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Heavy-Truck Field Operational Test Key Findings Report

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16. Abstract

This document presents key findings from the heavy-truck 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 effect of a prototype integrated crash warning system on driving behavior and driver acceptance. The heavy-truck platform included three integrated crash-warning subsystems (forward crash, lateral drift, and lane-change/merge crash warnings) installed on a fleet of 10 Class 8 tractors and operated by18 commercial drivers for 10 months. Each truck 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 and debriefings.

The key findings indicate that integrated crash warning systems not only offer benefits relative to improved driver performance (e.g., improved headway keeping), but that the majority of commercial drivers accepted the system and reported subjective benefits from the integrated system they used. Of the drivers who participated, 15 out of 18 stated that they preferred a truck with the integrated system, stating that they would also recommend that their company consider the purchase of vehicles with integrated safety systems installed. No negative behavioral adaptation effects from the drivers' 10-month use of the integrated system were observed.

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Table of Contents

List of Figures

List of Tables

List of Acronyms

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

Executive Summary

Overview

The purpose of the Integrated Vehicle-Based Safety Systems (IVBSS) program is to assess the potential safety benefits and driver acceptance associated with a prototype integrated crash warning system designed to address rear-end, roadway departure, and lane change/merge crashes for light vehicles and heavy commercial trucks. This report presents key findings from the field operational test for the heavy-truck platform. The system tested was developed and implemented by Eaton Corporation and Takata Corporation, with assistance from the University of Michigan Transportation Research Institute and the Battelle Memorial Institute. The heavy-truck 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; and
- Lane-change/merge warning (LCM): warns drivers of possible unsafe lateral maneuvers based on adjacent vehicles, or vehicles approaching in adjacent lanes, and includes full-time side-object-presence indicators.

The integrated system also performed warning arbitration in the event that more than one subsystem issued a warning at or very near, the same time. The arbitration process was based upon when the warning was issued and severity of the detected threat. A driver-vehicle interface (DVI) containing visual and auditory information was developed, although it relied mainly 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.

Commercial truck drivers were recruited to drive Class 8 tractors, like those they would normally operate as part of their employment, equipped with the integrated system and data collection hardware installed on-board. The trucks were instrumented to capture information on the driving environment, driver behavior, integrated warning system activity, and vehicle kinematics data. Subjective data on driver acceptance was collected using a post-drive survey and driver debriefing.

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

FOT Data Collection

Twenty drivers from Con-way Freight's Detroit terminal were recruited for the study; however, data from only 18 drivers is represented in the analyses. Each participant drove one of the specially equipped, Class 8 tractors for 10 months. The first 2 months represented the baseline driving period, in which no warnings were presented to the drivers, but all on-board data was being collected. The subsequent 8 months were the treatment condition, during which warnings were presented to the drivers and detailed data was collected. There were two types of delivery routes used during the field test; pick-up and delivery (P&D) routes, which operated during the daytime, and line-haul routes that predominantly ran at night. P&D routes typically used single trailers ranging in length from 28 to 53 feet, whereas line-haul routes typically towed a set of 28-foot-long double trailers. More detailed information on the vehicle instrumentation and experimental design can be found in the Integrated Vehicle-Based Safety Systems – Field Operational Test Plan (Sayer et al., 2008).

The data set collected represents 601,844 miles, 22,724 trips, and 13,678 hours of driving. The rates of warnings heard by drivers in the treatment condition were 3.3 per 100 miles for FCW, 13.0 per 100 miles for LDW, and 2.0 per 100 miles for LCM. The rate of invalid warnings across all drivers was 1.8 per 100 miles for FCW, 1.6 per 100 miles for LDW, and 1.6 for LCM.

Key Findings

The analyses performed were based upon specific research questions that emphasize the effect that the integrated warning system has on driver behavior and driver acceptance (also see the IVBSS Heavy-Truck 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 frequency of 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 in the baseline condition.
- In multiple-threat scenarios, the initial warning was generally enough to get the attention of drivers, and resulted in an appropriate action when necessary. Based on data collected during the FOT, it does not appear that secondary warnings were necessary in multiple-threat scenarios. However, multiple-threat scenarios are rare and other drivers operating different systems could respond differently.

Driver Acceptance Results:

- Drivers stated that the integrated system made them more aware of the traffic environment around their vehicles and their positions in the lane.

- Drivers prefer driving a truck equipped with the integrated warning system to a conventional truck (15 of 18 drivers).
- Drivers would recommend the purchase of such systems to increase safety (15 of 18 drivers).
- The invalid warning rate for lane-change merge warnings (1.6 per 100 miles), and forward collision warnings (1.8 per 100 miles), particularly for line-haul drivers, led some drivers to describe the warnings as “distracting” or “annoying.”
- The majority of drivers perceived that integrated crash warning systems would increase driving safety.
- Seven drivers reported that the integrated system potentially prevented them from having a crash.
- Drivers generally found the system convenient to use.
- Reducing the number of invalid warnings[1] will help to increase understanding of the integrated warning system, as nearly one-third of drivers reported that invalid warnings affected their understanding of the integrated system.
- Some drivers who received higher percentages of invalid warnings reported that they began to ignore the system. A reduction in the number of invalid warnings will reduce the likelihood of drivers ignoring the system.
- There was no direct relationship between driver’s subjective ratings of the subsystems (FCW, LDW, and LCM) and the corresponding rates of invalid warnings they experienced. Drivers had varying opinions of the invalid warnings they experienced based on the type of route they drove.

Lateral Control and Warnings Results

Driver Behavior Results:

- The integrated crash warning system had a statistically significant effect on lateral offset. On the limited-access roads drivers maintained lane positions slightly closer to the center of the lane in the treatment condition.
- The integrated crash warning system did not have a statistically significant effect on lane departure frequency.
- The change in duration and distance of lane incursions was not affected by the presence of the integrated crash warning system. However, there was a statistically

[1] Invalid warnings are characterized by an incorrect or inaccurate assessment of the driving environment by the warning system. They often appear to be spurious and random without any identifiable reason or model for their cause.

significant change toward longer and further excursions with increased hours of service.

- There was no statistically significant effect of the integrated system on turn-signal use during lane changes or frequency of lane changes.

Driver Acceptance Results:

- Drivers rated the LDW subsystem the highest in terms of satisfaction, and second highest in terms of perceived usefulness.
- Drivers liked the LCM subsystem the least. This is likely explained by the higher percentage of invalid warnings that drivers received (86% for line-haul drivers).
- Drivers reported increased safety and heightened awareness with the lateral warning subsystems overall.

Longitudinal Control and Warnings Results

Driver Behavior Results:

- Drivers maintained marginally longer average time headways with the integrated crash warning system, but despite being statistically significant the difference is of little practical significance (0.05s).
- There was no statistically significant effect of the integrated crash warning system on forward conflict levels when approaching preceding vehicles. The integrated crash warning system did not affect either the frequency of hard-braking events (less than 0.2g [1.96 m/s^2]), or the maximum deceleration levels achieved during hard braking events.
- Drivers responded more quickly to closing-conflict events in the treatment condition as compared to the baseline condition, and the effect was statistically significant.

Driver Acceptance Results:

- Both line-haul and P&D drivers specifically mentioned valid FCW warnings and the headway-time margin display to be helpful.
- Driver acceptance, while favorable, would almost certainly have been higher had invalid warnings due to fixed roadside objects (poles, signs and guardrails) and overhead road structures (overpasses and bridges) that were encountered repeatedly been lower. Crash warning systems that maintained records of the locations of where warnings were generated, thereby reducing the number of repeated invalid warnings, can potentially improve driver acceptance.

Summary

Overall, the heavy-truck 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 10 months of the field test with no significant downtime. Other than damage sustained as a result of two minor crashes, few repairs or adjustments were necessary.

The average rate of invalid warnings for all warning types across all drivers was 5 per 100 miles. While this rate was below the performance criteria established earlier in the program, it was still not high enough to meet many of the drivers' expectations. This was particularly true for FCWs due to fixed roadside objects and overhead road structures and the LCM subsystem in general. Nevertheless, drivers generally accepted the integrated crash warning system and some specific benefits in terms of driver behavioral changes were observed. Actionable outcomes and implications for deployment to come out of the field test include:

- The need for location-based filtering for FCW system to be deployed to reduce instances of invalid warnings due to fixed roadside objects and overhead road structures.
- Additional development of radar systems and algorithms to address trailer reflections for double-trailer configurations to reduce invalid LCM warnings.
- Addressing multiple, simultaneous, or near-simultaneous threats in commercial truck applications might not be as critical as once thought. Multiple-threat scenarios are very rare, and when they occurred in the FOT, drivers responded appropriately to the initial warnings.
- Drivers reported that they did not rely on the integrated system and the results of examining their engagement in secondary behaviors support this claim. The lack of evidence for any signs of increased risk compensation or behavioral adaptation seems to suggest that, if there are negative behavior consequences to the integrated system, they are relatively minor.
- Given the increased exposure that line-haul drivers have, and the perceived benefits to be gained from crash warning systems, carriers that are considering the purchase of crash warning systems might first consider their installation on tractors that are used most frequently for line-haul operations.

1. Introduction

1.1 Program Overview

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

Three crash-warning subsystems were integrated into both light vehicles and heavy trucks in the IVBSS program: forward crash warning, lateral drift warning, and lane-change/merge crash warning.

- Forward crash warning: warns drivers of the potential for a rear-end crash with another vehicle;
- Lateral drift warning: warns drivers that they may be drifting inadvertently from their lane or departing the roadway; and
- Lane-change/merge warning: 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.

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

1.1.1 Program Approach

The IVBSS program is a 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 on 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 heavy-truck platform only.

1.1.2 IVBSS Program Team

UMTRI was the lead organization responsible for managing the program, coordinating the development of the integrated crash warning system on both light-vehicle and heavy-truck platforms, developing data acquisition systems, and conducting the field operational tests. Eaton, with support from Takata, served as the lead system developer and systems integrator, while International Truck and Engine provided engineering assistance and was responsible for some of the system installations. Battelle supported Eaton in the development of the driver-vehicle interface and warning arbitration, and Con-way Freight served as the heavy-truck fleet for conducting the field test.

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

1.1.3 Phase I Effort

During Phase I of the program (November 2005 to May 2008), several key accomplishments were achieved. The system architecture was developed, the sensor suite was identified, human factors testing in support of the driver-vehicle interface development was conducted (Green et al., 2008; McCallum & Campbell, 2007), 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 (Bogard 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 (McCallum & Campbell, 2008).

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 October 2010) consisted of continued system refinement, construction of a fleet of 10 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 on the 10 Class 8 trucks, 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 use in a commercial work environment. 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 (Bogard et al., 2009) from November 10, 2008, through December 18, 2008. The results of this test were used to make specific modifications to system performance and functionality prior to conducting the field operational tests; this proved to be a valuable undertaking by improving the systems being fielded. The pilot test also provided evidence of sufficient system performance and driver acceptance to warrant moving forward to conduct the field test.

The FOT was launched in February 2009, with 20 participants representing a sample of commercial drivers operating within Con-way Freight's fleet. The FOT was completed in December 2009 with 18 of the 20 original participants, after approximately 10 months of continuous data collection.

1.2 The Heavy-Truck Integrated System and Driver-Vehicle Interface

The driver-vehicle interface included a dash-mounted input and display device and two A-pillar mounted displays, one on each side of the cabin. The interface was a combination of prototype and off-the-shelf hardware that had been modified. Drivers used the center display to input the trailer length at the start of each trip, to adjust the volume of the auditory warnings, brightness of the display, and to mute auditory warnings. The dash-mounted device continuously displayed the availability of the lane tracking for the lateral warning system, provided time-headway information to the driver, and displayed visual warnings.

The two A-pillar mounted displays each contained a red and a yellow LED. When a vehicle or other object was adjacent to the tractor or trailer, the yellow LED on the corresponding side of the cabin would become illuminated. If the driver then used the turn signal in the corresponding direction (indicating they intended to make a lane change), the yellow LED turned off and the red LED became illuminated. Table 1 describes the visual and audio elements of warnings in each of the subsystems. Figure 1 illustrates the location of the various components of the driver-vehicle interface. Detailed information on the DVI audible and visual displays is contained in the IVBSS Human Factors and Driver-Vehicle Interface Summary Report (Green et al., 2008).

Table 1. IVBSS heavy-truck DVI elements

Subsystem	Warning	Auditory Modality	Visual Modality
FCW	Hazard ahead	Forward sound source from DVI. One short tone when time-headway drops to 3 seconds, 2 seconds, or 1 second. Warning tone when "collision alert" given.	Yellow time-headway LEDs and red collision warning LEDs on DVI. Information-only graphic on LCD indicating forward object being tracked. Time-headway displayed when at 3 seconds or less, accompanied by yellow sequential LEDs. "Collision alert" graphic presented on LCD accompanied red LEDs for forward collision warnings.
LDW	Drifting across a lane boundary	Directional, from side of threat, using speakers (crossing solid or dashed boundary)	Informational only; "left/right drift" graphic on LCD of DVI, status and availability icon on LCD of DVI
LCM	Entering occupied lane	Directional, from side of threat, using speakers	Side display LEDs near each side mirror that indicate that the adjacent lane is occupied

Figure 1. Heavy-truck DVI component locations

1.3 Conduct of the Field Operational Test

The vehicles used in the field test were 2008 International TransStar 8600s. These trucks were built to specification for Con-way Freight. The tractors were built with specialty wiring harnesses by International Truck and Engine, and subsequently equipped with the integrated crash warning and data acquisition systems by Eaton and UMTRI. Twenty commercial drivers from Con-way's Detroit terminal were recruited to participate in the field test. Ultimately, only

18 of these drivers completed the study. All drivers were male, but represented a range of age and years of experience driving commercial trucks. Drivers operated the specially instrumented trucks, conducting Con-way's normal business, over a 10-month period. Con-way Freight's operation consisted of two types of routes for five days a week out of the Detroit terminal; pick-up and delivery (P&D) routes that operated during the daytime with single trailers ranging from 28 to 53 feet in length (82% were 45 feet or longer); and, line-haul routes that ran predominantly during the nighttime and generally used a set of two 28-foot trailers. Two drivers used the same truck on a daily basis, one for the P&D and one for line-haul routes. The nature of the P&D routes includes significant driving on surface streets, whereas line-haul routes are almost exclusively conducted on limited access roads. This combination of route types allowed for the evaluation of the integrated system in two distinctly different roadway environments.

The field test employed a within-subject experimental design where each driver operated a truck in both baseline and treatment conditions. For the first two months of the field test, the trucks operated in the baseline condition with no integrated system functionalities provided to the drivers, but with all sensors and equipment running in the background. At the beginning of the third month, the integrated system's functionality was made available and warnings were provided to drivers. Objective measures of the integrated system, vehicle, and driver performance were collected during the entire test period. The valid data set collected for the 18 drivers who participated represented 601,844 miles, 22,724 trips, and 13,678 hours of driving.

1.4 Deviations from the Field Operational Test Plan

Only one notable deviation from the heavy-truck field operational test plan (Sayer et al., 2008) occurred during the conduct of the FOT. UMTRI was unable to obtain useable data from all 20 recruited drivers. Two P&D drivers were not able to participate for the full 10-month period; one driver left the study for personal reasons and the other driver was withdrawn from the study due to an economic downturn. The regularity and frequency with which they drove their routes was too sporadic to include their data in the analyses. The loss of these two drivers had two effects on the analyses: first, the sample size was smaller for the P&D driver population than for the line-haul drivers and, second, mileage was lower than would otherwise have been accumulated in the field test. The impact on statistical power resulting from the loss of the two drivers is not expected to be large due to the initially small number of original participants (10) – a constraint largely associated with the limited pool of trucks and available drivers.

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 were the general linear model and linear mixed-model techniques, depending on the nature of the dependent variable. Findings that are based on results of a mixed linear model are derived from a model, not directly from raw data per se. 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 heavy-truck field test data can be found in the IVBSS Heavy-Truck 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 chosen in order to offer a relatively short report that would more readily convey what are thought to be 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 commercial vehicles.

A much larger report on the analysis of the data is available. The Integrated Vehicle-Based Safety Systems (IVBSS) Heavy-Truck 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 the key results for the 29 research questions identified in the data analysis plan. These questions are thought to 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 warnings 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

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

It should be noted that characteristics of exposure accumulated by the P&D drivers differ markedly from those accumulated by the line-haul drivers. P&D driving generally took place during the daytime, with single-trailer combinations, in an urban setting, on surface streets, at relatively low speeds. Conversely, line-haul driving generally occurred at night, with double-trailer combinations, in rural settings, on limited-access roads, at higher speeds.

Figure 2 shows the accumulation of FOT mileage over time and indicates the dates when the 10 tractors were released into the field test and the dates the integrated crash warning systems were enabled. By mid-March of 2009, 8 of the 10 tractors had been deployed, and thereafter accumulation of mileage was rather steady. All tractors were deployed by mid-April.

The 10 IVBSS-equipped tractors traveled a total of 671,036 miles during the field test. Data was recorded for approximately 96.4 percent of that distance. Since drivers who were not participating in the field test occasionally drove the equipped tractors, and 2 drivers originally in the field test were eventually dropped from the study, a total of 601,884 miles, or 93 percent of the recorded distance, is represented in the field test dataset. Of this total, 87.4 percent was accumulated by the 10 line-haul drivers and 12.6 percent by the 8 P&D drivers. The accumulated mileage in the baseline and treatment conditions for P&D and line-haul drivers is shown in Table 2. Approximately 21.5 percent of the mileage was accumulated in the baseline condition, and 78.5 percent took place in the treatment condition.

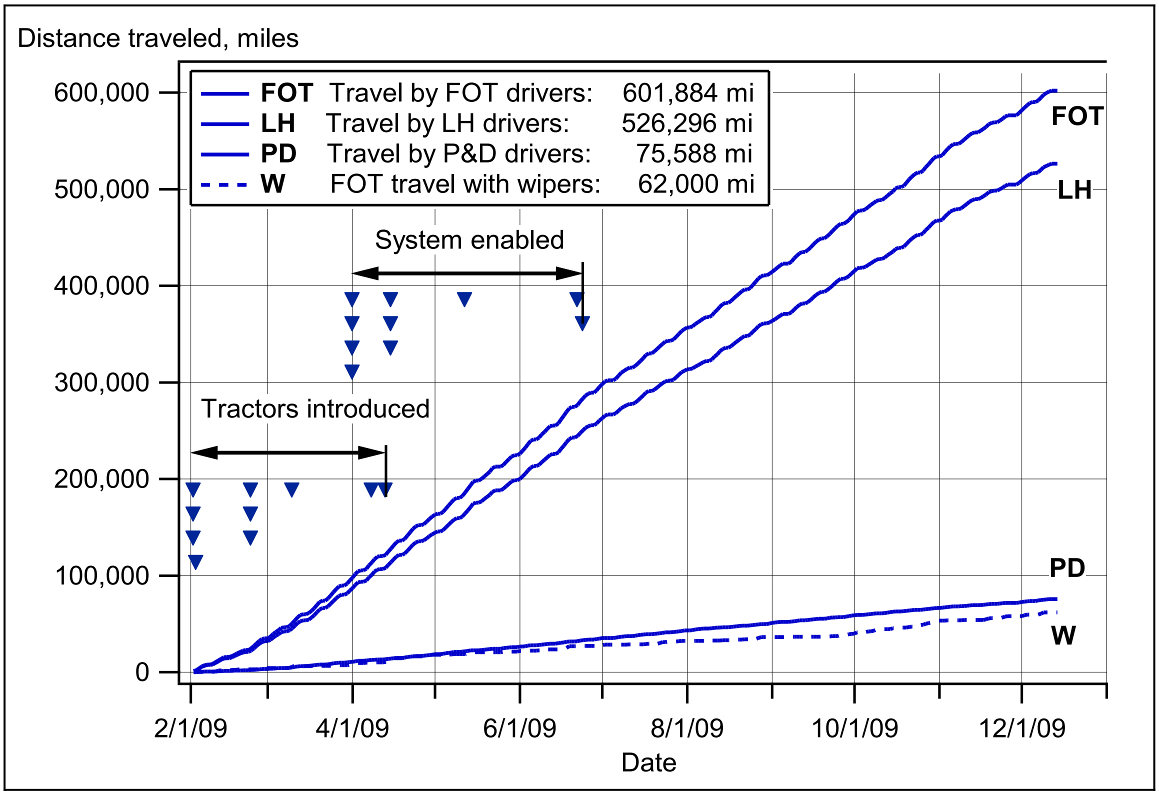

Figure 2. Distance accumulations during the heavy-truck field test

Table 2. Distance accumulations by route type and condition

Condition	P&D		Line-Haul		P&D and Line-Haul	
	Miles	Percent	Miles	Percent	Miles	Percent
Baseline	14,862	19.7	114,520	21.8	129,382	21.5
Treatment	60,726	80.3	411,776	78.2	472,502	78.5
Total	75,588	100.0	526,296	100.0	601,884	100.0

2.1.1.1 Travel Patterns

Almost all driving in the field test originated from the Con-way Freight terminal in Romulus, Michigan, located in the southwestern portion of the Detroit metropolitan area. In terms of mileage, most driving took place in the lower peninsula of Michigan (63%) and in Ohio (33%), with a small portion taking place in northern Indiana (4%). Figures 3 and 4 show the geographical ranges of driving by the P&D and line-haul drivers, respectively. As shown in Figure 3, more than 99 percent of mileage for P&D drivers took place in the southwest portion of the Detroit metropolitan area. The few excursions outside the area appear to have resulted from occasional assignment to daytime line-haul operations.

