based Safety System (IVBSS). If you like, you may include comments alongside the questions to clarify your responses.

Example:

A.) Strawberry ice cream is better than chocolate.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

If you prefer chocolate ice cream over strawberry, you would circle the "1", "2" or "3" according to how strongly you like chocolate ice cream, and therefore disagree with the statement.

However, if you prefer strawberry ice cream, you would circle "5", "6" or "7" according to how strongly you like strawberry ice cream, and therefore agree with the statement.

If a question does not apply:

Write "NA," for "not applicable," next to any question which does not apply to your driving experience with the system. For example, you might not experience every type of warning the questionnaire addresses.

General Impression of the Integrated System

1. **What did you like most about the integrated system?**

____

____

____

____

2. **What did you like least about the integrated system?**

____

____

____

____

3. **Is there anything about the integrated system that you would change?**

____

____

____

____

4. **How helpful were the integrated system's warnings?**

1 2 3 4 5 6 7

Not all Helpful

Very Helpful

5. **In which situations were the warnings from the integrated system helpful?**

____

____

____

6. **Overall, I think that the integrated system is going to increase my driving safety.**

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

7. **Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane.**

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

8. **The integrated system made driving easier.**

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

9. Overall, I felt that the integrated system was predictable and consistent.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

10. I was not distracted by the warnings.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

11. Overall, how satisfied were you with the integrated system?

1	2	3	4	5	6	7
Very Dissatisfied						Very Satisfied

12. Did you rely on the integrated system? Yes____ No____

a. If yes, please explain?

____

____

13. As a result of driving with the integrated system did you notice any changes in your driving behavior? Yes____ No____

a. If yes, please explain.

14. Overall, I received warnings . . .

1	2	3	4	5	6	7
Too Frequently						Too Infrequently

If you answered Question 14 with a 1, 2, or 3, answer Question 14a below. If your answer was a 5, 6, or 7, answer Question 14b. If your answer was a 4, skip to Question 15.

a. If you received warnings too frequently, which type (s) of warnings did you receive too frequently? (circle all that apply)

Left/Right Hazard   Left/Right Drift   Hazard Ahead   Sharp Curve

:

b. If you received warnings too infrequently, which type (s) of warnings did you receive too infrequently? (circle all that apply)

Left/Right Hazard   Left/Right Drift   Hazard Ahead   Sharp Curve

15. I always understood why the integrated system provided me with a warning.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

16. I always knew what to do when the integrated system provided a warning.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

17. The auditory warnings' tones got my attention.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

18. I always understood why the integrated system provided me with an auditory warning tone.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

19. The auditory warnings' tones were not annoying.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

20. The seat vibration warnings got my attention.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

21. I always understood why the integrated system provided me with a seat vibration.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

22. The seat vibration warnings were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

23. The brake pulse warnings got my attention.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

24. I always understood why the integrated system provided me with a brake pulse warning.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

25. The brake pulse warning was not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

26. The yellow lights in the mirrors got my attention.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

27. I always understood why the integrated system provided me with a yellow light in the mirror.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

28. The yellow lights in the mirrors were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

29. Did you receive more than one warning within a few seconds (approximately three seconds)? Please place a check mark next to your answer.

Yes ____ No____

30. The integrated system gave me warnings when I did not need them (i.e., nuisance warnings)

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

31. Overall, I received nuisance warnings . . .

1	2	3	4	5	6	7
Too Frequently						Never

32. The nuisance warnings were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

33. The integrated system gave me left/right hazard warnings when I did not need them.

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

34. The integrated system gave me left/right drift warnings when I did not need them.

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

35. The integrated system gave me hazard ahead warnings when I did not need them.

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

36. The integrated system gave me sharp curve warnings when I did not need them.

1 2 3 4 5 6 7

Strongly Disagree

Strongly Agree

Overall Acceptance of the Integrated System

37. Please indicate your overall acceptance rating of the integrated system *warnings*

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The integrated system **warnings** were:

useful	☐	☐	☐	☐	☐	useless
pleasant	☐	☐	☐	☐	☐	unpleasant
bad	☐	☐	☐	☐	☐	good
nice	☐	☐	☐	☐	☐	annoying
effective	☐	☐	☐	☐	☐	superfluous
irritating	☐	☐	☐	☐	☐	likeable
assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

