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Light-Vehicle Field Operational Test Key Findings Report

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16. Abstract

This document presents key findings 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, lateral-drift, lane-change/merge crash, and curve-speed warnings) installed on a fleet of 16 passenger cars and operated by 108 randomly-sampled drivers for a period of six weeks each. Each car 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. The 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 crash warning system and 72 percent of all drivers said they would like to have an integrated warning system in their personal vehicles. Drivers also reported that they found the blind-spot detection component of the lane-change/merge crash warning system to be the most useful and satisfying aspect of the integrated system.

17. Key Words
Collision warning, intelligent vehicles, passenger vehicle safety

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List of Acronyms

AMR	Available maneuvering room
BSD	Blind-spot detection
CSW	Curve-speed warning
DVI	Driver-vehicle interface
FCW	Forward collision warning
FOT	Field operational test
GPS	Global positioning system
IVBSS	Integrated Vehicle-Based Safety Systems
LCM	Lane change-merge
LDW	Lateral-drift warning
LED	Light-emitting diode
LV	Light vehicle
POV	Principal other vehicle
RDCW	Roadway Departure Crash Warning
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 when 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 on when the warning was issued and a prioritization scheme for the detected threat. A driver-vehicle interface (DVI) was developed that consisted of auditory and haptic cues, as well as visual feedback. 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, 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 the vehicle. The vehicles were instrumented to capture information on the driving environment, driver behavior, integrated warning system activity, and vehicle kinematics. Subjective data on driver acceptance was collected using a post-drive survey, driver debriefings 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.

Field Operational Test 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.

Approximately 21 percent of the distance traveled was driven at night, 15 percent of driving took place in freezing temperature conditions, and 7 percent of the miles had wipers on. Most trips were rather short (18.5% of trips were less than 1 mile and 89.5% less than 22.5 miles). Forty-three percent of the driving was performed on freeways, and 37 percent on surface streets, and the remaining occurred on local roads, ramps, or unknown road types (e.g., private roads and parking lots). The data set collected represented 213,309 miles, 22,657 trips, and 6,164 hours of driving.

More detailed information on vehicle instrumentation and the 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%).

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[1] Lateral offset is the distance between the centerline of the vehicle and the centerline of the lane (see Figure 30, page 48).

- 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.

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 avoid crashes.

Three crash-warning subsystems were integrated into both light vehicles and heavy trucks: forward-crash warning, lateral-drift warning, and lane-change/merge crash warning. The light-vehicle platform also included a curve-speed warning 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;
- 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 when they are traveling at a rate of speed too high to safely negotiate an upcoming curve.

Preliminary analyses by U.S. DOT indicate that 61.6 percent (3,541,000) of police-reported, light-vehicle crashes can be addressed through the widespread deployment of integrated crash warning systems that include rear-end, roadway departure, and lane-change/merge warning functions. 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 has the potential to 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 5-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 during the program included sharing sensor data across multiple subsystems, arbitration of warnings based upon threat severity, 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 the heavy-truck platforms, developing data acquisition systems, and conducting the field operational tests. Visteon Corporation, with support from Takata Corporation, 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 also included senior technical staff from the National Highway Traffic Safety Administration, the Federal Motor Carrier Safety Administration, the Research and Innovative Technology Administration (RITA), the National Institute for Standards and Technology, and the Volpe National Transportation Systems Center. RITA's Intelligent Transportation Systems Joint Program Office was the program 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

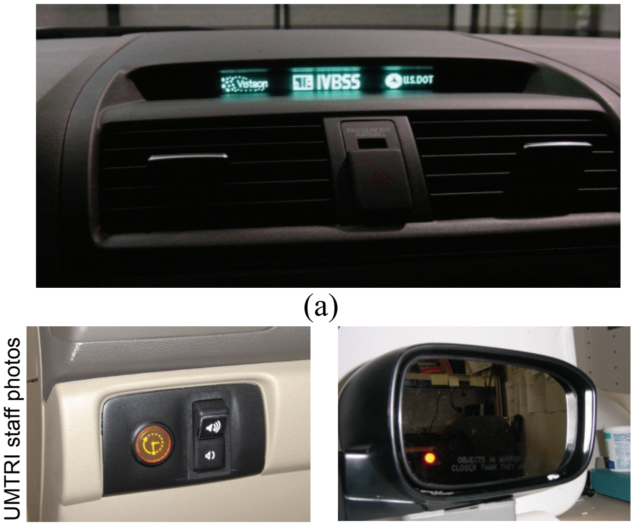
Phase II (June 2008 to November 2010) consisted of continued system refinement, construction of a fleet of 16 vehicles equipped with the integrated system, extended pilot testing, conduct of the FOT, and analysis of the field test data. Refinements to the system hardware and software continued, with 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 test; this proved to be a valuable undertaking, as final system enhancements were incorporated before the field test officially began. 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.

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

Primary crash warning information is presented 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[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 1. For lateral maneuvers, Table 1 indicates that drifting into an adjacent lane without activating a turn signal or onto a shoulder that is occupied triggers a haptic seat cue. Drifting into an occupied lane or shoulder produces an audible tone meant to be more salient to the driver; an intentional lane-change or merge maneuver (i.e., with turn signal applied) into an occupied lane results in the same audible tone and visual text display, as shown in Table 1. The same audible tone and text are used because the crash threat is similar and the driver responses will likely be similar.

Table 1 also shows that the two longitudinal crash threats (rear-end and curve-speed warning) are addressed using similar, but not identical warnings to the driver. The FCW subsystem provides an audible tone and a brake pulse, while the CSW subsystem provides the same tone, but without the brake pulse. A visual display of text confirming the meaning of the warnings is different for these two, as indicated in the table.



(a)

UMTRI staff photos

(b) (c)

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

Table 1: Crash warning and blind-spot detection cues to the driver

Displayed text	Primary cues to driver	Subsystem	Crash type addressed
"Hazard Ahead"	Audible tone #1, Brake pulse	FCW	Rear-end crash
"Sharp Curve"	Audible tone #1	CSW	Curve-over speed 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 has an adjustable volume control for the audio component of warnings using a three-position rocker switch mounted near the driver's left knee bolster. Drivers were not allowed to disable 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 in two-minute increments, up to six minutes at a time. This function provided drivers some relief in the unusual case of travel through an environment that could lead to a series of false warnings. An example is traveling through a freeway construction zone in which a travel lane has been shifted with partial removal of the painted lane markers.

1.3 Conduct of the Field Operational Test

Sixteen late-model Honda Accords were used as research vehicles, with one vehicle serving as a backup unit. A total of 117 participants were recruited in order to ensure that data from the 108 drivers needed to satisfy the experimental design was obtained. The final data set included 108 drivers, stratified by age and gender. The age groups examined were 20 to 30, 40 to 50, and 60 to 70 years old, with a balance for gender within each age group. Consenting drivers used the test vehicles in an unsupervised manner, to pursue their normal trip-taking behavior over a 40-day period, using the test vehicles as their own personal vehicles.

The field test used a within-subjects experimental design where each driver operated a vehicle in both baseline and treatment conditions. The first 12 days of vehicle use was the baseline period during which no system functions were provided to the driver, but all subsystems and equipment operated in the background and on-board data was recorded. On the 13th day of their participation, the system was enabled, providing warnings when appropriate. This treatment period lasted for 28 days, after which the participant returned the research vehicle to UMTRI. Use of the vehicles by anyone other than designated participants was prohibited, unless it could be considered an emergency. Objective measures of the integrated system, vehicle, and driver performance were collected during the entire test period. The valid data set collected for the 108 drivers represented 213,309 miles, 22,657 trips, and 6,164 hours of driving.

1.4 Deviations from the Field Operational Test Plan

There were no deviations from the light-vehicle field operational test plan (Sayer et al., 2008).

1.5 Report Preparation

1.5.1 Data Analysis Techniques

Several statistical techniques were employed in the field test data analysis. The two most common techniques used were the general linear model and linear mixed model techniques, depending on the nature of the dependent variable. Both the general linear model and the linear mixed-model are under the generalized linear mixed model category. Each model serves a different purpose, and should be used with different types of data. The main factors that must be considered in model selection include type of outcome variable (nominal, ordinal, or interval) and type of input variable (nominal, ordinal, or interval) and the outcome (fixed or random effect). Generally speaking, the linear mixed-model works better for continuous output variables (e.g., headway and reaction time), while the generalized linear model works better for ordinal output variables (e.g., frequency data).

Findings that are based on results of a linear mixed model are derived from a model, not directly from raw data. However, the means and probabilities predicted by the model were always checked against queries of the raw data set to substantiate the models developed. In all uses of the linear mixed model technique, drivers were treated as a random effect. Significant factors in the linear mixed model approach were determined using a backwards step-wise method. Additional information regarding the statistical techniques used in analyzing the light-vehicle field test data can be found in the IVBSS Light-Vehicle Field Operational Test Data Analysis Plan (Sayer et al., 2009).

1.5.2 Identification of Key Findings

The approach taken in preparing this report was to present key findings only. This approach was selected in order to offer a relatively short report that would more readily convey the most important results from the field test. Key findings were defined as results that are most likely to be actionable, or may have the greatest impact, relative to the development and deployment of integrated, and non-integrated, crash warning systems for passenger vehicles.

A much larger report on the analysis of the data is available. The IVBSS Light-Vehicle Platform Field Operational Test: Methodology and Results (Sayer et al., 2010) contains a comprehensive description of the FOT and results of all research questions outlined in the data analysis plan.

1.5.3 Report Structure

The remainder of this report presents key results for the 31 research questions identified in the data analysis plan. These questions address the most relevant topics related to evaluation of the integrated crash warning system's effects on driver behavior and driver acceptance. The results section is organized to present findings for the integrated system overall, including warning arbitration (Section 2.1), lateral control and warnings (Section 2.2), longitudinal control and warnings (Section 2.3), and the driver-vehicle interface (Section 2.4). Within each of these subsections are descriptive statistics summarizing vehicle exposure and the integrated warning system activity, results on differences in driving behavior with and without the system, and evaluations of driver acceptance. Appendix A provides a summary table of the research questions, as well as high-level results for each question, and Appendix B consists of the Variable Definitions Table.

2. Results

2.1 Warning Arbitration and Overall System 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.

2.1.1 Vehicle Exposure

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

The FOT began on April 16, 2009, and ended on May 13, 2010. Table 2 summarizes categories of mileage accumulated during that period by 108 drivers. The 117 participants drove research vehicles a total of 234,397 miles during the FOT. Data was collected for 98.7 percent of this distance; 1.3 percent of the lost data was associated with distance covered during system start-up at the beginning of a trip.

Table 2: 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 117 drivers who participated in the FOT, 108 were selected as subjects for the analyses. The 108 drivers were distributed equally among six age and gender groups; drivers with the highest quality data were included in the analysis. The 108 drivers traveled 222,508 miles, and data was recorded for 98.7 percent of that distance. These drivers took a total of 24,989 "trips," which can be defined by a vehicle ignition cycle (i.e., from the time the vehicle ignition is turned on until it is turned off). Of the 24,989 trips, 2,105 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 data acquisition system 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 6,164 hours of driving. It is these trips and the related data that form the basis for the analyses performed. As shown in Table 2, approximately one-third of the valid distance was accumulated during the baseline period and approximately two-thirds were accumulated during the treatment period.

Figure 2 shows the chronology of valid trip distance accumulated over the course of the FOT. Approximately 21 percent of the valid distance, or 42,571 miles, was driven at night and 14,831 miles (7%) was accumulated with the windshield wipers on. Approximately 15 percent of driving took place in freezing temperatures as the FOT was conducted over almost 13 months, included a full Michigan winter.

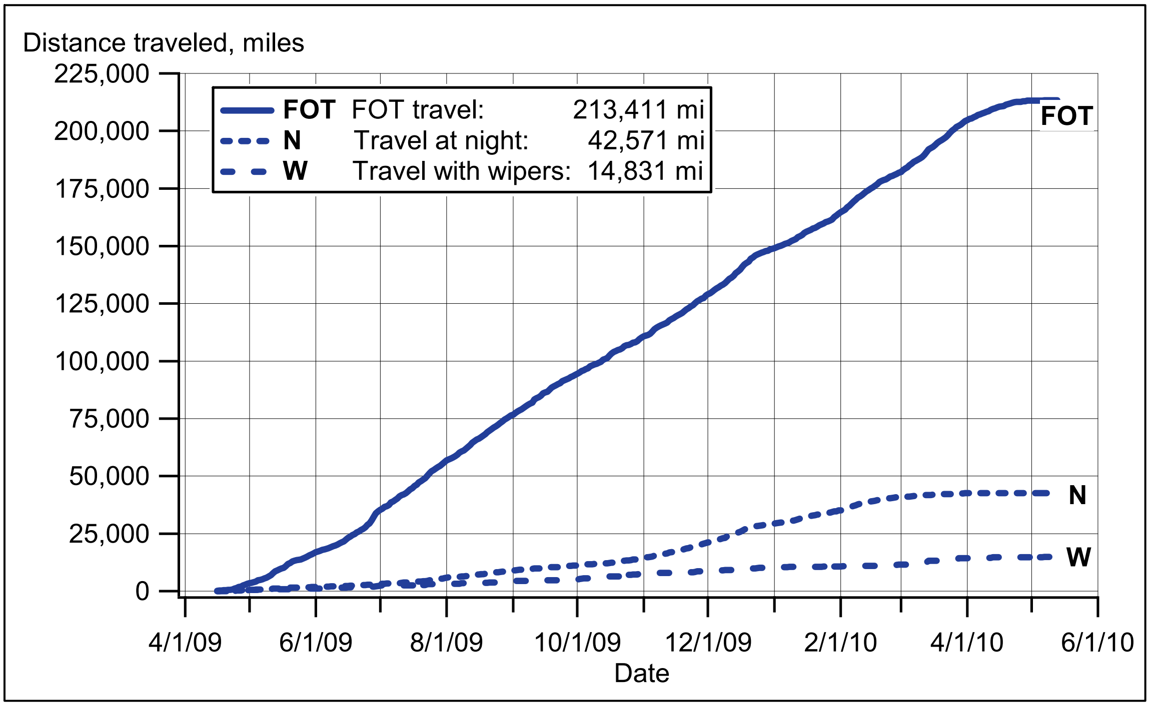


Figure 2: Chronology of the accumulation of valid travel distances

Table 3: 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	22,181	10	27,023	13	19,666	9	68,870	32
Treatment	46,688	22	54,706	26	43,045	20	144,439	68
Total	68,869	32	81,729	39	62,711	29	213,309	100

2.1.1.1 Travel Patterns

Figure 3 shows the geographical range of 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, DC, and eastern North Carolina. The boundary between the central and eastern time zones is shown with the heavy dashed line.

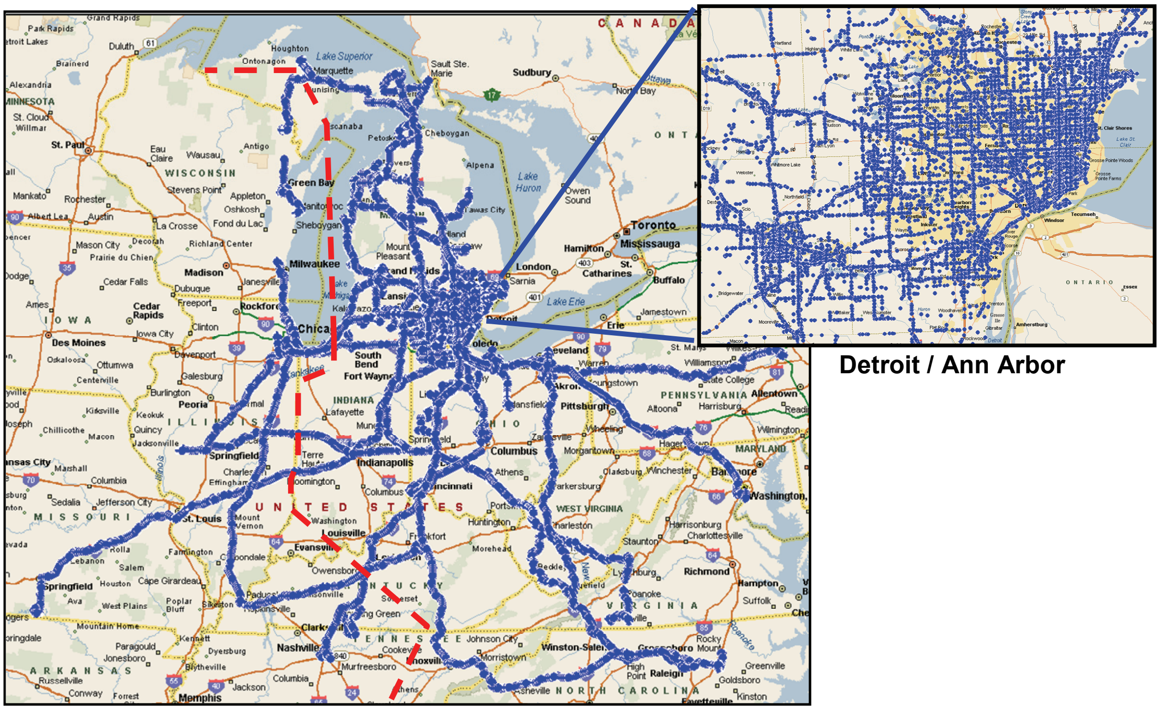


Figure 3: Geographical range of travel by FOT drivers

2.1.1.2 Trips and Travel Segments

Most trips were relatively short distances (18.5% of trips were less than 1 mile and 89.5% less than 22.5 miles). 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.

2.1.1.3 Roadway Variables

Certain analyses that follow will distinguish between travel on surface streets and roads, limited access highways, and highway ramps. The data base distinguishes between limited access highways, entrance and exit ramps, major and minor surface streets, and local roads. Figure 4 shows the distribution of valid travel distance and time-in-motion by road type and travel on unknown surfaces (largely parking lots and private roads). Table 4 presents average, median and most likely speeds by road type and also the percentage of time the vehicles were in motion while on each road type.

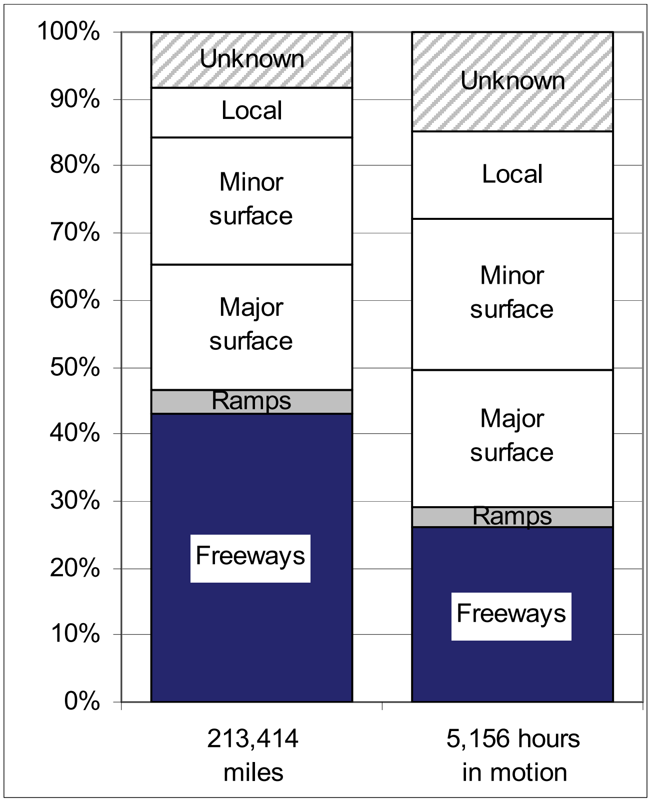


Figure 4: Distribution of travel by road type

Table 4: Average, median and most likely travel speed 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

2.1.1.4 Environmental Factors

Figure 5 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 windshield 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 greater than -6 degrees.

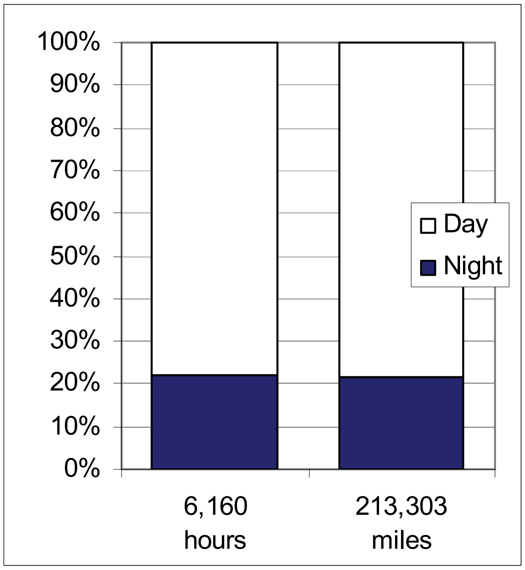


Figure 5: Portions of travel in daylight and nighttime

2.1.1.5 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 6 illustrates the warning rates for the baseline and treatment conditions. The decrease in warning rate is due to increased turn signal use during lane changes in the treatment period (see Section 2.2.2).

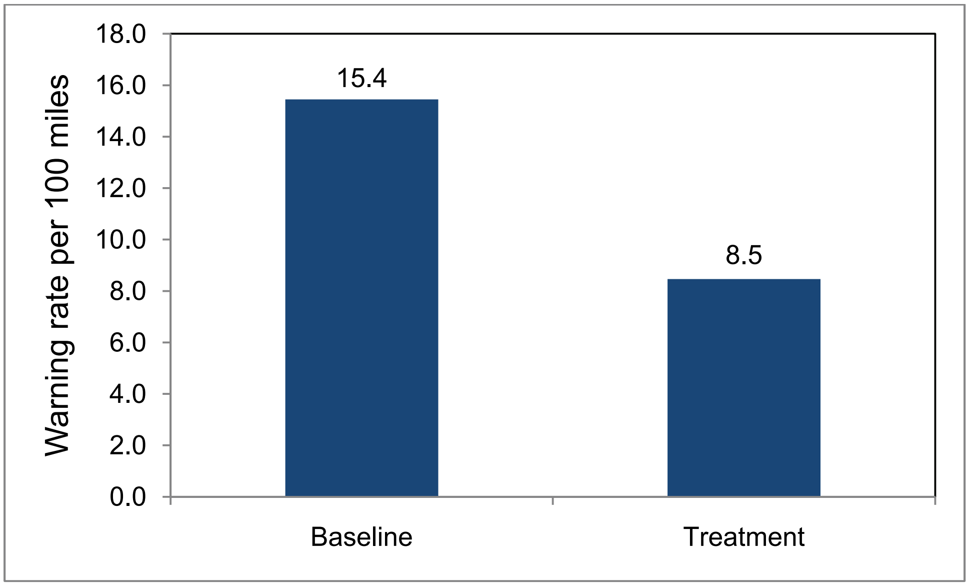


Figure 6: Overall warning rates for baseline and treatment conditions

2.1.2 Driver Behavior

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 5-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 to 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 must also contain windshield wiper use.

A total of 2,160 video clips 5 seconds long were visually coded for the presence of secondary tasks. These video clips were chosen with the following criteria:

- 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 or after the video clip.
- Video clips were at least 5 minutes apart.

Results: A list of secondary tasks and the coded frequencies for the 2,160 video clips is listed in Table 5. A total of 111 video clips from the sample contained multiple secondary tasks; each individual task is uniquely represented in the table.

Table 5: 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

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 use of wireless communication devices, grooming was found to be the next most common secondary task (4.9%). In this analysis, eating, drinking, grooming, and smoking were 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 cigarettes, etc.) were scored as high involvement. Tasks involving one hand were scored as low involvement (for example, a driver simply holding a cigarette and any one-handed grooming such as touching the face, head, or hair).

Table 6 provides descriptive statistics for secondary task involvement by several different variables. There was 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 limited access 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 involvement, though it should be noted that there were only 24 exposure clips that had windshield wiper activity.

Table 6: 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

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 that drivers performed 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).

Interpretation: Drivers were no more likely to be involved 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 number of times drivers were involved 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 fully 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 due to an insufficient number of valid warnings. A total of 2,040 5-second video clips were selected. For each driver, 20 video clips were selected, 10 preceding a warning and 10 that did not precede a warning. Where possible, the number and types of warnings selected for each driver were: 1 CSW, 1 FCW, 1 LDW imminent, 2 LCM, and 5 LDWs.

This mix of warnings roughly corresponded to the overall percentage of each warning type observed during the FOT, but not necessarily for each particular driver. Only valid warnings were included. (See Sections 2.2.1.1 and 2.3.1.1 for definitions of valid warnings). 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, LDWs were selected from those in which the driver drifted in the lane and made a correction. Numerous LDWs that were triggered as a result of unsignaled lane changes were not included in this analysis.

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 7 lists the 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, or 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 7: 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 integrated system arbitrates between multiple threats, which threat 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: Twenty-three multiple threat warnings were recorded during the FOT. Of these events, six occurred during the treatment period. Three of the six events involved an LDW followed by a CSW. In these cases, although occurring close in time, the LDWs were unrelated to the CSWs. Analysis of the three remaining events and the driver's response is given below:

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 or steer.

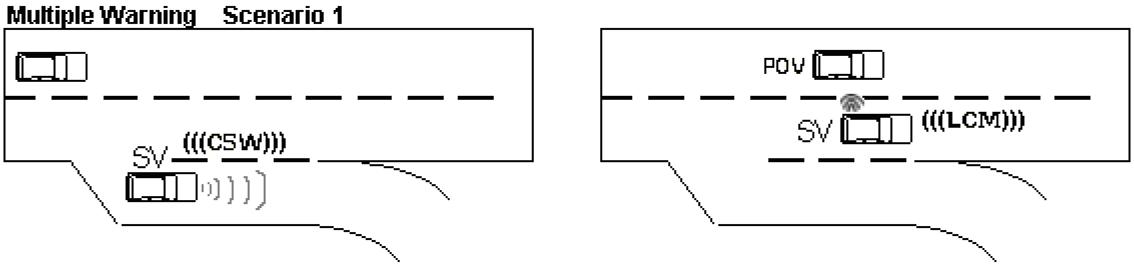


Figure 7: Multiple warning scenario 1

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, as 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 moved back into the center of her lane.

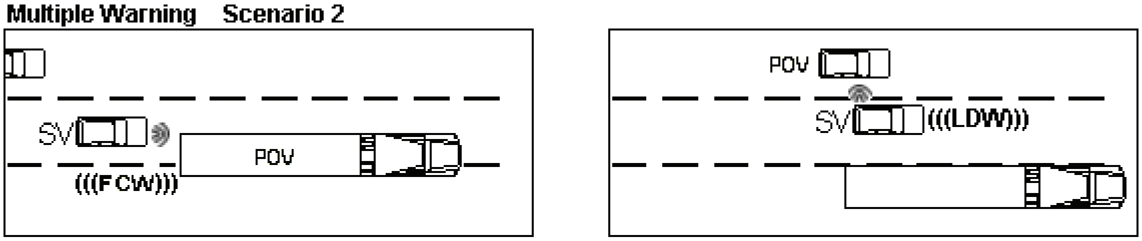


Figure 8: Multiple warning scenario 2

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 his right. He received an LDW as he crossed a dashed line without using his turn signal, then an FCW as he moved to pass the stopped vehicle due to passing at close range. He was already steering to initiate a passing maneuver when he received the FCW.

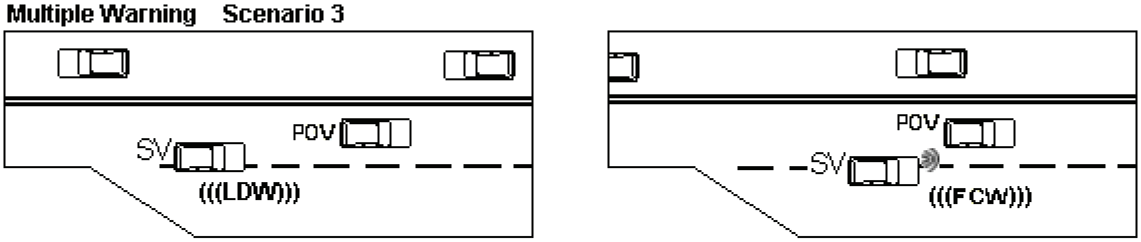


Figure 9: Multiple warning scenario 3

Interpretation: Multiple warning events are quite 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 during the FOT, no patterns could be observed about which warning drivers responded to, if at all.

2.1.3 Driver Acceptance Research Questions

This section discusses key findings on driver acceptance of the overall integrated system. Results are predominantly based on post-drive survey responses. The majority of the questions employed a 7-point rating scale where 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 a 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 5-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 a more favorable view about a technology.