Conversely, the map for the 10 line-haul drivers (Figure 4) shows that the majority (90%) of miles were accumulated outside the area covered by the P&D drivers. Line-haul travel ranged from Gaylord, Michigan, to the north; Cincinnati, Ohio, to the south; Lordstown, Ohio, to the east; and Gary, Indiana, to the west. Thus, P&D driving took place primarily in urban settings on surface streets, while line-haul driving occurred mostly on main, but rural limited-access roadways.

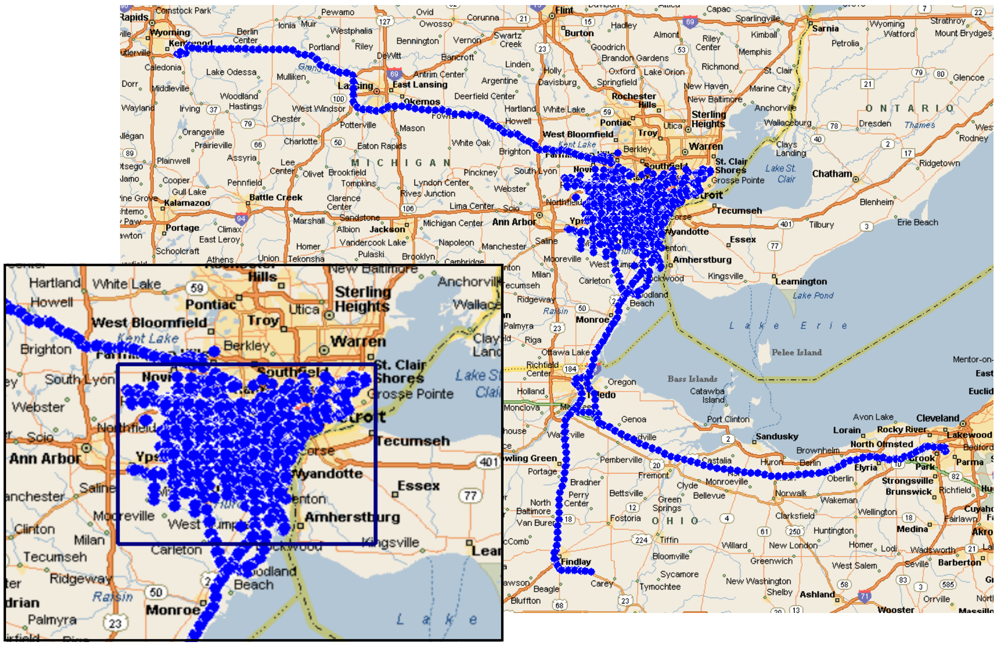

Figure 3. Geographical range of driving by P&D drivers, with insert of area of the most driving

2.1.1.2 Trips and Travel Segments

For the purposes of this field test, a trip is defined as the data-gathering period associated with an ignition cycle. That is, a trip begins when the vehicle ignition key is switched on and the integrated crash warning system and data acquisition system both boot up. A trip ends when the ignition switch is turned off, the integrated crash warning system shuts down, and the data acquisition system halts data collection.

Given this definition, and the fact that commercial trucking operations involve a great deal of activity confined to the carrier's terminal or customer work lots, numerous trips were either very short or involved no travel on public roads and, hence, no travel during which the integrated system could be expected to operate or influence driving behavior.

The FOT included 37,268 trips with one of the 18 participants identified as the driver. Table 3 indicates that more than a third (37.2%) were trips involving fewer than 0.5 miles of recorded travel. Nearly 5 percent of all trips had no travel distance at all.

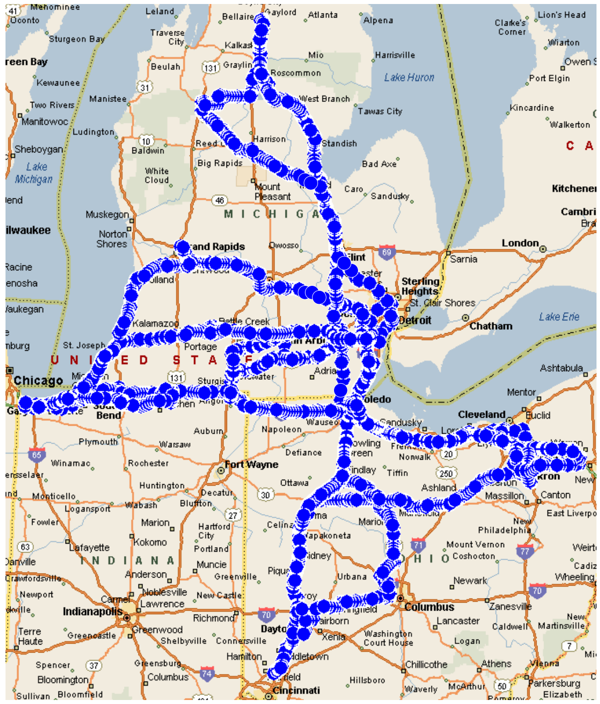

Figure 4. Geographical range of driving by line-haul drivers

Table 3. Very short trips by the FOT drivers

Trip Statistics	Distance Traveled, Miles			
	0	**0 to 0.1**	**0.1 to 0.5**	**all < 0.5**
Counts of short trips	1,709	3,613	8,553	13,875
Percent of the 37,268 FOT trips	4.6%	9.7%	22.9%	37.2%

To avoid including truck terminal or work-lot activity in the analyses, only trips meeting the following criteria were considered:

- The distance traveled was greater, or equal to, 100 meters (0.06 miles);
- A speed of at least 11.2 m/s (25 mph) was achieved; or
- Some portion of the trip took place on a public roadway.

These criteria yielded a dataset composed of 22,724 trips, totaling 601,884 miles of travel.

Although a single trip could be very short in terms of travel distance, it could also be very long in terms of time. At each pick-up or delivery location, a P&D driver might turn off his truck, thus ending one trip and, later, starting another. However, he might not turn off the truck; he might just set the parking brake and leave the truck running. Line-haul drivers did not have as many stops in a single shift, but they could have one or more at which they might, or might not, turn off the tractor. P&D drivers spent about 10.2 percent of their total trip time with the parking brake on; line-haul drivers had the parking brake on only about 3.5 percent of their trip time.

To further examine this issue, trips were broken down into travel segments, where a segment is a period of “significant travel” whose beginning and end are marked, respectively, either by the beginning or end of a trip or by the release or application of the parking brake. Using this approach, there were, on average, 1.76 segments per trip in the dataset. While many trips (17,392) had only one segment, 91 trips included 10 or more segments.

“Significant travel” was defined as a minimum of 750 meters (0.5 miles) traveled at speeds of 25 mph or higher, with sufficient data to estimate the gross vehicle mass and identify the vehicle configuration.

The length of a travel segment was very different for P&D and line-haul drivers (Table 4). Even though the line-haul drivers covered a much greater distance than the P&D drivers did, P&D driving was broken into many more segments. Average and median distances were much smaller for P&D drivers than for line-haul drivers.

Table 4. Statistics for segments traveled by P&D and line-haul drivers

Route Type	Segments	Distances, Miles		
		Average	Median	Maximum
P & D	14,361	5.0	3.1	158.9
Line-haul	4,689	111.9	105.6	267.4

2.1.1.3 Roadway Variables

Some of the analyses that follow distinguish between travel on limited-access roadways,[2] surface streets, and highway ramps. Figure 5 presents the distribution of driving on these types of roads. Road type could not be determined for 9 percent of the total miles traveled and 15 percent of the total hours in motion. As is apparent from the figure, travel by P&D drivers was predominantly on surface streets, but was very heavily biased toward limited-access highways for the line-haul drivers.

The dominance of different road types for P&D and line-haul driving resulted in a substantial difference in average speed of travel by the two groups of drivers. P&D drivers averaged about 29 mph while moving compared to an average of about 58 mph for line-haul drivers.

[2] A limited access roadway is defined as one where access from adjacent properties is restricted in some way; in most cases, it is a divided highway with grade-separated intersections where non-motorized modes of transportation are prohibited.

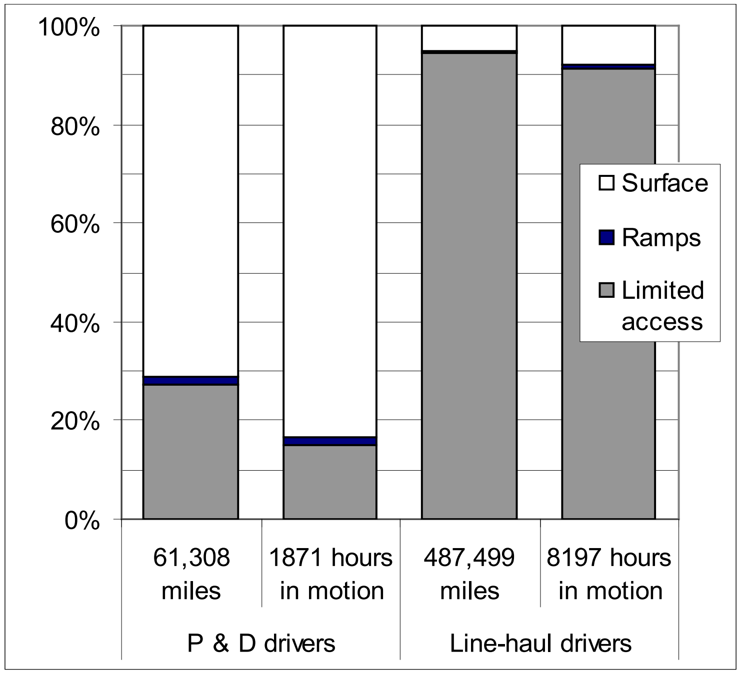

Figure 5. Portions of distance traveled and time in motion of each driver group by road type

2.1.1.4 Environmental Factors

As noted in Section 1.3, most P&D drivers worked the day shift and line-haul drivers worked the night shift. As a result, slightly more than 98 percent of P&D driving (measured both by time in motion and by distance traveled) was during daytime, while slightly more than 77 percent of line-haul driving (also, by both time and distance) was during nighttime (after civil twilight in the evening, and before civil twilight in the morning). It should be noted that a high degree of correlation exists between the time of day and route type. However, a fairly large percentage of the driving (23%) for the line-haul operation was done during daylight hours – precluding the need to merge the two independent variables.

Relative to inclement weather, approximately 10 percent of the distance driven during the field test was with the windshield wipers active (roughly 62,000 miles).

Figure 6 shows the average travel temperature calculated on a daily basis. About 7 percent of driving took place in freezing temperatures. The temperature records distinguish between the experience of P&D and line-haul drivers. Since most P&D driving was during the day and most line-haul driving took place at night, line-haul drivers experienced somewhat lower temperatures, particularly during the summer months.

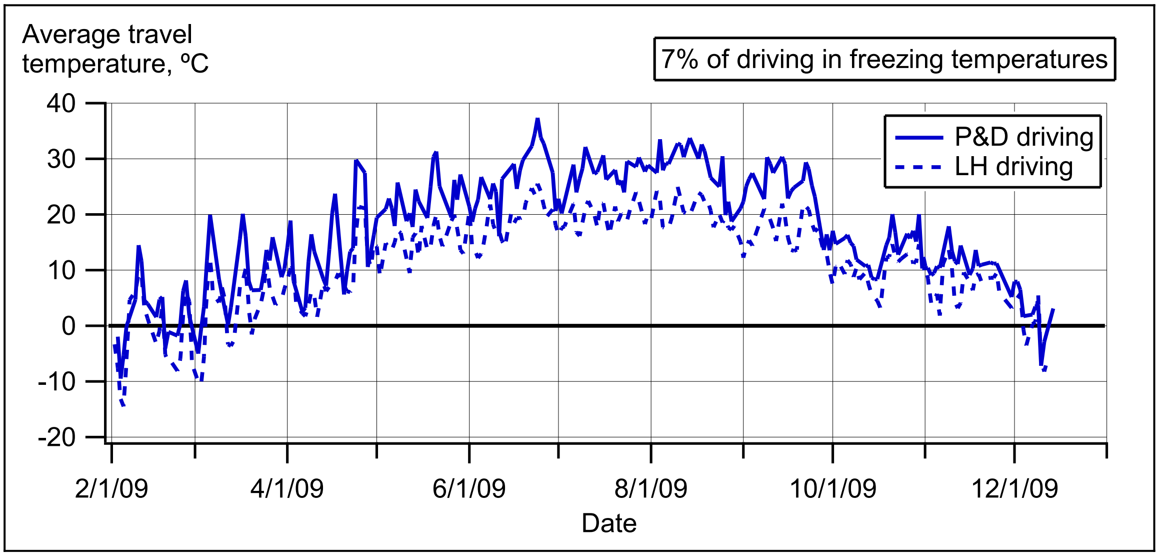

Figure 6. Average travel temperature

2.1.1.5 Vehicle Configuration

The trucks in the field test were all two-axle units and were operated in combination with several different trailer configurations. P&D operations were generally conducted with one trailer in tow, a short (28 to 32 feet), single-axle trailer or a longer (45 to 53 feet), tandem-axle trailer. Line-haul operations were typically conducted with the vehicle configured as a "western double," composed of the tractor with two short, single-axle trailers in tow. Including the axle of the dolly, which supports the front of the second trailer of a double, the western double is a five-axle configuration.

Occasionally, in either service, the tractor traveled with no trailer. Even more rarely, a short single-trailer configuration might have an empty dolly in tow behind the trailer. This condition was not distinguished in the data, but was included as a very small portion of the short-single data. Figure 7 shows the portions of travel by P&D and line-haul drivers for several trailer configurations. Ninety-eight percent of travel by P&D drivers was with a single trailer. Conversely, almost 99 percent of travel by line-haul drivers was with the western double configuration.

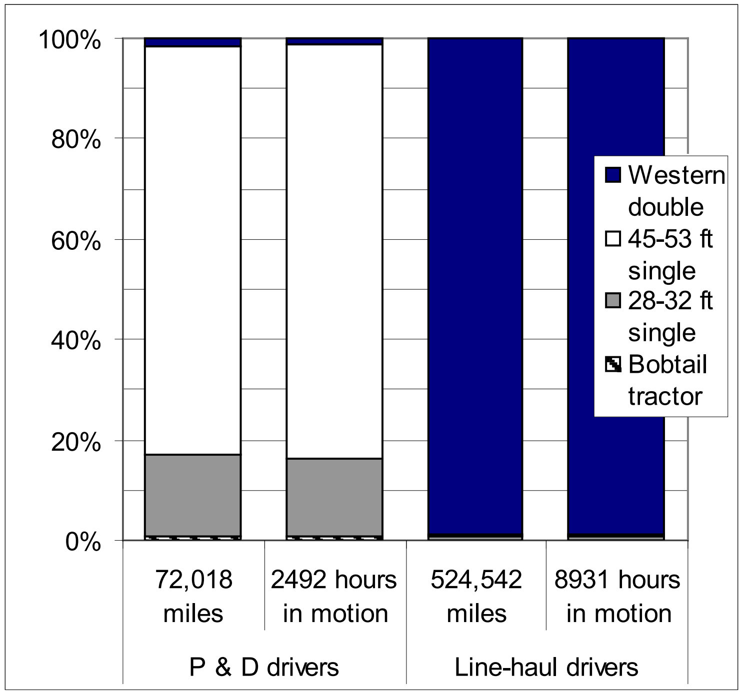

Figure 7. Portions of distance traveled and time in motion of each driver group by vehicle configuration

2.1.1.6 Overall Warning Activity

Overall, there were 110,867 crash warnings issued during both conditions of the field test. Of these, 22 percent were recorded in the baseline condition and 78 percent were recorded in the treatment condition. Figure 8 displays the warning rates for the baseline and treatment conditions. The frequency of warnings did fall slightly from the baseline condition to the treatment condition.

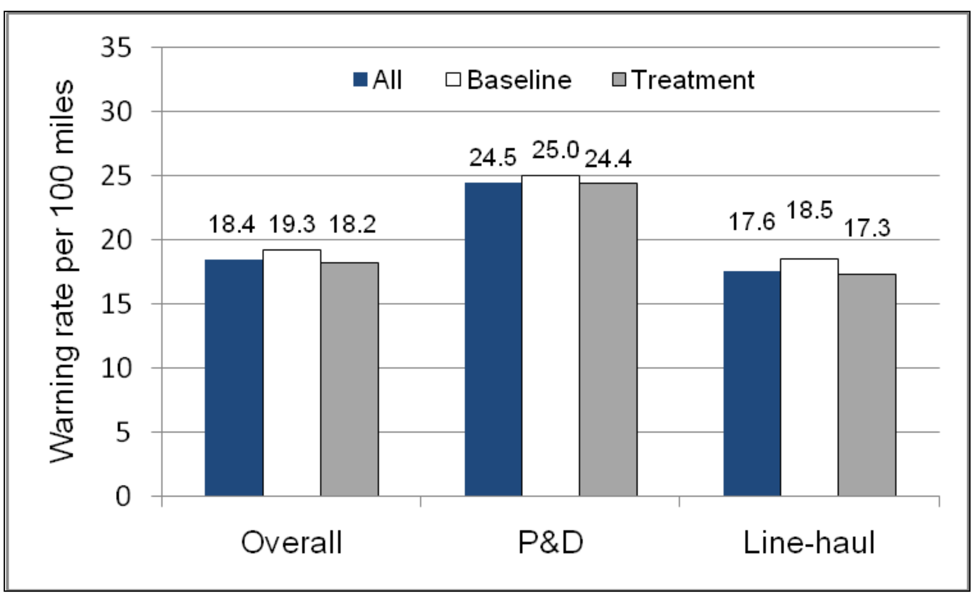

Figure 8: Warning rates during FOT

Of the three subsystems, the LDW subsystem issued the most warnings, or about 13.3 per 100 miles driven. A plot of the warning rates for each subsystem is presented below in Figure 9. While overall warnings were less frequent under the treatment condition relative to the baseline condition, there was actually a slightly higher frequency of FCWs and LCMs under the treatment condition.

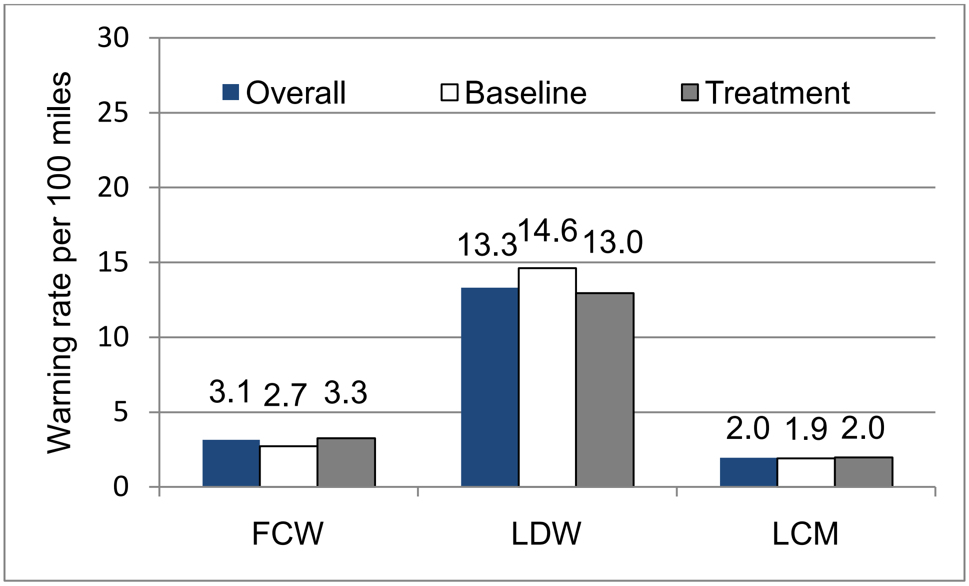

Figure 9: Warning rates by subsystem during the FOT for P&D and line-haul

2.1.2 Driver Behavior Research Questions

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 video clips from each of the 18 drivers were taken for both the baseline and treatment condition. Out of a possible 86,163 video clips, 1,980 clips were chosen (110 from each driver, 55 under both baseline and treatment conditions).