Displays and Controls

38. The integrated system display was useful.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

39. The mute button was useful.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

40. The volume adjustment control was useful.

1	2	3	4	5	6	7
Strongly						Strongly
Disagree						Agree

41. Would you like to have the integrated system in your personal vehicle?

1	2	3	4	5
Definitely Not	Probably Not	Might or Might not	Probably Would	Definitely Would

42. What is the maximum amount that you would pay for the integrated system? Circle one price range.

0

$250-500

$500-750

$750-1000

$1000-1500

$1500-2000

More than $2000

Hazard Ahead warning acceptance

The Hazard Ahead warning provided an auditory warning accompanied by a brake pulse whenever you were approaching the rear of the vehicle in front of you and there was potential for a collision. When you received this type of warning, the display read “Hazard Ahead”.

43. Please indicate your overall acceptance rating of the Hazard Ahead warnings.

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The hazard ahead **warnings** when I was approaching a vehicle ahead were:

Useful	☐	☐	☐	☐	☐	useless
Pleasant	☐	☐	☐	☐	☐	unpleasant
Bad	☐	☐	☐	☐	☐	good
Nice	☐	☐	☐	☐	☐	annoying
Effective	☐	☐	☐	☐	☐	superfluous
Irritating	☐	☐	☐	☐	☐	likeable
Assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

Sharp Curve warning acceptance

The Sharp Curve warning provided an auditory warning whenever you were approaching a curve at too great a speed. When you received this type of warning, the display read “Sharp Curve”.

44. Please indicate your overall acceptance rating of the Sharp Curve warnings.

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The sharp curve **warnings** when I approached a curve at too great a speed were:

Useful	☐	☐	☐	☐	☐	useless
pleasant	☐	☐	☐	☐	☐	unpleasant
Bad	☐	☐	☐	☐	☐	good
Nice	☐	☐	☐	☐	☐	annoying
effective	☐	☐	☐	☐	☐	superfluous
irritating	☐	☐	☐	☐	☐	likeable
assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

Left/Right Hazard warning acceptance

The Left/Right Hazard warning provided an auditory warning whenever your turn signal was on AND you were changing lanes or merging and there was the possibility of a collision with a vehicle in the lane to which you were moving. Or, The Left/Right Hazard warning provided an auditory warning whenever your turn signal was not on and you were drifting out of your lane and there was the possibility of a collision with another vehicle or a solid object (e.g. a guard rail). When you received this type of warning, the display read “Left Hazard” or “Right Hazard” depending on your direction of travel.

45. Please indicate your overall acceptance rating of the Left/Right Hazard warnings.

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The left/right hazard **warnings** were:

Useful	☐	☐	☐	☐	☐	useless
Pleasant	☐	☐	☐	☐	☐	unpleasant
Bad	☐	☐	☐	☐	☐	good
Nice	☐	☐	☐	☐	☐	annoying
Effective	☐	☐	☐	☐	☐	superfluous
Irritating	☐	☐	☐	☐	☐	likeable
Assisting	☐	☐	☐	☐	☐	worthless
Undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

Left/Right Drift warning acceptance

If you were drifting out of your lane and there was no danger of you striking a solid object, you received a seat vibration and the display read “Left Drift” or “Right Drift” depending on the direction in which you were drifting.

46. Please indicate your overall acceptance rating of the Left/Right Drift warnings.

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The left/right drift **warnings** were:

Useful	☐	☐	☐	☐	☐	useless
Pleasant	☐	☐	☐	☐	☐	unpleasant
Bad	☐	☐	☐	☐	☐	good
Nice	☐	☐	☐	☐	☐	annoying
Effective	☐	☐	☐	☐	☐	superfluous
Irritating	☐	☐	☐	☐	☐	likeable
Assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

Yellow lights in the mirrors acceptance

When a vehicle was approaching or was in the research vehicle’s blind spots, a yellow light in the exterior mirrors was illuminated.