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 using the integrated system, 28 percent of all drivers replied that their driving behavior did not change. Nearly 25 percent of drivers said their use of turn signals increased with the integrated system. Changes in driving behavior such as drifting less often, driving more carefully, and increased awareness (Figure 10) were each mentioned by about 20 percent of the drivers. Increased awareness of vehicles in their blind spots, 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 said that they relied on the blind-spot detection system when changing lanes.

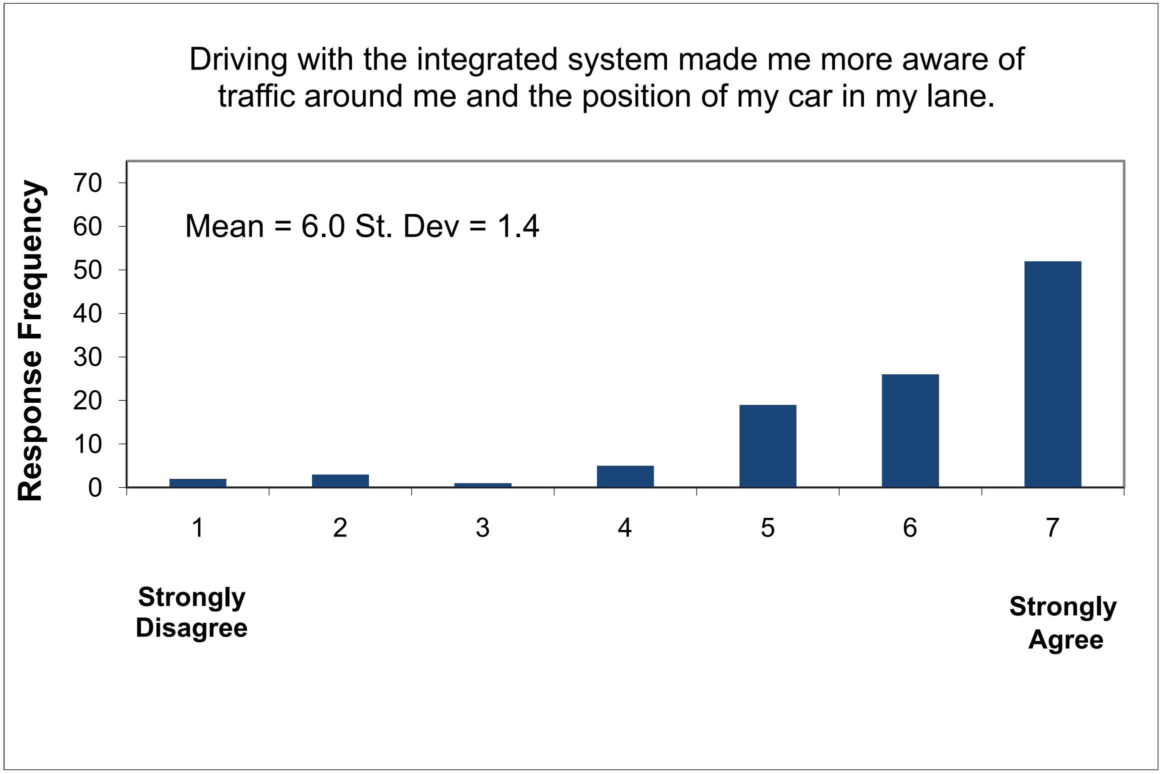


Figure 10: Drivers' perception of increased awareness of traffic and their position in their lane

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, 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 LDWs triggered 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 accepted the integrated system and were willing to make allowances for some of its shortcomings (e.g., invalid warnings). Van der Laan scores were calculated to indicate how useful drivers perceived the system and how satisfied they were. 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. At the subsystem level:

- Drivers were largely indifferent toward the CSW and FCW functions, and rated them neutral with regard to satisfaction, while recognizing they had some utility.
- Both LDW and LCM were rated favorably for both utility and satisfaction and were commensurate with the rating of the overall integrated system.
- BSD was rated very highly for both utility and satisfaction, higher than the overall integrated system rating.

Overall, drivers rated the integrated system favorably (mean = 5.7). While somewhat satisfied with the integrated system, younger drivers indicated less satisfaction than middle-aged and older drivers (Figure 11). Whether or not drivers would like to have the integrated system in their personal vehicles is a measure of their degree of acceptance of the integrated system. The majority of drivers (72%) indicated that they “probably would” or “definitely would” like to have the integrated system in their personal vehicle, while younger drivers were less likely to want the integrated system 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 in their personal vehicles (Figure 12).

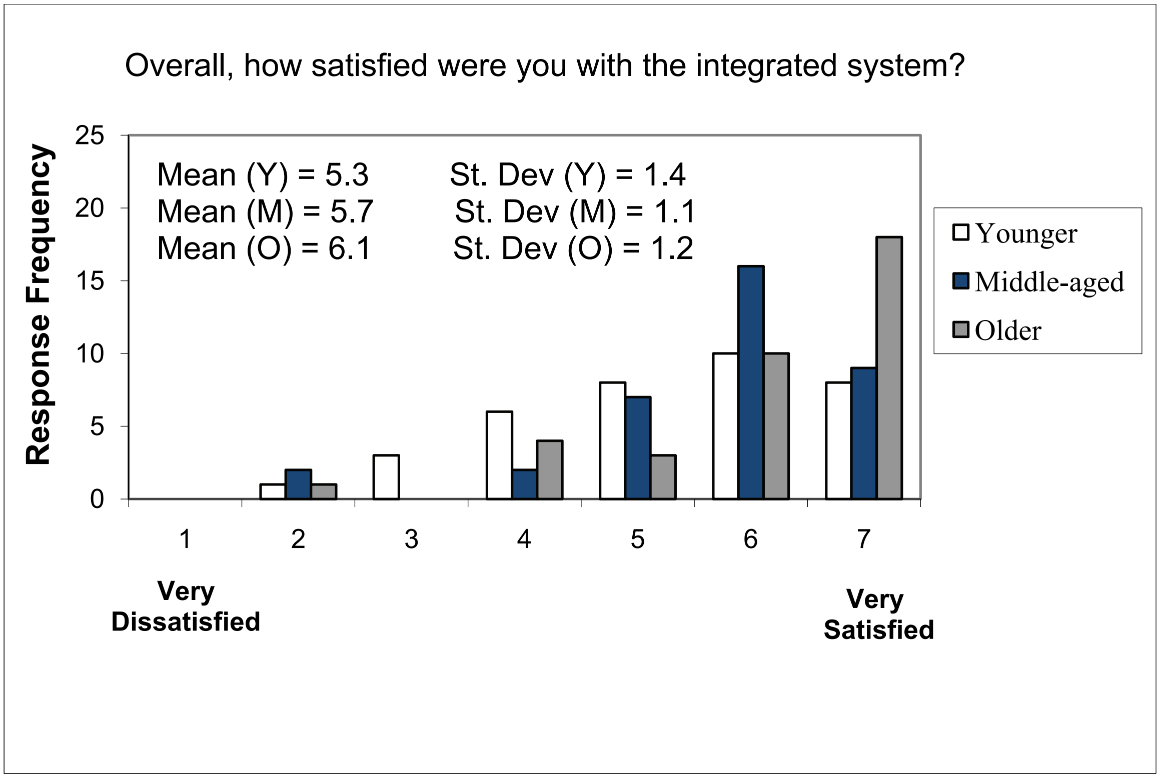


Figure 11: Overall driver satisfaction with the integrated system

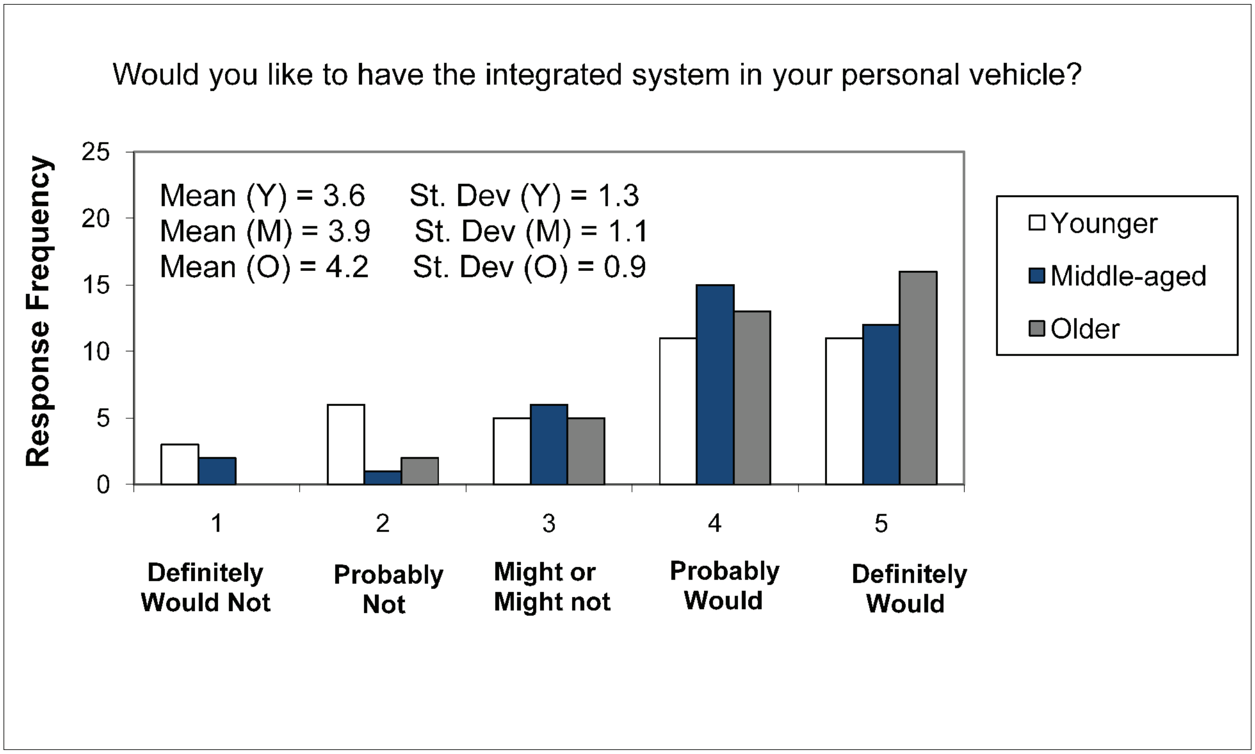


Figure 12: Drivers' willingness to have the integrated system in their personal vehicle

Interpretation: Drivers accepted the integrated system and rated it favorably in terms of both usefulness and satisfaction. Van der Laan scores enable comparisons between different automotive technologies. Test participants who drove the test vehicles during the IVBSS FOT 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 Roadway Departure Crash Warning (RDCW) FOT (LeBlanc et al, 2007). While 25 percent of the younger drivers were not interested in having the integrated system in their personal vehicles, 72 percent of all drivers said they would like to have the integrated system. It is not clear why younger drivers were reluctant to purchase an integrated warning system; however, it most likely based on their perception of need and system cost. Younger drivers have less driving experience to base their need for such a system, and they are less likely to be able to afford such a costly option.

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

Results: Drivers reported that all warning types were attention-getting. Table 8 provides mean ratings for the attention-getting properties and ratings of annoyance for all the warning modalities. The most attention-getting of the warnings was seat vibration, which drivers found to be unique and interesting. As illustrated in Figure 13, while all of the warning modalities were attention-getting, drivers agreed with the statement “I was not distracted by the warnings” (mean = 5.3). 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 BSD yellow lights in the side-view mirrors. This may be explained by the fact that drivers only received information about vehicles in their blind spot when they looked directly at their mirrors. While the warning was salient, several drivers in debriefing sessions mentioned that they were “startled” or “alarmed” when they experienced a brake pulse, particularly if the warning they received was invalid.

Table 8: Warning modalities and ratings of attention-getting properties

Warning Modality	**Attention-Getting Properties** (Mean Rating: 1=Strong Disagree, 7= Strongly Agree)	**Warning Did Not Annoy** (Mean Rating: 1=Strong Disagree, 7= Strongly Agree)
Auditory	6.4	5.3
LDW Seat Vibration	6.6	6.0
FCW Brake Pulse	6.1	4.8
BSD Yellow Lights	6.2	6.8

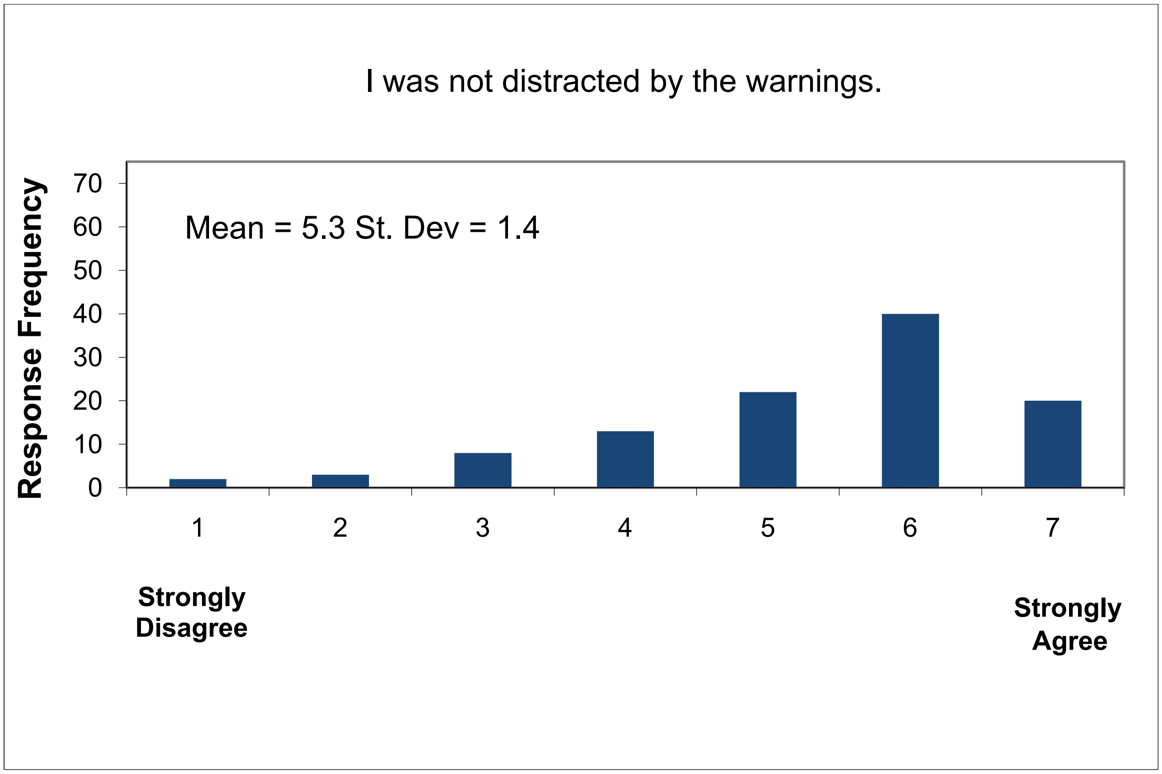


Figure 13: Drivers' perception of the warning levels of distraction

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 using the integrated system. They reported believing that the integrated system would increase their driving safety (mean = 5.5), and that this effect appears to increase with increasing driver age (Figure 14). Furthermore, drivers reported that the integrated system heightened their awareness while driving (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 15). 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 the 28 focus group attendees stated that the integrated system prevented them from crashing.

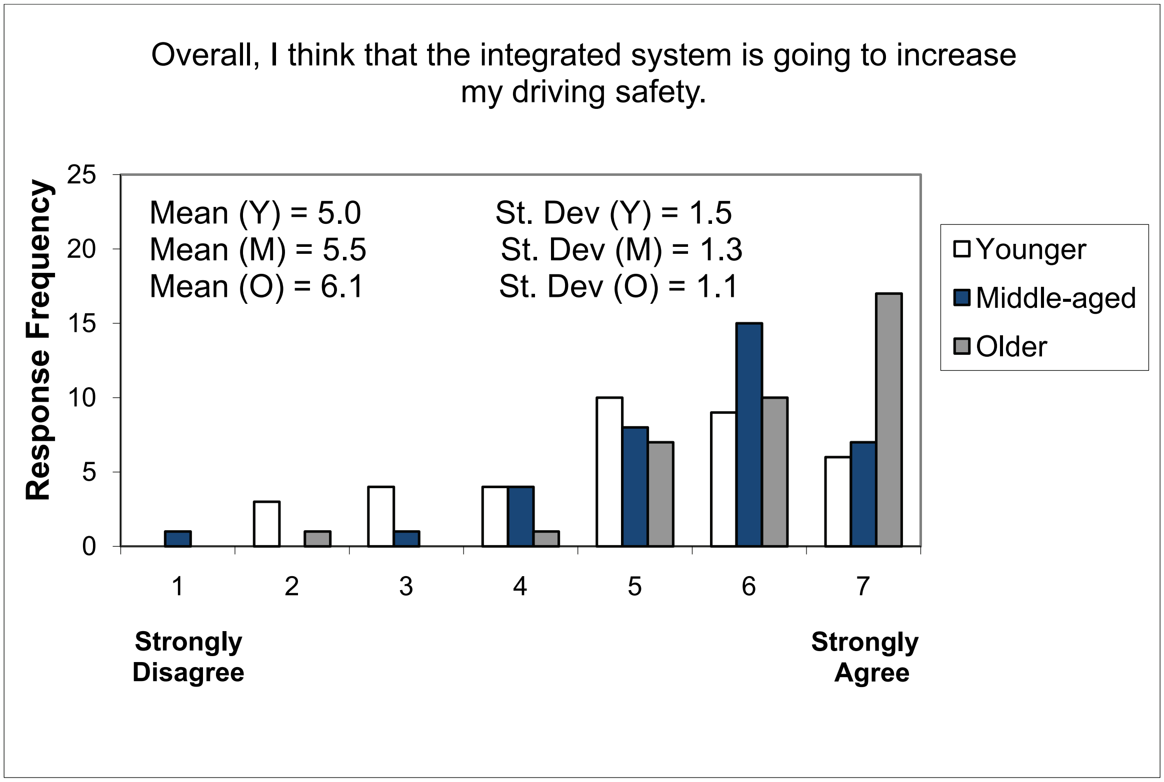


Figure 14: The integrated system's effect on safety

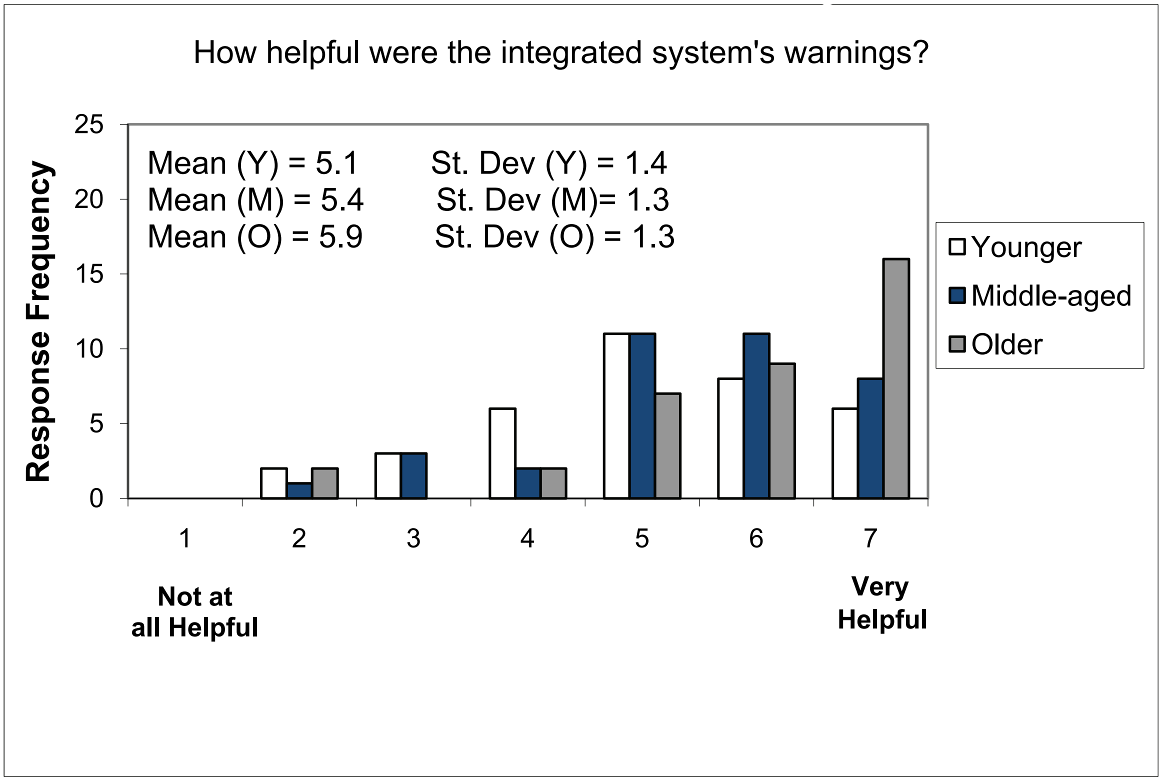


Figure 15: Drivers' perception of the integrated system's warnings helpfulness

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 a benefit from the system beyond more abstract benefits such as "increased awareness." If drivers believe that the presence of the integrated system 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 16). 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 present) affected their rating. There was no noticeable impact of age in response to this question.

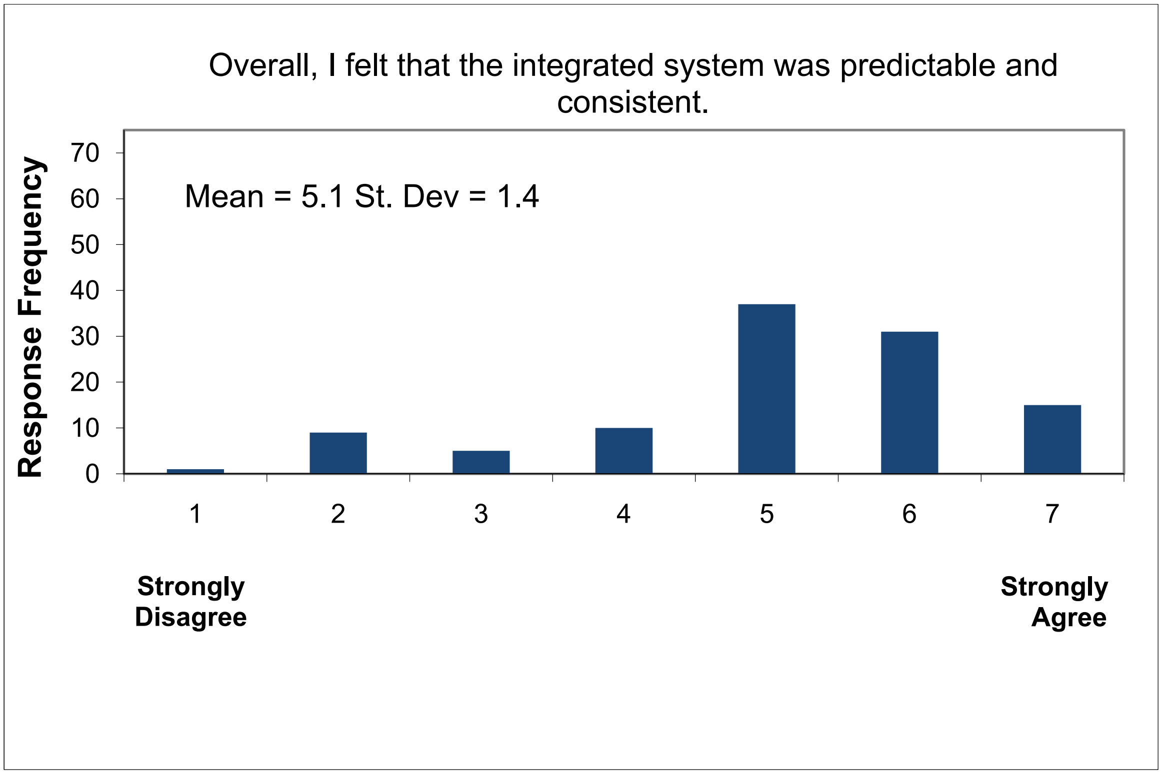


Figure 16: Ratings of the integrated system's predictability and consistency

Interpretation: In general, drivers rated the integrated system favorably in terms of predictability and consistency. Reducing the invalid warning rate would enable drivers to develop a more accurate mental model, which would likely result in improved ratings of predictability and consistency and an increase in confidence in the reliability of the warnings.

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

Results: In the questionnaire, the word, "nuisance" is used to include 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 systems provided warnings when drivers did not need them, participants did not feel that these warnings were provided too frequently (Figure 17 and Figure 18). Older drivers stated that they received nuisance warnings with the lowest frequency of all 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 groups. This effect is supported by data presented in Table 9. 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 all age groups.

For the individual subsystems, drivers reported receiving fewer nuisance warnings from the CSW and FCW subsystems than they did from the lateral subsystems (Figure 19). In fact, the most invalid warnings drivers received were cautionary LDWs, followed by FCWs per 100 miles of driving. It is quite possible that drivers were responding to the number of nuisance warnings they received rather than how frequently they received them when responding to this particular question. With the exception of left and right hazards, the subjective ratings of nuisance warnings increased with an increasing numbers of nuisance warnings. That is to say, drivers were able to perceive differences between the numbers of nuisance warnings provided by the subsystems. Table 10 summarizes the number of total (valid and invalid) and invalid warnings, the percentage of invalid warnings and invalid warning rate.

This relationship between the number of nuisance warnings received by drivers and their subjective ratings does not hold true for left and right hazards which were received for the LCM and LDW imminent warnings. Drivers received the fewest invalid warnings from these subsystems, yet agreed with the statement "The subsystem gave me warnings when I did not need them." Perhaps the type of warning and conditions under which drivers received them (e.g., making a lane change and other high workload situations) had a greater influence on their overall perception than the number of times they received these warning types.