For the baseline sample, video clips were chosen randomly for each driver without regard for the presence of the independent variables (ambient light, wipers, etc.). For the treatment condition sample, video clips were also selected randomly, but with the constraint that the independent variables' frequency must be matched to the baseline sample. For example, if a driver's baseline sample contained 5 video clips (out of 55) with windshield wiper use, 5 of the video clips for that driver from the treatment condition would also contain windshield wiper use.

A total of 1,980 video clips of 5 seconds each 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 highway (video clips recorded on unknown or ramp road types were not included).

- No warning was issued within 5 seconds before, during, or after the video clip.
- Video clips were at least 5 minutes apart from one another.

Results: A list of potential secondary tasks and the coded frequencies from the 1,980 video clips is displayed below in Table 5. (Note: A total of 110 video clips from the sample contained multiple secondary tasks; each individual task is uniquely represented in Table 5.)

Table 5. Frequency of secondary tasks among the 1,980 5-second video clips

Secondary Task	P&D	Line-haul	Overall
No secondary task	548	584	1132
Dialing phone	3	5	8
Text messaging	20	14	34
Talking/listening on hand-held phone	64	48	112
Talking/listening on headset or hands-free phone	8	187	195
Holding/talking on CB radio	0	61	61
Singing/whistling	1	1	2
Talking to/looking at passengers	3	5	8
Adjusting stereo controls	35	11	46
Adjusting HVAC controls	2	4	6
Adjusting other controls on dashboard	1	3	4
Adjusting satellite radio	0	0	0
Adjusting navigation system	0	0	0
Adjusting other mounted aftermarket device	0	0	0
Holding/manipulating in-hand device	11	5	16
Writing on manifest	0	1	1
Reading manifest	2	1	3
Eating: High involvement	4	10	14
Eating: Low involvement	54	65	119
Drinking: High involvement	14	6	20
Drinking: Low involvement	28	34	62
Grooming: High involvement	0	3	3
Grooming: Low involvement	34	33	67
Smoking: High involvement	1	1	2
Smoking: Low involvement	53	30	83
Reading	0	1	1
Writing	0	3	3
Searching interior	0	2	2
Reaching for object in vehicle	36	44	80

Secondary tasks relating to communication were the most commonly seen (20.7%). Hands-free phone use was most prevalent, occurring in 195 of the 1,980 video clips (9.8%).

After communication devices, eating was found to be the next most common secondary task (9.7%). In this analysis, eating, drinking, grooming, and smoking are broken into two categories: low involvement and high involvement. The two levels are primarily distinguished by the hand position of the driver. Tasks requiring two hands (opening food or drink packaging, removing cigarette, etc.) were scored as high involvement. Tasks involving one hand were scored as low involvement (e.g., a driver simply holding a cigarette and any one-handed grooming such as touching the face, head, or hair).

Drivers with their wipers on were the least likely to perform secondary tasks, while drivers at night were the most likely to perform secondary tasks. Drivers in the baseline condition were slightly more likely to perform secondary tasks. For the entire sample, drivers were seen performing secondary tasks in 43 percent of all video clips.

Statistics from the sample of 1,980 video clips are presented in Table 6 and Table 7.

Table 6. Overall statistics for secondary task performance by drivers

Overall	Count	Secondary Task %
Secondary Task	848	43%
No Secondary Task	1132	57%

Table 7. Descriptive statistics for secondary task performance by drivers

Independent Variable	Level	Secondary Task	No Secondary Task	Secondary Task %
Condition	Baseline	431	559	43.5%
	Treatment	417	573	42.1%
Route Type	P&D	332	548	37.7%
	Line-haul	516	584	46.9%
Road Type	Limited Access	499	594	45.7%
	Surface	349	538	39.3%
Time of Day	Day	453	671	40.3%
	Night	395	461	46.1%
Weather	Wipers on	77	122	38.7%
	Wipers off	771	1010	43.3%

Not surprisingly, the secondary task percentages for line-haul versus P&D drivers closely match those for their corresponding road type and time of day. However, as these factors were not mutually exclusive, there are small differences seen in the proportion of clips with secondary tasks. As the proportion of clips with secondary tasks is slightly higher for both "Day" and "Surface Streets" than for "P&D," it appears that line-haul drivers continued their increased secondary task frequency even when driving during the day or on surface streets.

When the sample is broken down by driver, there appears to be no clear effect of the integrated system on secondary task frequency. A plot of each driver's secondary task frequency under both conditions is presented in Figure 10. This figure illustrates that eight drivers performed more secondary tasks in the baseline condition than in the treatment condition. Ten drivers performed more secondary tasks in the treatment condition than in the baseline condition.

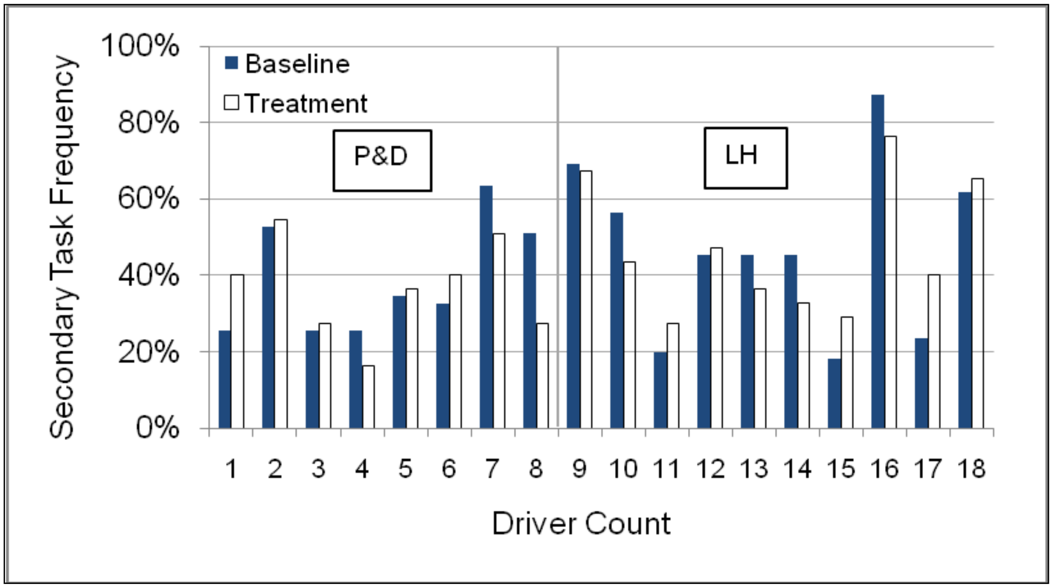

Figure 10. Secondary task frequency by condition for each driver

Statistical analysis using a general linear model was performed to determine whether the integrated system, or any other factors, affected the frequency of drivers performing secondary tasks. No factors were found to have a statistically significant effect on the frequency of secondary tasks.

Interpretation: While there was no effect of the integrated system on frequency of secondary tasks, this result suggests that drivers did not become overly reliant on the system. In general, drivers in more complex driving environments (on surface streets, in bad weather) were less likely to be seen performing secondary tasks. P&D drivers on surface streets during the day were making short trips in areas of high traffic density. These situations are less conducive for performing secondary tasks due to the complexity of the driving environment. Conversely, line-haul drivers on highways at night experience low traffic density over long continuous periods. While P&D drivers may be able to snack between stops or make a phone call while making a delivery, line-haul drivers eat and communicate while driving, both to break up the monotony and to maintain alertness. In summary, there was no evidence of risk compensation or over reliance on the integrated system—that is, there was no evident effect of the integrated system on the frequency of secondary tasks.

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 the 18 drivers were visually coded from the treatment condition. A total of 1,980 5-second video clips were selected. For each driver, 110 video clips were selected, 55 preceding a warning and 55 not preceding a warning. The video clips were chosen at random. Of the video clips for each driver that preceded warnings, researchers randomly chose 40 clips that preceded lateral warnings and 15 clips that preceded forward warnings. For the preceding-warning sample, video clips were selected randomly, but with the constraint that key independent variables matched the sample of clips that did not precede warnings. For example, if a driver's no-warning sample contained 5 video clips (out of 55) with windshield wiper use, 5 of the video clips for that preceding-warnings sample would also contain windshield wiper use. The set of video clips meeting all necessary criteria (in terms of the independent variables and the conditions listed below) were then randomly sampled to provide the final set for analysis.

To focus on clips with warnings that the driver likely considered valid, only forward warning scenarios that resulted in braking responses within 5 seconds of the warning, or in high lateral accelerations within 2 seconds of the warning, were used. For lateral warnings, only those warnings that were a result of a drift or a legitimate lateral hazard were used. Lateral warnings could be either LDW or LCM. Forward collision warnings where no threat was observed in the forward scene at the time of warning were excluded as well as lateral alerts with no drift or no lateral threat (depending on the nature of the lateral alert.).

Video clips that met the following criteria were included in the 1,980 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 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 from one another. Table 8 shows a list of secondary tasks along with the coded frequencies from the 1,980 video clips.

Video clips not associated with warnings were more likely to show hands-free phone use. Video clips associated with warnings were more likely to show drivers involved in light grooming or dialing a phone. In general, video clips preceding warnings were slightly less likely to show involvement in secondary tasks (39.2%) than those when there was no warning (42.1%).

Statistical analyses using a general linear model were performed to determine whether the integrated system, or any other factors, affected the frequency of warnings preceded by a secondary task. No factors were found to have a significant effect.

Interpretation: Warnings from the integrated crash warning system were no more likely to occur when drivers were engaged in a secondary task. This was at least partially due to this group of professional drivers being aware of their environment and making determinations about when it was relatively safe to perform secondary tasks while driving. This result also suggests that drivers did not become overly reliant on the integrated system.

Table 8. Frequency of secondary tasks among 1,980 5-second video clips

Task	Not Associated With Warnings	Preceding Warnings
No secondary task	573	602
Dialing phone	4	11
Text messaging	18	21
Talking/listening on hand-held phone	51	44
Talking/listening on headset or hands-free phone	93	46
Holding/talking on CB radio	14	12
Singing/whistling	2	3
Talking to/looking at passengers	9	4
Adjusting stereo controls	15	16
Adjusting HVAC controls	3	6
Adjusting other controls on dash	0	2
Adjusting satellite radio	0	0
Adjusting navigation system	0	0
Adjusting other mounted aftermarket device	0	2
Holding/manipulating in-hand device	3	9
Writing on manifest	1	4
Reading manifest	1	2
Eating: High involvement	0	2
Eating: Low involvement	61	57
Drinking: High involvement	13	8
Drinking: Low involvement	21	11
Grooming: High involvement	1	2
Grooming: Low involvement	30	54
Smoking: High involvement	0	1
Smoking: Low involvement	43	40
Reading	0	5
Writing	2	2
Searching interior	0	3
Reaching for object in vehicle	30	38
Unknown	2	5

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

Method: Eighty-three events considered valid multiple-threat scenarios were identified in the treatment condition. Valid multiple-threat scenarios were instances where two warnings occurred within 3 seconds of each other, and actual threats were associated with each. In these cases, drivers heard both warnings. Furthermore, the threats needed to be related in that the second warning resulted from a response to, or the cause of the first warning. The multiple-threat warnings observed in the field test can each be described by one of the following five scenarios; Figures 11 through 15 illustrate the different scenarios and follow the descriptions. For the purposes of this discussion, “SV” (subject vehicle) refers to the vehicle driven by test participants, and “POV” (primary other vehicle) refers to the vehicle that the system identifies as the principle threat when a warning is issued.

1. ***FCW from slow lead POV, followed by LCM.*** The SV approached a slower POV, and an FCW is issued. The SV driver begins to move laterally to initiate a lane change around the slower vehicle, using turn signals. However, a second POV is in the adjacent lane and so an LCM warning is generated.

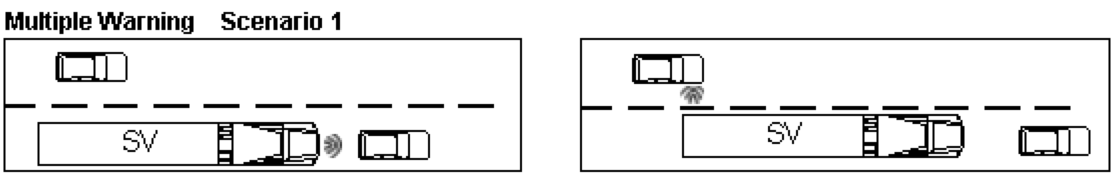

Figure 11. Illustration of Multiple Warning Scenario 1

2. ***LCM followed by FCW from slow lead POV.*** Similar to scenario 1, the SV is attempting to make a lane change, using turn signals, around the slower POV. A second POV is in the adjacent lane and so an LCM warning is issued. This is followed by an FCW in response to the first POV that the SV was originally attempting to pass.

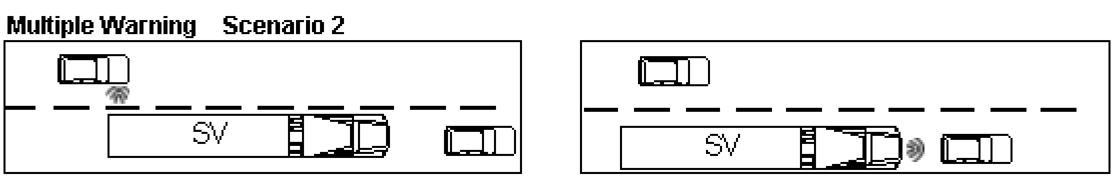

Figure 12. Illustration of Multiple Warning Scenario 2

3. ***LCM followed by FCW from newly acquired POV – passing.*** Similar to scenario 2, but the driver does not get the FCW until completing the lane change. The POV is in the new travel lane (now the lead vehicle). In this instance, the same POV is the subject of both warnings.

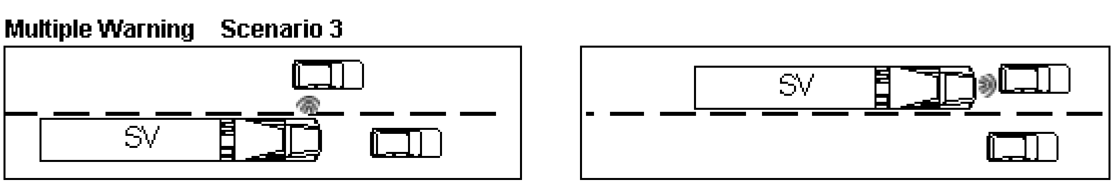

Figure 13. Illustration of Multiple Warning Scenario 3

4. ***LCM followed by FCW from newly acquired POV – merging.*** Similar to scenario 3, but there is no initial slower POV. The driver initiated the lane change for reasons other than passing (often to allow for merging traffic). In this instance, the same POV is the subject of both warnings.

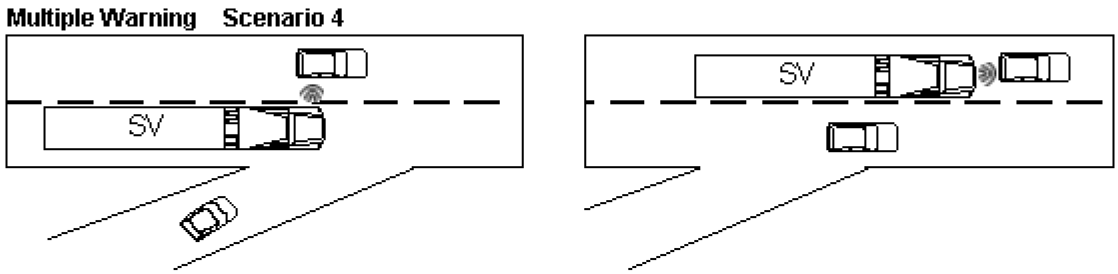

Figure 14. Illustration of Multiple Warning Scenario 4

5. ***LDW followed by FCW from roadside object.*** The driver of the SV is either distracted or drowsy, and drifts over a lane boundary, triggering an LDW. Either the LDW is ignored or the SV driver does not respond quickly enough, and an FCW is issued for a roadside object detected in the path of the SV.

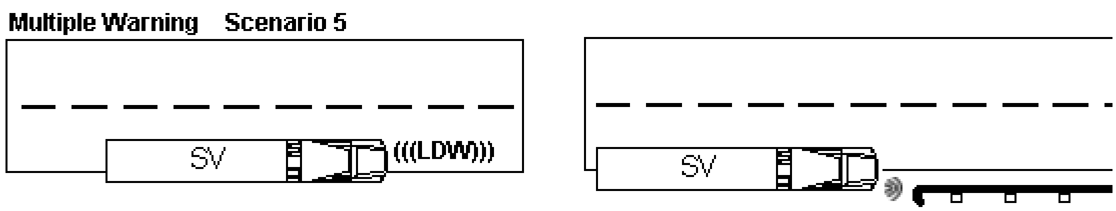

Figure 15. Illustration of Multiple Warning Scenario 5

Results: Of the 83 multiple-threat warning events, 94 percent took place on limited access roads and 6 percent took place on surface streets. Twenty-five percent of warnings took place at night, while 75 percent took place during the day. P&D drivers accounted for 24 percent of these events while line-haul drivers accounted for 76 percent.

Table 9 shows counts for events for each of the scenarios. In scenarios 1 through 4, drivers were generally aware of their driving environment and preparing to make a lane change.

Table 9. Counts for each category of multiple warnings

Code	Description	Count
1	FCW from slow lead POV, followed by LCM	2
2	LCM followed by FCW from slow lead POV	30
3	LCM followed by FCW from newly acquired POV - passing	27
4	LCM followed by FCW from newly acquired POV - merging	19
5	LDW followed by FCW from roadside object	5
	Total Count	83

Three behaviors contributed to nearly all cases of multiple warnings:

- Drivers tend to begin moving laterally for lane changes before the POV in the adjacent lane has completely exited the zone in which an LCM warning will be issued. If drivers wait to begin moving laterally until adjacent POVs are completely clear, the gap they want to enter may be filled by another, faster moving vehicle.
- Drivers tend to be willing to get very close to lead POVs before and after lane changes. In only 20 of 78 events under scenarios 1-4 were drivers forced to decelerate in response to the lead POV, despite receiving FCWs.
- In the case of Scenario 5, drivers of the SV were not attentive. In 4 of these events, the LDW they received was enough to trigger a response from the driver, but the SV was already leaving the lane at such a large angle that the system also detected a forward threat that resulted in an FCW. In the remaining event, the driver ignored the first warning (LDW) and continued towards the guardrail until the second warning occurred (FCW).

Interpretation: Multiple warnings may be useful for inattentive drivers. However, based upon the multiple-threat events observed in this field test, the initial warning was generally enough to get the driver's attention and resulted in an appropriate driver action. Table 10 shows the number of occurrences of initial and secondary responses to warnings. Based upon the judgment of drivers, and as observed in reviewing objective data, only 11 of the 83 multiple-threat events required a response to the second warning. This field test demonstrated that multiple warning scenarios are rare events. Rarer still, is a multiple-threat scenario in which the driver responds to the second warning. The driver responded to the second warning scenario 13 percent of the time. Because of the apparent low utility of a second warning within three seconds of the first warning, designers of crash warning systems might consider suppressing the second warning all together.

Table 10. Counts for initial and secondary responses

Initial Response (IR)	IR Count	Secondary Response (SR)	SR Count
Smooth lane change (no response)	37	Not applicable	0
Release throttle	15	Brake	6
Steer back away from lateral threat	26	Release throttle	5

2.1.3 Driver Acceptance Research Questions

This section discusses key findings on driver acceptance of the overall integrated system based on results from the post-drive survey.

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

Fifteen of 18 drivers reported that they did not change their driving behavior when driving with the integrated system. When the responses are examined, it appears that route type largely influenced drivers' opinions. Nine of 10 P&D drivers responded affirmatively to this question, indicating that they were more likely to report a change in driving behavior. Among the 10 line-haul drivers, only 2 responded that they changed their behavior as a result of driving with the integrated system. When allowed to provide open-ended responses, 3 drivers stated that the integrated system made them more alert, and 2 drivers said they used their turn signals more.

When asked if they relied on the integrated system, line-haul drivers were more likely than P&D drivers to agree to having relied on the system. Lane-keeping was the one aspect of the system that drivers were willing to admit to relying on to some degree. One driver commented that he relied on the blind spot detection or the presence indicator component of the LCM subsystem, when making lane changes in bad weather or in bright sunlight.

When asked whether the integrated system made them more aware of the traffic environment around the truck, the majority of drivers agreed, with more P&D drivers responding affirmatively than line-haul drivers. Three drivers disagreed that the integrated system made them more aware of the traffic environment. Figure 16 details these findings.