47. Please indicate your overall acceptance rating of the yellow lights in the mirrors.

For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The **yellow lights** in the mirrors were:

Useful	☐	☐	☐	☐	☐	useless
pleasant	☐	☐	☐	☐	☐	unpleasant
bad	☐	☐	☐	☐	☐	good
nice	☐	☐	☐	☐	☐	annoying
effective	☐	☐	☐	☐	☐	superfluous
irritating	☐	☐	☐	☐	☐	likeable
assisting	☐	☐	☐	☐	☐	worthless
undesirable	☐	☐	☐	☐	☐	Desirable
raising alertness	☐	☐	☐	☐	☐	sleep-inducing

48. What is the maximum amount that you would pay for a system that warns you for hazards ahead? Circle one price range.

$0

$100-200

$200-300

$400-500

$500-750

$750-1000

More than $1000

49. What is the maximum amount that you would pay for a system that warns you when you are approaching a sharp curve too fast? Circle one price range.

$0

$100-200

$200-300

$400-500

$500-750

$750-1000

More than $1000

50. What is the maximum amount that you would pay for a system that warns you for drifting out of you lane? Circle one price range.

$0

$100-200

$200-300

$400-500

$500-750

$750-1000

More than $1000

51. **What is the maximum amount that you would pay for a system that lets you know if you are about to make an unsafe lane change? Circle one price range.**

    $0

    $100-200

    $200-300

    $400-500

    $500-750

    $750-1000

    More than $1000

52. **What is the maximum amount that you would pay for a system that lets you know if someone is in your blind spot? Circle one price range.**

    $0

    $100-200

    $200-300

    $400-500

    $500-750

    $750-1000

    More than $1000

Appendix E: Summary of Light-Vehicle Post-Drive Questionnaire Responses

		Overall		Younger		Middle-aged		Older	
Question	**Anchors**	**Mean**	**St Dev.**	**Mean**	**St Dev.**	**Mean**	**St Dev.**	**Mean**	**St Dev.**
How helpful were the integrated system's warnings?	1=Not at all helpful, 7=Very helpful	5.4	1.4	5.1	1.4	5.4	1.3	5.9	1.3
Overall, I think that the integrated system is going to increase my driving safety.	1=Strongly disagree, 7=Strongly agree	5.5	1.4	5.0	1.5	5.5	1.3	6.1	1.1
Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane	1=Strongly disagree, 7=Strongly agree	6.0	1.4	5.6	1.7	5.9	1.3	6.4	0.8
The integrated system made driving easier.	1=Strongly disagree, 7=Strongly agree	4.7	1.7	4.2	1.8	4.5	1.6	5.6	1.4
Overall, I felt that the integrated system was predictable and consistent	1=Strongly disagree, 7=Strongly agree	5.1	1.4	5.1	1.3	5.1	1.2	5.1	1.8
I was not distracted by the warnings	1=Strongly disagree, 7=Strongly agree	5.3	1.4	5.2	1.6	5.1	1.4	5.7	1.1

		Overall		Younger		Middle-aged		Older	
Question	**Anchors**	**Mean**	**St Dev.**	**Mean**	**St Dev.**	**Mean**	**St Dev.**	**Mean**	**St Dev.**
Overall, how satisfied were you with the integrated system?	1=Very dissatisfied, 7=Very satisfied	5.7	1.3	5.3	1.4	5.7	1.2	6.1	1.2
Overall, I received warnings . . .	1=Too frequently, 7=Never	3.9	1.0	3.7	0.9	3.6	0.9	4.2	1.5
I always understood why the integrated system provided me with a warning.	1=Strongly disagree, 7=Strongly agree	4.8	1.8	4.8	1.8	4.4	1.9	5.2	1.8
I always knew what to do when the integrated system provided a warning.	1=Strongly disagree, 7=Strongly agree	5.8	1.4	5.9	1.3	5.5	1.5	5.9	1.3
The auditory warnings got my attention.	1=Strongly disagree, 7=Strongly agree	6.4	1.1	6.6	0.5	6.3	1.2	6.5	1.2
I always understood why the integrated system provided me with an auditory warning.	1=Strongly disagree, 7=Strongly agree	4.9	1.9	5.1	1.9	4.2	2.1	5.2	1.7
The auditory warnings were not annoying.	1=Strongly disagree, 7=Strongly agree	5.3	1.9	5.0	1.8	4.8	2.0	6.0	1.7
The seat vibration warnings got my attention	1=Strongly disagree, 7=Strongly agree	6.6	0.8	6.6	0.6	6.6	0.8	6.6	0.8