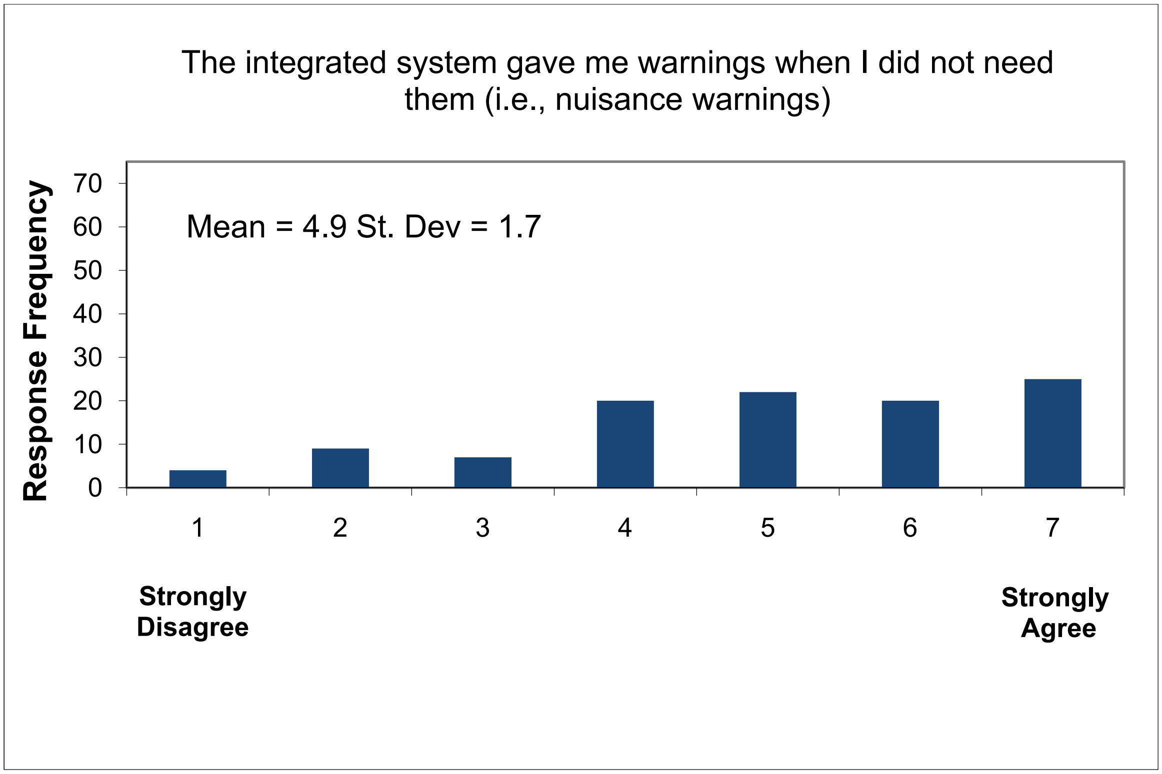


Figure 17: Drivers' perception of nuisance warnings

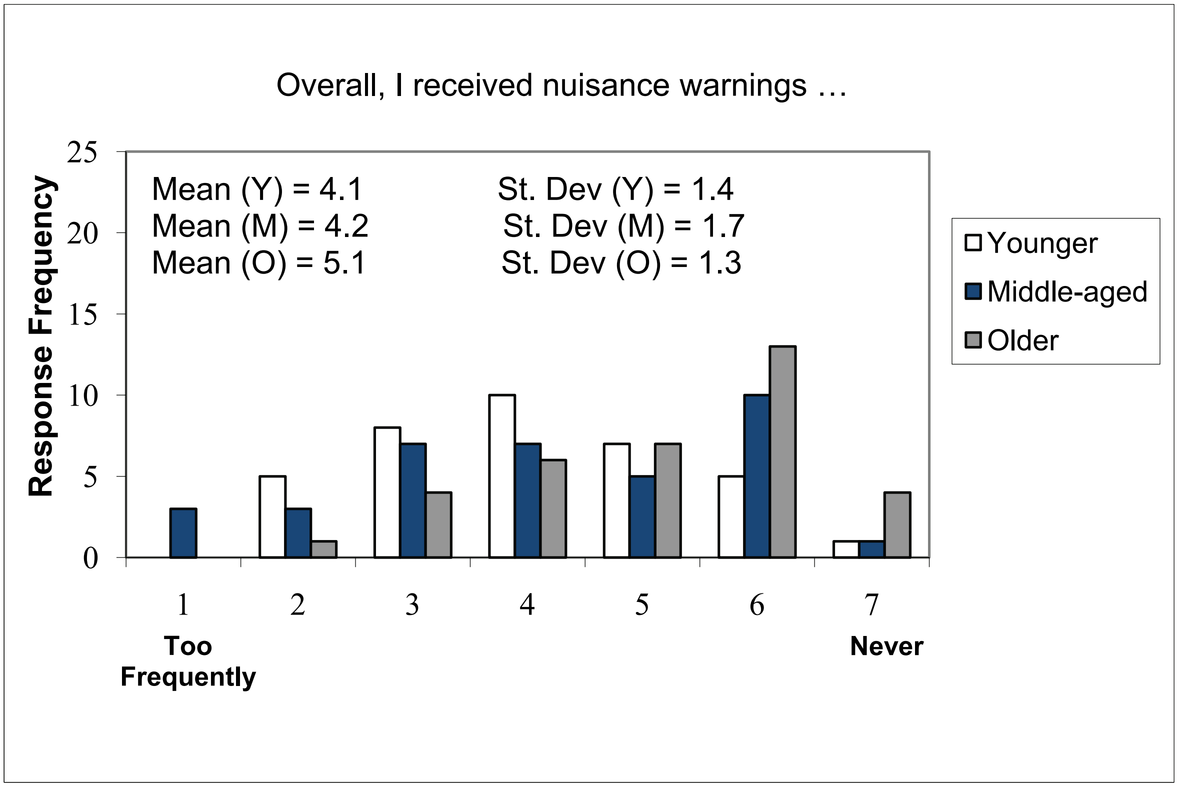


Figure 18: Frequency of nuisance warnings.

Table 9: Invalid warnings and invalid warning rates by age group

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

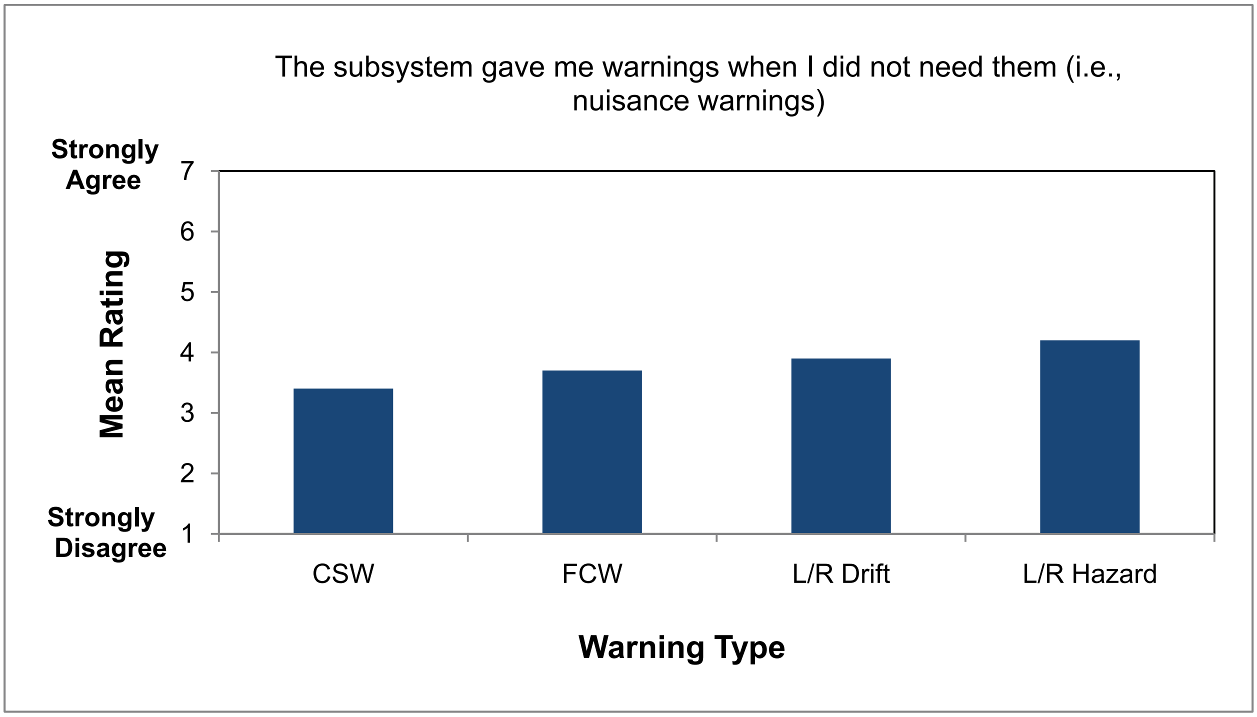


Figure 19: Mean ratings for each subsystem's nuisance warnings

Table 10: 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, 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.

Drivers received nearly 10 times more total warnings from the lateral than longitudinal subsystems, while receiving only 15 percent more nuisance warnings per 100 miles from the lateral subsystems. However, the percentage of longitudinal subsystem invalid warnings was much higher than for the lateral subsystems. Further reduction of invalid warnings, particularly for repeated warnings occurring at the same location might be addressed by mapping these locations, is recommended for future system designs.

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 the integrated system provided warnings, drivers generally knew how to respond (Figure 20).

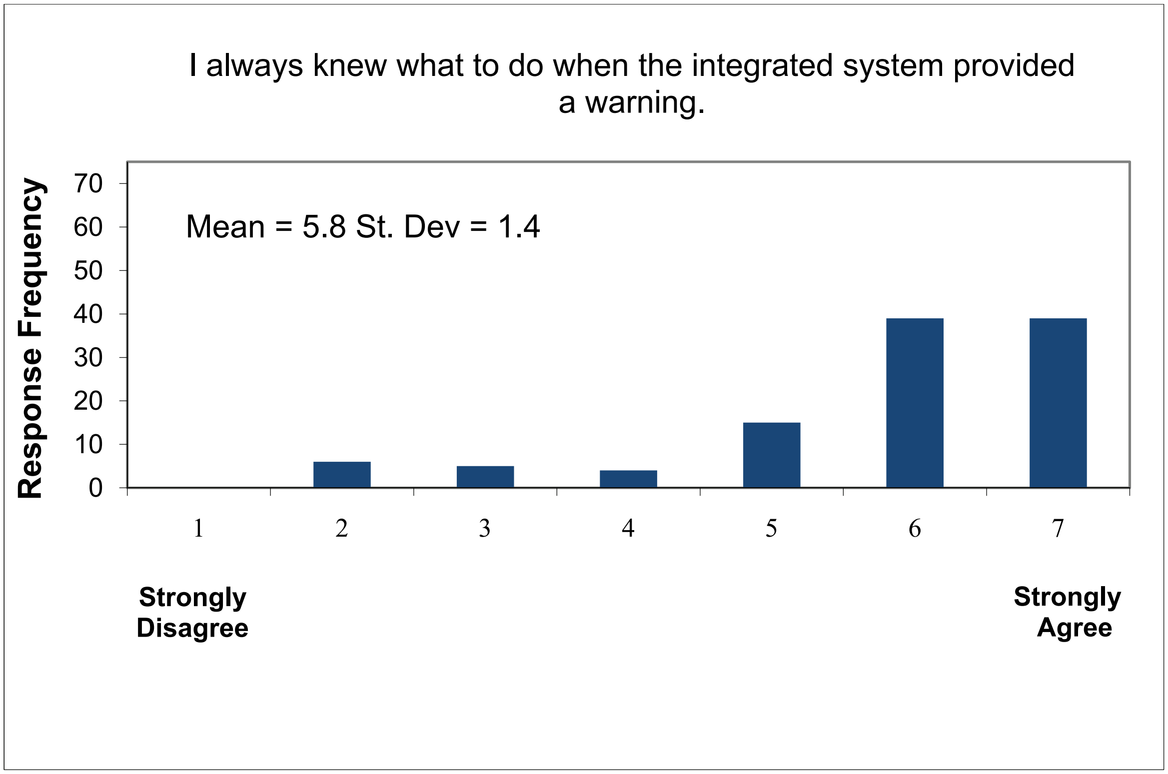


Figure 20: Drivers' understanding about how to respond to warnings

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 adoption and 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 21) and understood what to do (e.g., brake in response to an FCW) when the integrated system provided a warning (Figure 20). There was no effect of driver age on understanding of the integrated system.

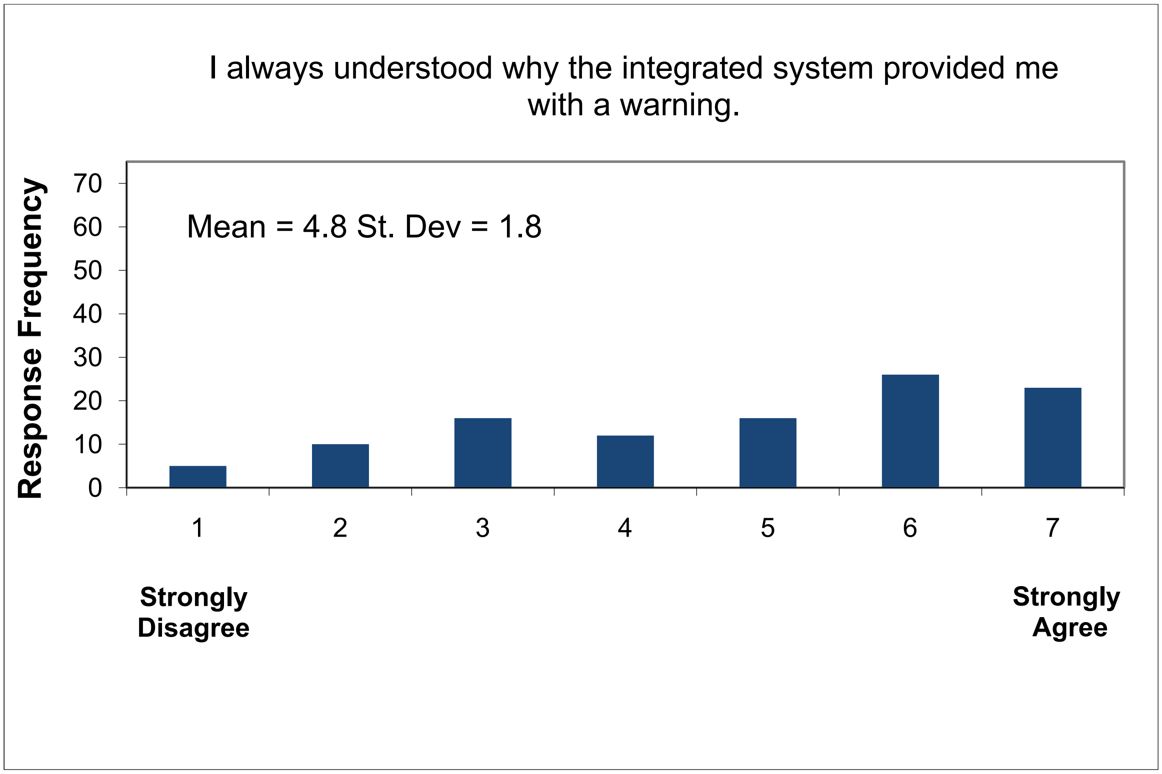


Figure 21: Drivers' level of understanding of the integrated system

Drivers clearly understood why the yellow lights BSD appeared in their side-view mirrors (indicating that a vehicle was in, or approaching their blind spot), while they did not always understand why they received brake pulse warning cues (Table 11). This result is not surprising given the high percentage of FCW warnings that were invalid, even if the overall FCW warning rate was lower than that for other subsystems.

Table 11: 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 them; however, they indicated that they not like 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?

Overall, drivers found the frequency with which they received warnings to be acceptable. This result is displayed in Figure 22. Of the drivers who reported receiving warnings less frequently, 70 percent reported that they thought 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; this was supported by the fact that the LDW subsystem produced the most of warnings of any subsystem and also issued the highest number of warnings per 100 miles of driving. There was no effect of driver age on the response to this question.

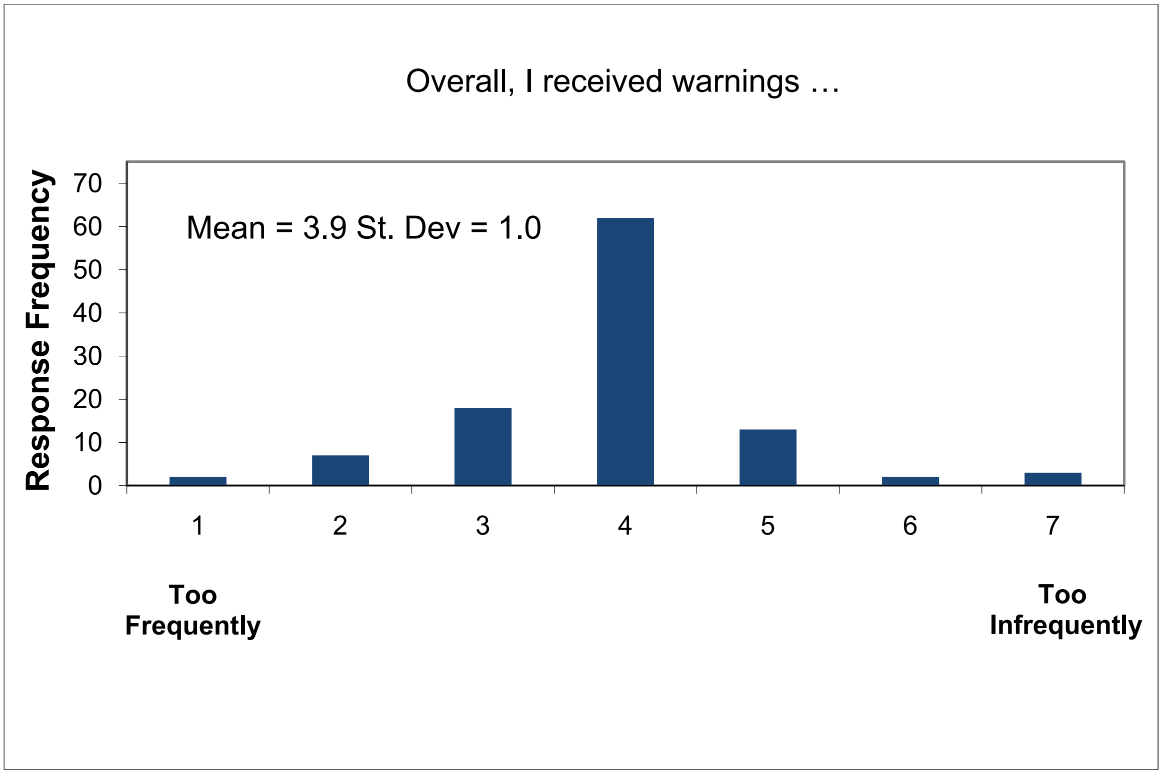


Figure 22: Ratings of frequency with which drivers received warnings

Interpretation: Overall, drivers reported receiving warnings with about the right frequency. For the drivers who believed they should have received more warnings than they did, they said 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 did not use their turn signals, even if they were making lane changes when other vehicles were not present.

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 shown in Figure 23, more than half of the younger drivers (56%) found the nuisance warnings to be annoying, more so than the other age groups. 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 as much by nuisance warnings. In debriefing sessions, several drivers stated that they were willing to tolerate some nuisance warnings in order to realize the benefit of being warned in the event of a serious crash.

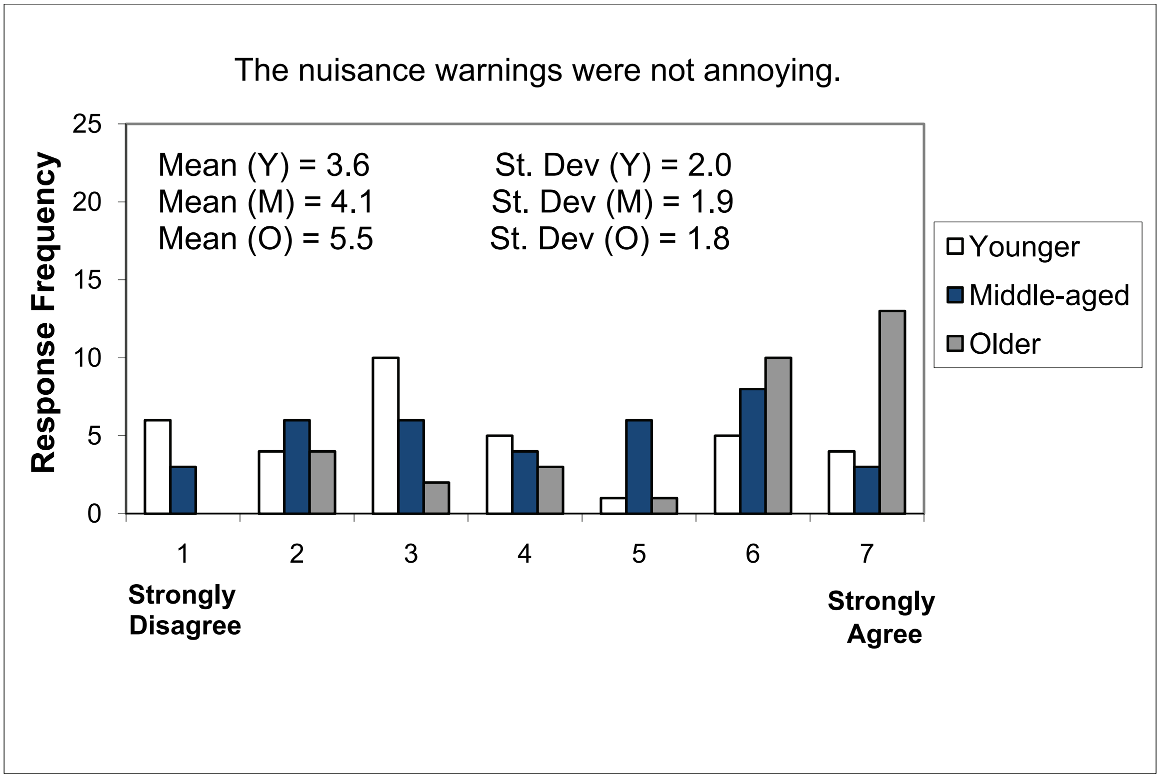


Figure 23: Drivers' perception of nuisance warnings' annoyance

Interpretation: Even though more than half of younger drivers were annoyed by nuisance warnings, in general, drivers as a group 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, in focus groups and debriefing sessions drivers stated that they were willing to overlook some of the shortcomings of new technologies in order to realize a 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 expressed their willingness to purchase the integrated system, as well as the individual subsystems. Figure 24 shows that about half of the drivers reported their willingness to spend between $250 and $750 for the integrated system. Of the group of drivers who said that they would not be willing to pay for the integrated system, several reported that they felt that the integrated system should come as standard equipment on all vehicles.

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 25).

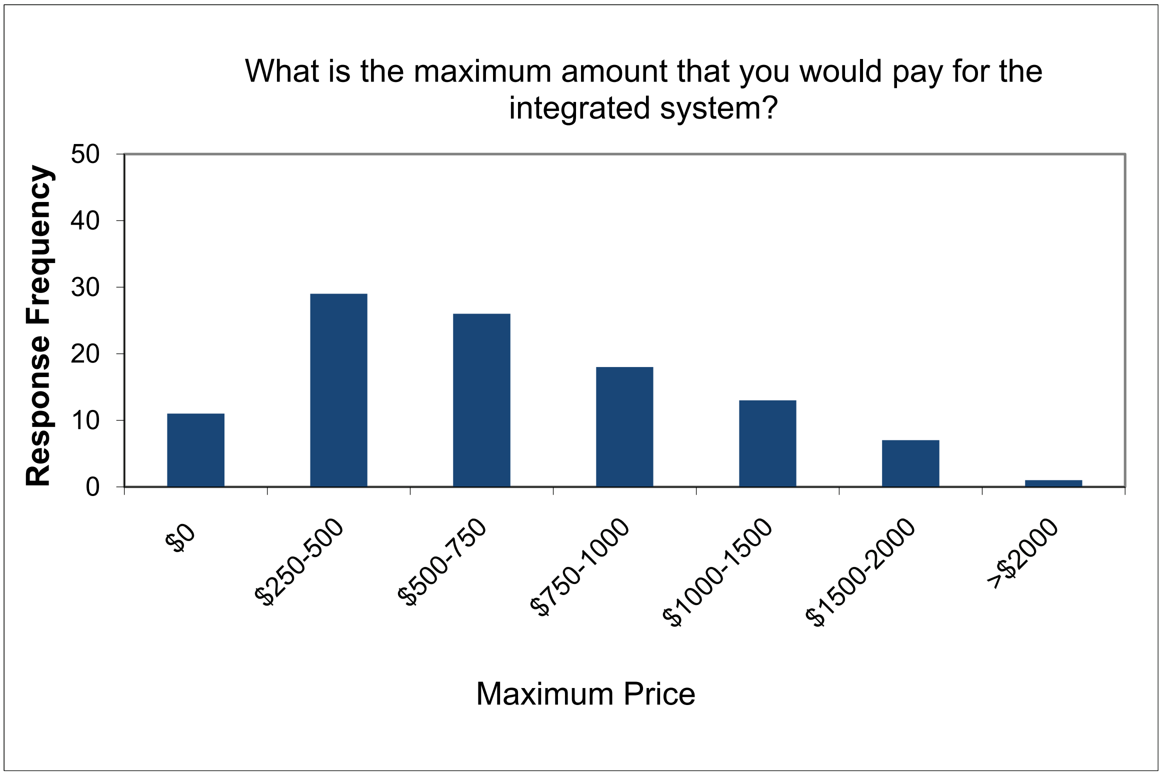


Figure 24: Maximum price that drivers would pay for the integrated system

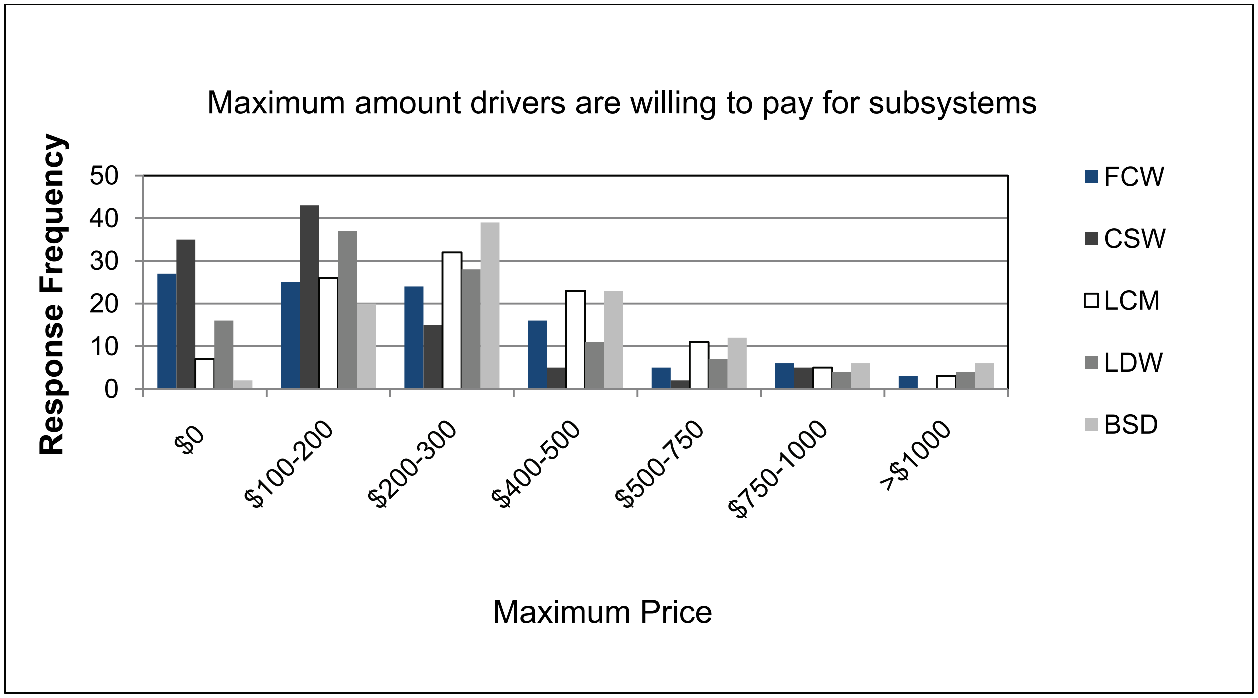


Figure 25: Maximum price that drivers would pay for each of the subsystems

Interpretation: A majority of drivers reported that they would be willing to purchase the integrated system, but would not spend more than $750 for these advanced safety features. Drivers were more willing to purchase lateral subsystems such as LDW and LCM, and pay up to $300 for these subsystems, whereas they were only willing to spend up to $200 for CSW.

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

2.2 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.

2.2.1 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 during the baseline condition and 7.6 lateral warnings per

100 miles during the treatment condition. A summary of the overall lateral warning activity as a function of condition and road type is given in Table 12. The highest overall warning rate was consistently on exit ramps, while the lowest rate was on unknown road types (e.g., parking lots and other low-speed areas).

Table 12: 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

2.2.1.1 Lateral Warning Classification and Validity

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 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 that 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 environment (e.g., no vehicle present in the forward path, or the driver does not traverse the road branch with the curve), or there are complex situations (e.g., 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 present in the current situation—and one does not develop. While the system may be operating according to the system design intent, from the driver's point-of-view, the warning appears to be spurious, without any identifiable cause, and is therefore not predictable by the driver. Some

invalid warnings will be unavoidable, as it is not possible to predict future vehicle movements in all situations.

The logic for sorting all LDW events was based on the analysis of driver intent and reaction to the warning explained below. However, note that 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 was involved in a secondary task and inadvertently drifts into an adjacent lane, but upon hearing the warning, the driver actively corrects by steering the vehicle 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 taken by the driver occurred within a 5-second time window.
- **Valid and intentional**—the warning occurs when a driver makes an unsignaled (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 equipped vehicle occupies the adjacent space. For example, on a three lane road with one lane unoccupied, both the equipped vehicle and POV move laterally in a synchronous fashion, both changing lanes at the same time. Another common example is when the equipped vehicle 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 warning being issued.

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

2.2.1.2 Lateral Warning Summary

In this section, the lateral warning exposure is presented using terms defining lateral warning type and validity. Figure 26 shows the overall lateral warning rate per 100 miles for valid and invalid warnings during the treatment period. 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, which accounted for six percent of all lateral warnings, were characterized by an incorrect or inaccurate assessment of the driving environment by the warning system.

Figure 27 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 lateral warning type. Low boundary confidence was the leading contributor to the LDW cautionary invalid warning rate.