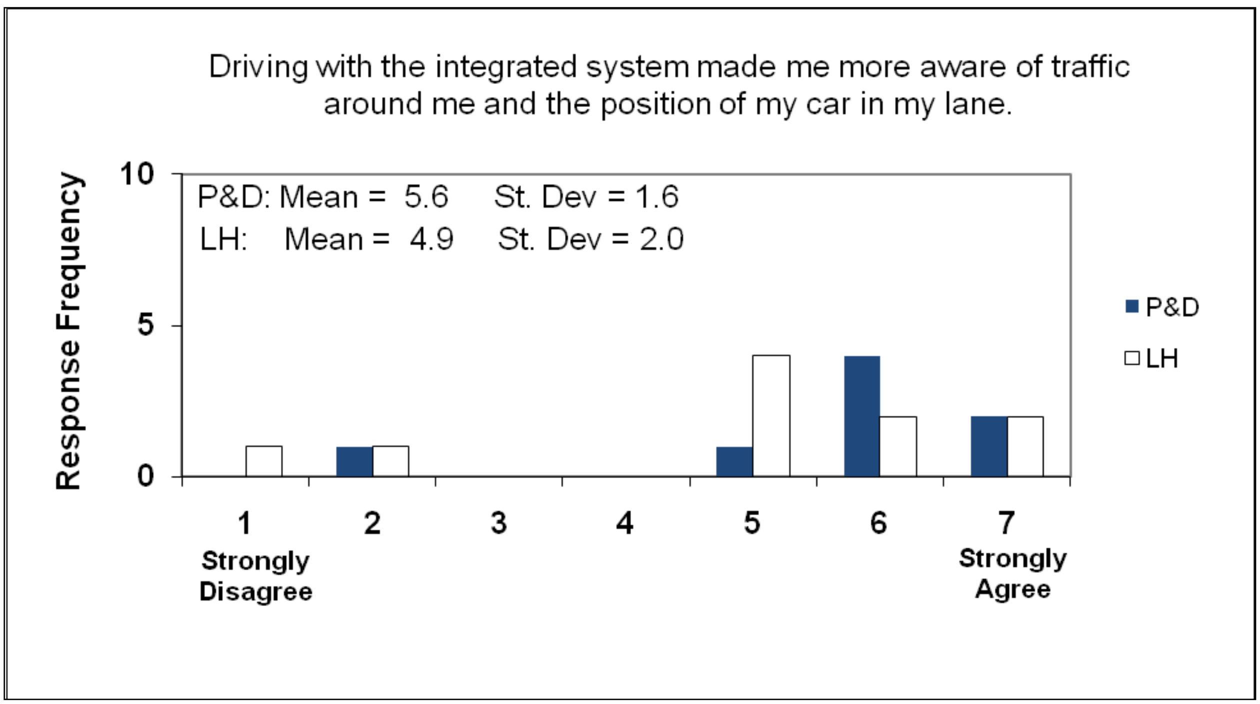

Figure 16. Responses to "Driving with the integrated system made me more aware of traffic around me and the position of my truck in my lane."

Interpretation: Driving behavior was generally unaffected by the presence and use of the integrated warning system. Drivers stated that the integrated system made them more aware of the traffic environment, which itself is a positive outcome. However, drivers did claim to have relied on the system for lane keeping assistance. This result suggests that drivers find benefit in having the integrated system, perhaps even beyond the warnings themselves (i.e., headway time display, indicators of vehicles on the left or right, etc.).

QC5: Do drivers accept the integrated system (i.e., do drivers want the system on their vehicles)?

As shown in Figure 17 below, responses relating to driver acceptance were generally favorable, with little difference between P&D and line-haul drivers. Both groups were largely satisfied with the system overall, with P&D drivers giving it a slightly higher mean score. Only 2 drivers responded that they were dissatisfied with the system overall, while the remaining drivers were neutral to very satisfied.

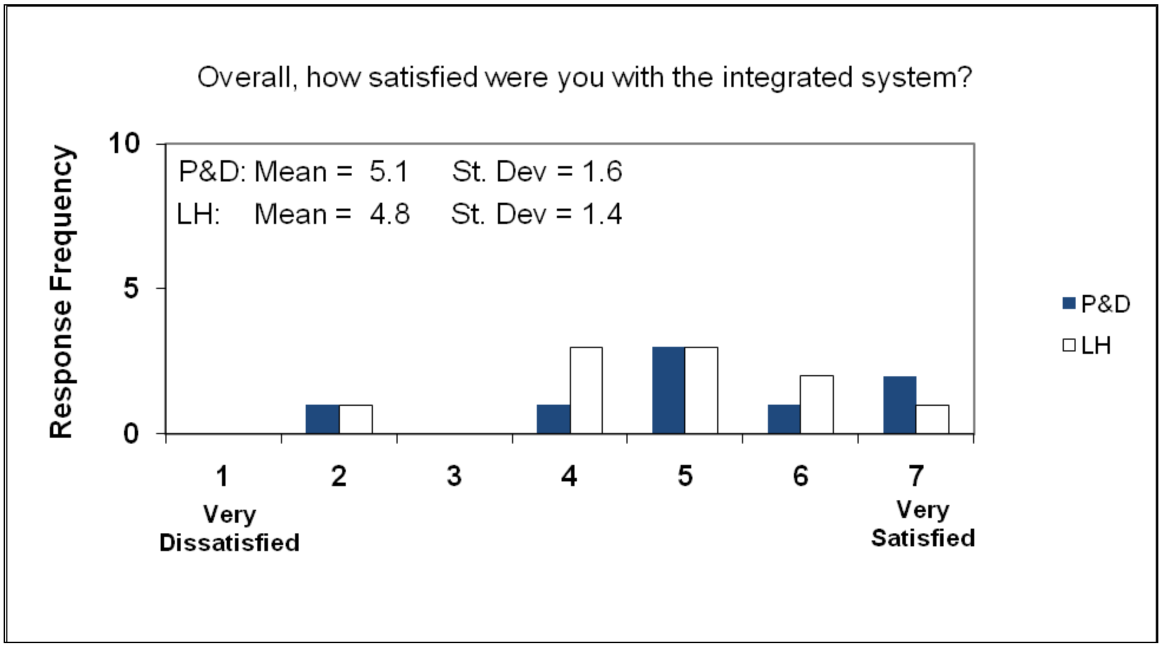

Figure 17. Responses to "Overall, how satisfied were you with the integrated system?"

When asked specifically if they preferred a truck equipped with an integrated system, 15 of the 18 drivers responded that they would prefer a truck with the integrated system to a conventional truck. This was relatively consistent across both route types. Only 3 drivers (2 P&D, 1 line haul) responded that they would not prefer a truck with the integrated system. Five drivers remarked that they felt the system made them more alert when driving. A line haul driver who preferred his conventional truck remarked, "The system made too much a noise and gave me too many false warnings."

When drivers were asked if they would recommend that their company buy trucks equipped with the integrated system, 12 out of 18 drivers responded that they would. Comments from these drivers that recommended purchase of the integrated system generally referred to increased safety associated with the integrated system. Four drivers specifically mentioned that they thought the integrated system would reduce crashes. Of the 3 drivers (1 P&D, 2 line-haul) who responded that they would not recommend that their company purchase the integrated system, the 2 line-haul drivers cited the frequency of invalid warnings as the reason.

Interpretation: Drivers overwhelmingly responded that they prefer driving a truck equipped with the integrated warning system to a conventional truck. Furthermore, they recommend the purchase of such systems to increase safety. The fact that drivers stated that they preferred the trucks equipped with the integrated system suggests that despite any shortcomings in system performance, drivers still found benefit in the integrated system as it performed during their experience in the field test.

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

Responses relating to drivers' opinions of the warning modalities (visual and audio) are mostly neutral. P&D drivers slightly disagreed that the auditory warnings were distracting or annoying, while line-haul drivers as a group found the auditory warnings somewhat distracting or annoying. Otherwise, drivers seemed largely comfortable with the manner in which warnings were presented.

The auditory warnings were prominent enough to capture the driver's attention, which inevitably led to some drivers to feel they were too loud or intrusive. This was particularly true for line-haul drivers who were more often in low stimulus environments (limited access roads, at night with low traffic volumes).

When asked whether the warnings were distracting or annoying, drivers stated that they more were annoyed by the number or frequency of unnecessary warnings than the actual sound or loudness of the warnings.

The largest subset of invalid warnings was forward collision warnings, resulting from the integrated system issuing warnings for fixed roadside objects and overhead road structures; these warnings were 99 percent invalid. Most of these were a result of an overpass, or an object on the roadside out of the vehicle's travel lane or forward path. Line-haul drivers received 10 times as many of these invalid warnings as P&D drivers, with 72 percent of all FCWs issued for line-haul drivers were invalid warnings due to fixed roadside objects, overpasses and bridges.

When the number of invalid FCWs is plotted against line-haul drivers' responses for annoyance of the warnings, an emerging trend can be seen. Specifically, the larger the percentage of invalid FCWs that a driver received, the more likely he was to judge auditory warnings annoying (see Figure 18).

Drivers reported that the blind-spot detection side-warning lights were useful, but that the lights should be located in another location to catch drivers' attention. The blind spot side-warning lights located on the left and right A-pillars were not considered annoying to drivers.

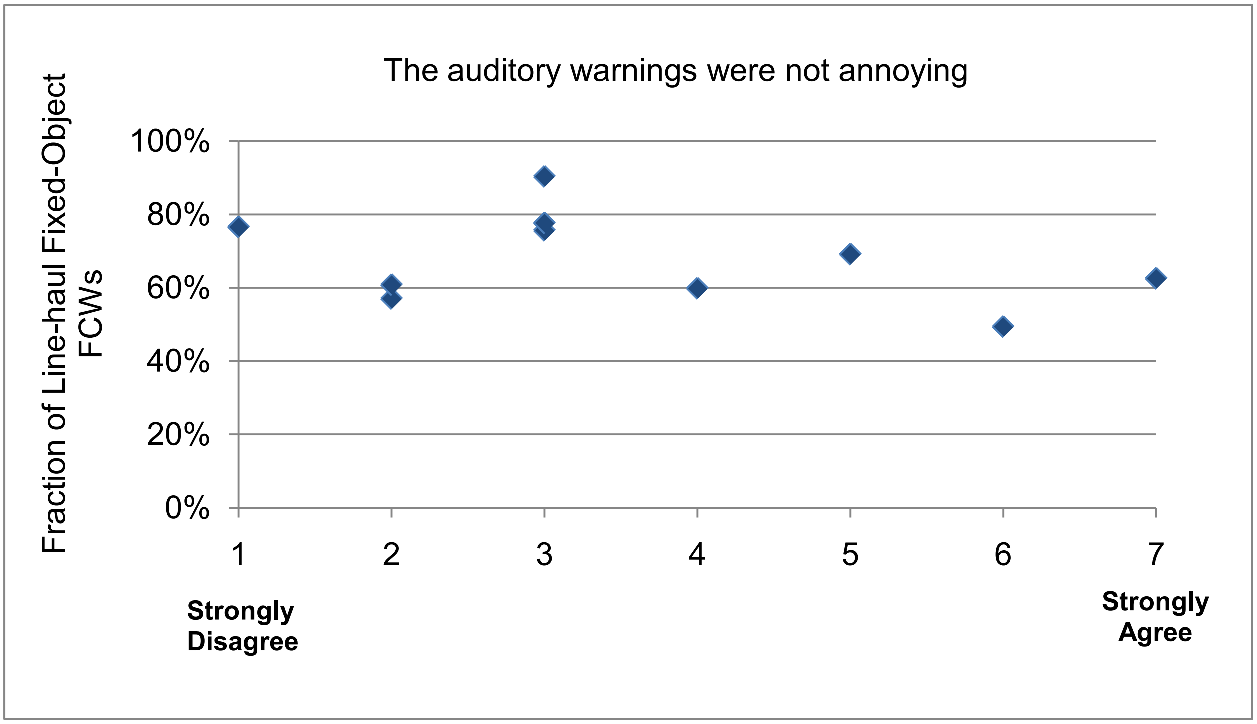

Figure 18. Fraction of invalid FCWs versus line-haul drivers' ratings of warning annoyance

Interpretation: While the auditory warnings were attention-getting, the high invalid warning rate for LCMs and FCWs, particularly for line-haul drivers, resulted in some drivers describing the warnings as "distracting" or "annoying." There is a fine line between a warning being "alerting" or being "distracting" or "annoying." To be effective, the warning must capture the attention of the driver regardless of what he is doing. If a warning legitimately helps a driver, it is unlikely that the warning would be annoying. However, when the warnings sound on a regular basis when no threat is apparent, any tone may become annoying over time. Reducing the invalid warning rate should result in drivers finding the warnings to be helpful without being distracting or annoying.

While the auditory warnings were attention-getting, the high invalid warning rate for LCMs and FCWs, particularly for line-haul drivers, resulted in drivers describing the warnings as "distracting" or "annoying." Reducing the invalid warning rate should result in drivers finding the warnings to be noticeable without being distracting or annoying.

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

Driver responses about perceived safety benefits from using the integrated system were largely favorable. Overall, drivers felt that the system would increase their driving safety, with P&D drivers feeling slightly stronger about this than their line-haul counterparts did. Figure 19 displays responses to the statement "Overall, I think the integrated system is going to increase my driving safety." All but 5 of the drivers felt that their driving safety was at least somewhat increased by the integrated system, but 3 drivers did not feel they received any safety benefit.

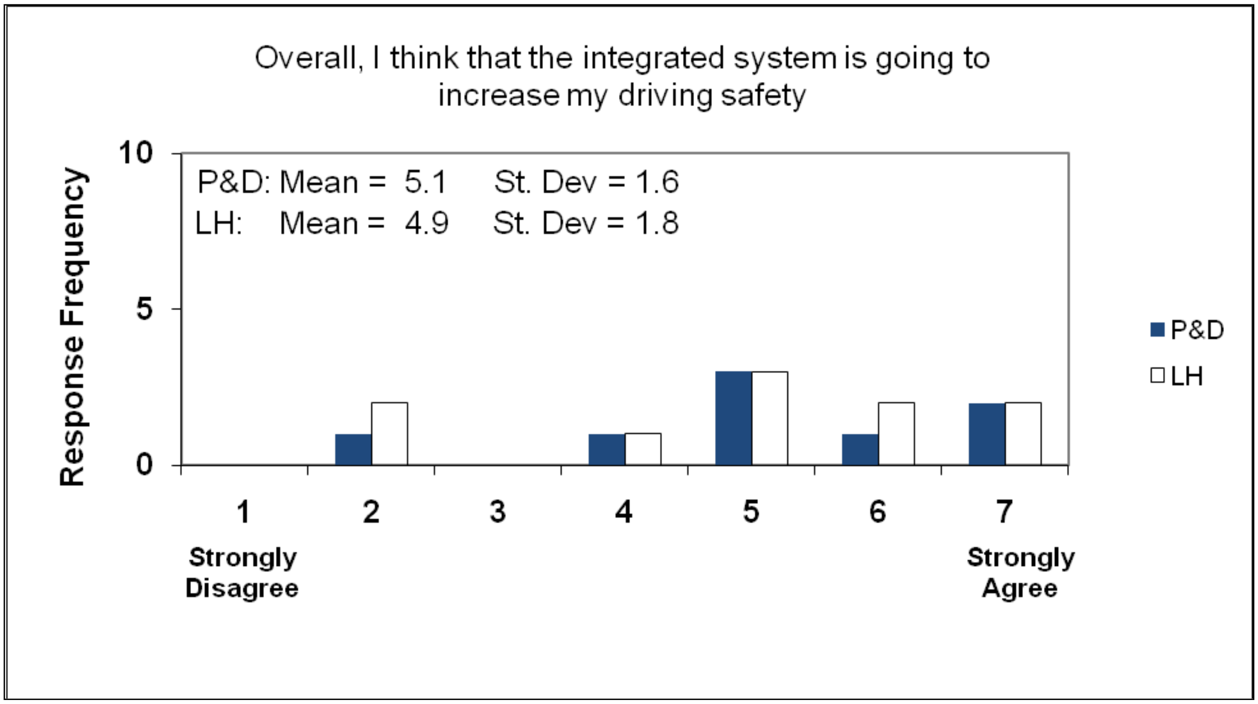

Figure 19. Responses to "Overall, I think the integrated system is going to increase my driving safety"

Responses to similar questions regarding the helpfulness of warnings and the improved awareness of the traffic environment followed a similar pattern, where most drivers provided a slightly better than neutral response.

When asked directly whether the integrated system prevented a crash or near crash, almost half of the drivers responded affirmatively. Three drivers (1 P&D, 2 line-haul) commented that the integrated system prevented some type of lateral crash and 4 (3 P&D, 1 line-haul) drivers commented that it helped them avoid some type of forward crash. Interestingly, 2 drivers who consistently rated the system less favorably than others mentioned that they received a tangible benefit from the integrated system in that it they thought it helped them avoid a crash.

When asked in which situations the warnings were helpful, drivers gave a variety of responses. The aggregated responses by warning type are displayed in Figure 20. Line-haul drivers clearly found the LDW subsystem more helpful than did P&D drivers. In terms of the FCW subsystem, both line-haul and P&D drivers specifically mentioned finding the FCW warnings and the headway-time margin display feature to be helpful.

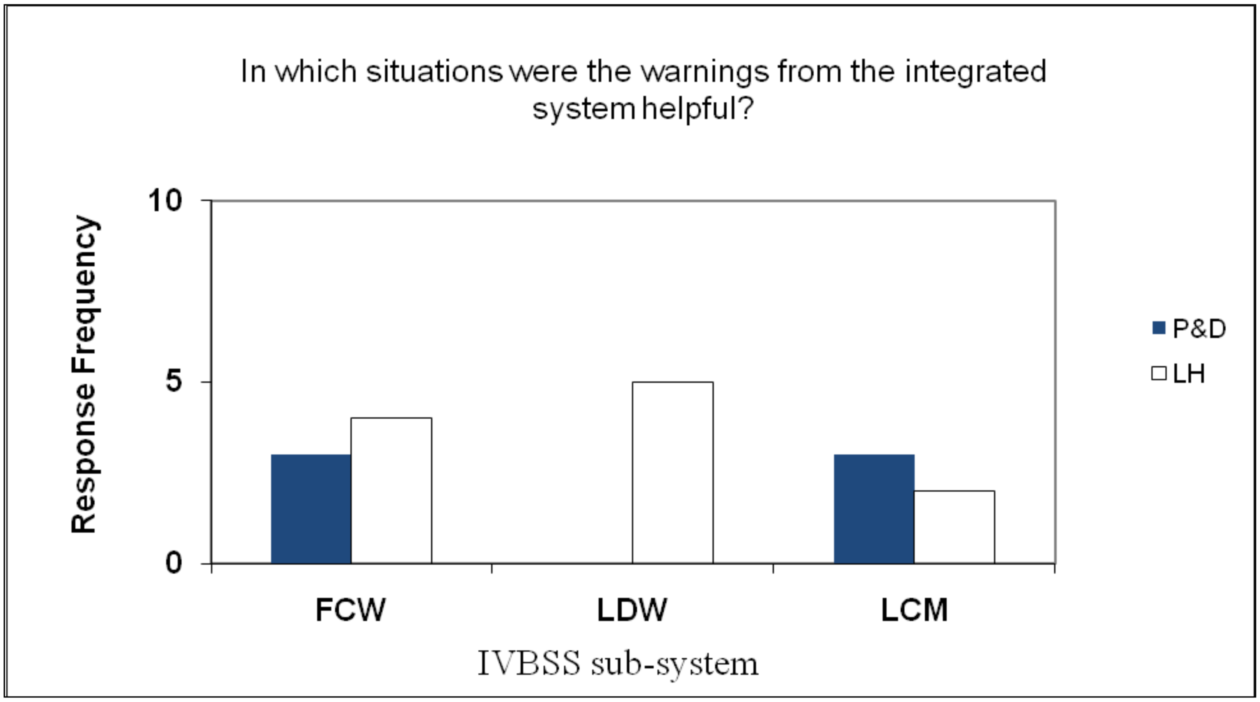

Figure 20. Aggregated summary of responses by warning type to "In which situations were the warnings from the integrated system helpful?"

Interpretation: Drivers' perceptions were that the integrated warning system would increase driving safety, at least marginally. Seven drivers reported that the integrated system prevented them from having a crash, or a near crash. These responses were the clearest indication that this subset of drivers received a tangible benefit from the system beyond the more abstract benefits such as "increased awareness." Drivers of commercial vehicles, whose livelihood depends upon safe driving, are acutely aware of the consequences of crashes. If they believe that the presence of the integrated system specifically prevented a crash, they are very likely to accept the integrated system, even if all aspects of it did not perform as they may have expected.