		Overall		Younger		Middle-aged		Older	
Question	Anchors	Mean	St Dev.	Mean	St Dev.	Mean	St Dev.	Mean	St Dev.
I always understood why the integrated system provided me with a seat vibration	1=Strongly disagree, 7=Strongly agree	6.0	1.3	6.4	0.7	5.4	1.5	6.2	1.4
The seat vibration warnings were not annoying.	1=Strongly disagree, 7=Strongly agree	6.0	1.6	5.6	1.8	6.0	1.3	6.3	1.6
The brake pulse warnings got my attention.	1=Strongly disagree, 7=Strongly agree	6.1	1.6	6.5	1.0	5.8	2.2	4.6	2.7
I always understood why the integrated system provided me with a brake pulse warning.	1=Strongly disagree, 7=Strongly agree	4.5	2.1	4.9	2.1	3.7	2.6	3.7	2.4
The brake pulse warning was not annoying.	1=Strongly disagree, 7=Strongly agree	4.8	2.1	4.6	2.3	4.1	2.5	4.7	2.6
The yellow lights in the mirrors got my attention.	1=Strongly disagree, 7=Strongly agree	6.2	1.2	6.4	0.9	5.9	1.2	6.2	1.3

Question	Anchors	Overall		Younger		Middle-aged		Older	
		Mean	St Dev.	Mean	St Dev.	Mean	St Dev.	Mean	St Dev.
I always understood why the integrated system provided me with a yellow light in the mirror.	1=Strongly disagree, 7=Strongly agree	6.6	0.9	6.8	0.6	6.6	0.6	6.5	1.2
The yellow lights in the mirrors were not annoying.	1=Strongly disagree, 7=Strongly agree	6.8	0.7	6.9	0.3	6.9	0.3	6.7	1.1
The integrated system gave me warnings when I did not need them (i.e., nuisance warnings)	1=Strongly disagree, 7=Strongly agree	4.9	1.7	4.8	1.6	5.3	1.8	4.7	1.8
Overall, I received nuisance warnings . . .	1=Too frequently, 7=Never	4.4	1.5	4.1	1.4	4.2	1.7	5.1	1.3
The integrated system gave me a left/right hazard warning when I did not need one.	1=Strongly disagree, 7=Strongly agree	4.2	2.1	4.6	2.0	4.3	2.1	3.7	2.1
The integrated system gave me a left/right drift warning when I did not need one.	1=Strongly disagree, 7=Strongly agree	4.0	1.9	3.6	1.8	4.5	1.9	3.8	2.0
The integrated system gave me a hazard ahead warning when I did not need one.	1=Strongly disagree, 7=Strongly agree	3.8	2.3	3.9	2.5	4.0	2.6	3.2	1.9
The integrated system gave me a sharp curve warning when I did not need one.	1=Strongly disagree, 7=Strongly agree	3.4	2.1	3.4	2.2	3.2	2.2	3.3	2.0

Question	Anchors	Overall		Younger		Middle-aged		Older	
		Mean	St Dev.	Mean	St Dev.	Mean	St Dev.	Mean	St Dev.
The integrated system display was useful.	1=Strongly disagree, 7=Strongly agree	5.6	1.6	5.5	1.8	5.4	1.8	5.8	1.5
The mute button was useful.	1=Strongly disagree, 7=Strongly agree	4.5	2.0	4.4	2.4	3.9	2.2	3.8	2.4
The volume adjustment control was useful.	1=Strongly disagree, 7=Strongly agree	5.6	1.8	5.5	1.9	5.5	2.0	5.1	2.4
Would you like to have the integrated system in your personal vehicle?	1=Definitely not, 5=Definitely would	3.9	1.1	3.6	1.3	3.9	1.1	4.2	0.9

Appendix F: Descriptions of Data Analysis Techniques

A. Linear Mixed Models

Linear Mixed Models (LMM) is a maximum-likelihood modeling approach that accommodates estimation of the effect of virtually any combination of random and fixed effects on a continuous dependent measure. Random effects are those in which the tested examples are considered a sample from a wider population. For example, in this study, tested drivers are a sample from the broad population of all drivers. Random effects are generally modeled as covariances. Fixed effects are those in which the specific levels tests are all that are of interest. In the present study, the state of a warning system (on or off) is of specific interest and means are estimated and compared.