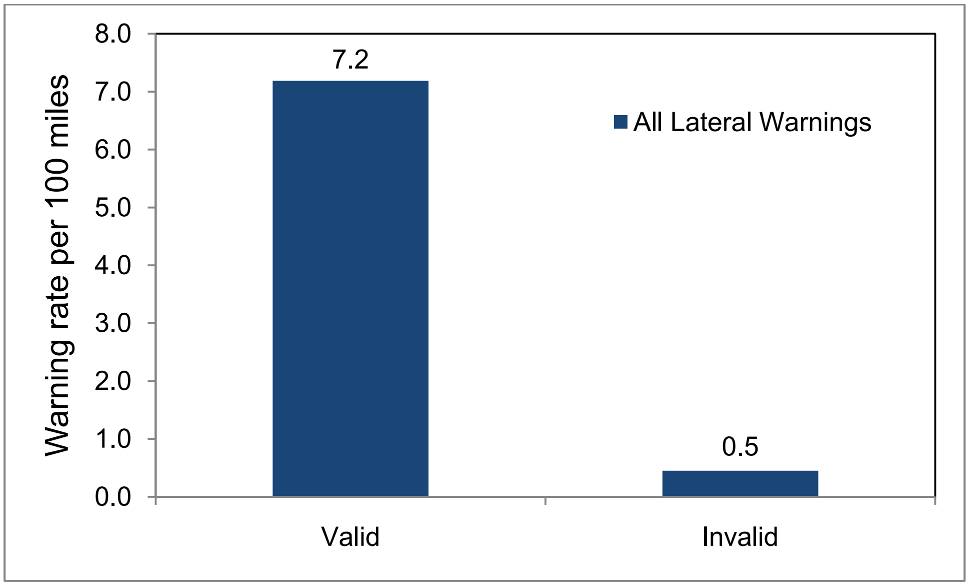


Figure 26: Overall lateral warning rate per 100 miles during treatment period

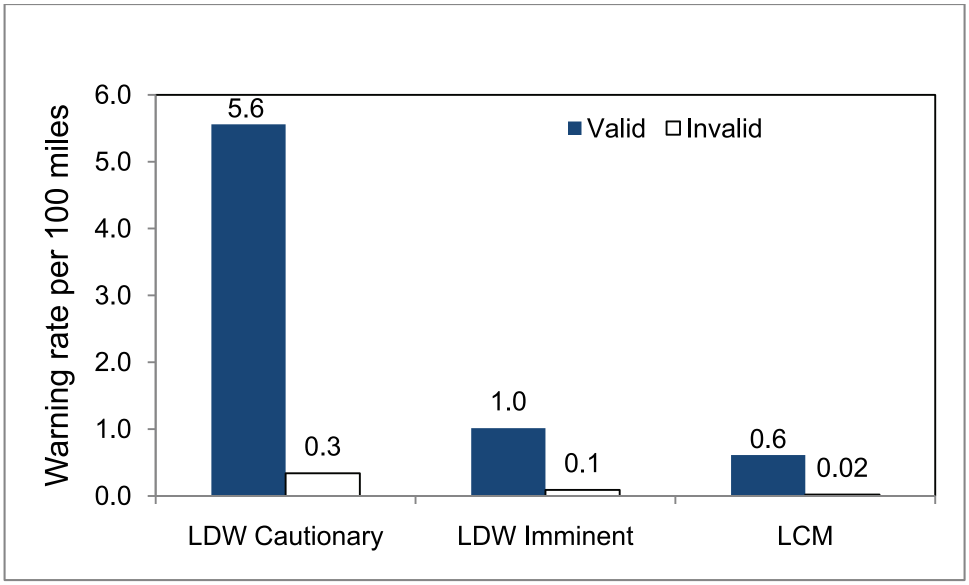


Figure 27: Lateral warning rate per 100 miles for each warning type during treatment period

Figure 28 and Figure 29 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 equipped vehicle 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 and right side of the vehicle. A left-side bias for LDW cautionary warnings was also observed. For this type of warning, 68 percent resulted from drifting to the left, as opposed to the right.

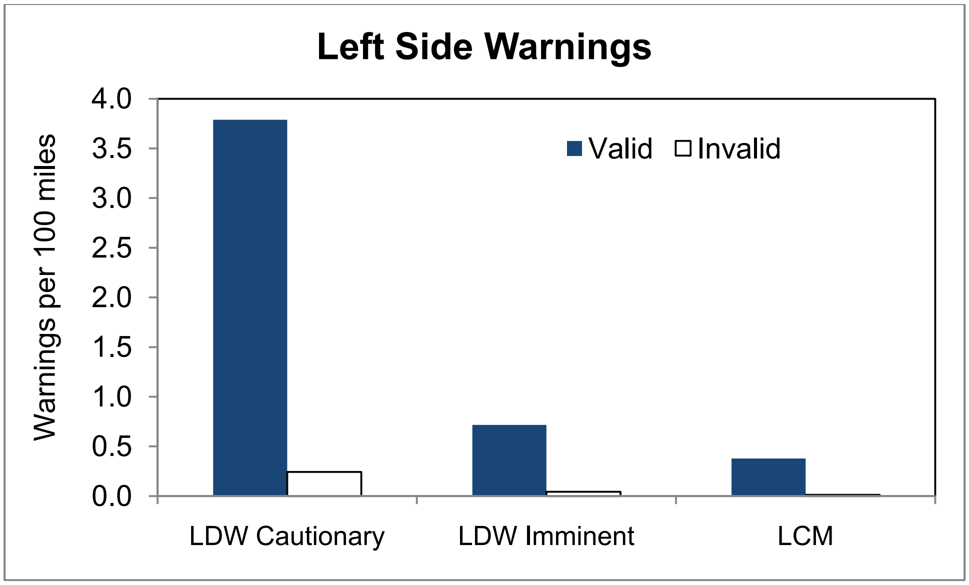


Figure 28: Overall lateral warning rate per 100 miles as a function of type on the left side

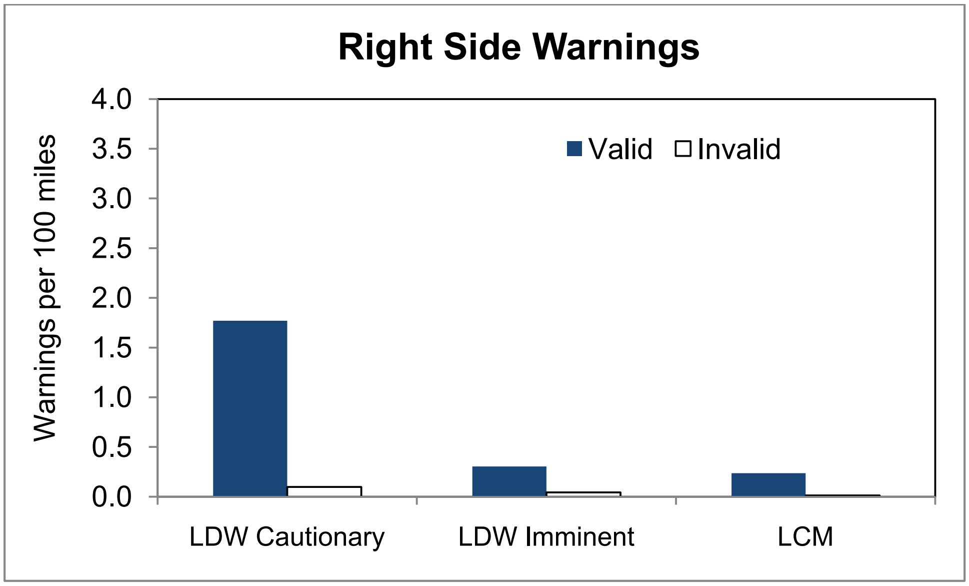


Figure 29: Overall lateral warning rate per 100 miles as a function of type on the right side

The number of warnings, percentage, and rate as a function of warning type and classification are illustrated in Table 1. The highest rate is for valid LDW cautionary warnings, at 5.56 warnings per 100 miles. This rate is largely caused by drivers' failure to use their turn signals when changing lanes.

Table 13: Lateral warning rate by condition and 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

2.2.2 Driver Behavior

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

Method: 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 30. If the vehicle is perfectly centered in the lane, lateral offset is zero.

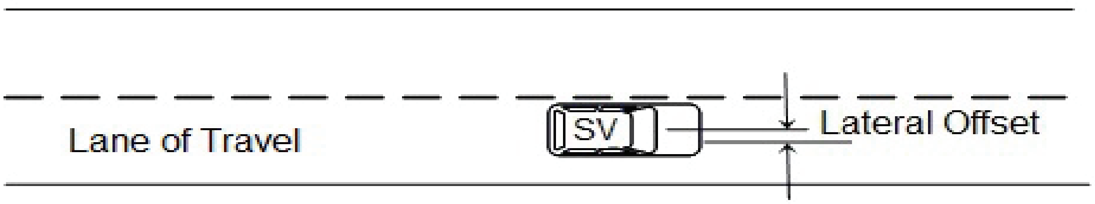


Figure 30: Conceptual drawing of lateral offset

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 possibly preparing for the next maneuver. Additional lane tracking system criteria required known boundaries on both sides and 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 found in Table 14.

Table 14: 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 above, 128,626 events consisting of 794 hours (21% of driving when speeds were greater than 25 mph) and 53,560 miles (27% of driving when speeds greater than 25 mph) were identified. 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 lateral offset. 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 were also verified against the raw FOT data.

Results: The only independent variables that had a statistically significant effect on lateral offset were ambient light ($F(1,96) = 136.86$; $p < 0.0001$) and average speed ($F(1,93) = 5.67$; $p = 0.0193$). These variables 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 31 illustrates lateral offset as a function of average speed for both day and night conditions. It should be noted that a negative offset means that the vehicle's centerline is to the left of the center of their travel lane. Figure 32 shows the least square means for the ambient light interaction on lateral offset.

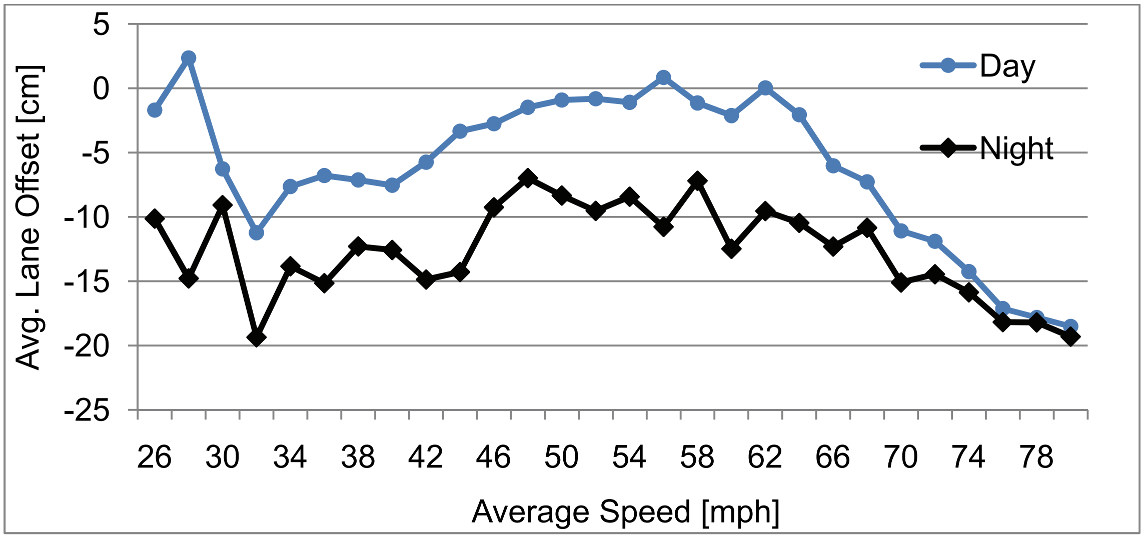


Figure 31: Average lateral offset for day and night conditions versus average speed during steady-state lane-keeping

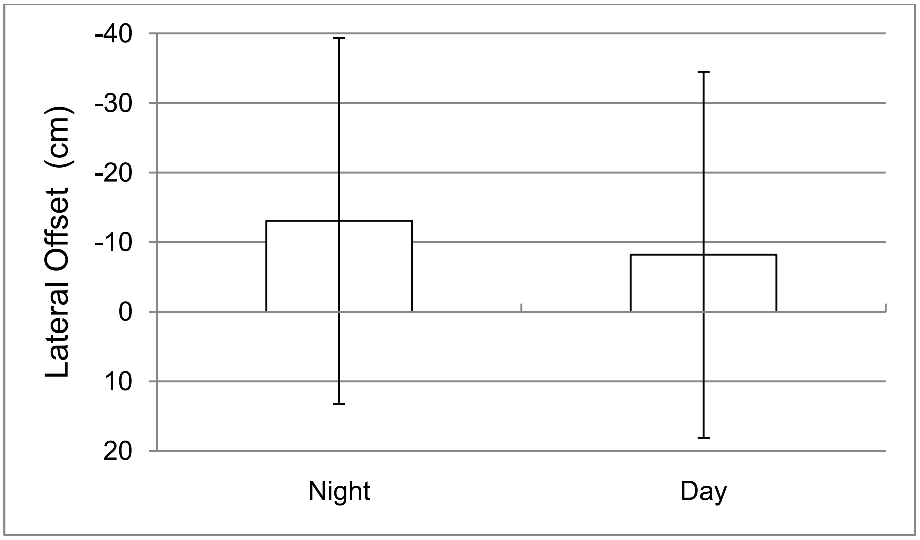


Figure 32: Lateral offset for day and night during steady-state lane-keeping, including standard error

Descriptive Statistics: A slight change in lateral offset can be seen in the data shown in Figure 33. The figure shows the percentage of travel time spent at various lateral-offset locations including 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.

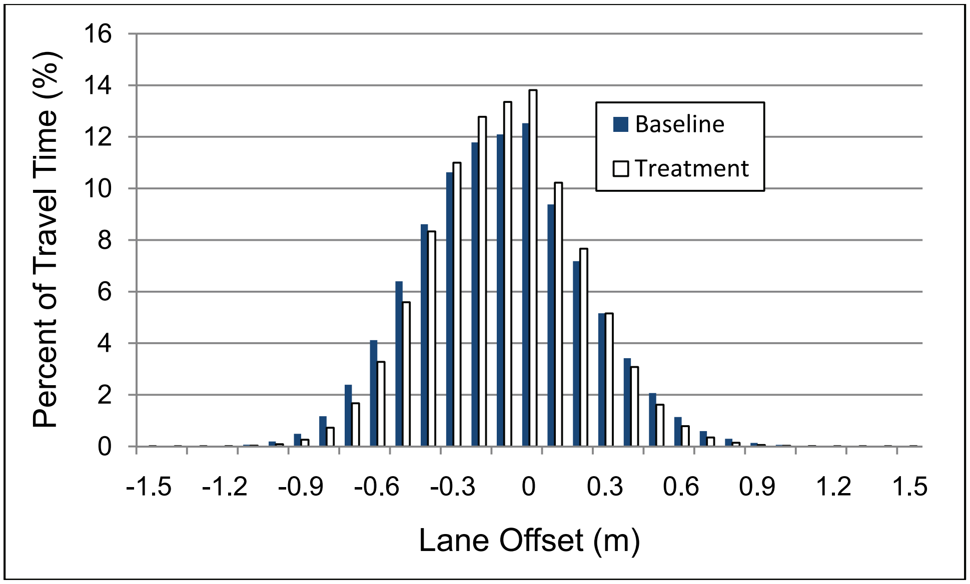


Figure 33: Percentage of driving time spent at a given lateral offset location for all drivers in both treatment conditions

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

QL2: Does lane departure frequency vary between baseline and treatment conditions?

Method: The lane departures used in this analysis were extracted from periods of steady-state lane-keeping and excluded active maneuvers such as changing lanes or braking. A lane departure does not always trigger a lane departure warning due to the sophisticated warning algorithms using 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 on 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 returning back to the original lane.

The previous research question (QL1) focused on periods of driving when maintaining proper lane position was the primary task, and includes the unintentional lane departures of interest for this research question. Table 15 shows the constraints used to identify 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 11 events over 20 seconds were not valid departure events, due to poor lane tracking or intentional maneuvers near construction or roadway hazards.

Table 15: 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 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 to determine the lane departure frequency (departures per 100 miles). The normalized departures were then used for modeling the significant interactions.

This analysis used a linear mixed model with the driver as a random effect to determine the significant factors in predicting lane departure frequency. 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 34 provides the least square means of 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.

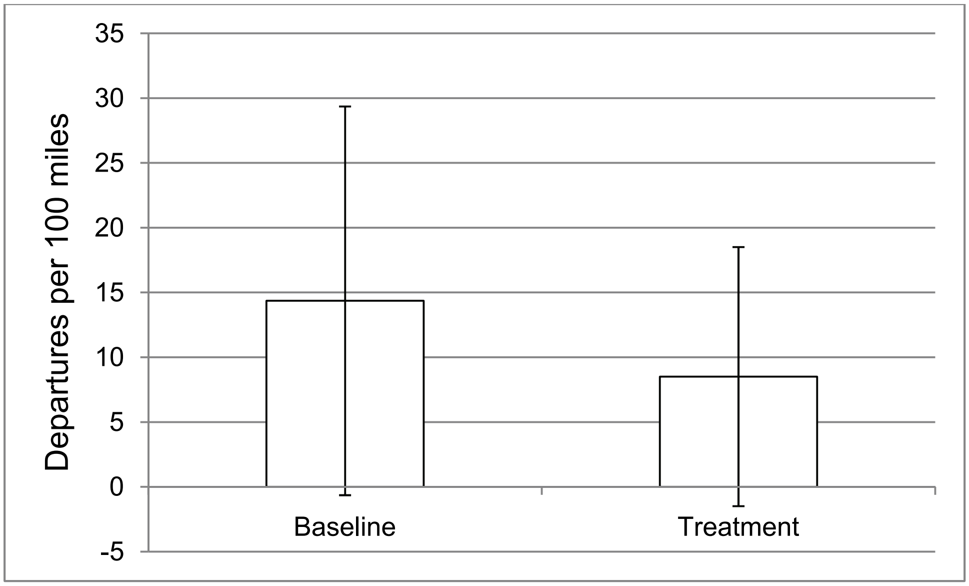


Figure 34: Means of departure rates for experimental condition, including standard error

The direction of the departure, either to the left or right, had a statistically significant effect on the departure frequency ($p = 0.0002$). Figure 35 shows that the departure rate over the left boundary was much higher for both the model and FOT data. In both data sources, the departure rate to the left was more than three times that to the right.

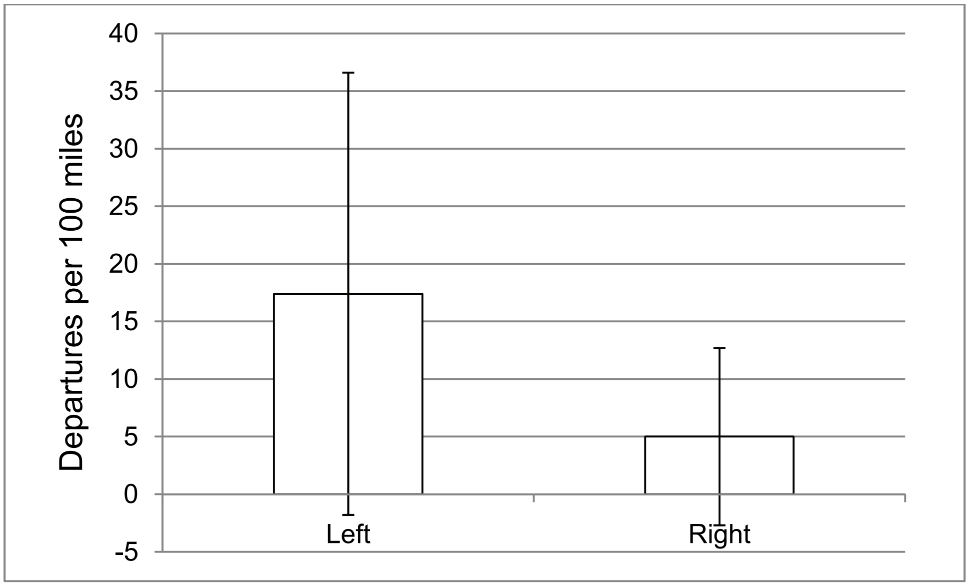


Figure 35: Means of departure rates by direction during steady-state lane-keeping, including standard error

Descriptive Statistics: As stated above, this analysis was based on the 12,760 lane departure events that occurred during steady-state lane-keeping. The frequency of lane departures shows a change over the course of the FOT, as shown in Figure 36. The variable, week number, did not show a statistically significant interaction with the departure frequency, but there is a definite change in behavior from week to week. The largest change in driver behavior occurred between weeks two and three, when the integrated warning system was enabled, followed by a slight increase during the remaining weeks of the FOT.

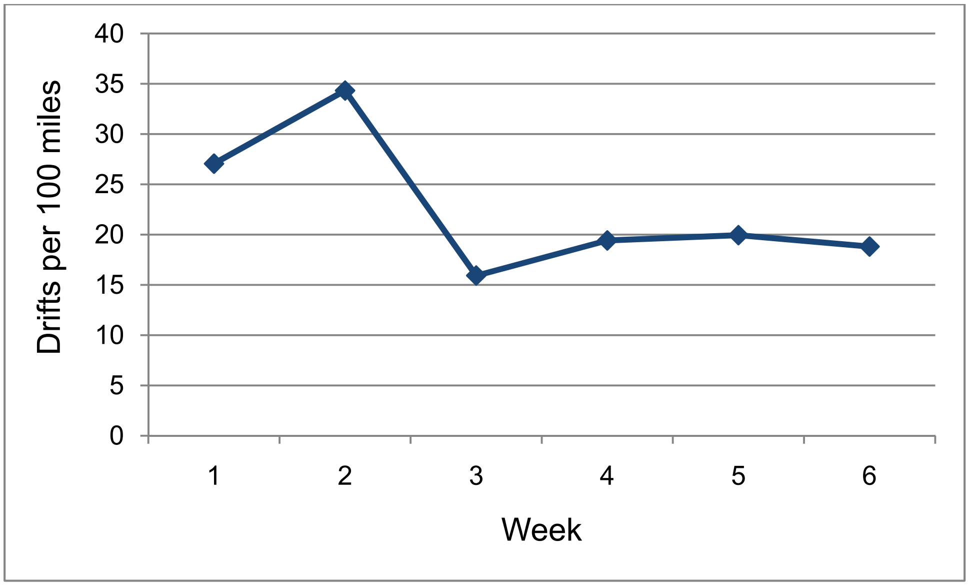


Figure 36: Average departure frequency by week during steady-state lane-keeping

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. During the third week, when the system was enabled and warnings were presented to the driver, the departure rate was reduced by more than half from the rate observed 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?

Method: The same 12,760 lane departure events used in research question QL2 were also used in this analysis. They were extracted from the steady-state, lane-keeping events and excluded active maneuvers. For each lane departure, the time when the edge of the vehicle first crosses the lane boundary to the time 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 15 summarizes the constraints used for this research question.

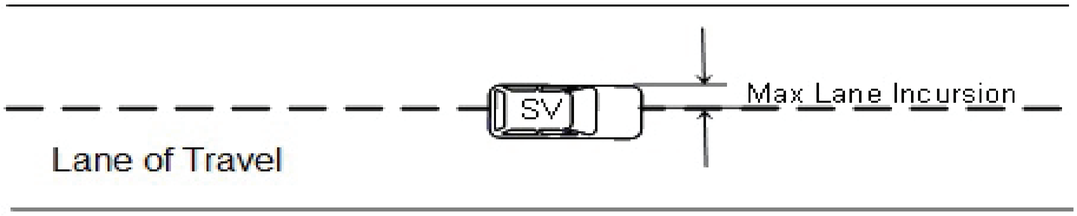


Figure 37: Illustration of lane incursion

Results:

Departure Duration

The variable, experimental condition (i.e., baseline or treatment), 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, changing from 1.98 to 1.66 seconds (Figure 38).

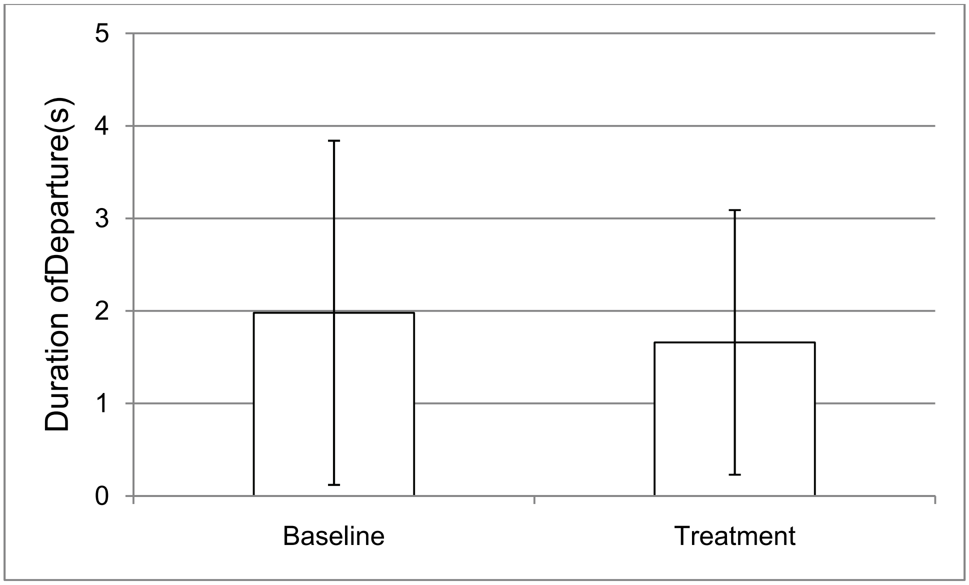


Figure 38: Duration least square means for experimental condition, including standard error

The presence of a vehicle in the adjacent lane, 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, in the direction away from the POV, when an adjacent POV was present (Figure 40). The average duration of a lane departure with no POV was 1.80

seconds compared to 2.28 seconds with a POV present. Only 128 of the 11,855 departures (about 1%) had an adjacent POV present, so the above result may be an effect of an extremely small sample of unusually long departure durations.

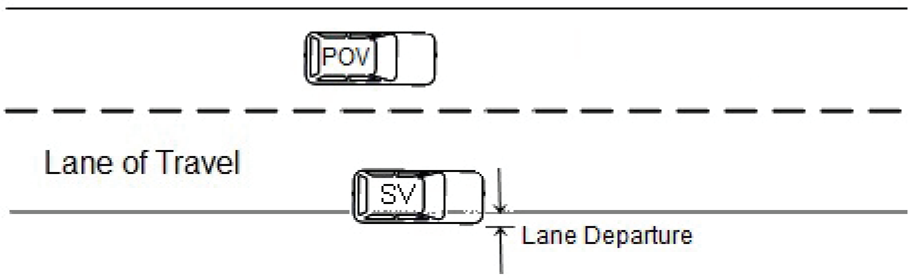


Figure 39: Illustration of lane departure with another vehicle present in the adjacent lane

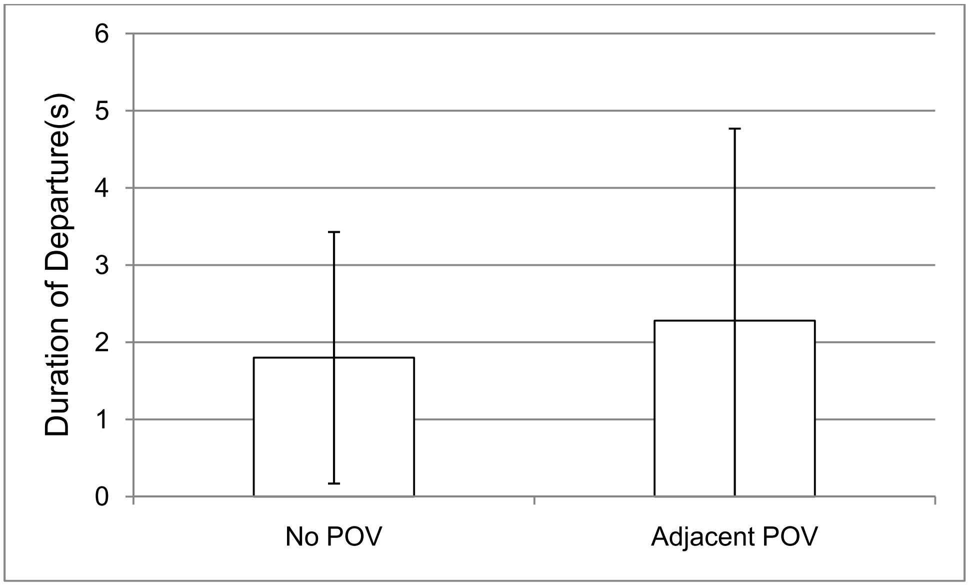


Figure 40: Duration least square means for POV in adjacent lane during departure, including standard error

Results:

Maximum Incursion Distance

The maximum incursion distance of the departures was statistically significant, affected by the experimental condition ($F(1,98) = 30.15$; $p < 0.0001$); however, the practical significance was very small. On the average, lane departures decreased by 1.2 cm during the treatment condition. Figure 41 shows the average maximum incursion measured during the FOT.