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

In general, drivers found the system interface convenient to use in terms of both the auditory warnings and the dash-mounted display. Regarding drivers' ability to easily understand what the auditory warnings were meant to convey, nearly all drivers of both route types rated the nature of the auditory warnings favorably, with only one driver scoring it below neutral. All but one line-haul driver agreed that the integrated system gave unnecessary warnings.

Invalid warnings affected drivers' perceptions of the system differently. Line-haul drivers were much more likely to agree that the invalid warnings caused them to begin to ignore the integrated system. As mentioned in QC6, line-haul drivers received the majority of invalid FCWs and this likely influenced their response relative to P&D drivers. Line-haul drivers also drove identical routes night after night, and so they began to expect certain invalid warnings associated with specific pieces of infrastructure (overpasses, guardrails) at consistent locations along their route.

One line-haul driver received the same invalid FCW from the same overpass 205 times over the course of the FOT, and other line-haul drivers had similar experiences. A total of 972 invalid FCWs were associated with eight different overpasses, which may be attributed to the fact. While it is not known what physical characteristics of the eight overpasses resulted in an FCW to be issued, the primary reason for the high incidence of invalid FCWs was due the number of times several drivers encountered these overpasses on their delivery routes throughout the field test.

P&D drivers were more likely to get invalid warnings in more complex driving situations (surface streets, high traffic density, daytime). Cars cutting in front of the trucks, or occupying blind spots, were much more common for P&D drivers. P&D drivers receiving warnings in these situations were less likely to dismiss them until they could confirm the validity of the warning.

Interpretation: In general, drivers found the system convenient to use. Drivers who received a high percentage of invalid warnings reported that they began to ignore the system. A reduction in the number of invalid warnings will reduce the likelihood of drivers ignoring the system.

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

Both line-haul and P&D drivers offered the same mean rating for the statement "The integrated system gave me warnings when I did not need them." Both sets of drivers provided a mean rating of 5.9 out of 7 (where 1 = strongly disagree and 7 = strongly agree), indicating that they felt strongly that they received warnings they did not need.

However, when asked about the prevalence of specific types of warnings that they did not need, P&D and line-haul drivers offered different responses, with line-haul drivers feeling more strongly that they received unneeded warnings from each of the three subsystems. Of the three subsystems, P&D drivers felt that the FCW subsystem produced the most warnings they did not need, while the line-haul drivers felt that the LCM warnings were the most prevalent unnecessary warning. When comparing the actual invalid warning rates to individual driver's subjective ratings, no discernable trend can be observed (Figure 21).

In this analysis, 99 percent of all forward collision warnings were in response to fixed roadside objects or overhead road structures and were considered invalid. Lane change/merge warnings were considered invalid when there was no vehicle present in an adjacent lane; while lane departure warnings with no adjacent vehicle present and when the driver did not drift far enough to trigger a cautionary drift warning were also considered invalid.

Surprisingly, the 2 drivers with the highest rates of invalid warnings were among those least bothered by them, and 2 of the 3 drivers with the lowest rates of invalid warnings were among the most bothered by them.

When the subsystems are examined individually, responses also do not reflect the objective warning rates closely. Figure 22 presents the percentage of valid warnings for each of the subsystems.

Drivers of both route types received roughly an equal proportion of valid LDW warnings, while P&D drivers received a much higher proportion of valid LCM and FCW warnings.

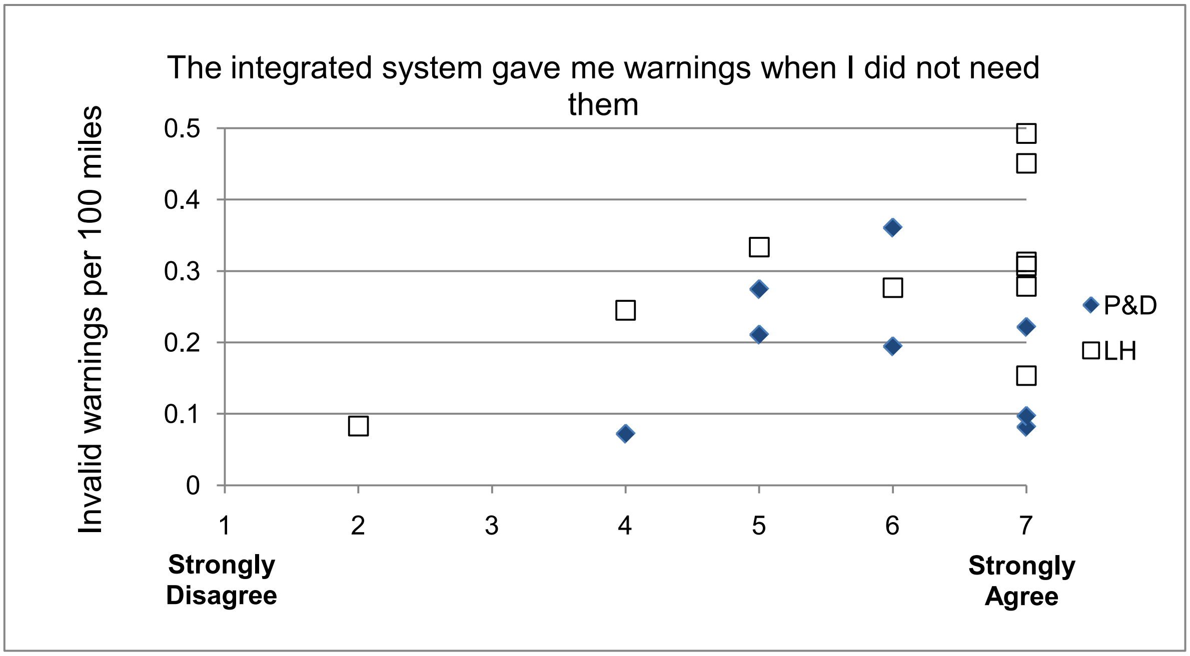

Figure 21. Invalid warning rates versus individual drivers' responses to "The integrated system gave me warnings when I did not need them."

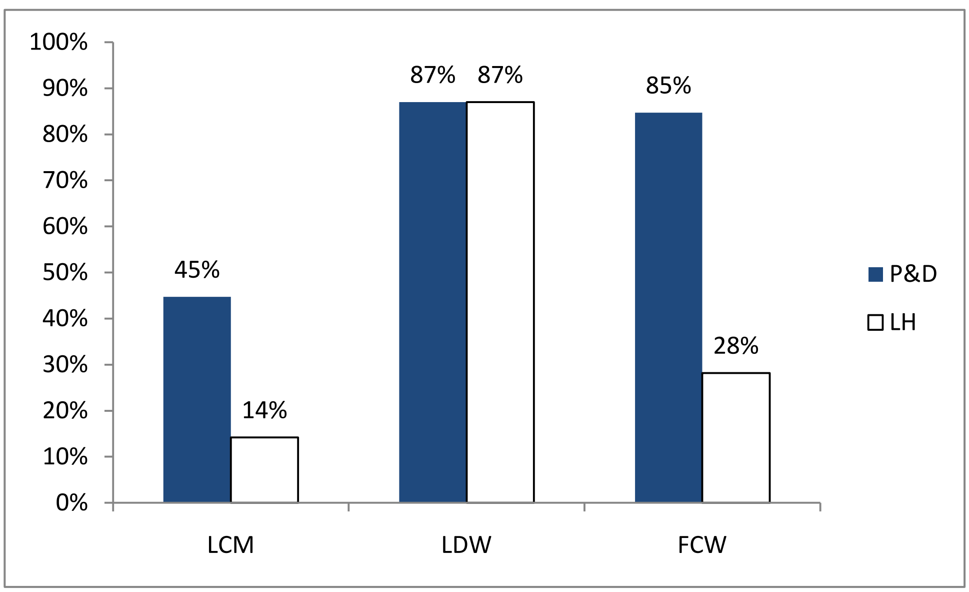

Figure 22. Proportion of valid warnings for each warning type

Overall, drivers' subjective responses to whether they received invalid warnings did not closely correlate with the results presented in Figure 22. The figure plots the drivers' mean subjective responses (higher ratings correspond to a perceived higher frequency of invalid warnings for the individual subsystems). The relationship of valid LDW warnings for line-haul drivers, and valid FCW warnings for P&D drivers, as shown in Figure 22, was not reflected in drivers' opinions of the invalid warnings presented earlier in Figure 13. P&D drivers' subjectively responded that they received a high percentage of FCW warnings that they did not need, despite the fact that most of these warnings (85%) were considered valid, and should have been perceived as being at least somewhat useful. Figure 23 shows the mean subjective responses by route type for each subsystem.

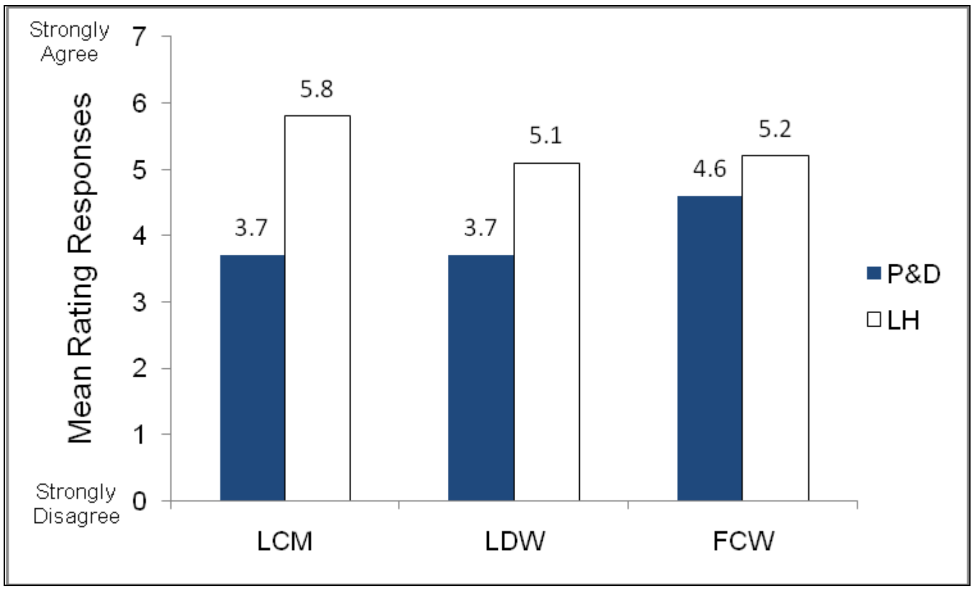

Figure 23: Mean subjective responses by route type on perceived frequency of invalid warnings

Table 11. Counts of invalid warnings for subsystems under treatment condition

Drivers	LDW	LCM	FCW	All warnings
P&D	1213 (8%)	849 (6%)	645 (4%)	14772
Line-haul	6527 (9%)	6672 (9%)	8041 (11%)	71161

One consistency between the subjective ratings and the objective invalid warning frequencies was that line-haul drivers received the highest proportion of invalid LCM warnings (relative to the other subsystems) and most strongly responded that they received LCM warnings they did not need.

While line-haul drivers generally received consistent invalid forward-crash warnings, this was not the case for P&D drivers. P&D drivers received a much higher fraction of valid forward crash warnings than line-haul drivers did, but the invalid warnings that P&D drivers did receive may have been much more surprising and generally more unexpected. The environment in which the P&D drivers operate (surface streets during the daytime with higher levels of traffic density where it is possible that vehicles can quickly move in front of the tractor) may have had a greater negative influence on P&D drivers' perception of the invalid FCWs.

Interpretation: In general, there was no direct correlation between driver's subjective ratings of the subsystems and the corresponding rates of invalid warnings they experienced. Drivers had varying opinions of the invalid warnings they experienced based on the type of route they drove. Responses show that line-haul drivers indicated that they began to ignore warnings, while P&D drivers did not. The discrepancy in responses between route types was likely a result of the nature of the invalid warnings received. P&D drivers were much more likely to receive invalid FCWs at unpredictable times, which would be difficult to ignore, as there was usually some lead vehicle present at the time of the warning. Line-haul drivers on the other hand received many FCWs from overpasses and fixed roadside objects in the same locations, night after night on empty roads where it would be unlikely for a forward hazard to appear suddenly. LDW warnings, while largely valid, did not receive substantially better subjective scores than the other sub-systems, likely because of the high overall frequency of these warnings especially for line-haul drivers. Subjective ratings of the invalid LCM warning frequency for line-haul drivers did match the objective counts in that drivers felt they received the most LCM warnings they did not need, and this was supported by the invalid warning counts.

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

Regarding the ease of use of the integrated system, drivers from both route types found the integrated system easy to use. P&D drivers indicated they understood what to do when the integrated system provided a warning more strongly than the line-haul drivers. Responses show drivers had a good understanding of the operation of the integrated system, with only one driver disagreeing with the statement "I always knew what to do when the integrated system provided a warning."

Based on the training they received at the beginning of the treatment condition, which consisted of an explanation of system operation, a truck walk-around and a 30-minute test drive, drivers agreed that the system generally performed as they expected it to. Four line-haul drivers cited invalid warnings as the main aspect of the system that did meet their expectations.

Figure 24 summarizes the responses to the question: "I always knew what to do when the integrated system provided a warning."

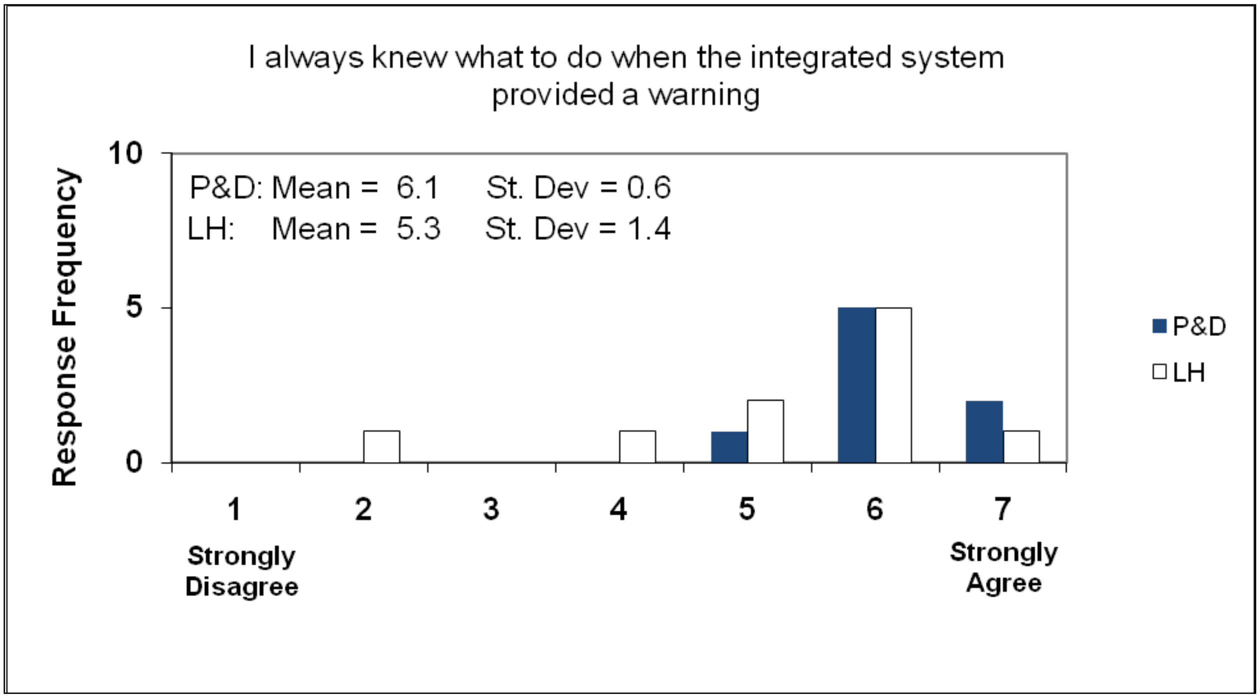

Figure 24. Mean subjective rating regarding ease of use.

Interpretation: Drivers found the integrated system easy to use and felt that they had a good understanding of what to expect from it. While the warnings may not have always been received in response to actual threats, drivers generally understood what the system was trying to convey when it did provide warnings, and therefore would still be able to determine the correct (or expected) response quickly.

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

Responses to survey questions show that both P&D and line-haul drivers found the integrated system easy to understand. Responses show drivers quickly felt familiar with the integrated crash warning system after an accompanied test drive and just a few shifts alone with the system.

Most important in drivers' understanding of the system was their ability to interpret the warnings that they received correctly. When directly asked about this, drivers strongly agreed that they could tell what the system was attempting to convey through the auditory warnings.

While drivers of both route types received many invalid or unnecessary warnings over the course of the field test, the responses to "The number of false warnings affected my ability to correctly understand and become familiar with the system" were very diverse (see Figure 25).

The prevalence of invalid warnings appeared to be an issue with most drivers' understanding of the integrated system. In response to the statement "The number of invalid warnings affected my ability to correctly understand and become familiar with the system," 5 drivers responded that invalid warnings affected their understanding of the warnings, with 2 drivers strongly agreeing with the statement.

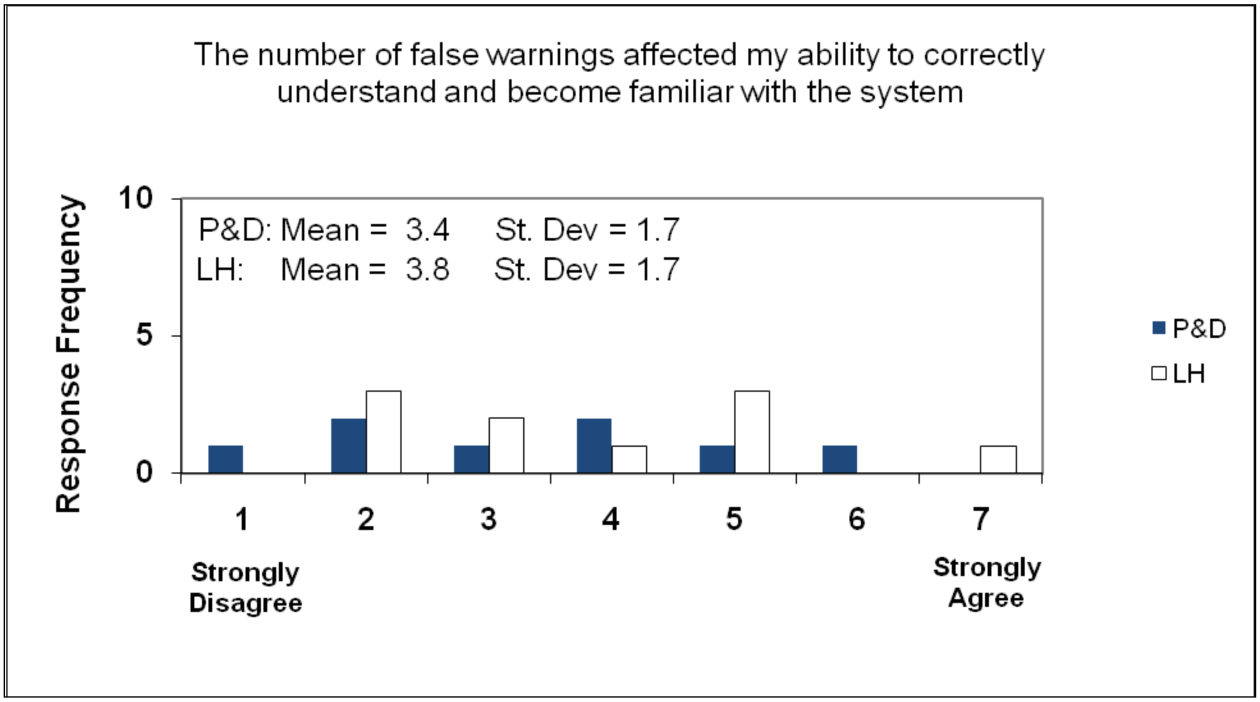

Figure 25. Responses to "The number of false warnings affected my ability to correctly understand and become familiar with the system."

Interpretation: While the operation of the integrated system was generally understood, nearly one-third of the drivers reported that invalid warnings affected their understanding of how the integrated system actually operated. Reducing the number of invalid warnings will help to increase understanding of the integrated warning system. The gap between the drivers' understanding of the functionality of the integrated system, and its actual operation, stemmed from their confusion as to why the system would produce warnings when no threat was present. No clear explanation of why certain bridges or certain trailer reflections caused invalid warnings could always be given to the drivers, so there was some level of uncertainty about system operation.

2.2 Lateral Control and Warnings Results

This section synthesizes 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 lateral warning scenarios.

During the 10-month field test period, a total of 98,915 lateral warnings (LCM and LDW cautionary and imminent) were recorded. Of this set, 91,912 warnings were attributed to the 18 participants. The overall warning rate across all drivers, speeds, and other conditions was 15.2 lateral warnings per 100 miles of travel. A summary of the overall lateral warning activity as a function of condition, route type, and road type is given in Table 12. The highest overall rate was consistently on exit ramps. The lowest rate was on unknown road types, which include parking lots, staging areas, terminals and other typically low speed areas. In general, P&D drivers had a higher lateral warning rate than line-haul drivers.