Unlike General Linear Models (GLM), which is the more traditional way to model continuous dependent measures, LMM does not require case-wise deletion of missing data. In the present study, this is an important feature, as many analyses will make use of events that may occur once for some drivers and many times for others. All such data points can be used with LMM and the covariance between observations from the same driver can be accounted for using random effects.

B. General Linear Mixed Models

General Linear Mixed Models (GLMM) is an extension of LMM in which additional link functions may be used to expand estimation to dependent measures that do not fit the standard LMM format. For example, mixed logistic models can be estimated using GLMM for binary dependent measures by using a logit link and a logistic distribution. Similarly, categorical dependent measures can be analyzed using a generalized logit link and a multinomial distribution.

In the present study, GLMM is important because many drivers will provide more than one data point per analysis. Most notably, comparisons of baseline to system-enabled performance will be done within drivers by comparison their performance in the two phases. When the dependent measure is categorical or involves count data, a link function is required to transform the dependent measure to one that is linear in the estimated parameters. The inclusion of random effects in GLMM, as contrasted with traditional logistic regression, for example, allows us to account for covariance between observations from the same driver.

C. Logistic Regression

When the dependent measure is binary and each driver provides one data point, logistic regression can be used to predict the probability of an event (one of the two states of the binary variable). The logit link is used to transform the dependent measure to one that is linear in the parameters. The logit link is given in Equation 1:

$$\log it(p) = \log\left(\frac{p}{1-p}\right) = \log(p) - \log(1-p) \tag{1}$$

where p is the probability of the event.

Logistic regression models the relationship between various predictors (e.g., driver age, road type, time of day) and the binary outcome (e.g., responded to second warning vs. did not respond).

D. Generalized Logit Models

When the dependent measure has more than two categories and they are not ordinal (e.g., three levels of injury), generalized logit models can be used to predict the probability of each outcome category as a function of predictor variables. In this case, one category is chosen as the reference, and the generalized logit is the log of the ratio of the probability of the category of interest to the reference, as in Equation 2:

$$\log it(p_i) = \log\left(\frac{p_i}{p_k}\right) = \log(p_i) - \log(p_k) \tag{2}$$

where i is the category of interest and k is the reference category.

E. Case Cross-Over and Case-Control

In a case-crossover study, individual drivers are used as their own control. A random set of events of interest are identified (i.e., warnings) and identified as event windows. In addition, a nominally “matched” set of control windows for each driver is also drawn from the data set and referred to as control windows. If an individual driver is chosen for multiple warning events, his/her control window will be sampled relative to the specific warning event and treated as independent. The control windows will be defined based on a fixed period prior to the event of interest (i.e., the warning).

The events and the matched control windows are then reviewed for behaviors that might contribute to warning events, namely secondary behaviors. The basic table from a case-crossover study is shown in Table C.1 below. Equation 3 shows the computation of the estimate of the odds of a warning given secondary behaviors compared to no secondary behaviors (odds ratio).

Table C.1. Case Cross-Over Design Table

		Event Window (Warning)	
		Secondary behavior	No secondary behavior
Control Window	Secondary behavior	a	b
	No secondary behavior	c	d

$$\frac{c}{b} = \frac{p(s \mid w)p(s' \mid w')}{p(s' \mid w)p(s \mid w')} = \frac{p(w \mid s)p(s)p(w' \mid s')p(s')p(w)p(w')}{p(w)p(w')p(w \mid s')p(s')p(w' \mid s)p(s)}$$

$$= \frac{p(w \mid s)p(w' \mid s')}{p(w \mid s')p(w' \mid s)} = \frac{odds(w \mid s)}{odds(w \mid s')} \tag{3}$$

Case-crossover design is a powerful tool, particularly because it uses individual drivers as their own control. However, it relies on selection based on a warning event, thereby tending to over-represent drivers who receive more warnings. An alternative approach is the case-control study, in which a set of cases (warning events) and a set of controls (non-warning events) are selected at random. These video clips are then inspected for the presence of secondary behaviors. The ratio of the resulting conditional probabilities is an estimate of the odds ratio of warning for secondary behavior vs. no secondary behavior.