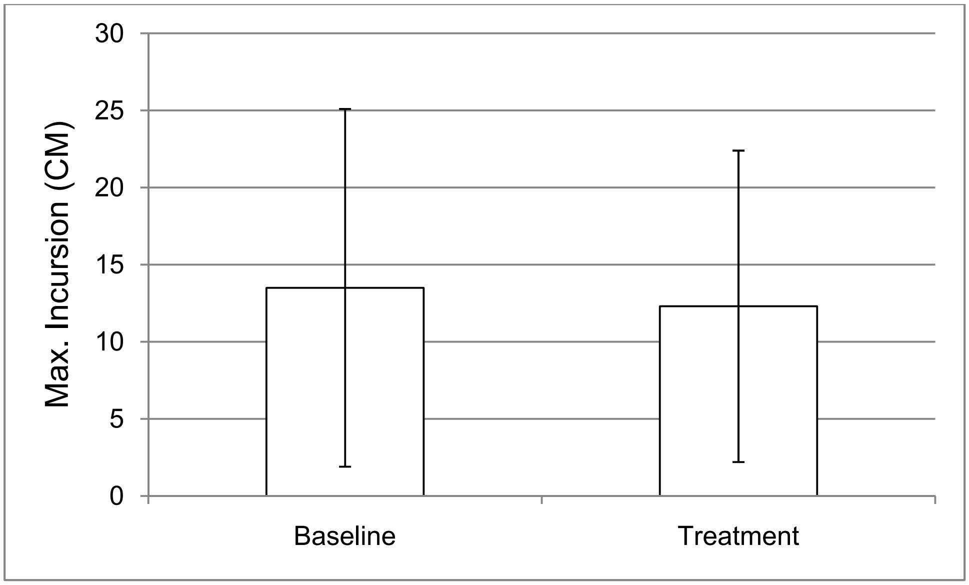


Figure 41: Maximum incursion distance least square means for experimental condition during steady-state lane-keeping, including standard error

Finally, the presence of a POV also had a statistically significant effect on lane incursion distance ($F(1,42) = 11.9$; $p = 0.0013$). The FOT data shows a 3.5 cm increase in the maximum incursion distance with an adjacent POV present (Figure 44). This increase is similar to the increase in duration discussed earlier (see Figure 40).

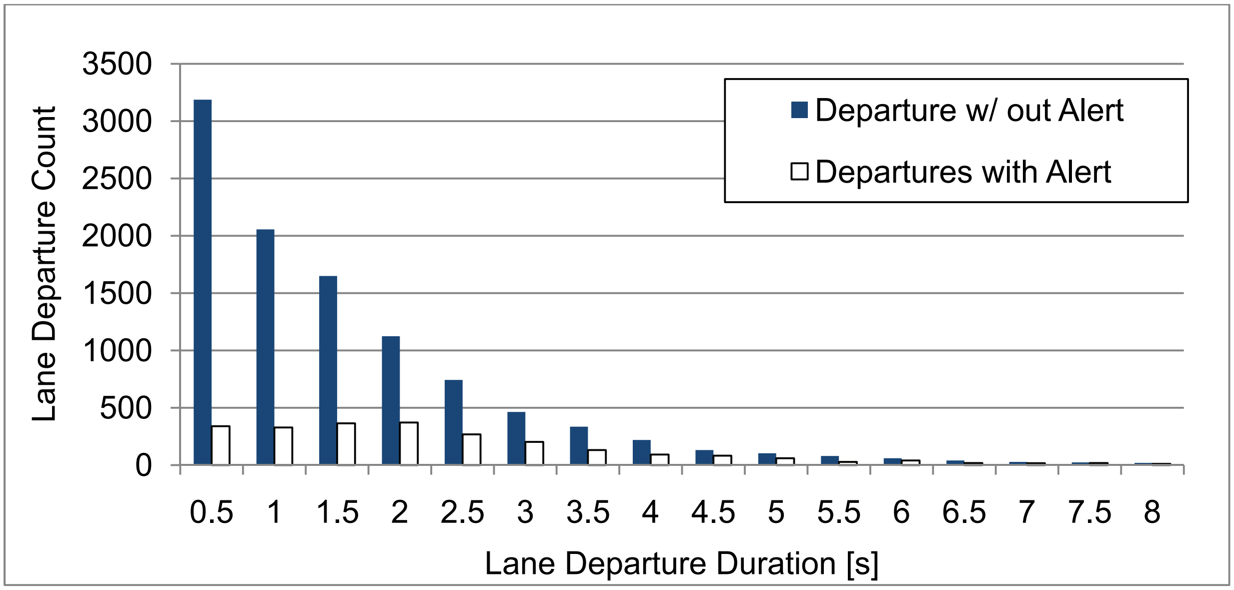


Figure 42: Histogram of departure durations

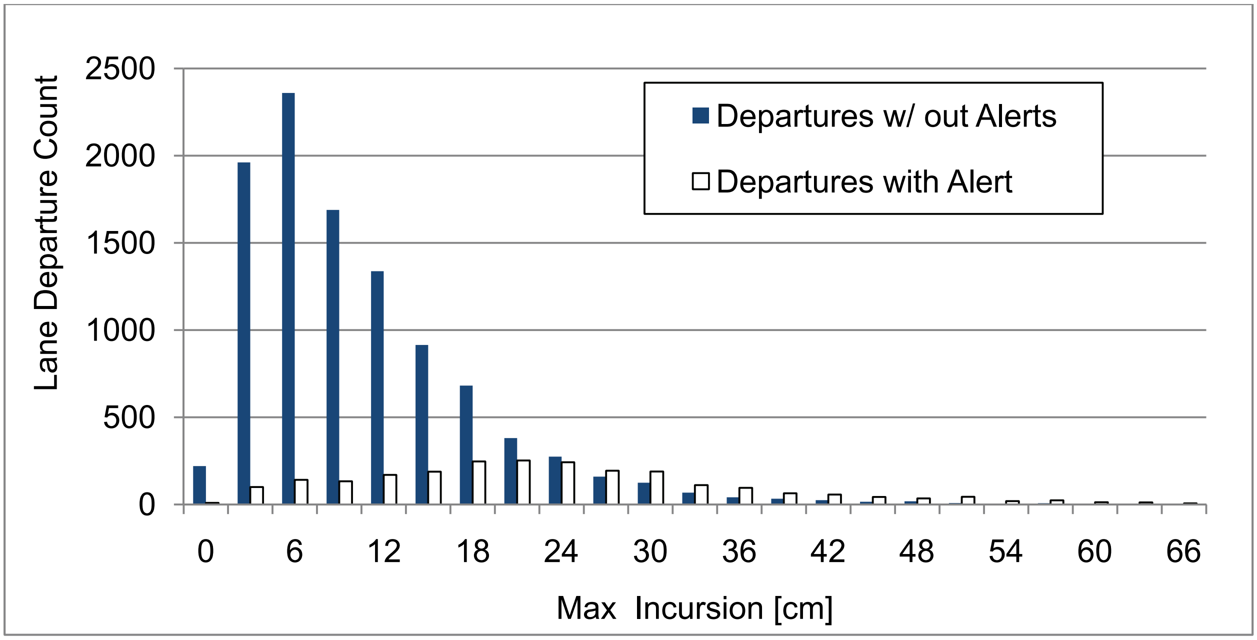


Figure 43: Histogram of maximum incursion during steady-state lane-keeping events

A linear mixed model was used to determine if the trajectory of lane departures varied with the independent variables for both 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.

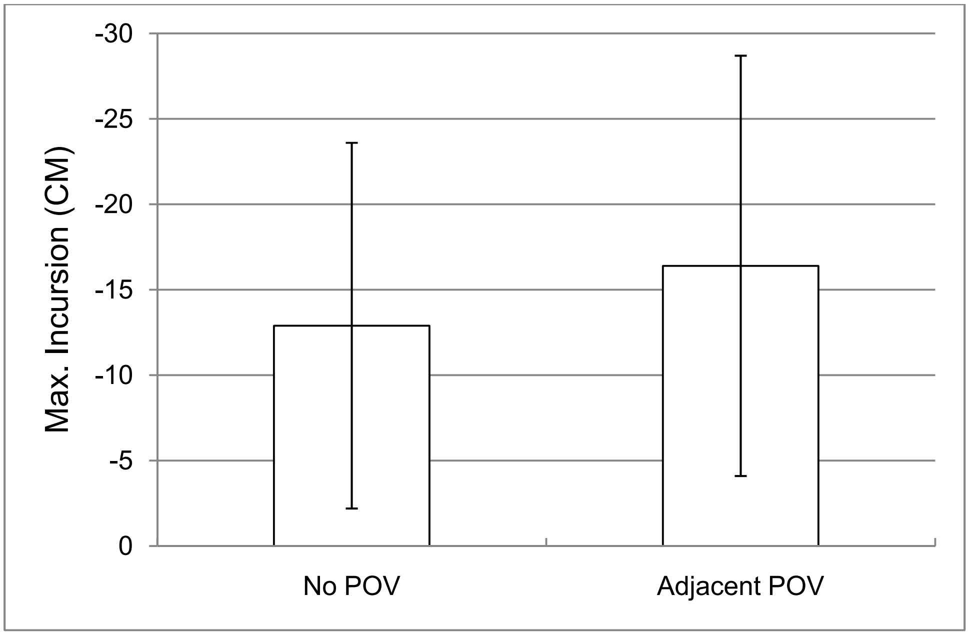


Figure 44: Maximum incursion distance least square means for departures with POV in adjacent lane, including standard error

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

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

Method: A subset 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 equipped vehicle relative to the roadway in which it 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 equipped vehicle's centerline crosses the shared boundary between the two adjacent traffic lanes.

The principal findings of this analysis are based on the results of a linear mixed 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 unsignaled lane-changes during the baseline condition. Turn-signal use data is presented below in Figure 45.

Results: The presence of the integrated system had a statistically significant effect on turn-signal use during lane changes ($F(1,106) = 77.76$; $p < 0.0001$). During the baseline condition, drivers did not use turn signals in 18.6 percent of lane changes, while during the treatment condition, drivers made unsignaled lane changes only 6 percent of the time.

Also found to be statistically significant was the effect of road type ($F(1,106) = 112.44$; $p < 0.0001$) on turn-signal usage. On limited access highways, drivers made unsignaled lane changes 8.9 percent of the time, while on surface streets; they did not use their turn signal in 12.9 percent of lane changes.

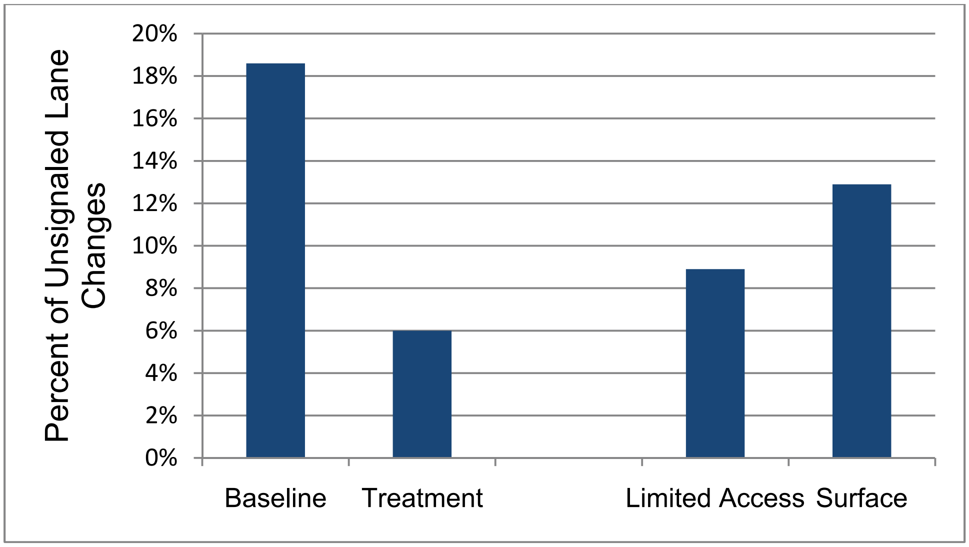


Figure 45: Percent of unsignaled lane changes over two significant independent variables

As shown in Figure 46, a statistically significant interaction ($F(1,106) = 30.01$; $p<.0001$) exists between road type and treatment condition. During baseline driving, drivers were less likely to use their turn signals when making lane changes on surface streets, failing to use turn signals 20.6 percent of the time. However, lane changes on surface streets were relatively uncommon events, with only 8.7 percent of all lane changes taking place on surface streets during baseline driving.

The most common scenario in which lane changes occurred was on highways during the treatment condition, accounting for 47.8 percent of all lane changes. This was also the case with the highest turn-signal use, with drivers making unsignaled lane changes only 4.5 percent of the time.

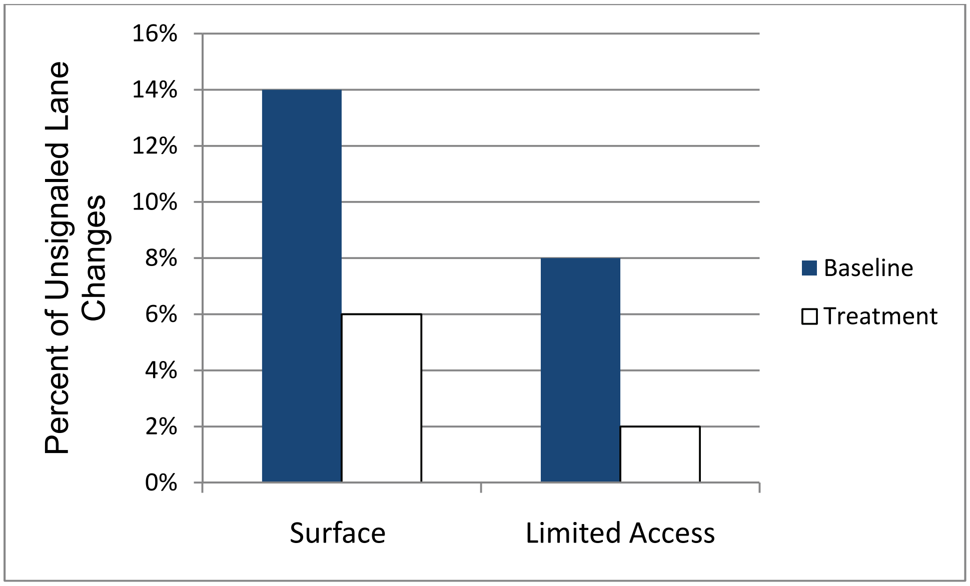


Figure 46: Interaction between condition and road type

Interpretation: The results show a statistically significant effect of the integrated system on turn-signal use during lane changes. Drivers were three times more likely to make unsignaled lane changes during baseline driving than during the treatment condition. Also, the effect of road type was statistically significant as drivers were more likely to make unsignaled lane changes on surface streets than on limited-access highways.

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

Method: A group of 99,680 randomly sampled events, 5 seconds in duration, were identified in the FOT data. For each event, a lateral-offset 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 equipped vehicle. In the analysis comparing lane position with or without the presence of a POV on the left side of the equipped vehicle, the AMR on the right side was always unoccupied and, conversely in the analysis for the right side of the vehicle, the AMR on the left was always unoccupied. Figure 47 shows the conditions for the analysis on the left side of the vehicle. 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.

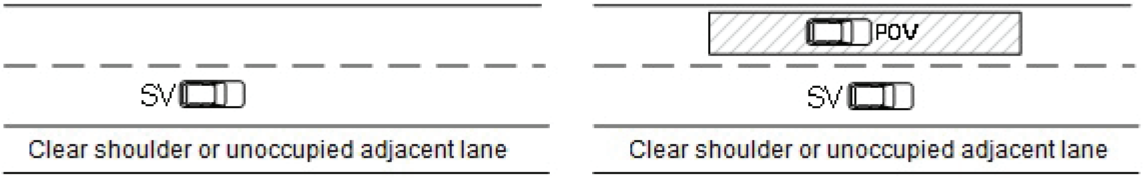


Figure 47: Lateral offset change away from an occupied space

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

On average, drivers had a lateral offset of 11.5 cm to the left of the center of their travel lane. The independent measures found to have a statistically significant effect on lateral position were the integrated system, ambient light, and the presence of a vehicle in an adjacent lane. During the treatment condition, there was a statistically significant, but slight shift of 1.3 cm toward the center of the lane (*F*(1,107)=7.99; *p*=0.0056) as shown in Figure 48.

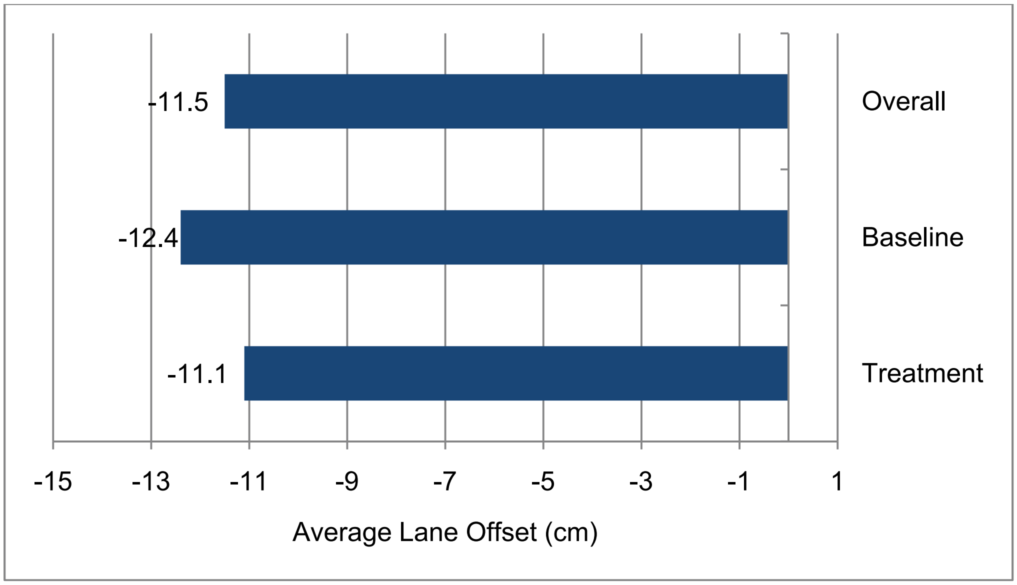


Figure 48: Lateral offset with an adjacent vehicle by condition

When an adjacent lane was occupied, ambient light was also found to have a statistically significant effect on lateral offset (*F*(1,102)=24.52; *p*<0.0001), with drivers having, on average, a lateral offset of 15.5 cm to the left of the center of the lane at night and a 10.4 cm offset during the day. Average lateral offsets as a function of the adjacent lane state are presented in Figure 49.

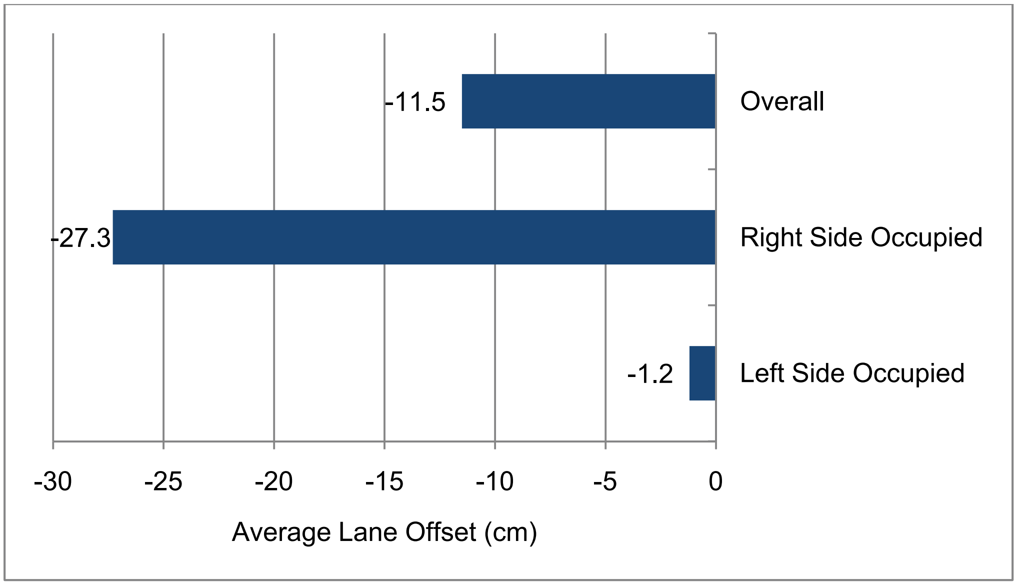


Figure 49: Lateral offset as a function of adjacent lane state

When the right lane was occupied by a POV, drivers moved to the left an additional 16.4 cm compared to when the right lane was unoccupied ($F(1,107)=280.5$; $p<0.0001$). This placed the average driver over 27 cm to the left of the center of the lane when a vehicle was directly adjacent on their 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 another vehicle adjacent to the equipped vehicle on the left side, on average, drivers stayed slightly to the left of center in their travel lane.

Interpretation: Generally speaking, drivers maintained a lateral offset of approximately 11.5 cm to the left of the center of their travel lane. In addition, although there was a statistically significant reduction in lateral offset associated with use of the integrated system, the magnitude of the difference was quite small. A greater effect was found when the space adjacent to the equipped vehicle was occupied. Drivers adjusted their lane position away from the vehicle in an adjacent lane regardless of which side was occupied. This suggests that drivers' awareness of 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 lanes.

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

Method: The purpose of this research question is to study sensor performance by analyzing POV position relative to the SV when LCM warnings are issued. In order to address this question, the areas adjacent to the equipped vehicle were divided into three zones, as shown in Figure 50. LCM warnings for conditions in which the space adjacent to the vehicle was occupied by another vehicle traveling in the same direction 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 warning, the zones on the corresponding sides 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 listed in Table 16. These rules helped establish a steady-state condition for the equipped vehicle and dictate how long the turn signal and adjacent vehicles must be present for the event to be considered a candidate for this analysis. Warning validity was determined by reviewing video associated with the events.

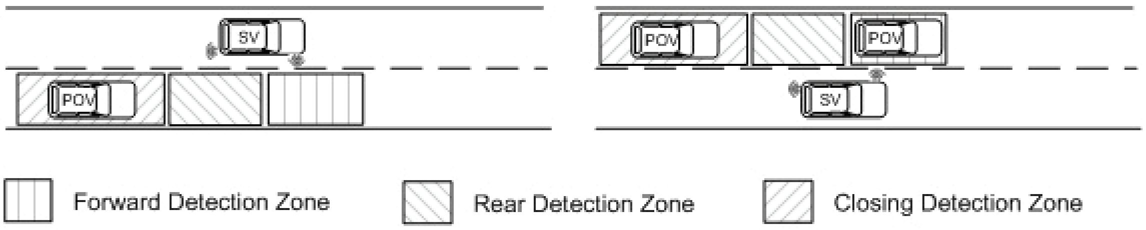


Figure 50: Location of zones for adjacent vehicles for valid LCM warnings

Table 16: 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)

Results: The principal findings of this analysis are based on results of a chi-square test. 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 equipped vehicle is combined, and used to classify each LCM warning based on the presence of a vehicle in each of the three radars' detection zones. Depending on which radars detected adjacent vehicles, a different "zone code" was assigned to each unique combination of target location. The eight possible zone codes and their definitions are listed in Table 17.

Table 17: 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 LCM warnings resulting from zone codes one, seven and eight, these zones could not be used in the statistical analysis.

For the analysis, 1,270 valid LCM warnings (772 to the left and 498 to the right) were examined and five zones (zones 2, 3, 4, 5, 6) were considered. Figure 51 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 meters behind the vehicle) which was occupied in 40 percent of the warnings issued. The second most active zone was the closing-zone radar which covers the rear approach area adjacent to the vehicle. This zone was occupied in 24 percent of these LCM warnings.

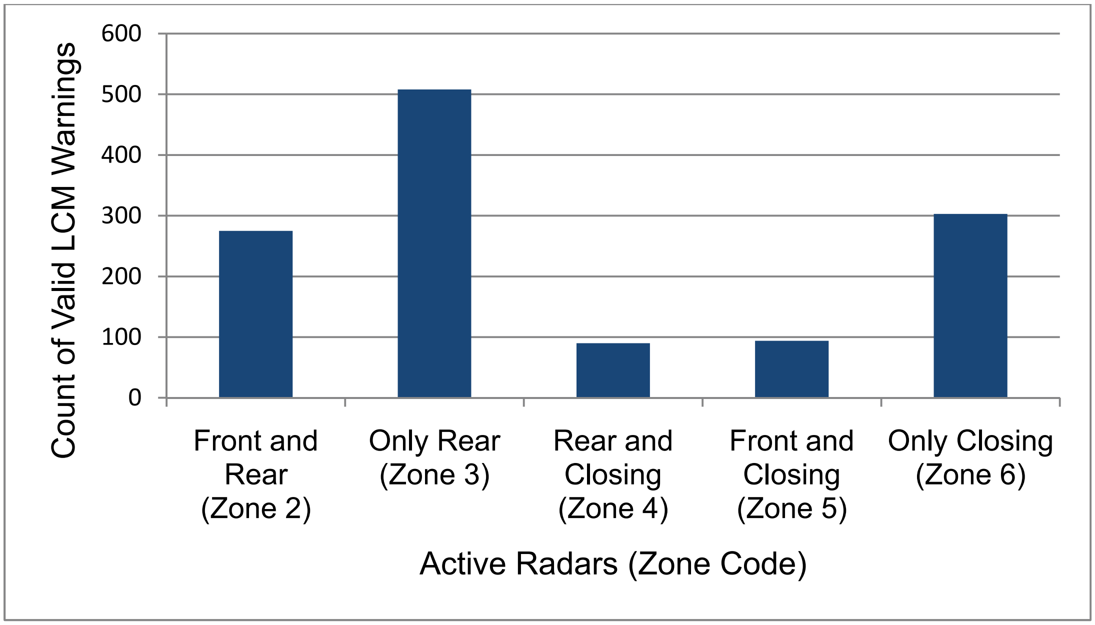


Figure 51: Summary of the distribution of LCM warnings by adjacent zone

The effect of experimental 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 52 shows the distribution of LCM warnings for the baseline and treatment conditions. For the baseline condition, there were 398 LCM warnings and 872 during the treatment condition. When exposure is considered, the warning rate is marginally higher (4%) for the treatment condition. It should be noted that a total of 68,870 and 144,439 miles were used in the normalization for the baseline and treatment conditions, respectively.

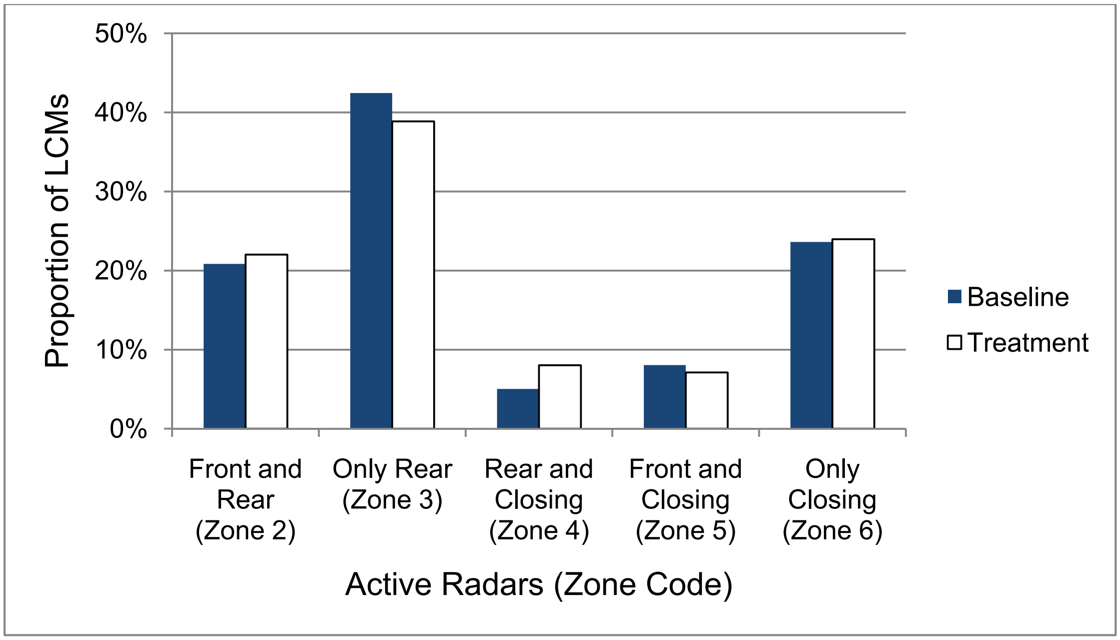


Figure 52: Summary of the distribution of LCM warnings as function of condition

Several dependent variables were found to be statistically significant. The results are summarized in Table 18.