Table 12. Overall lateral warning activity by condition, route, and road type.

Condition	Route type	Road type	Count	Percent	Rate, per 100 miles
Baseline	P&D	Limited access	630	0.7	19.9
		Surface	1845	2.0	19.7
		Ramps	72	0.1	23.0
		Unknown	193	0.2	9.5
	Line-Haul	Limited access	15788	17.2	15.9
		Surface	1889	2.1	20.8
		Ramps	143	0.2	23.7
		Unknown	814	0.9	15.8
Treatment	P&D	Limited access	2362	2.6	19.4
		Surface	6372	6.9	18.4
		Ramps	264	0.3	27.3
		Unknown	1563	1.7	12.2
	Line-Haul	Limited access	53066	57.7	14.7
		Surface	2353	2.6	15.3
		Ramps	475	0.5	23.5
		Unknown	4083	4.4	12.6

2.2.1.1 Lateral Warning Classification and Validity

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

- **Valid**—warnings are helpful to the driver since they bring additional awareness to the driving task and can mitigate ignorance of an unrecognized conflict in the current driving situation. Warnings that are predictable and probable are also defined as valid. After a valid warning, the driver becomes more vigilant and makes an assessment of urgency. A valid warning may not be helpful in the immediate sense, but can be informative in that typically the driver is assuming normal driving behavior and actions will resolve the situation.
- **Invalid**—warnings are characterized by an incorrect or inaccurate assessment of the driving environment by the warning system. They often appear to be spurious and random without any identifiable reason or model for their cause.

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

- **Valid**—there was a lateral drift sufficient for a warning followed by a measurable reaction by the driver to return to the original lane within a 5-second time window. For example, the driver is involved in a secondary task and inadvertently drifts into an adjacent lane, but upon hearing the warning, the driver actively corrects back toward the center of the original lane.
- **Valid and not corrected**—there was a lateral drift sufficient for a warning but no immediate correction in lane offset by the driver occurred within a 5-second time window. For example, most miles by line-haul drivers occur at night on limited access roads with very light traffic. In these situations, drivers appear to unintentionally drift into an adjacent lane but do not attempt to return to the lane for an extended period of time. They continue down the road straddling the lane boundary marker.
- **Valid and intentional**—the warning occurs when a driver makes an un-signalized (or late turn signal) lane change or intentionally moves outside of the lane due to road construction or a stopped vehicle on a shoulder. In these events, the driver drifts far enough outside of the lane that the center of the vehicle crosses the common boundary between lanes, triggering the lane change flag.
- **Invalid**—the warning was issued during a period of poor boundary-tracking confidence or around transitions in boundary-tracking confidence.
- **Invalid (imminent only)** —the adjacent lane was mistakenly classified as occupied and the maximum lane 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 lane 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 lane position information and the driver times the lane change such that the POV clears the adjacent space as the SV occupies the adjacent space. For example, on a three lane road with one lane unoccupied, both the SV and POV move laterally in a synchronous fashion, both changing lanes at the same time. Another common example is when the SV changes lanes behind a faster moving POV just as the POV clears the adjacent lane but is still in the field of view of the forward lateral-facing proximity radar.
- **Valid and delayed lane change**—the space adjacent to the vehicle was occupied and there is valid lane position information but the driver is waiting for the space to become available and during that time exceeds the lateral position or velocity warning criteria resulting in an LCM.
- **Invalid**—the space adjacent to the vehicle was misclassified as occupied so no LCM should have been given when the driver signaled and moved laterally into the adjacent lane.

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. Drivers had an overall valid lateral warning rate of 12.1 per 100 miles, and made measurable lane position corrections following these valid warnings at a rate of 9.3 warnings per 100 miles. Drivers made no measurable lane position correction following valid warnings at a rate of 2.8 per 100 miles. Drivers had an invalid lateral warning rate of 3.2 per 100 miles. The invalid warnings, 21 percent of all lateral warnings, are 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 high levels of invalid warnings for the LDW imminent and LCM warning. In fact, 17,610 (92%) of the 19,130 invalid warnings were due to the area adjacent to the SV being flagged as occupied when it was not. The remaining 1,520 invalid warnings can be attributed to low boundary tracking confidence.

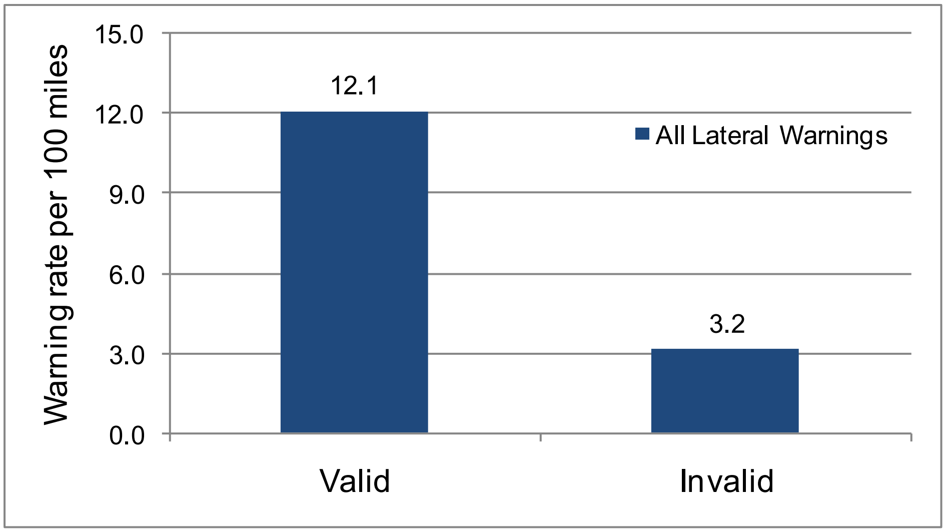

Figure 26. Overall lateral warning rate per 100 miles.

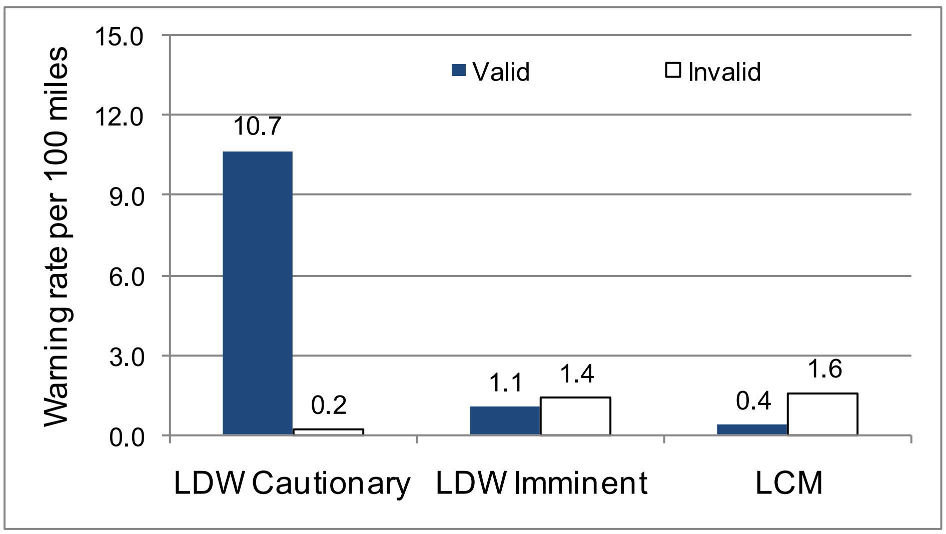

Figure 27. Overall lateral warning rate per 100 miles for each warning type.

Figure 28 shows the lateral warning rate per 100 miles as a function of warning type and side of the vehicle (from the driver's perspective). This figure shows that the rate of warning is higher on the left side of the SV as compared to the right in all categories. Of all LDW imminent warnings and LCM, 70 percent and 82 percent, respectively, were to the left side of the SV. This is not surprising since most of the exposure miles can be attributed to line-haul drivers on limited access roads traveling in the right-most lane with passing vehicles on the left, and a clear shoulder to the right. To a lesser extent is the left side bias for LDW cautionary warnings. For this type of warning, 61 percent resulted from drifting to the left as opposed to the right.

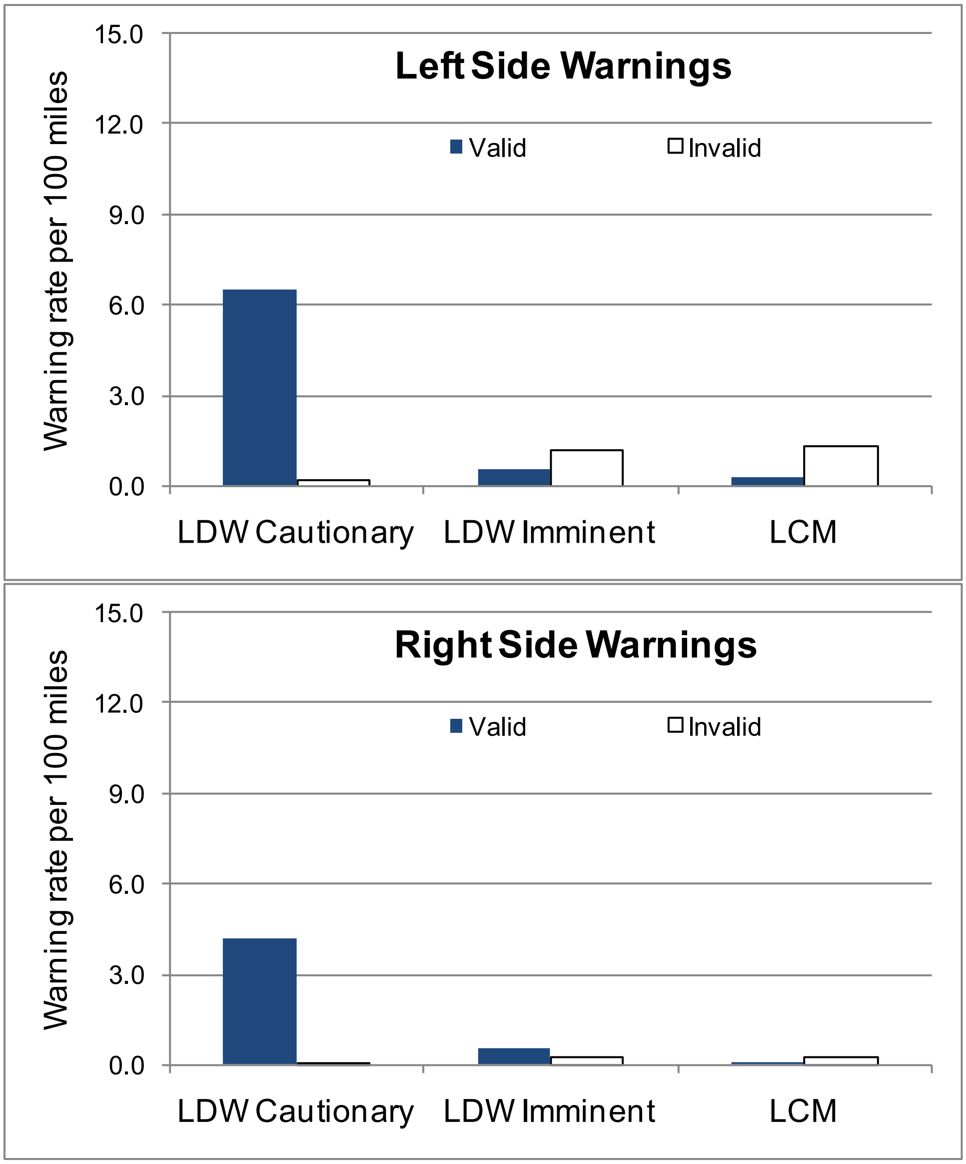

Figure 28. Overall lateral warning rate per 100 miles as a function of vehicle side and type.

In terms of the broader exposure variables of condition and route type, Table 13 shows the number of warnings, percentage, and rate as a function of warning type and classification. The highest rate is for valid LDW cautionary warnings for line-haul drivers in baseline, at 12.1 warnings per 100 miles. During the treatment period, this rate drops by 15 percent to 10.8 warnings per 100 miles. A drop in rate is also true for P&D drivers.

Table 13. Lateral warning rate by condition, route type, and classification

Condition	Route type	Warning type	Classification	Count	Percent	Rate, per 100 miles
Baseline	P&D	LDW Cautionary	Valid	1657	1.8	11.15
			Invalid	43	0.0	0.29
		LDW Imminent	Valid	387	0.4	2.61
			Invalid	214	0.2	1.44
		LCM	Valid	189	0.2	1.27
			Invalid	252	0.3	1.70
	Line-Haul	LDW Cautionary	Valid	13884	15.1	12.13
			Invalid	343	0.4	0.30
		LDW Imminent	Valid	1095	1.2	0.96
			Invalid	1295	1.4	1.13
		LCM	Valid	295	0.3	0.26
			Invalid	1722	1.9	1.50
Treatment	P&D	LDW Cautionary	Valid	6296	6.9	10.37
			Invalid	124	0.1	0.20
		LDW Imminent	Valid	1501	1.6	2.47
			Invalid	1089	1.2	1.79
		LCM	Valid	701	0.8	1.15
			Invalid	849	0.9	1.40
	Line-Haul	LDW Cautionary	Valid	42301	46.0	10.28
			Invalid	778	0.8	0.19
		LDW Imminent	Valid	3381	3.7	0.82
			Invalid	5749	6.3	1.40
		LCM	Valid	1095	1.2	0.27
			Invalid	6672	7.3	1.62

2.2.1.3 Trailer Reflections and LDW Imminent Warnings

As designed, the system issued three warning types, LDW cautionary (audible moderately aggressive sound), LDW imminent (audible aggressive series of beeps) and LCM (same as an LDW imminent). Critical in the warning logic and warning selection is the state of the available maneuvering room (AMR) adjacent to the SV. When AMR is unoccupied and the turn signal is off, the integrated system issues an LDW cautionary warning when the SV drifts toward or across the lane boundary. When AMR is occupied and the turn signal is off, the integrated system issues an LDW imminent warning when the SV drifts toward the lane boundary. An important distinction between LDW cautionary and imminent warnings, aside from the AMR state and warning sound, is the timing of the warning. Imminent warnings generally occur sooner than cautionary (before or when crossing the boundary) since the situation is considered more urgent with a reduced AMR and the driver may need more time to make corrections. During the FOT, 57 percent of all LDW events were imminent. This was the largest warning category and for many of these imminent warnings (86%—39,049 warnings), AMR was set to occupied due to trailer reflection targets being misidentified as an object occupying the adjacent space to the SV.

Available maneuvering room is fundamental to the type of lane-departure warning issued and the algorithm to determine AMR state was among the most challenging tasks in the heavy truck system development. The system used three sensors for object detection on each side of the equipped vehicle. Two of these sensors covered the area adjacent to the tractor and forward area of the trailer approximately to the landing gear. These sensors had a wide field of view, very limited ranging capability and were mounted to sense objects in direct lateral proximity to the vehicle and had no interference from other tractor and trailer components. To cover the space adjacent to the trailer and aft of the landing gear, a short-range (30 m), wide field-of-view ranging radar was mounted on each rear-view mirror and oriented to sense the lane adjacent to the trailer. However, along with sensing the adjacent lane, these sensors also detected many radar returns from the tractor and trailer and it was distinguishing these trailer returns from actual vehicles in the adjacent lane that was technically challenging. Also, since the rear-looking radar was at a shallow angle relative to the side of the trailer, trailer reflections tended to have an inconsistent range or azimuth angle, compounding the problem. Furthermore, tractor yaw-rate, lateral trailer motions (especially with double trailer combinations), and different trailer-side material and design (smooth versus ribbed) also tended to make the reflections inconsistent and widely dispersed.

The technique used to discriminate between valid targets and trailer reflections involved sampling the radar data at defined intervals to properly identify trailer reflection azimuth and range characteristics. Radar returns that did not match trailer reflection azimuth and range profiles were considered valid targets.

Unfortunately, the integrated system that was deployed in the extended pilot and field test struggled with properly categorizing trailer reflections particularly on the vehicle's left side. The primary manifestation of this was in the LDW imminent versus LDW cautionary distinction. (Since LCM warnings are only issued with the turn signal on, which constitutes about 7 percent of all ignition-on time, the total number of LCM warnings was relatively small (15%) as compared to LDW.)

To address this issue in the analysis and in categorizing warnings, the targets from the left side radar where post-processed to more accurately distinguish times when AMR was occupied or not and the effect of this processing was a 42-percent reduction in occupied AMR time.

2.2.2 Driver Behavior Research Questions

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

Method: The lateral offset is defined as the distance between the centerline of the vehicle and the centerline of the lane, as shown in Figure 29. If the vehicle is perfectly centered in the lane, the lateral offset is zero.

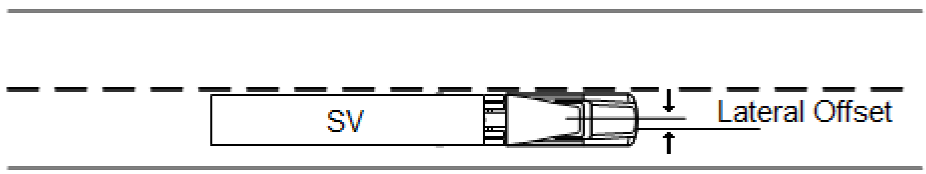

Figure 29. Conceptual drawing of lateral offset

This analysis 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. A buffer time of 5 seconds before and after intentional maneuvers 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. This ensured that the driver settled into the driving task, and eliminated short periods of driving where the driver might have been preparing for the next maneuver. Additional criteria required the lane tracking system to have known boundaries on both sides and the lane tracking status enabled to ensure that good estimates of the lateral offset were used.

A total of 213,500 events, consisting of 4,481 hours (44.5% of driving at speeds greater than 25 mph) and 275,315 miles of driving (47.3% of driving at speeds greater than 25 mph), were identified. The median lane-keeping event duration was 49 seconds, and the longest was over 13 minutes. For each lane-keeping event, the mean lateral offset was calculated and used as a dependent variable.

A difficulty associated with this analysis was the lack of steady-state lane-keeping events for the P&D drivers specifically, and, at lower speeds, for all drivers. Figure 30 shows a histogram of the fractional time versus average speed for observed steady-state events based on the above criteria. Most of the data is for high-speed driving, and is therefore largely associated with limited access roadways and line-haul drivers. The relatively complex and diverse urban, surface-street environment driven by the P&D drivers does not conform well to the analysis constraints, and therefore only represents a small fraction of the data examined.

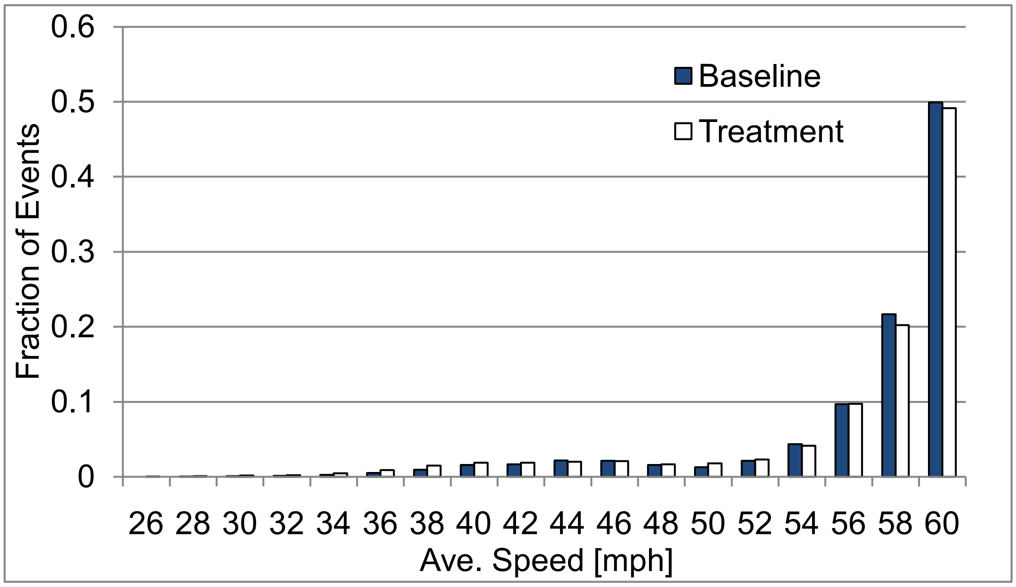

Figure 30. Histogram of average speeds for both experimental conditions for the steady-state lane keeping events

Results: This analysis used a linear mixed model with the driver as a random effect to determine the significant factors in predicting the lateral offset in steady-state lane-keeping events.

The presence of the integrated crash warning system had a statistically significant, but very small, effect on lateral offset ($F(1,17) = 52.48$; $p < 0.0001$). For a majority of the steady-state lane-keeping events, which were on limited access roads during the night at high speeds, a 1.7 cm move toward the center of the lane was associated with the treatment condition (from 10.8 cm to 9.1 cm to the right of the lane's centerline). However, the overall effect of the integrated system across all conditions is much smaller, and represents a shift of 0.9 cm to the right, away from the centerline, relative to the baseline condition (Figure 31).

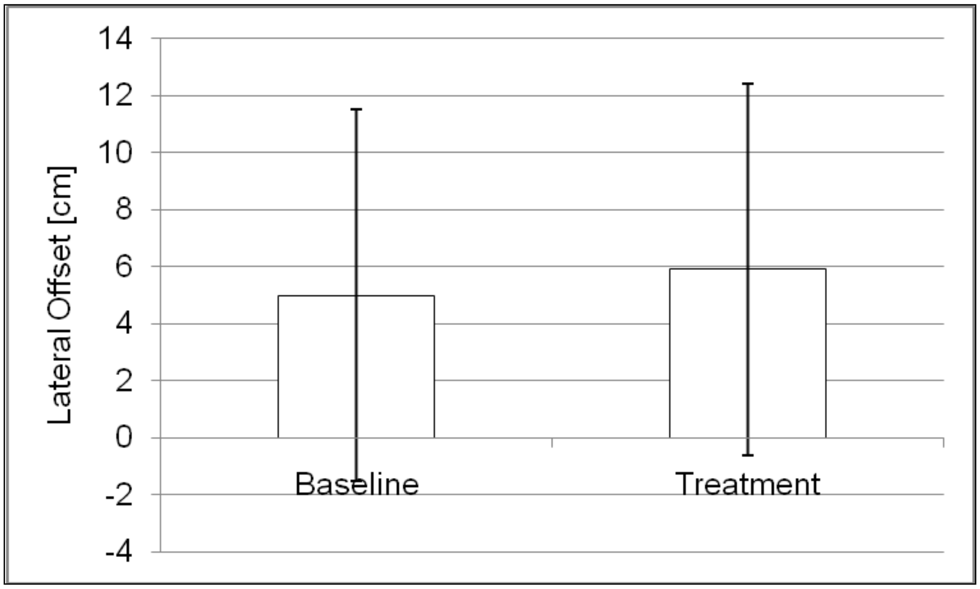

Figure 31. The main effect of the integrated system on lane offset, including standard error

The average speed ($F(1,18) = 11.97$; $p = 0.003$) and road type ($F(1,11) = 22.53$; $p = 0.0006$) were also found to have a statistically significant effect on lateral position. The interaction of average speed and treatment condition, along with predictive models (linear mixed model) of the same data, is shown in Figures 32 and 33. The lateral offset changes dramatically around 48 mph, which is associated with a shift from surface streets to limited-access roadways with wider lanes.

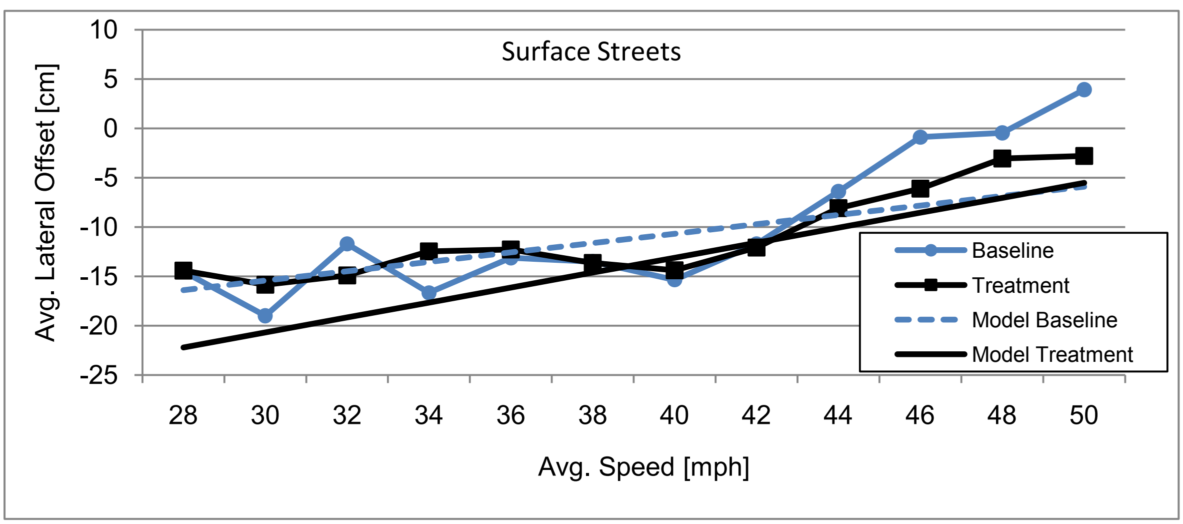

Figure 32. Average lateral offset for both experimental conditions versus average speed during steady-state lane keeping on surface streets

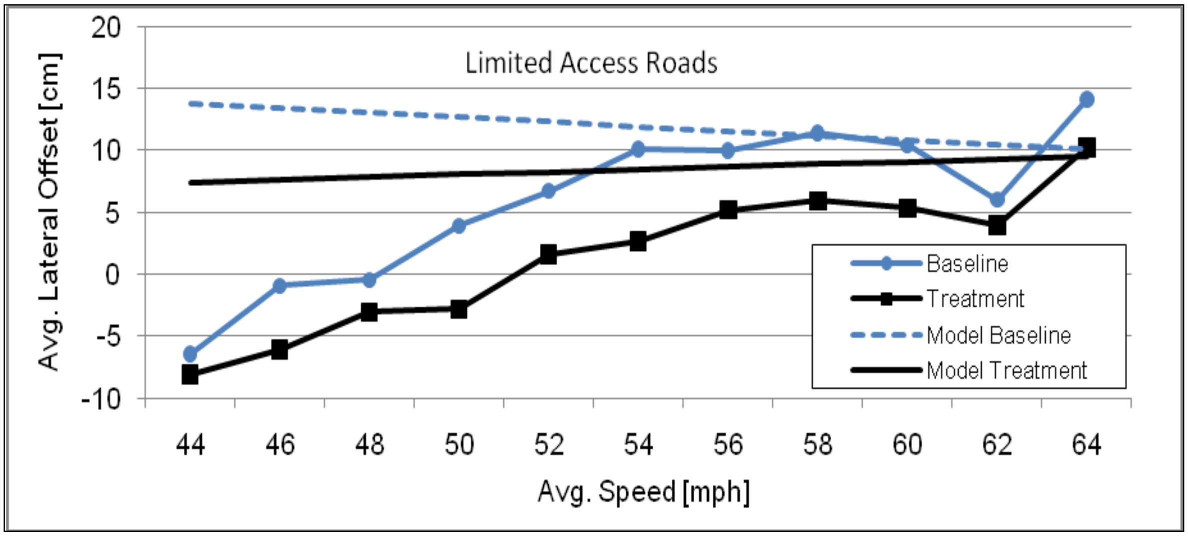

Figure 33. Average lateral offset for both experimental conditions versus average speed during steady-state lane keeping on limited access roads

Figure 34 illustrates the effect of treatment condition and roadway type on lane offset. On limited-access roadways, drivers tended to move closer to the center of the lane in the treatment condition than in the baseline condition. On surface streets, drivers ventured away from the center of the lane more in the treatment condition than was observed in the baseline condition. Drivers demonstrated a preference for the right side of the lane for the baseline condition on both road types. However, the treatment condition shows a shift to the left for both road types (2.5 cm for limited-access roads and 3.7 cm for surface streets). The route type did not have a statistically significant effect on lateral offset, although the route type was indicative of the road type driven.

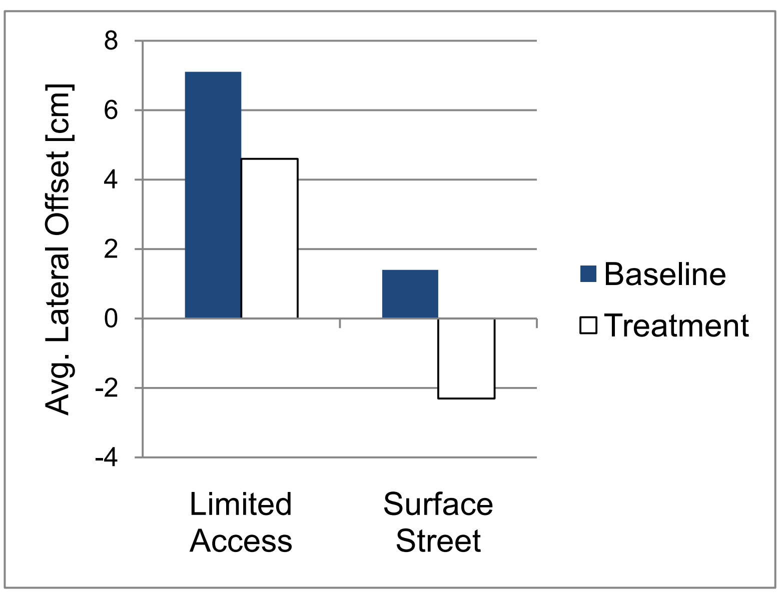

Figure 34. Average lateral offset for both experimental conditions and road type during steady-state lane keeping

Interpretation: There is a statistically significant effect on lateral offset associated with the integrated crash warning system. The effect is most prevalent for steady-state lane-keeping events for travel on limited-access roadways (that took place predominantly at night and at higher speeds). A change in average lateral offset for the limited-access road type showed that in the treatment condition drivers maintaining lane positions slightly closer to the center of the lane. A preference was also found for driving to the left of the center of the lane on surface streets and at lower speeds in the treatment condition. It appears that drivers favor different lane positions for the variety of road types and driving situations encountered, this could be based on experience or personal preference. These results are based on steady-state lane-keeping events representative of the conditions encountered by line-haul drivers more so than those of P&D drivers. These findings may aid designers of crash warning systems by highlighting drivers' general preferences for lane keeping, whereby refinements can be made in warning thresholds for warning algorithms.

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 an LDW due to the sophisticated warning algorithms that incorporate numerous factors involving the vehicle relative to the roadway. This analysis focused on all lateral drifts beyond the lane boundary, without focusing only on those events that triggered warnings from the integrated system. A lane departure is defined as an excursion on either side of the vehicle into an adjacent lane as measured by the lane-tracking component of the LDW subsystem. The event must include both the exit from, and the return to, the original lane. A lane departure was considered to have occurred when the entire lane boundary was covered by the vehicle's tires.

Table 14 shows the constraints used in defining lane departures for addressing this question. A maximum duration for lane departures was implemented after video review determined that 76 percent of lane-departure events over 20 seconds were not valid (due to inability to detect poor lane tracking markings in high glare situations or construction zones).

Table 14. Constraints used in defining lane-departure events

Constraints
1. Outer edge of vehicle beyond the estimated lane boundary
2. Boundary types known and real (virtual boundaries are not included)
3. Lane offset confidence 100 percent
4. No braking, lane changes, or turn signal use detected
5. Buffer time of 5 seconds before and after any intentional maneuver
6. Vehicle returns to lane in less than 20 seconds
7. Speed greater than 11.2 m/s (25 mph)

During the steady-state lane keeping, as previously defined in QL1, there were 68,976 lane-departure events used in performing this analysis. Figure 35 shows the number of lane-departure events preceded by steady-state lane keeping for individual drivers. The number of lane departures was then normalized by the number of miles driven to determine the lane departure frequency.

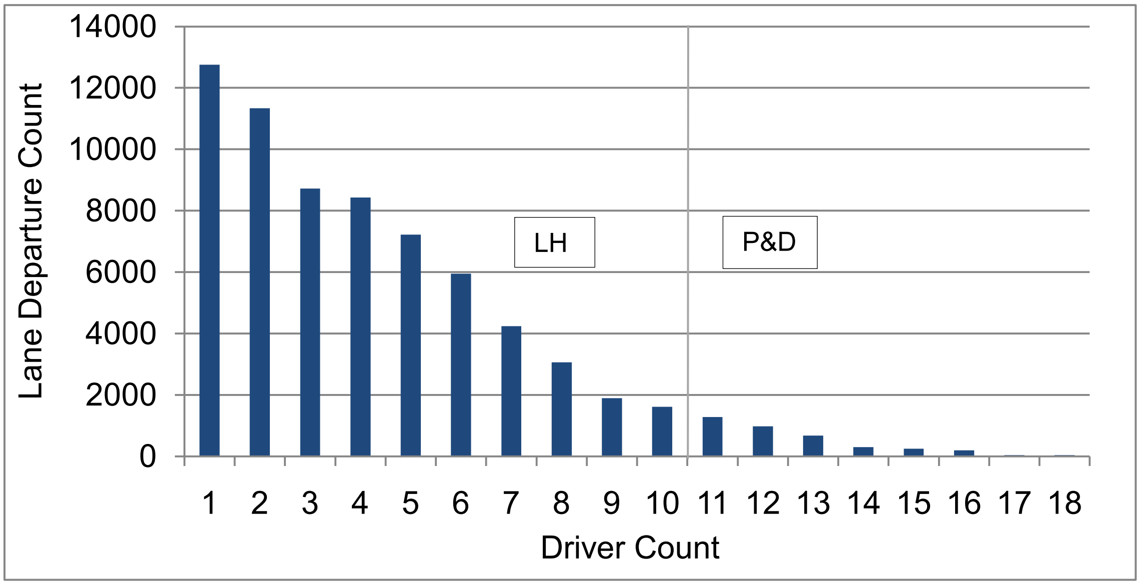

Figure 35. Distribution of lane-departure counts for individual drivers during steady-state lane keeping

Results: The principal findings of this analysis are based on the results of a linear mixed model that examined the frequency of all lane departures, not just those that would, or did, result in lateral drift warnings.

The presence of the integrated crash warning system did not have a statistically significant effect on the frequency of lane departures ($F(1,17) = 0.39$; $p = 0.5385$), although the rate of departures did decrease for 13 of the 18 drivers (Figure 36). For 6 of drivers, the rate of lane departures was reduced by 50 percent or more.

The frequency of lane departures was higher on surface streets than on limited-access roads, with the size of the effect being statistically significant ($F(1,17) = 4.96$; $p = 0.0397$). For the entire field study, lane departures on surface streets were 15.4 per 100 miles compared to 6.5 per 100 miles for limited-access roads.

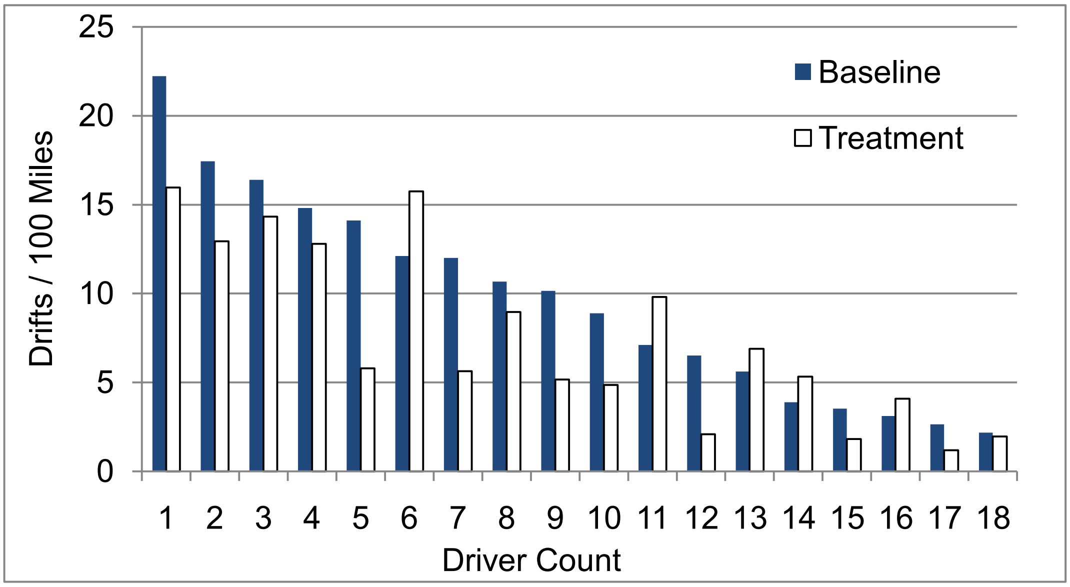

Figure 36. Drift rate for the individual drivers during steady-state lane keeping

Interpretation: The integrated crash warning system did not have a statistically significant effect on lane departure frequency, although the normalized number of lane departures did decrease. A decrease in lane departures was observed for 13 of the 18 drivers. The frequency of lane departures was higher on surface streets than on limited-access roads, which is likely associated with narrower lane widths on surface streets relative to limited-access roadways. It is also important to note that there is a large difference between individual drivers and their preferred buffer zone between the vehicle and lane boundaries. This might suggest the need for some level of adjustability to warning thresholds that can be tuned to specific driver preferences.

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: Of the 68,976 total lane departures during the steady-state lane-keeping events, 15 percent were associated with lateral-drift warnings. This analysis focused on all lateral drifts beyond the lane boundary, without focusing on those events that triggered warnings from the integrated system. A lane departure is defined as an excursion on either side of the vehicle into an adjacent lane as measured by the lane-tracking component of the LDW subsystem. The event must include both the exit from, and the return to, the original lane. A lane departure was considered to have occurred when the entire lane boundary was covered by the vehicle's tires. Figures 37 and 38 show histograms for the durations and maximum incursions for lane departures preceded by steady-state lane keeping.

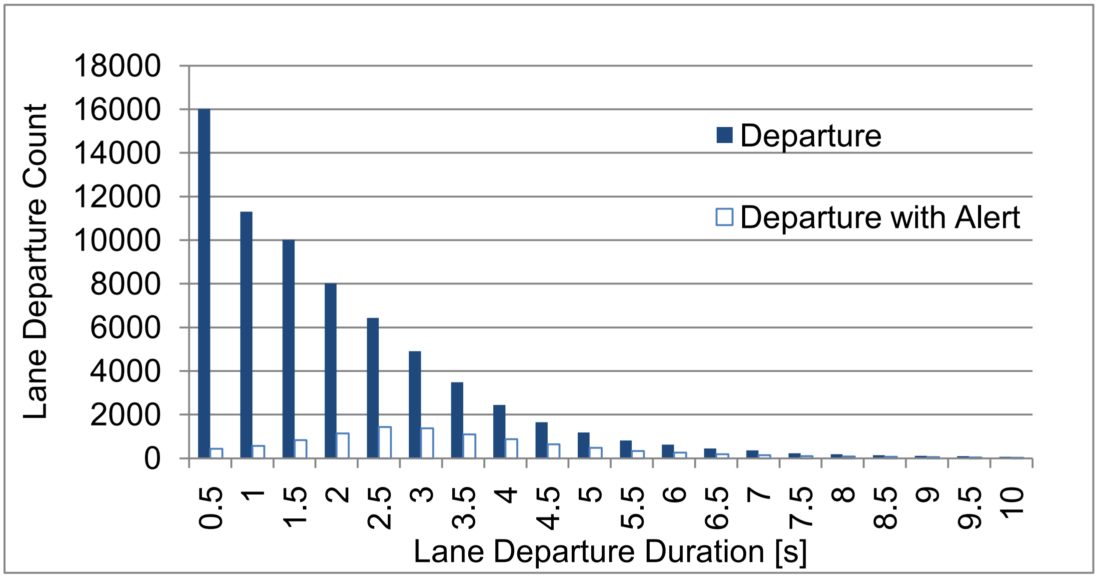

Figure 37. Lane departure count by duration of the departure

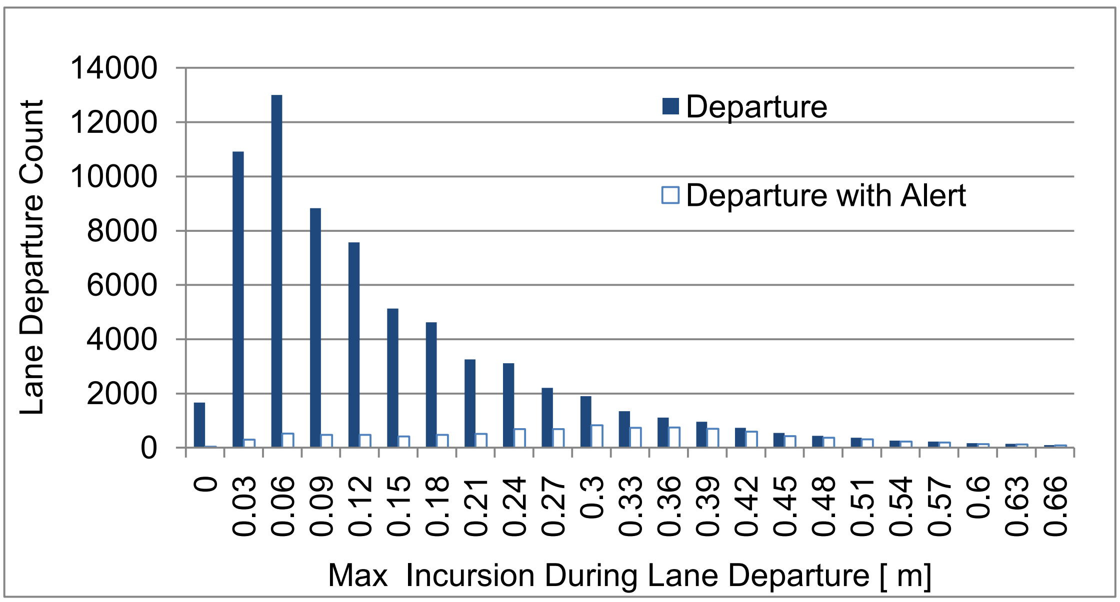

Figure 38. Lane departure count by maximum incursion distance

Results: The principal findings of this analysis are based on the results of a mixed linear model that examined the distance and duration of all lane departures, not just those that would, or did, result in lateral drift warnings.