Table 18: 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 location and equipped vehicle side are shown in Figure 53. Of the 1,270 LCM warnings, 772 (61 percent) resulted from a POV on the left side of the equipped vehicle. For LCM warnings to the right of the equipped vehicle, almost half (49%) were issued with a vehicle in the rear "blind-spot" zone. From an exposure perspective, an LCM warning in the left closing zone is more likely to occur than in the right closing zone. This is probably a result of lane selection of the adjacent vehicle for passing the equipped vehicle.

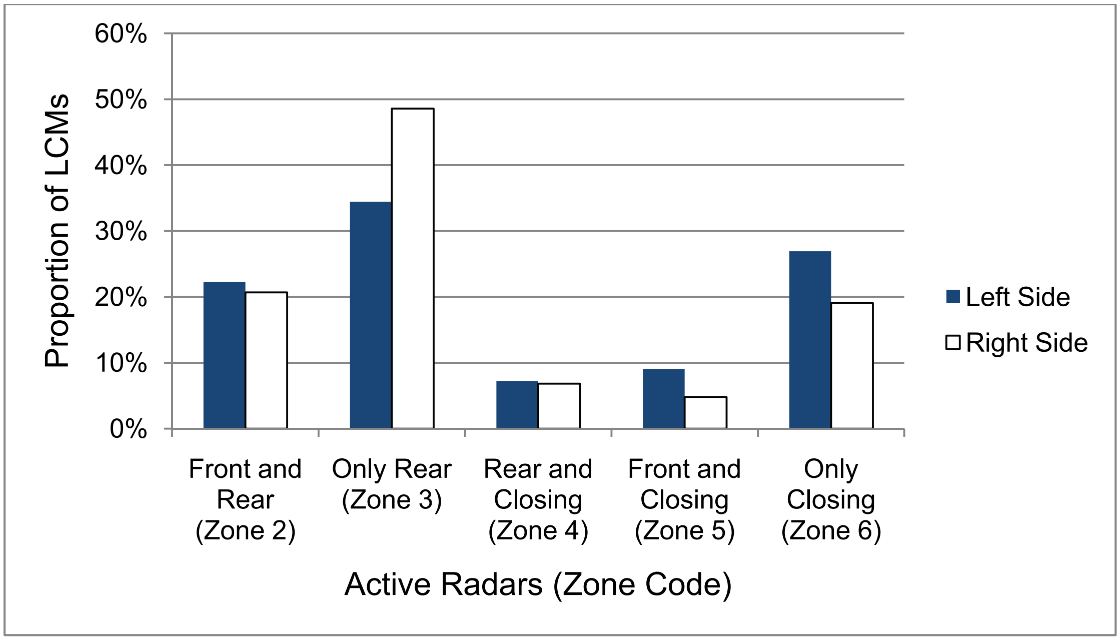


Figure 53: Main effect of side on POV location during LCM warnings

The main effect of road type is shown in Figure 54. A total of 828 LCM warnings (65%) were issued on limited access highways and 342 on surface streets. Adjusted for exposure (based on 92,092 miles on limited access highways and 96,656 miles on surface streets) and assuming the distribution of this data set is representative of all LCM warnings, LCM warnings were 2.5 times more likely to occur on limited access highways as compared to surface streets 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 equipped vehicle in the rear-side radar zone (Zone 3). On surface streets, LCMs were more likely to be triggered from the front and rear radars together (26.9% on surface streets and 22.1% on highways), while on highways, LCMs were more likely to be issued from targets in the closing zone (22.5% on surface streets and 27.3% on highways).

The main effect of age group is shown in Figure 55. A total of 531 LCM warnings (42 percent) were produced by younger drivers, 457 (36 percent) middle-aged, and 282 for older drivers. Adjusted for exposure, LCM warnings were 38 percent more likely with younger drivers than middle-aged drivers and 71 percent more likely with younger drivers than older drivers. For all age groups, the rear zone (Zone 3) accounted for the majority of all warnings. It should be noted that the exposure ratios for younger, middle-aged, and older drivers, were based on 68,868, 81,730, and 62,710 miles, respectively.

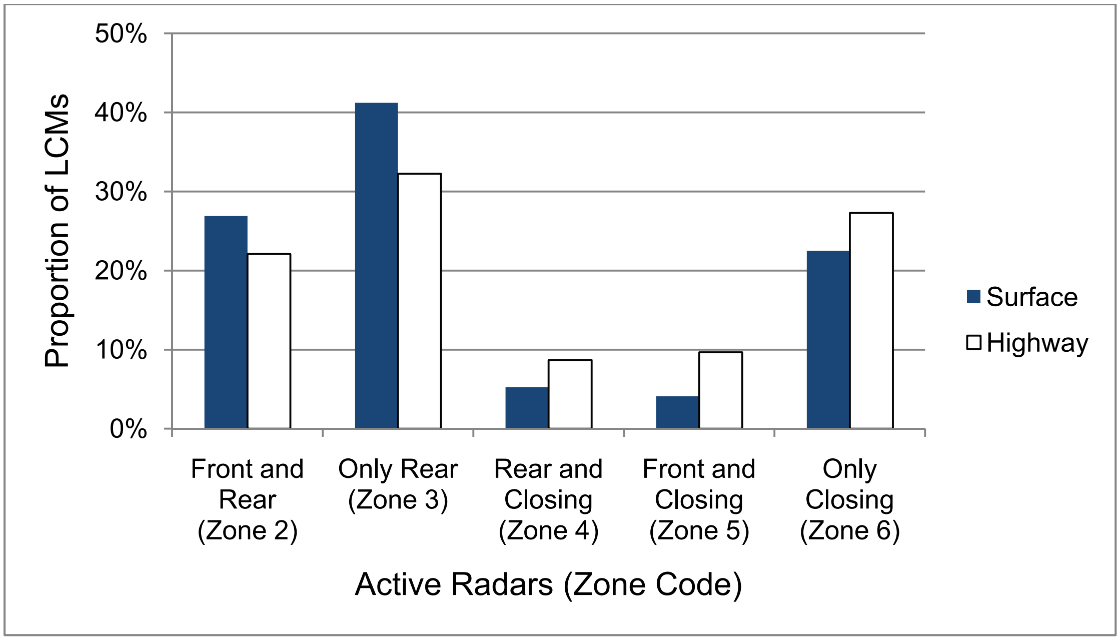


Figure 54: Main effect of road type on POV location during LCM warnings

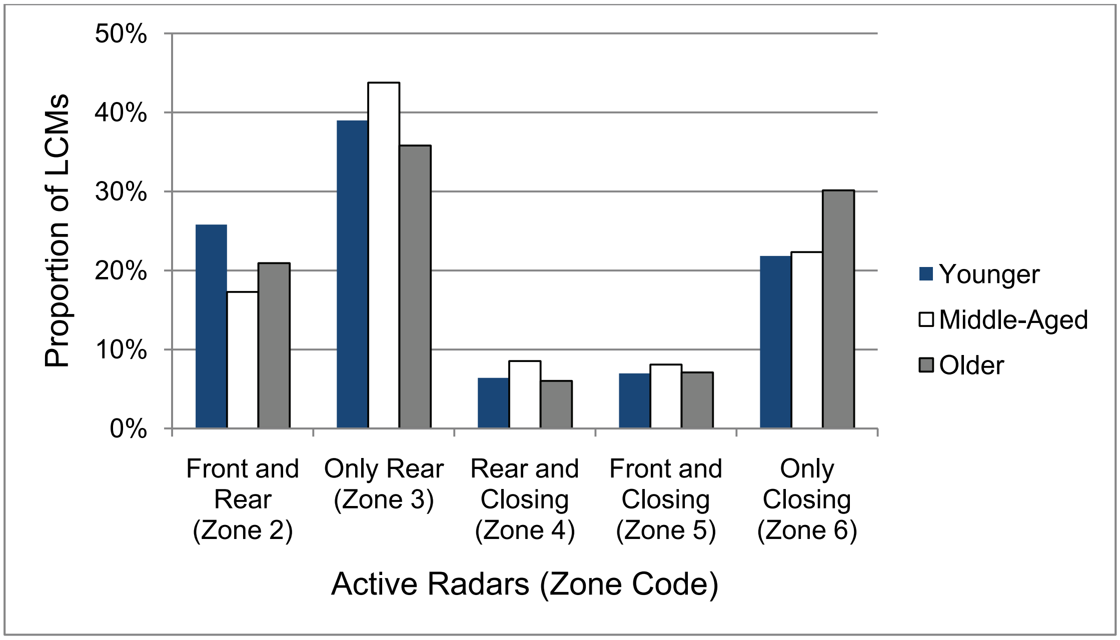


Figure 55: Main effect of age group on POV location during LCM warnings

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 was issued. Of the 1,270 LCM warnings, 772 (61%) resulted from a POV on the left side of the equipped vehicle. All effects showed that an adjacent vehicle present in the rear zone accounted for most of the valid LCM warnings issued.

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 (Zone 3) than for LCMs on the right. This is probably a result of lane changes to the left where a vehicle is encroaching into the equipped vehicle's blind spot and would be more likely than the case where the equipped vehicle has passed a car in the left lane and receives an LCM warning as it returns to the right lane.

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

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

Method: The investigation into differences in lane-change rates 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 equipped vehicle relative to the roadway in which it 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 exact instant in time of the lane-change is defined as the moment when the equipped vehicle's 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-change events used in this analysis was determined by the rules listed in Table 19. These constraints ensure that the set of lane changes analyzed does not contain events that were not intended to be lane changes by the 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 19: 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)

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

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 increase in the rate of lane changes associated with the windshield 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 highways to surface streets ($F(1,106)=38.97$; $p<.0001$). 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 sparse to dense traffic conditions. The estimated lane-change rates (per 100 miles) for the main effects are shown in Figure 56.

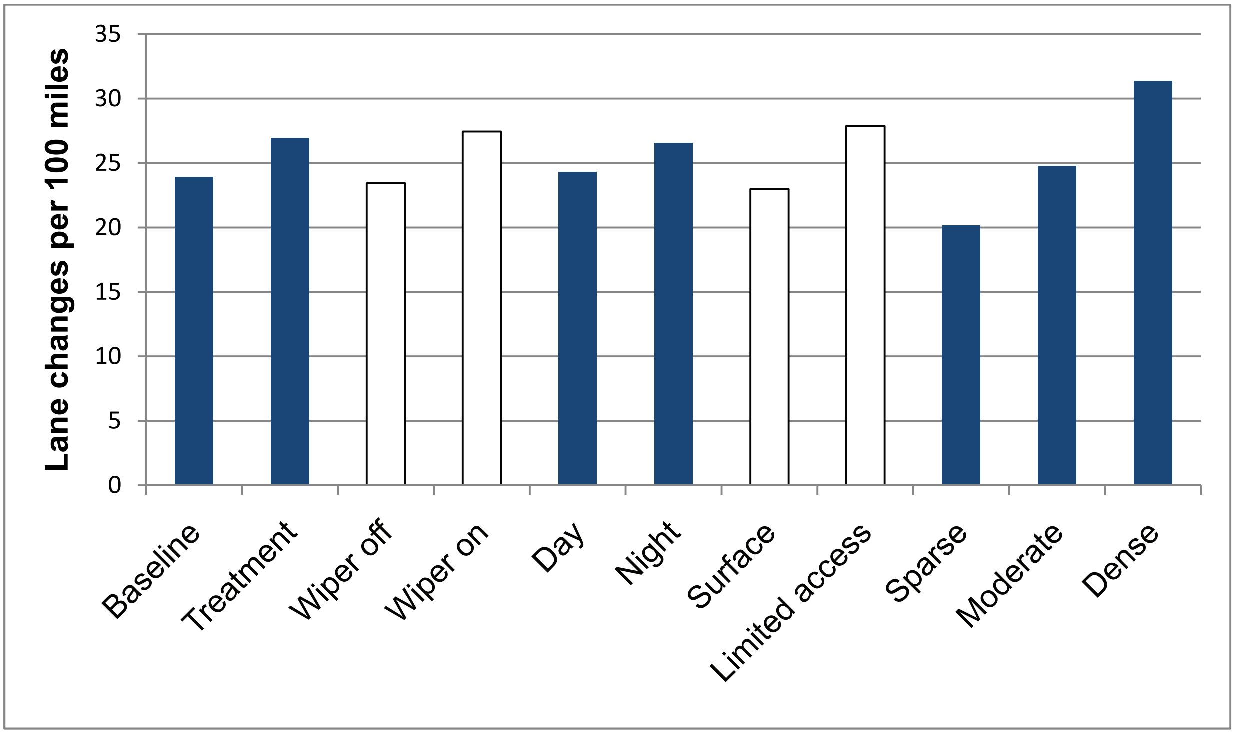


Figure 56: Main effects of condition, wiper state, ambient light, road type, and traffic on lane-change frequency

Interpretation: There was a statistically significant increase in the lane-change rate with the integrated crash warning system (12.6%). It is not readily apparent why drivers would modify their lane-change behavior, but it is potentially related to an increased sense of confidence provided by the LCM function of the crash warning system. The most pronounced effect 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?

Method: This analysis identified instances in which the equipped vehicle approaches a lead vehicle in its travel lane and makes a lane change behind a passing POV1 in an adjacent lane on the left (Figure 57). The range and range-rate to POV1 and POV2 were determined at the instant when the equipped vehicle's left front tire crossed the boundary. It was assumed that lane changes to the right under similar circumstances are far less frequent, and therefore only lane changes to the left were considered. The constraints in Table 20 were used to ensure that the events were reliable and consistent with the scenario definition.

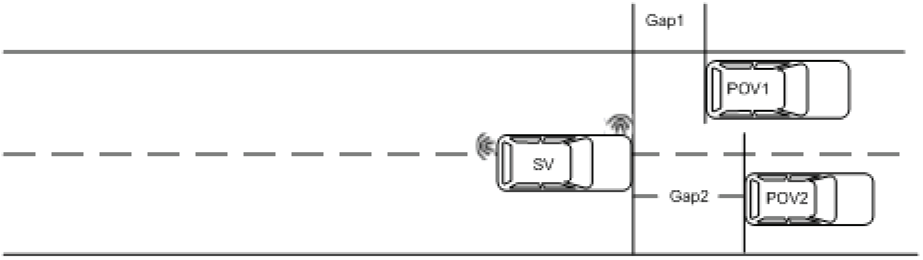


Figure 57: Location of adjacent and forward vehicles relative to the subject vehicle during lane-changes

Table 20: 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)

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

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

Analyses were performed initially with all of the independent variables and, based on this, variables 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 not to be 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. Over all conditions, as speed increased, so did the predicted gap between the equipped vehicle or 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.

Vehicle speed on highways has a major effect on the gap between the equipped vehicle and the initial lead POV ($F(1,97)=96$; $p <.0001$). This is likely because when a driver is traveling on a highway at low speeds (i.e., under 50 mph), it is almost exclusively because of heavy traffic 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-aged 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 observed for rainy weather conditions ($F(1,78)=6.27$; $p = 0.0144$), 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 equipped vehicle and POV1 just after the lane change was 4.1 meters greater than when the windshield wipers were off. Drivers were also predicted to increase the gap between their vehicle 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 that in more dangerous situations, drivers tend to behave more conservatively when deciding how close they are willing to get to the POV1 after a 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 effect of speed found was that the range rate to POV2 is linearly related to speed. On highways, as vehicle speed increases, the range rate between the equipped vehicle and POV2 decreases. When the range rate is positive, an increase in speed results in the gap between the equipped vehicle and POV2 to widen more slowly. On surface streets, as speed increases, the range rate between the equipped vehicle and POV2 increases. For younger and middle-aged drivers, this effectively reduces the closing speed to POV2. For older drivers, the already widening gap between their vehicle and POV2 increases.

Interpretation: The results indicate 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 equipped vehicle and the POV before lane changes during the treatment condition. Other independent measures such as road type, ambient light level, vehicle speed, and age group had a greater effect on driver performance when conducting these maneuvers.

2.2.3 Driver Acceptance

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 and LCM subsystems (i.e., do drivers want LDW and LCM on their vehicles?)

Results: The lateral subsystem provides both auditory and haptic warnings. Auditory warnings are triggered whenever a driver drifts in their lane and there is an adjacent threat present (e.g., another vehicle, a guardrail), while haptic warnings are issued whenever the driver drifts in their lane without an adjacent threat or changed lanes without using a turn signal (the LDW component). Figure 58 displays the van der Laan scores for the integrated system, as well as the individual subsystems. BSD was part of the LCM subsystem where yellow lights in the side view mirrors are illuminated whenever another vehicle was in or approaching the driver's blind spot, indicating that it is unsafe to make a lane change. Drivers rated BSD the highest for usefulness and satisfaction. In terms of usefulness, drivers rated the lateral subsystems equally with the integrated system as a whole, but somewhat less useful than BSD. The same can be said of their rating of satisfaction for the lateral subsystems. In addition, the lateral subsystems were rated more highly than the longitudinal subsystems.

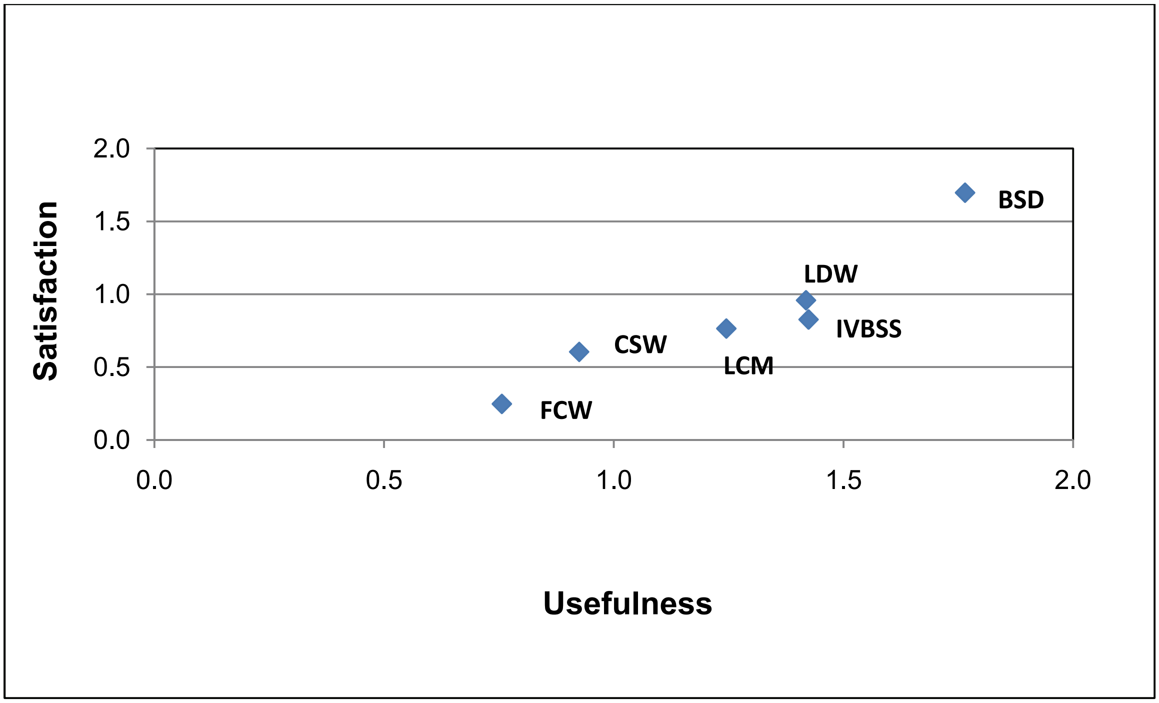


Figure 58: Van der Laan scores for the integrated system and subsystems

In the post-drive questionnaire, drivers were asked if they received lateral warnings when they did not need them. While Figure 59 and Figure 60 demonstrate that drivers were mostly neutral in their ratings of lateral nuisance warnings, Figure 61 indicates that younger drivers reported they received more left and right hazard nuisance warnings than the other age groups.

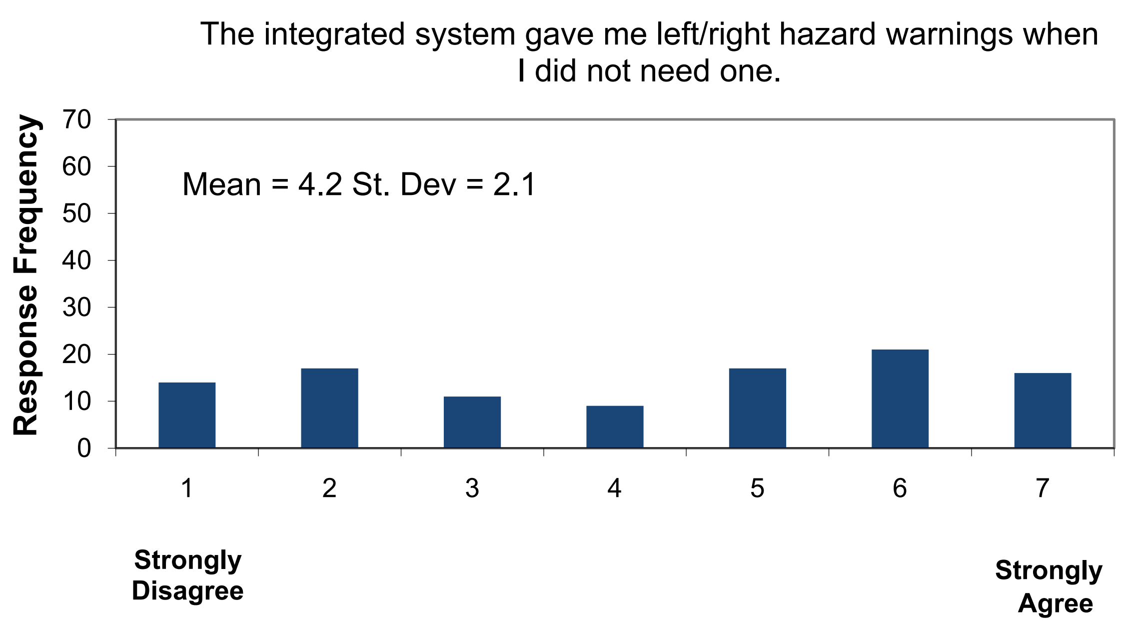


Figure 59: Drivers' perceptions regarding LCM nuisance warnings

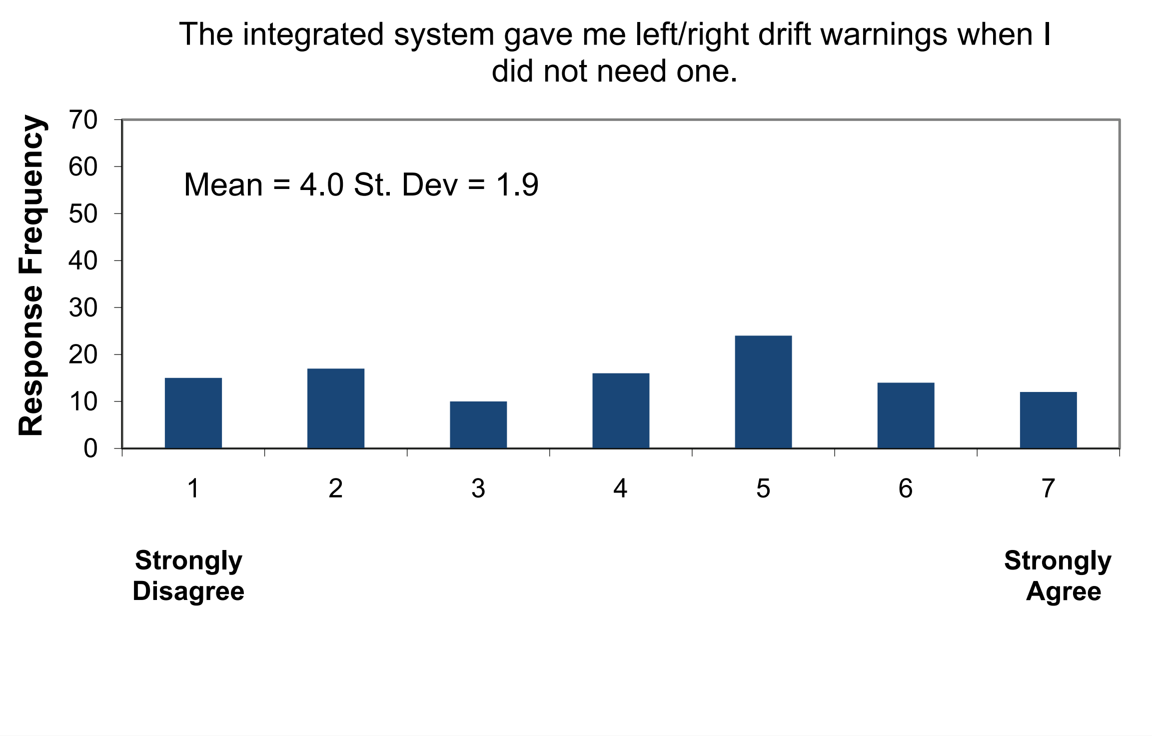


Figure 60: Drivers' perceptions regarding LDW nuisance warnings

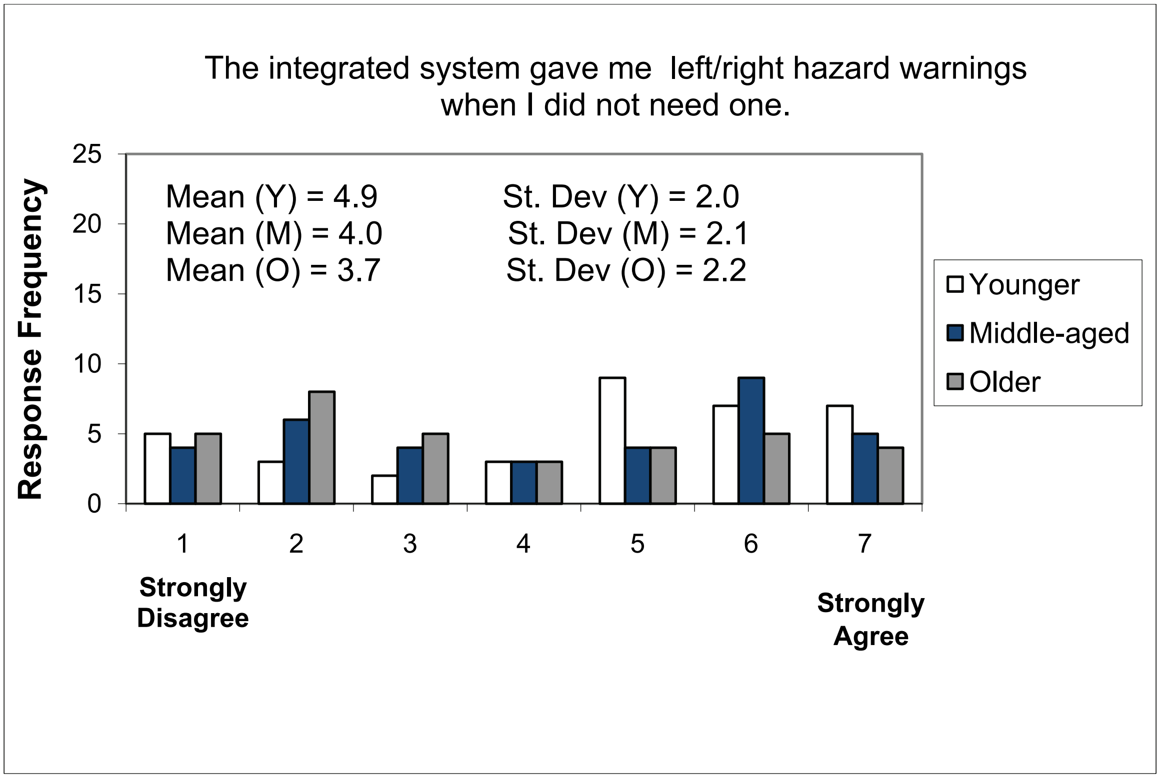


Figure 61: Drivers' perceptions regarding LCM nuisance warnings by age group

Interpretation: While drivers rated all of the subsystems and the integrated system favorably in terms of satisfaction and usefulness, they rated the lateral subsystems (LCM with BSD and LDW) more favorably than the longitudinal subsystems. Overall, drivers were most satisfied with the BSD component of the LCM subsystem. Drivers' mean subjective rating as to whether the integrated system issued 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 58 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), implying that 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 when changing lanes or merging into traffic. The second most mentioned situation was drifting within a lane and that the LDW subsystem provided a heightened awareness to distraction and their general lane-keeping behavior.

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

- Invalid warnings (approximately 40% of all drivers raised this issue).
- Brake pulse that accompanied FCW.
- Auditory tones: some drivers described them as too startling; others did not 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 heightened awareness if the driver was distracted. Reducing the invalid warning rate will undoubtedly increase the usefulness ratings of the integrated system.

2.3 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 forward-crash and curve-speed warnings, and changes in warning rate both with and without the integrated system.

2.3.1 Vehicle Exposure and Warning Activity

Over the course of the 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 Tables 21 and 22, respectively. In general, the highest overall warning rate for the FCW subsystem was on unknown roads, followed by surface streets. For the CSW subsystem, the highest warning rate was on highway ramps where drivers received over eight curve-speed warnings per 100 miles driven.

Table 21: 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 22: 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

2.3.1.1 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 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 equipped vehicle at the time of the FCW, and whether or not there was a curve in the forward path that the equipped vehicle traversed for CSW. FCWs and CSWs were 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 videos for each warning type. Curve-speed warnings resulting from curves in front of the vehicle, but out-of-path were considered invalid—as were warnings where no curve was present. 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 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 characterized by an incorrect or inaccurate assessment of the current or future driving environment (e.g., no vehicle present in the forward path, or the driver does not traverse the road branch with the curve), or there are complex situations (e.g., 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 present in the current situation—and one does not develop. While the system may be operating according to the system design intent, from the driver's point-of-view, the warning appears to be spurious, without any identifiable cause, and is therefore not predictable by the driver.

Some invalid warnings will be unavoidable, as it is not possible to predict future vehicle movements 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 FCWs, 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 CSWs, this includes going too fast for a curve that is being traversed, or about to be traversed, given the curve's geometry.
- **Invalid, but necessary** – The system function according to design intent, but the warning provided little, or no, utility to the driver. In the case of FCWs, this could happen with momentary 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 CSWs, this could occur whenever a driver has a turn signal on, suggesting that the vehicle is about to use 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 FCWs, identifying a manhole cover as an in-path object is considered invalid. For CSWs, warning where no curve exists 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 62 shows the FCW warning rate per 100 miles for all 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 sensing environments (10.6%), and in response to drivers' sudden changes in heading that could cause the FCW subsystem to identify that roadside objects are in the travel lane (4.3%). Twenty-one drivers received 50 invalid FCW warnings (16.5% of all FCW alerts) that occurred more than once at the same road location.

Figure 63 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 fixed roadside objects.

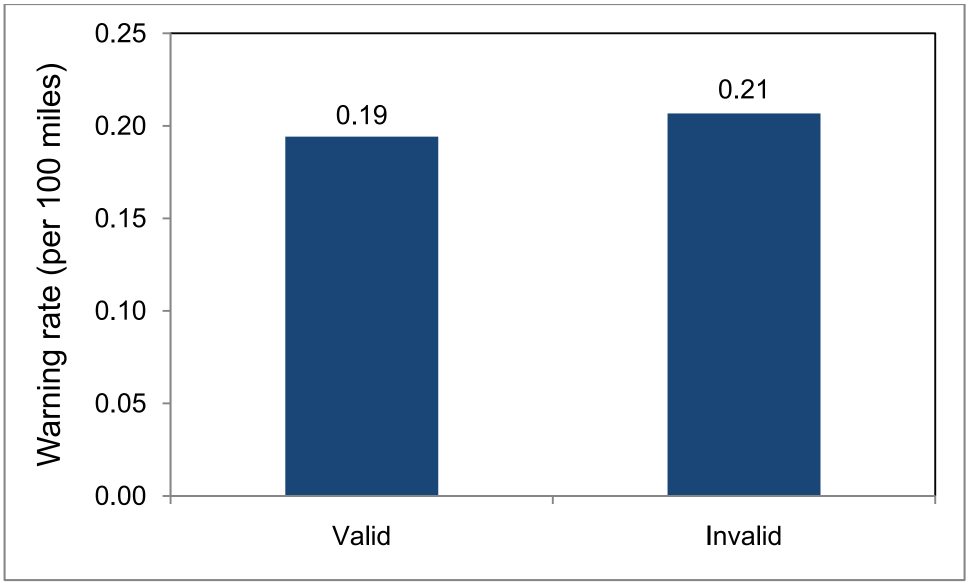


Figure 62: FCW warning rates during treatment period

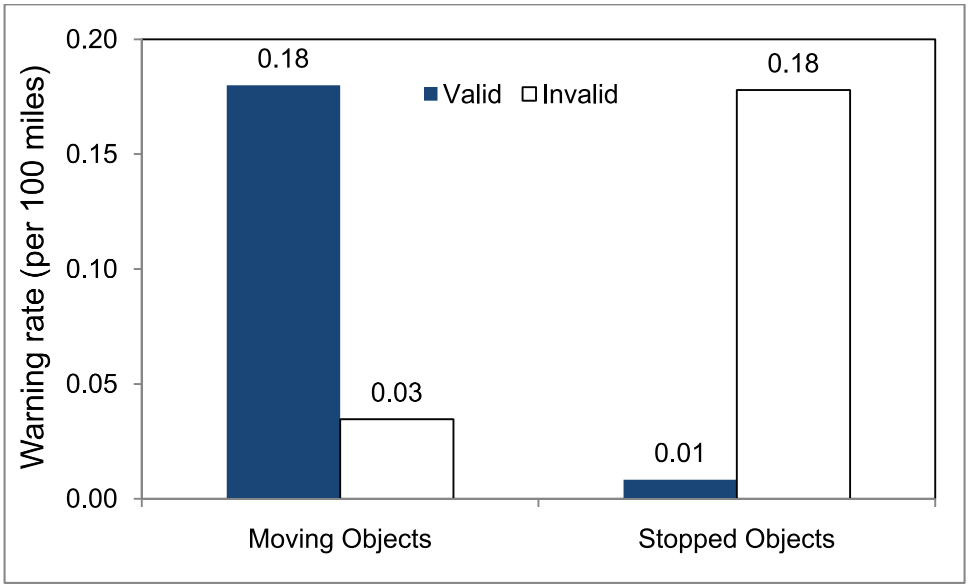


Figure 63: FCW warning rates by warning type during treatment period

In terms of the broader exposure variable of treatment condition, Table 23 shows the number of FCW warnings, percentage, and rate as a function of warning scenario and classification. Generally speaking, stopped object warnings have a much higher invalid rate than valid rate, while moving object warnings have a higher valid than invalid rate.

Table 23: FCW warning rate by condition and classification

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 64 presents the rate for valid and invalid curve-speed warnings received per 100 miles. Drivers had invalid and valid CSW warning rates of 0.12 and 0.31, respectively, per 100 miles, respectively. 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.

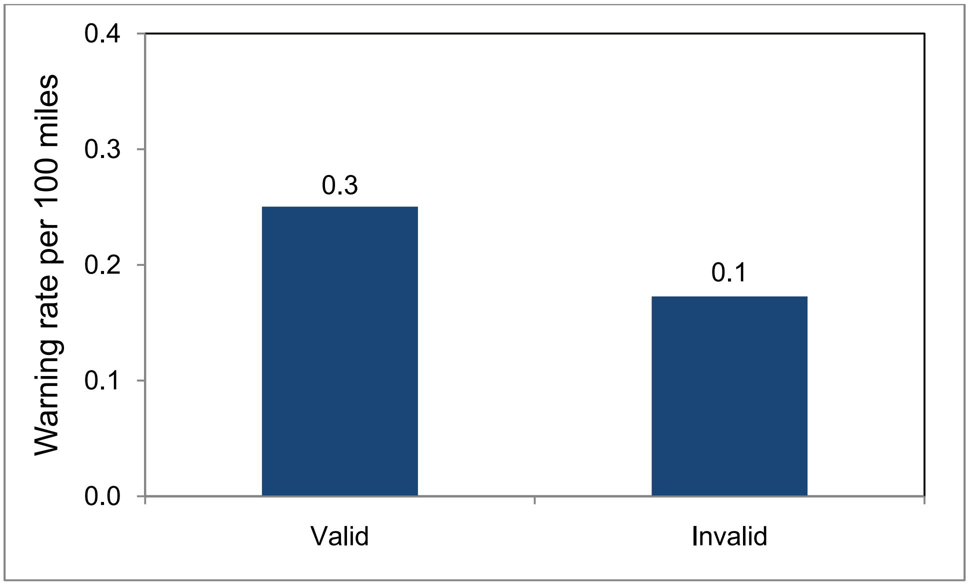


Figure 64: CSW warning rate per 100 miles

2.3.2 Driver Behavior

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

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 speeds between 11.2 and 35.8 m/sec (25 to 80 mph);
- Traveling with a time headway less than 3.5 seconds; 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 one second. This value was selected since analyses showed that it was this range of short headways that were most affected by a forward-crash warning system (Ervin et al., 2005). Also, time headways less than one second are usually considered to be following too closely for safety.

The method of analysis was a linear mixed 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.

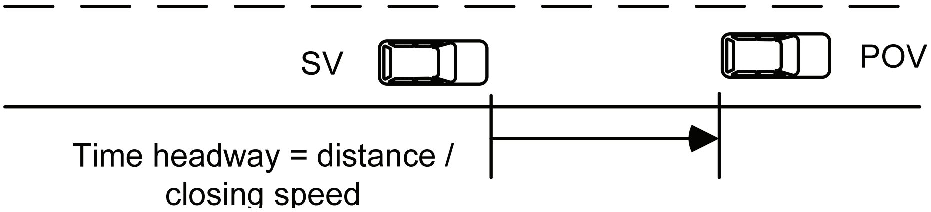


Figure 65: Steady-state following

Table 24: 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 time headway. Specifically, the fraction of following time at one second or less increased slightly 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 windshield wiper state. The direction of these effects is what might be expected (see Table 25). The principal findings of this analysis are based on the results of the linear mixed model. There were no statistically significant interactions that resulted from this analysis.

Table 25: 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 when the FOT vehicle is being driven within a 1-second time headway of the preceding vehicle. These events include each of the 108 FOT drivers, both for steady-state time and headway times of less than one second.

The variation among drivers in the percentage of following time at short headways is illustrated on the left side of Figure 66 below. The figure shows the number of drivers who spent different fractions of time with short headways, with the most common range being between 20 to 30 percent of steady-state following time. Note that since Table 25 showed that there are five other main effects, this figure illustrates that some drivers spent more time in conditions that apparently encourage short headways, such as higher speeds, limited access highways, and dry, daylight periods.

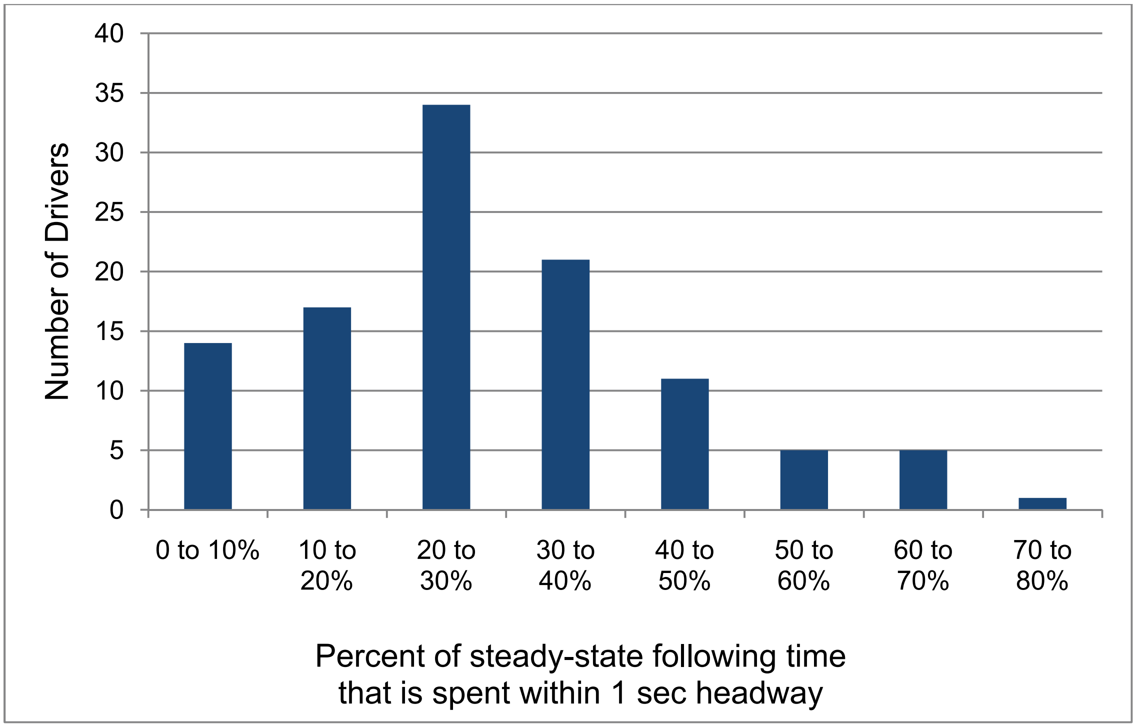


Figure 66: Percent time spent at headways of 1 second or less

Interpretation: There is a statistically significant effect of the integrated crash warning system on the time spent at short headways; i.e., more time was spent with shorter headways with the integrated system enabled than during baseline driving. The amount of travel spent at time headways less than one second increased slightly from 21 percent of steady-state following time during baseline driving to 24 percent during the treatment condition. The effect is weaker than the other main effects associated with driving context and driver age, but it is of some practical significance. Based on previous research with FCW systems, this result is unexpected. This analysis is similar to one conducted for the Automotive Collision Avoidance System (ACAS) Field Operational Test project (Ervin et. al., 2005). The ACAS 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 condition did not have a main effect, but had two second-order effects with daylight and freeway road types. Both effects were to slightly reduce the occurrence of short headways. Thus, the two studies appear contradictory in their findings.

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

Method: This analysis addressed forward conflicts with a lead vehicle in 20,096 events. The measure of forward conflict is the minimum level of required deceleration to avoid a collision during the event. The required deceleration is defined as the constant level of 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 26 apply, and in which either of the following are also true:

- The time-to-collision (the range to the lead vehicle divided by the following vehicle's 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 releasing the throttle. Many subsequent processing steps are needed to ensure that each event is truly a unique encounter with a lead vehicle. Thus, the radar data is filtered to identify and bridge signal dropouts, target index changes, and to recognize when a radar target shift is still associated with the same lead vehicle.

Additional constraints are used, as shown in Table 26, including limiting the analysis to shared-lane conflicts, in which the two involved vehicles continue to share the lane at least 5 seconds after the mild conflict ends (and share it 5 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 multiple-lane scenarios.

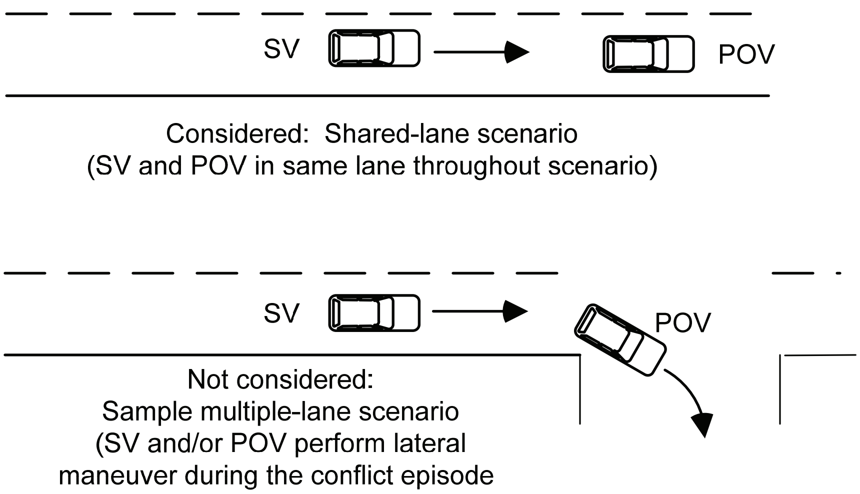


Figure 67: Forward conflict in shared-lane scenarios

Table 26: 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 linear mixed 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 a 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-aged drivers, and middle-aged drivers were found to have higher conflict levels than younger drivers.

Table 27: 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 68. The model mean values are -0.74 and -0.77 m/sec^2 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 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).

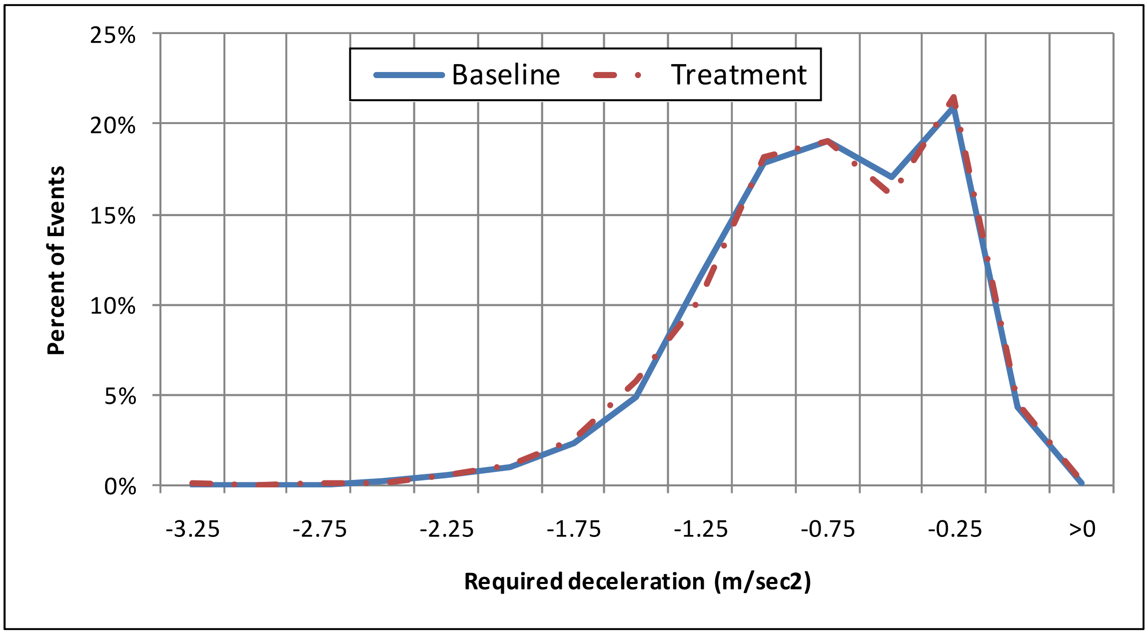


Figure 68: Required deceleration in baseline and treatment conditions

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, deceleration required, depends 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?

Method: The actual braking level is an important concept in driving safety measurement. The consideration 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 equipped vehicle 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 28.

Table 28: 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

Results: The results are based on a linear mixed model analysis. Pair wise comparisons using Tukey tests 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 under the treatment condition was 5.01 per 100 miles, while the mean rate under baseline condition was 4.45 per 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 highways (mean = 3.83 per 100 miles) as shown in Figure 69.

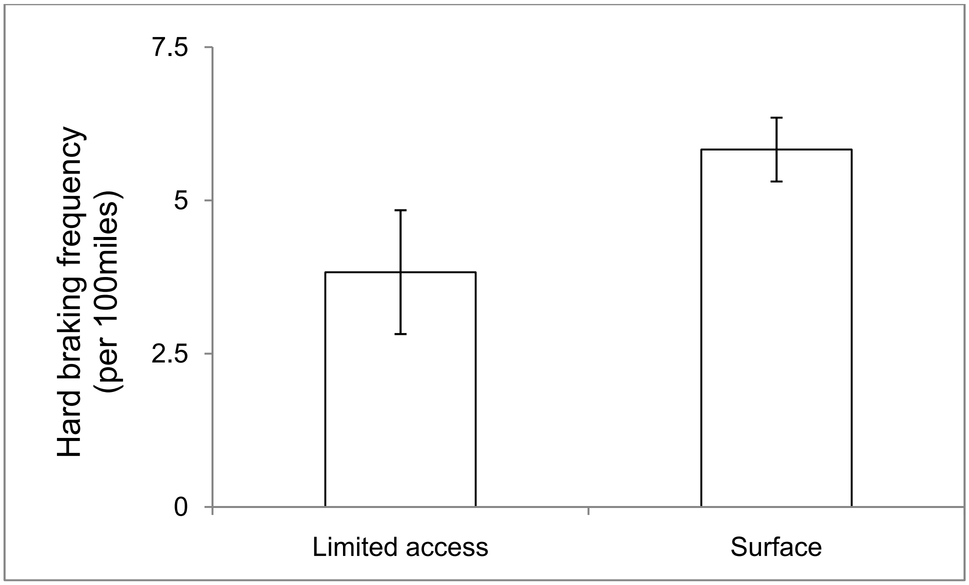


Figure 69: Least squares means of hard braking frequency on different road types, including standard error

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 70.

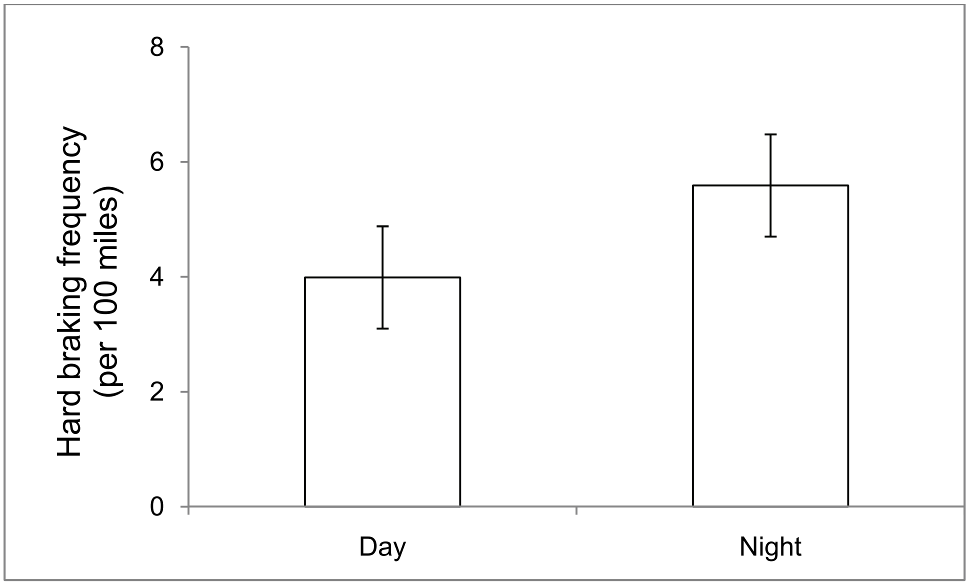


Figure 70: Least squares means of hard braking frequency at day or night, including standard error

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 streets compared to limited access highways. Given that the opportunity for interruptions in traffic flow associated with surface streets, this result might not be 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' responses to those forward conflicts in which closing-speed warnings occur?

Method: For this analysis, data from the closing conflict events (i.e. with issued FCW warnings) were examined and two dependent measures describing drivers' response to those warnings 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 (in seconds) between the warning onset and the time when the driver initiated braking.

The constraints shown in Table 29 were used to eliminate invalid FCW warnings (e.g., FCW warnings triggered with no lead vehicle present) and exclude events in which drivers responded to new conflicts that were unrelated to the initial FCW. The "5-second" 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).

Table 29: 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

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 71, brake reaction time (i.e., the time between when the warning is issued and when the driver applied the brake pedal), decreases with increasing traffic density (least squares mean 0.63 seconds for low traffic, 0.47 seconds for medium traffic, and 0.33 seconds for dense traffic). No other statistically significant differences were observed.

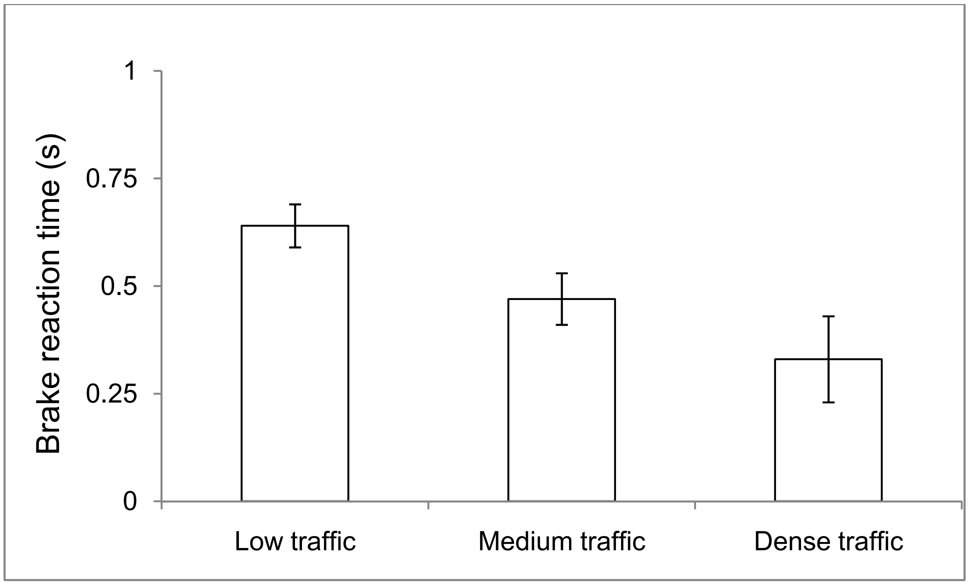


Figure 71: Least squares means of brake reaction time for three traffic density groups, including standard error

Interpretation: The integrated crash warning system did not have a statistically significant effect on drivers' brake reaction time. However, a statistically significant difference was found between the brake reaction times of drivers due 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 increased 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 braking reaction time to valid FCWs.

2.3.3 Driver Acceptance Research Questions

This section reports key findings on driver acceptance of the forward-crash warning subsystem. Post-drive survey results for the FCW subsystem 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 58). Chief among the issues was that drivers did not like the brake pulse feature of the FCW subsystem, despite agreeing with the statement, "The brake pulse warnings were not annoying" (Figure 72). Furthermore, in debriefing sessions, many drivers voiced their dislike of the brake pulse warning cue. Some drivers described it as "startling," while other drivers reported being frightened when they first received a brake pulse.

During debriefing sessions, several drivers reported receiving FCWs which could have prevented a crash. The most dramatic of these events involved a driver with both hands off the wheel and eyes off the road. He was texting and completely unaware of the vehicle braking ahead of him. The FCW alert drew 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 the road when the vehicle ahead began to brake. Her gaze returned to the forward scene as she received an FCW alert. She reported that receiving that FCW prevented a crash. Yet another driver reported in his debriefing session and in a focus group that receiving an alert while engaged in an emotional conversation with a passenger prevented him from crashing into a vehicle braking in front of him.

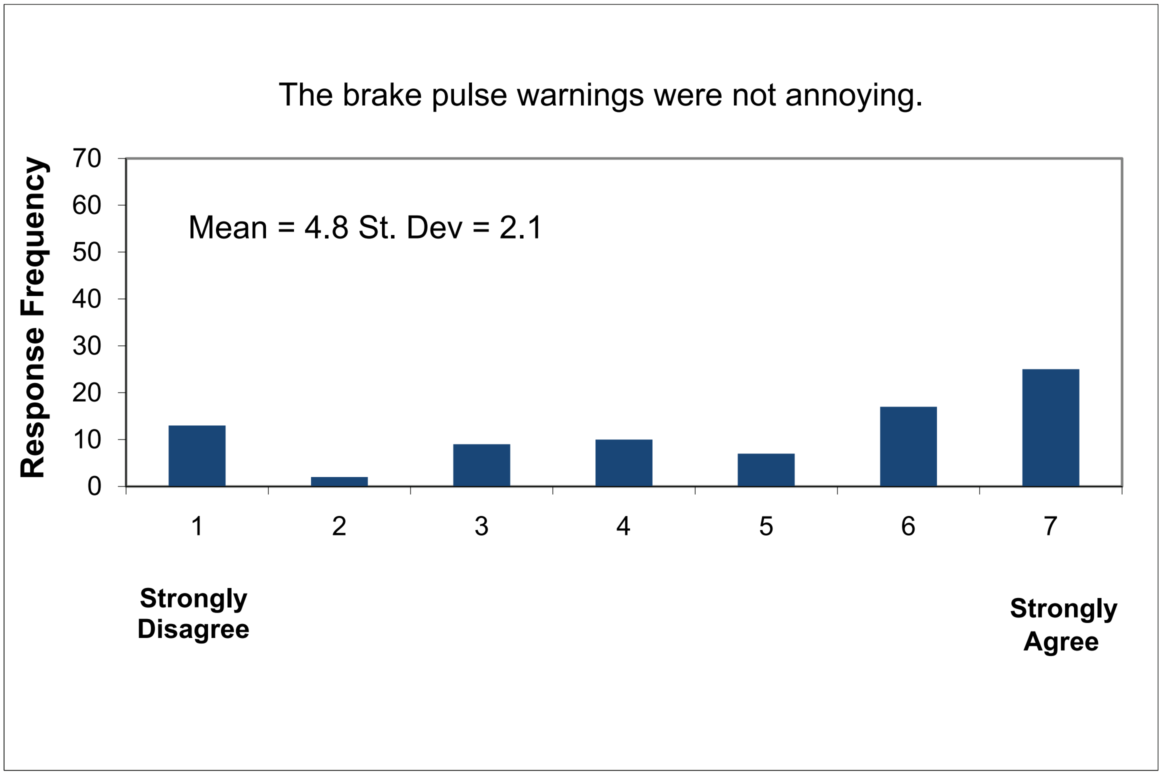


Figure 72: Drivers' perception of annoyance of the brake pulse warning which accompanied hazard-ahead warnings

As a group, drivers appeared to be divided 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 32 percent agreed with the statement. As shown in Figure 73, there appears to be little effect of driver age on results.

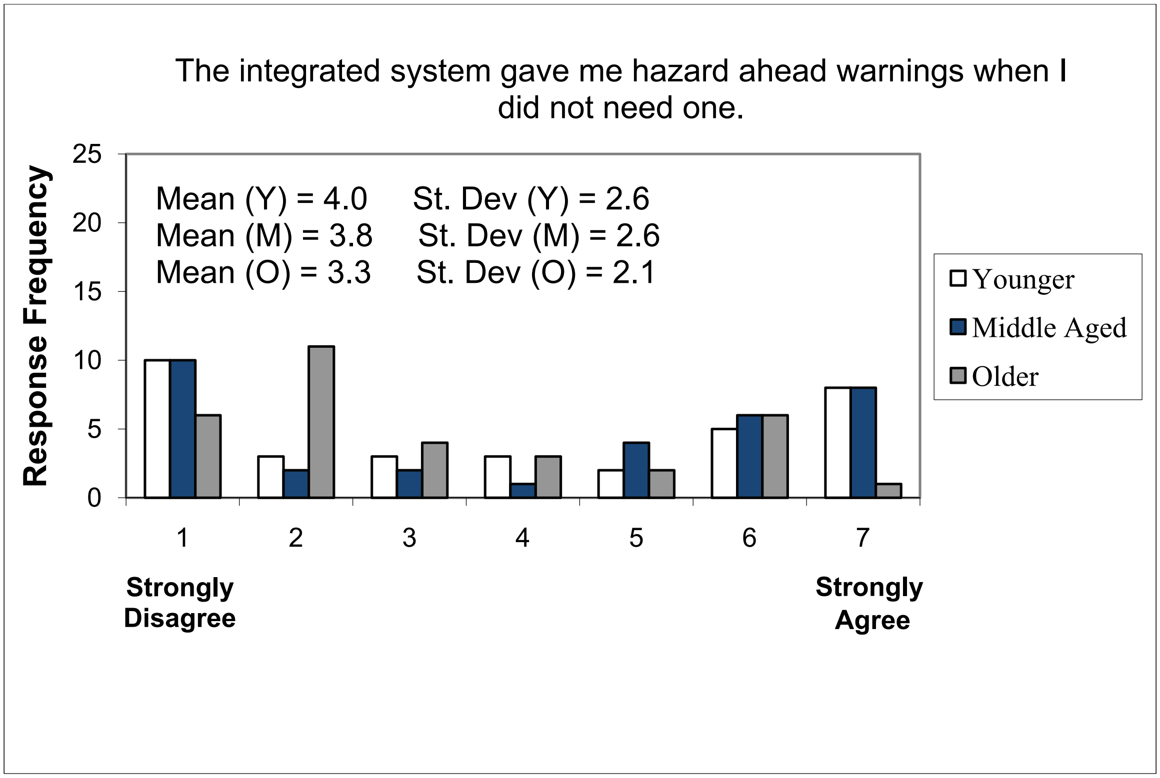


Figure 73: Drivers' perceptions regarding hazard-ahead nuisance warnings by age group

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 and the general dislike of the brake pulse feature, 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 comparable to the FCW subsystem (mean van der Laan scores of 0.9 and 0.8, respectively). They were, however, more satisfied with the CSW than the FCW subsystem (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 74).

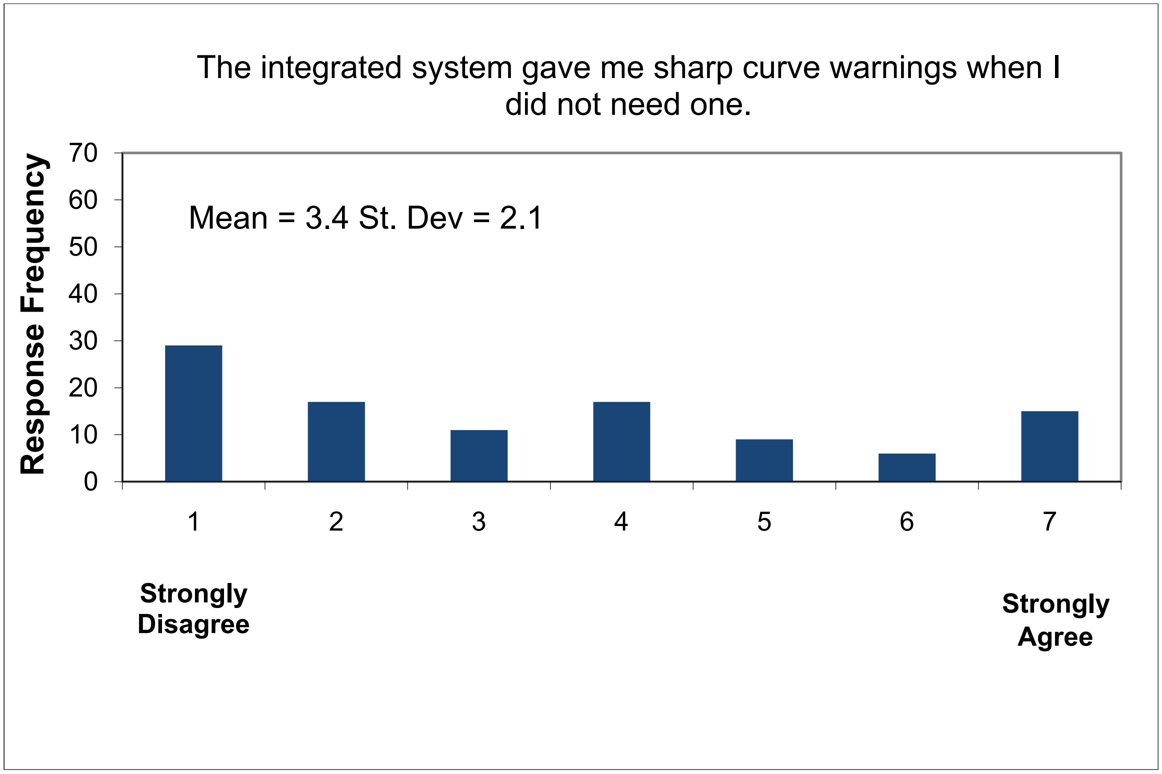


Figure 74: Drivers' perceptions regarding sharp curve nuisance warnings

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 accumulated was in southeastern Michigan, where roads tend to be straight, it is not too surprising that drivers did not find the CSW subsystem to be 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?

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

Table 30 lists the constraints employed in the analysis. The constraints limit the study to curve-taking events that are at speeds when the CSW subsystem was active and potentially influenced driver behavior. Furthermore, events were excluded if other factors were expected to strongly influence 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 30: 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 linear mixed model. As shown in Figure 75, a few drivers dominated the sample of curve traversals. One driver accounted for 349 out of the 1,632 curve traversals (21.4%). Removing this driver had only a negligible effect on the model, so the driver was left in the sample for analysis. The 8 drivers with the most curve traversals accounted for almost 50 percent of the total sample.

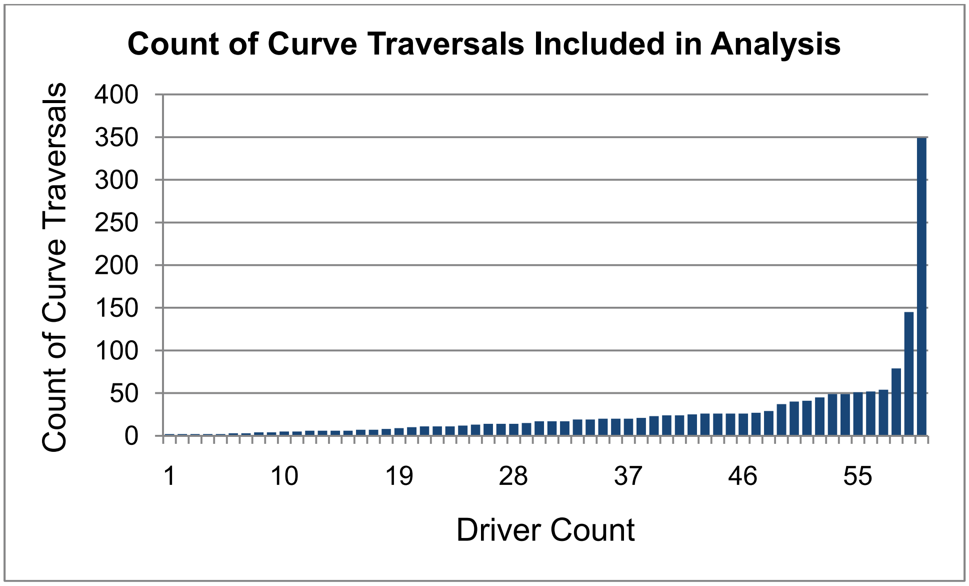


Figure 75: Count of curve traversals included in analysis by driver

Peak Sustained Lateral Acceleration

The integrated crash warning system did not have a statistically significant effect on peak sustained lateral acceleration. The independent measures that were found to have a statistically significant effect 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 acceleration 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 acceleration and older drivers the lowest.

Combined Peak Sustained Lateral Acceleration and Longitudinal Deceleration

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

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

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

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 determined. This analysis complements research question QC1, which studied acceleration components within a curve. Table 31 lists the analysis constraints used.

Table 31: 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 linear mixed model. From Figure 76, it can be seen that a few drivers dominated the sample of curve approaches. One driver accounted for 159 out of the 851 curve approaches (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 accounted for 50 percent of the total sample.

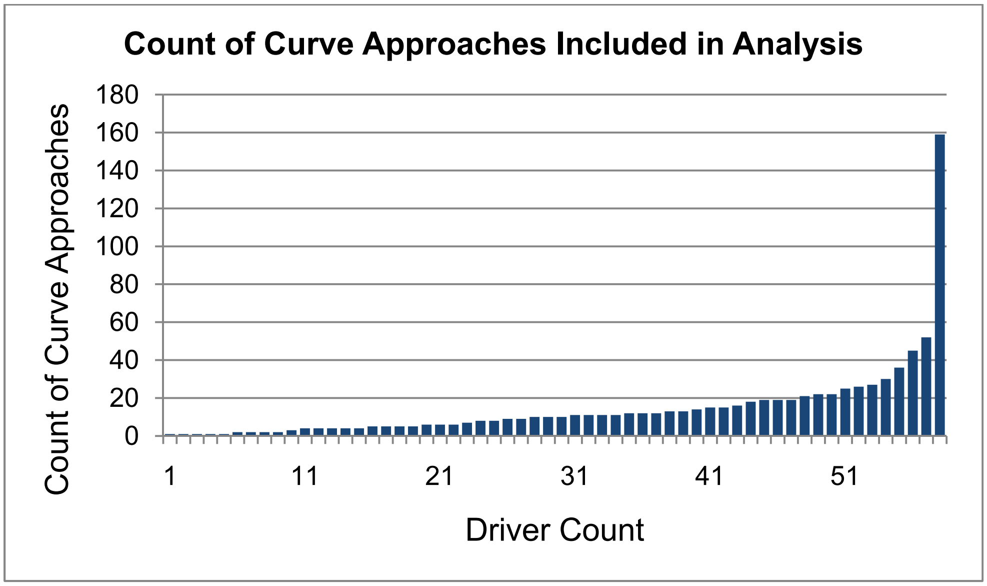


Figure 76: Count of curve approaches included in analysis by driver

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 was ambient light. For ambient light ($F(1,34)=4.8$ $p=0.035$), 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 was ambient light level, intuitively indicating that drivers approached curves at lower speeds and lower peak longitudinal decelerations after dark.

QD1: Did drivers perceive the driver-vehicle interface for the integrated system as 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 determine what may have triggered an invalid warning. They found the display to be useful (mean = 5.6, Figure 77); however, in focus groups, many drivers suggested moving the display to a more central location and having the messages displayed for a longer period of time.

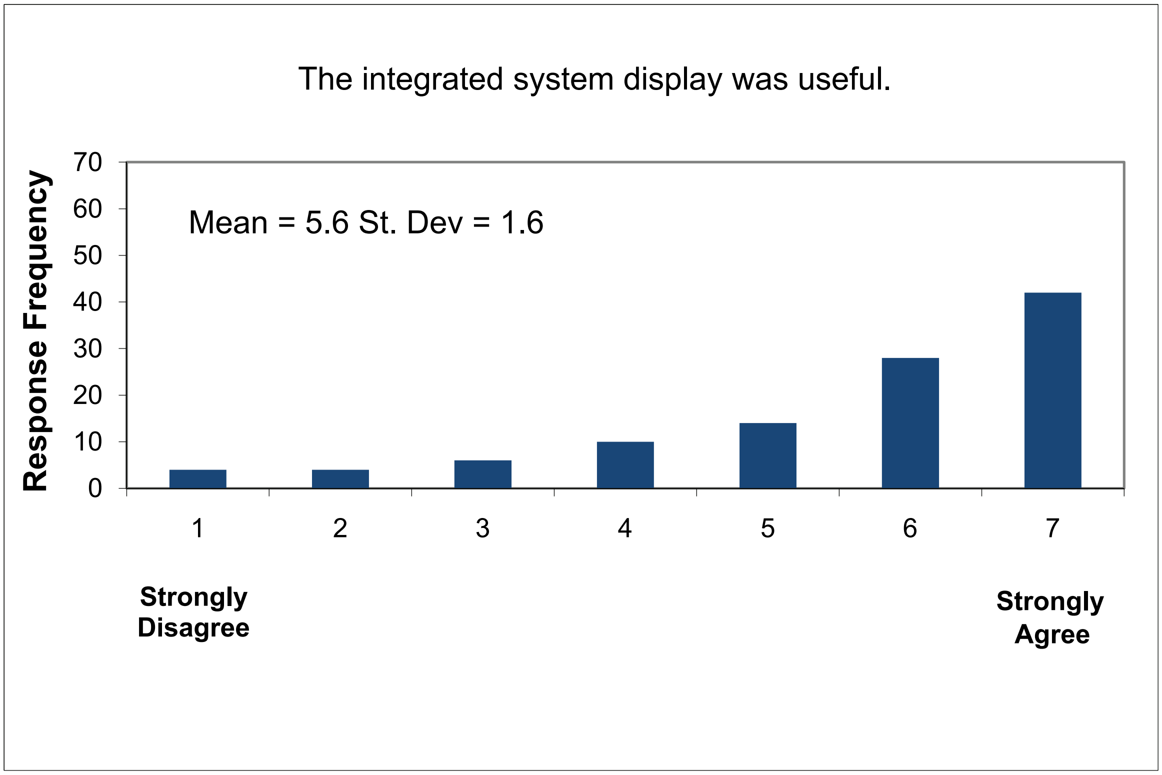


Figure 77: Drivers' ratings of the usefulness of the display

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; the first was a volume control switch they could use to select from three warning volume levels. They could also use a mute button, which would silence warnings in two minute increments, for up to six minutes at a time, in situations where the driver did not wish to receive warnings (e.g., construction zones with narrowed lanes, which could produce a high number of invalid warnings).

Only 35 percent of the drivers reported using 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 control was used by all drivers at least once.

Drivers had the volume control set to medium more frequently than either the low or high settings. Figure 78 illustrates the number of times drivers used each volume control setting. It should be noted that when drivers left 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 79 and Figure 80). There was no effect of age on drivers' assessment of the usefulness of the display, the mute button or the volume control.

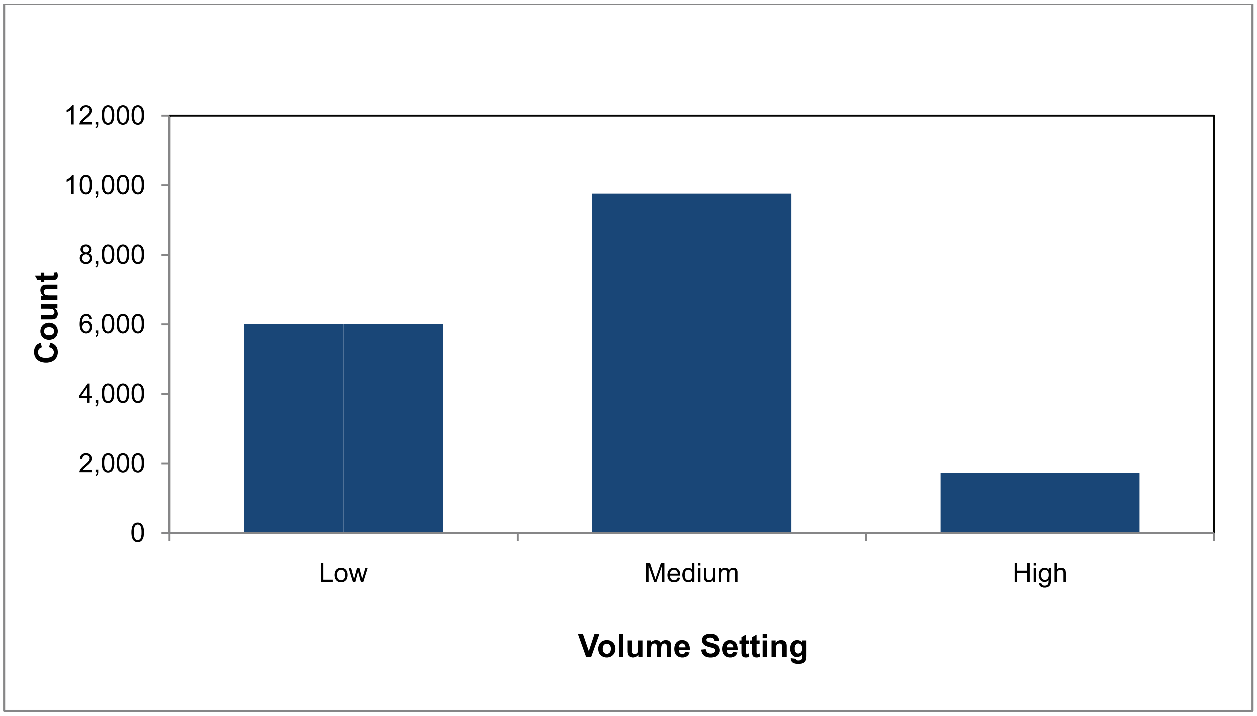


Figure 78: Use of the volume control adjustment

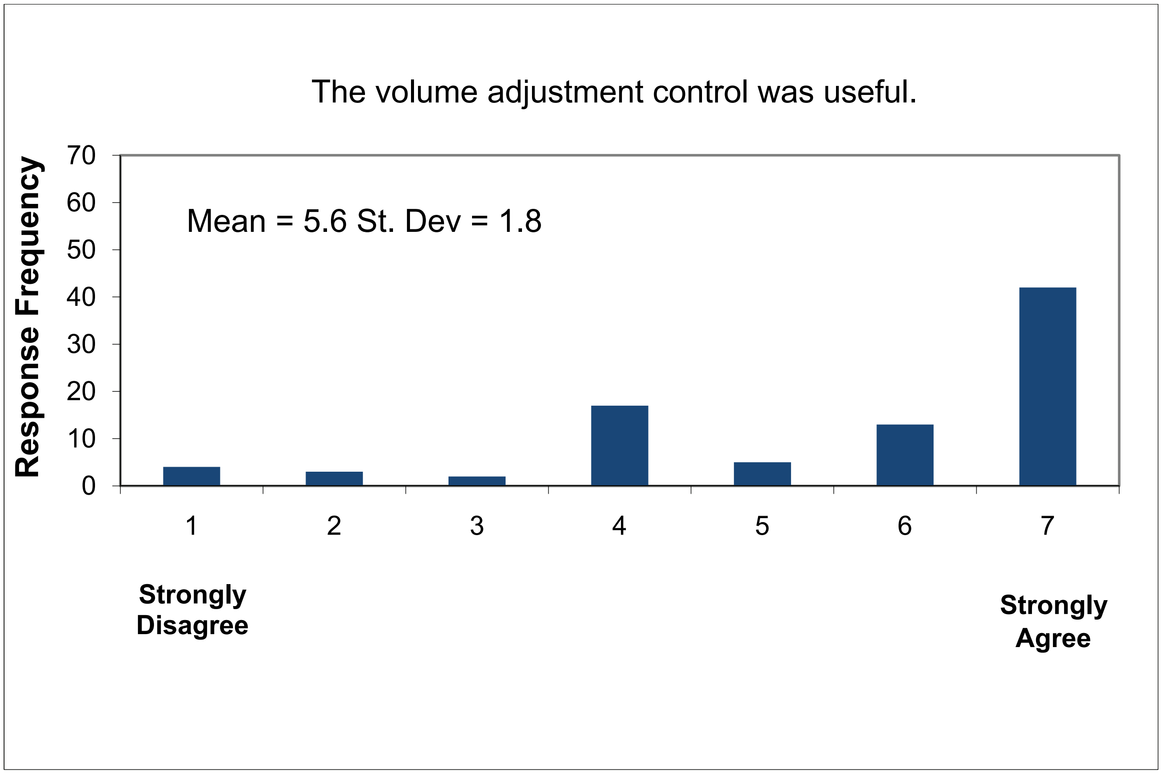


Figure 79: Usefulness of the volume adjustment control

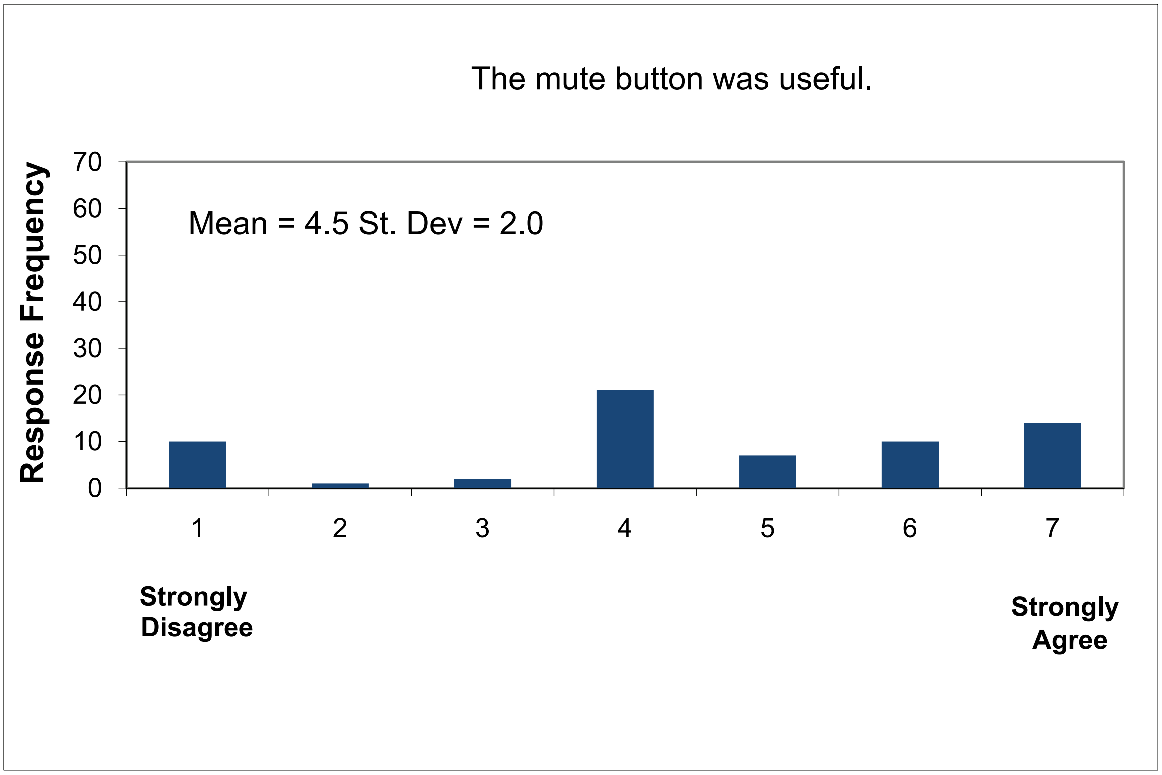


Figure 80: Usefulness of the mute button

Interpretation: The majority of drivers did not use 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 often 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.

2.4 Summary of Focus Groups Sessions

As part of the light-vehicle field test, three focus group sessions were as conducted at UMTRI, with each session lasting about two hours. Twenty-eight of the 108 drivers participated in the focus groups. Drivers were invited to participate 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 by 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 from 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 did not lend itself to quantitative analyses; rather, it was used to identify and explore themes about participant's experiences with the integrated system. One of the goals of the focus groups was to obtain information and experiences that drivers may have not thought of, or reported previously in questionnaires or debriefings.

Generally speaking, drivers became familiar with the integrated system after driving with it for one or two days. 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 divided as to whether they thought that the integrated system was ready for production. Half of the group 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 the BSD subsystem. Furthermore, 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). In addition, 7 drivers reported that an LCM warning 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 warning prevented him from having a rear-end crash.

Drivers were asked how false warnings affected their perception 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 provided 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 like construction zones.

3. System Maintenance and Reliability

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.

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 release of each vehicle to participants, problems can occur once a vehicle is 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 scrutiny and analysis of system data. As such, monitoring of the data from the vehicles was performed almost daily throughout the field test.

During the field test, the system performance data was monitored using files that UMTRI received via 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. Visteon also closely monitored system performance after receiving a copy of the data from UMTRI. When abnormal system behavior such as an exceptionally higher warning rate was observed, the team would look further into intermediate system performance signals to identify the potential root cause and work with UMTRI to schedule a diagnosis and repair if necessary.

3.3 Data Retrieval

Data retrieval was performed for each vehicle upon its return after six weeks of use, with three to four vehicles having data retrieved in any given week. Any other maintenance was handled on an as needed basis, and largely resulted from UMTRI's monitoring data collected via the cellular link.

3.4 System Repairs Associated with Crashes

There were a few instances 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 highway 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 or adjustments to the sensor suite.

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. Overall system performance and the 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

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.

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 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.
- 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 mirrors (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 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.

In summary, it is clear that the IVBSS light-vehicle FOT produced valuable findings. This report, which only covers the key findings, is further supported by a more detailed evaluation of the data in the IVBSS Light-Vehicle Field Operational Test: Methodology and Results Report. A comprehensive report covering integrated system performance, potential safety benefits, driver acceptance and willingness to purchase will be prepared and published in early 2011 by the Volpe National Transportation Systems Center, the IVBSS FOT independent evaluator.

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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.
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).
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.

Question Number	Research Question	Key Findings
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.
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 seconds in the baseline condition to 1.66 seconds 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.

Question Number	Research Question	Key Findings
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%).
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 one second 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.
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.

Question Number	Research Question	Key Findings
QF6	Are drivers accepting of the CSW subsystem (i.e., do drivers want CSW on their vehicles?)	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.
QCS1	Will the magnitude of lateral accelerations observed in curves be reduced between the baseline and treatment conditions?	The integrated system had no effect on the curve taking behavior of these drivers. The only factors significantly affecting the curve-taking behavior were environmental. Drivers took curves at lower peak sustained lateral accelerations when it was dark.
QCS2	Will the integrated system's warnings reduce hard braking upon approaches to curves?	The integrated system had no effect on driver behavior when approaching a curve.
QD1	Did drivers perceive the driver-vehicle interface for the integrated system easy to understand?	Drivers had a good understanding of both the integrated system and the warnings that the DVI was conveying.
QD2	Do drivers find the volume and mute controls useful, and do they use them?	The majority of drivers did not use the mute button, and drivers were neutral on its usefulness. While drivers used the volume control more than the mute function, the frequency of volume adjustments was still quite low.

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)
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
Lateral offset Confidence	%	0-100	Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem

Dependent Variable	Units	Levels	Description and Source
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
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 FOTs from UMTRI
Side	-	Left, Right	Left and right side of the vehicle
Speed	m/s		Estimate of forward speed
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)
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.
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

Other Terms	Units	Levels	Description
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.
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 vehicle's tire. Must include both and exit from and a return to the original lane.
Lane Incursion			See Lane Departure
Lateral offset Confidence	%		Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem
Lateral Position			See Lateral 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

Other Terms	Units	Levels	Description
M/A-COM 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
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
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 four possible warnings from the integrated system on the light-vehicle platform (FCW, CSW, LDW, LCM)

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