The presence of the integrated system alone did not have a statistically significant effect on the duration of lane incursions. However, the duration of the incursions was marginally shorter in the treatment condition (2.02 seconds), compared to the baseline condition (2.11 seconds). Lane incursions to the right were consistently longer, by 100 milliseconds, than incursions to the left ($F(1,17) = 18.61$; $p = 0.005$), with durations of incursions to the left averaging 1.8 seconds.

Hours of service had a statistically significant effect on the duration of lane incursions ($F(1,17) = 4.68$; $p = 0.0451$). Figure 39 shows the field test data associated with hours of service and the duration of lane departures. The data indicates that lane departure durations increase with increasing hours of service.

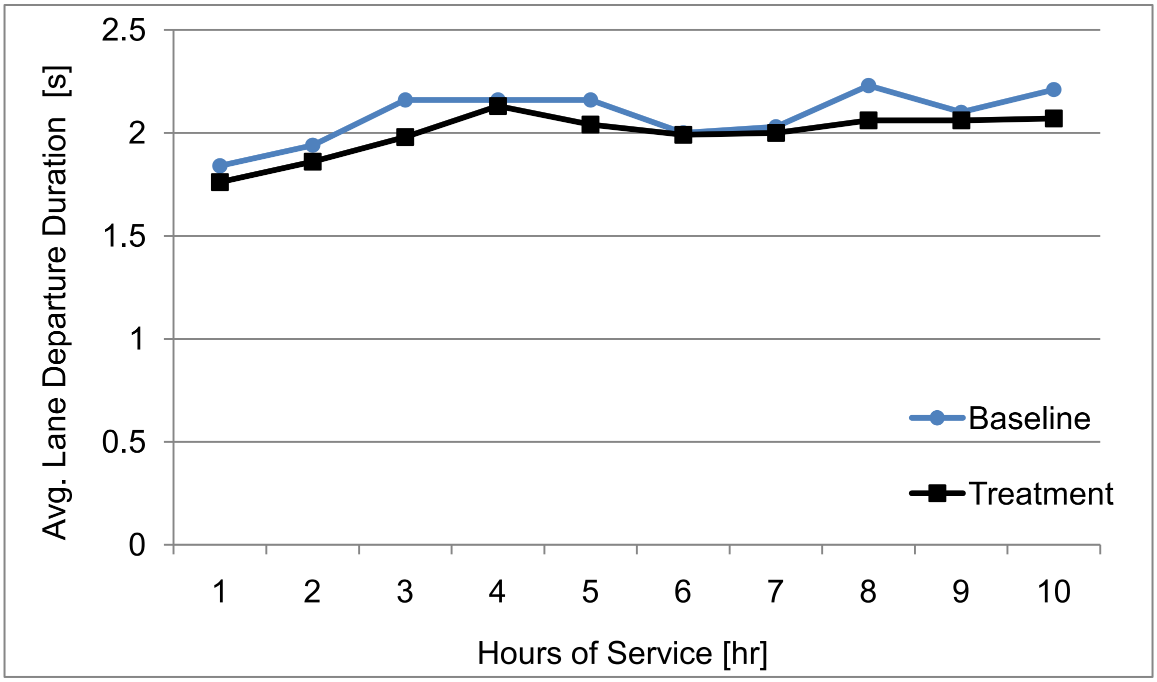

Figure 39. Duration of lane departures to the left on limited access roads for both conditions versus hours of service

The presence of the integrated system alone did not have a statistically significant effect on the maximum distance of lane incursions. Maximum distances of incursions were marginally larger in the treatment condition (14.5 cm) as compared to the baseline condition (13.9 cm). Lane incursions to the right were statistically significantly but slightly larger, by 1.4 cm, than incursions to the left, a statistically significant effect, ($F(1,17) = 9.22$; $p = 0.0074$), with the maximum distance of incursion to the right averaging 14.9 cm.

Hours of service had a statistically significant effect on distance of lane incursion ($F(1,17) = 13.00$; $p = 0.0022$), with the largest incursions occurring during the fifth hour of service in the baseline condition and the sixth hour of service in the treatment condition (Figure 40). However, the model indicates that lane departures increase gradually with increasing hours of service.

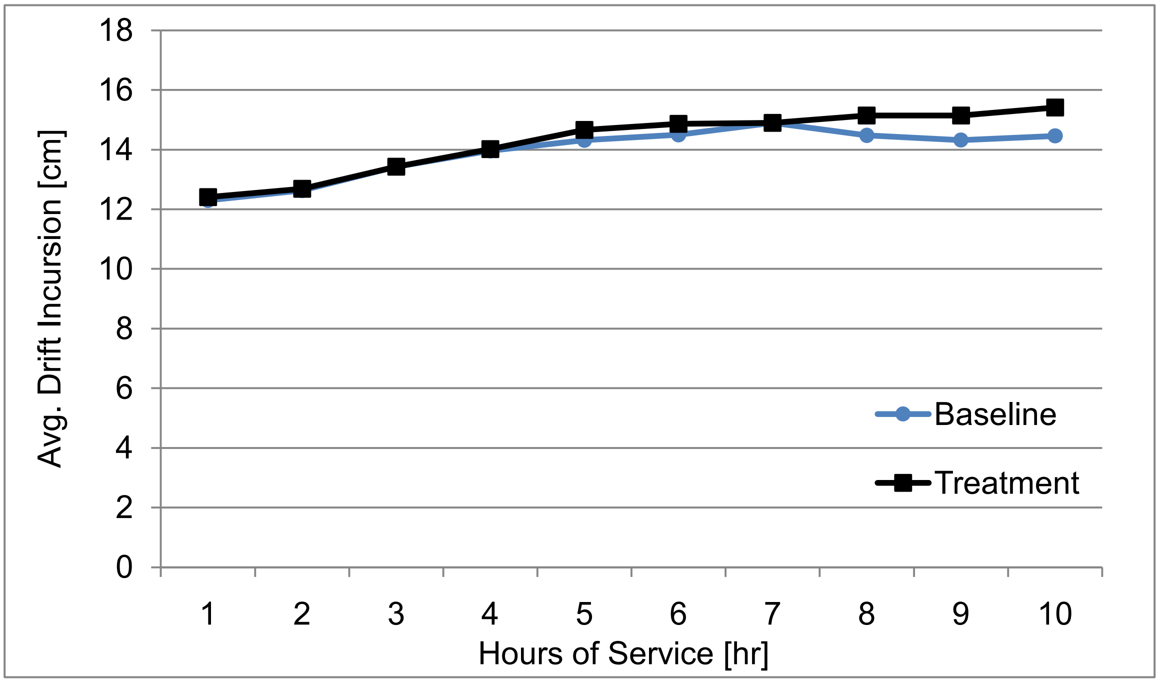

Figure 40. Incursion distance of lane departures in either direction on limited access roads at night for both conditions versus hours of service

Interpretation: The change in duration and distance of lane incursions is not affected by the presence of the integrated crash warning system. However, there was a statistically significant effect on incursion duration and distance for the hours of service. On average, an increase in incursion duration of 0.34 seconds and distance of 2.6 cm occurs from the first hour to the tenth hour of service. Furthermore, this effect was true for both P&D and line-haul drivers. This result suggests that the LDW subsystem has the greatest potential benefits the longer a driver has been behind the wheel.

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

Method: A subset of 53,221 left and right lane-change events was used to examine turn-signal use. The analysis addressed changes in the frequency of turn-signal use during lane changes. A lane change was defined as the lateral movement of the SV relative to the roadway in which the SV begins in the center of a defined traffic lane with boundary demarcations, and ends in the center of an adjacent traffic lane that also has defined boundary demarcations. A lane change is defined as the instant in time when the SV centerline crosses the shared boundary between the two adjacent traffic lanes.

Results: The principal findings of this analysis are based on the results of a mixed linear model that examined turn-signal usage during lane changes in the baseline and treatment conditions.

The presence of the integrated system alone did not have a statistically significant effect on turn-signal use during lane changes. Drivers did not use their turn signals when performing lane changes 6 percent of the time in the baseline condition, and more than 4 percent of the time in the treatment condition. Therefore, while the direction of the change is towards improved turn-signal use, the size of the difference did not reach a statistically significant level.

The direction of the lane change has an effect on turn-signal usage. The analyses indicate that drivers are 2.2 times more likely to make an unsignaled lane change to the left than to the right ($F(1,17) = 10.56$; $p = 0.0047$). As shown to the left in Figure 41, drivers did not use a turn signal in 6.4 percent of left-lane changes and in 2.9 percent of right-lane changes.

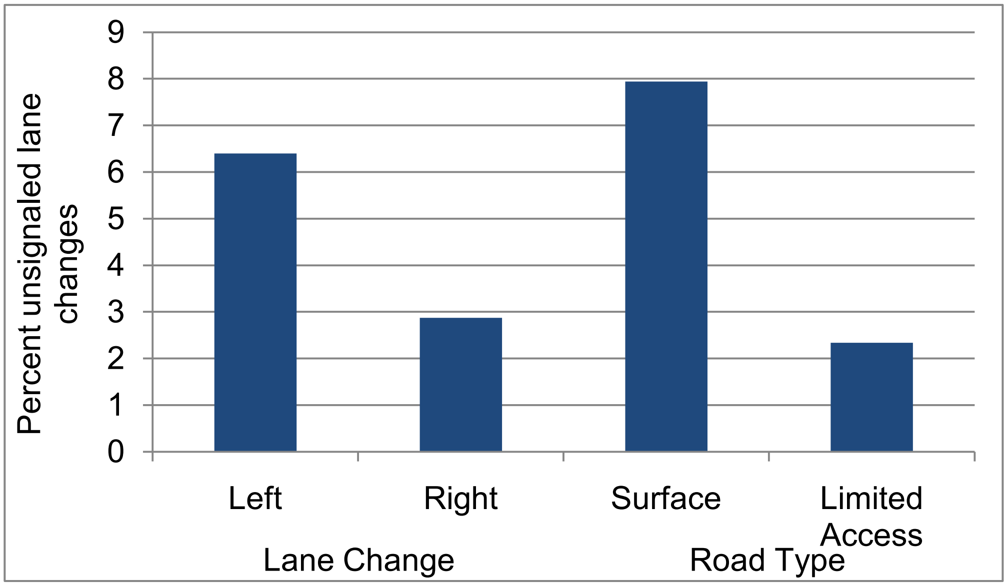

Figure 41. Main effects of lane-change direction and road type on unsignaled lane changes

Road type was found to have a statistically significant effect ($F(1,17) = 16.12$; $p = 0.0009$) on turn-signal usage. The analyses predict that drivers are 3.3 times more likely ***not*** to use a turn signal during a lane change on surface streets than on limited-access roads. As shown to the right in Figure 35, drivers failed to use a turn signal in 7.9 percent of the lane changes on surface streets and in 2.3 percent of lane changes on limited-access highways.

As shown in Figure 42, a statistically significant two-way interaction exists between road type and treatment condition. The analyses predict that drivers are 1.8 times more likely **not** to use a turn signal on surface streets during a lane change in the baseline condition than in the treatment condition ($F(1,17) = 2.67$; $p = 0.0503$). On surface streets, drivers failed to use a turn signal in 11 percent of lane changes in the baseline condition and in only 6 percent of lane changes in the treatment condition. On limited-access roads, the difference between baseline and treatment conditions was very small.

Two distinct groups of drivers for unsignaled lane changes were identified: a group of four drivers (three of whom drove P&D) with a proportionately higher fraction of unsignaled lane changes, and a group of 14 drivers who routinely signaled for lane changes. The four drivers who used turn signals the least accounted for over 54 percent of all unsignaled lane changes. One driver did not use his turn signals in almost 45 percent of his lane changes.

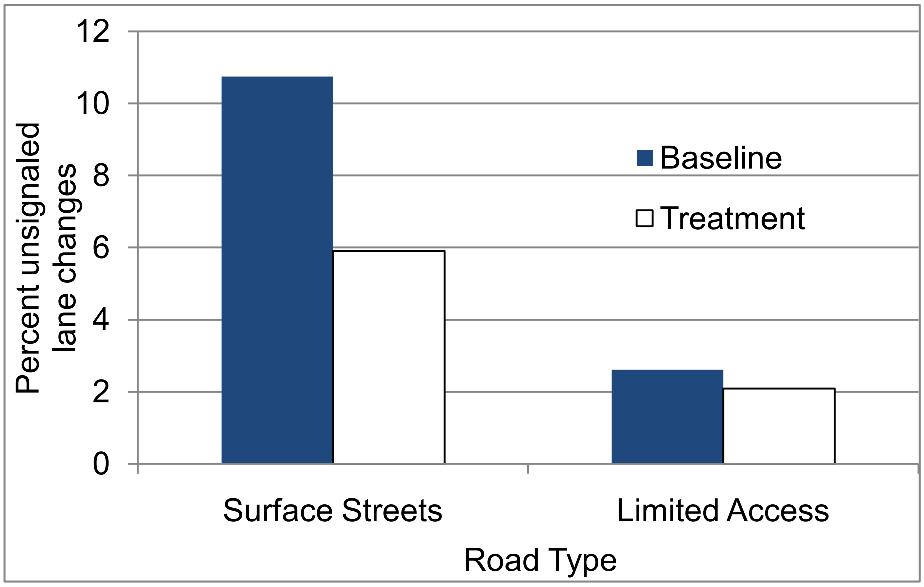

Figure 42. Interaction between condition and road type

The practice of making unsignaled lane changes appears to be based largely on the individual driver. Of the 4 drivers who were least likely to use turn signals when changing lanes, there was no pronounced change in turn-signal use with the integrated system, and at least 1 driver showed an increase in unsignaled lane changes.

The other independent variables: route type (i.e., line-haul or P&D), load, wiper state, ambient light, trailer type, and traffic showed no statistically significant difference on turn signal use and there were no two-way effects of condition and route type found in the analysis.

Interpretation: The results show no statistically significant effect of the integrated system on turn-signal use during lane changes, but an overall trend toward more frequent use of turn signals. The increased use of turn signals was most pronounced with the integrated system enabled on surface streets. With the exception of four drivers, turn signal use was high (used in 94% of lane changes) prior to exposure to the integrated system. It is not surprising then, to find no effect of the integrated system on turn signal use given the general high compliance of use to begin with. This result suggests that behavior changes in turn signal use are not likely with future implementations of these warning systems, but that, as a group, commercial drivers are not necessarily in need of a system that would help them improve their use of turn signals

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

Method: A set of 321,376 randomly sampled events, 5 seconds in duration, was identified in the data set. For every event, a lane-offset position that characterizes the lateral position of the vehicle within the lane, with respect to the lane boundary markers was calculated. Then an analysis was performed for each side of the SV. In the analysis comparing lane position with or without the presence of a POV on the left side of the SV, the AMR on the right side was always unoccupied and conversely in the analysis for the right side of the SV, the AMR on the left was always unoccupied. Figure 43 shows the conditions for the analysis on the left side of the SV. Additional constraints were: straight sections of road with good boundary markings, no intentional lateral maneuvers temporally near the sampled period by the driver, and a speed of 11.2 m/s (25 mph) or higher.

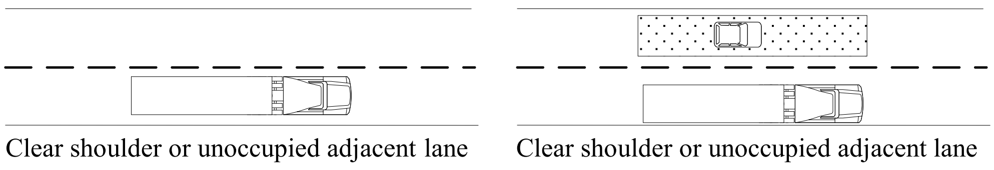

Figure 43. Change in lane offset away from an occupied space

Results: The principal findings for this question are based on the results of a linear mixed model analysis that examined a change in lateral offset associated with the presence of an adjacent vehicle.

When the right lane was occupied, drivers moved to the left 15 cm compared to when the right lane was unoccupied ($F(1,16)=178.26$; $p<0.0001$). If the left lane was occupied, drivers moved to the right 12 cm compared to when the left lane was unoccupied ($F(1,17)=52.03$; $p<0.0001$). Therefore, there was a statistically significant effect on lane offset due to the presence of vehicles in adjacent lanes on either side. However, the range in lane offset with an occupied lane varied considerably across drivers from 27 cm to as little as 0.7 cm.

Interpretation: Drivers adjusted their lane position away from a vehicle in an adjacent lane regardless of which side of the truck the adjacent vehicle is on. This suggests that drivers' situational awareness regarding the presence of other vehicles adjacent to them is rather high. This information may be beneficial for designers of crash warning systems in terms of understanding how best to establish thresholds for warnings when there are vehicles in the adjacent lane.

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

Method: The region adjacent to each side of the heavy truck was divided into three zones for the front (Front Blind Spot Detection Zone) and rear (Rear Blind Spot Detection Zone) lateral-proximity radar, and the rear-looking radar (M/A-COM Detection Zone), as shown in Figure 44. A set of 720 valid LCM-warning events was identified where the space adjacent to the truck was occupied by a vehicle. For each LCM event, the three zones on corresponding sides of the SV were characterized as having, or not having, a vehicle present. For vehicles in the rear-looking radar zone, the range and range rate of the closest vehicle in that zone were determined.

Figure 44. Location of zones for adjacent vehicles for valid LCM warnings

The analysis was performed using the constraints shown in Table 15. These constraints helped to establish a steady-state condition for the subject vehicle, and to dictate how long the turn signal had been activated and the POV was present in the adjacent lane for the event to be considered in the analysis.

Table 15. Constraints used for defining the location of valid LCM warnings

Constraints
1. Boundary types known and lane offset confidence 100 percent
2. Dashed boundary between the SV and POV(s)
3. Turn signal active for at least 1 second before LCM warning is issued
4. Speed greater than 11.2 m/s (25 mph)
5. M/A-COM radar: target duration greater than 2 seconds and a non-zero range rate
6. BackSpotter radar: vehicle present for at least 2 seconds at a range between 0 and 10 feet
7. No intentional lateral maneuvers by the SV driver in a 5-second window prior to the LCM (i.e., the SV is in a steady state condition within its lane)

Results: The principal findings of this analysis are based on the results of a Chi-square test. The significance level was determined based on an alpha level of 0.05. The dependent measure was the count of valid LCM warnings for zones around the vehicle.

Ultimately, a fourth zone that combined the front and rear BackSpotter radars was added. Figure 45 shows the percentage of warnings occurring as a function of the zone, independent of which side of the SV another vehicle was detected. For both sides of the SV, the most active zone was the area covered by the rear BackSpotter in which 30 percent of valid LCM warnings occurred. The M/A-COM coverage zone, which includes the area adjacent to the trailer and aft of the landing gear, was second most active with 29 percent of valid LCMs. The front BackSpotter and the overlap between both front and rear BackSpotter accounted for 17 percent and 24 percent of valid LCM warnings, respectively.

The integrated system did not have a statistically significant effect on the location of valid LCM warnings (χ^2 (3, N = 720) = 0.4923, p = 0.9206). Figure 46 shows the percentage distribution of valid LCM warnings for the baseline (149) and treatment (571) conditions combining all LCM warnings on both sides of the SV. When exposure is considered by normalizing by mileage, the warning rate is only marginally higher (5%) for the treatment condition.

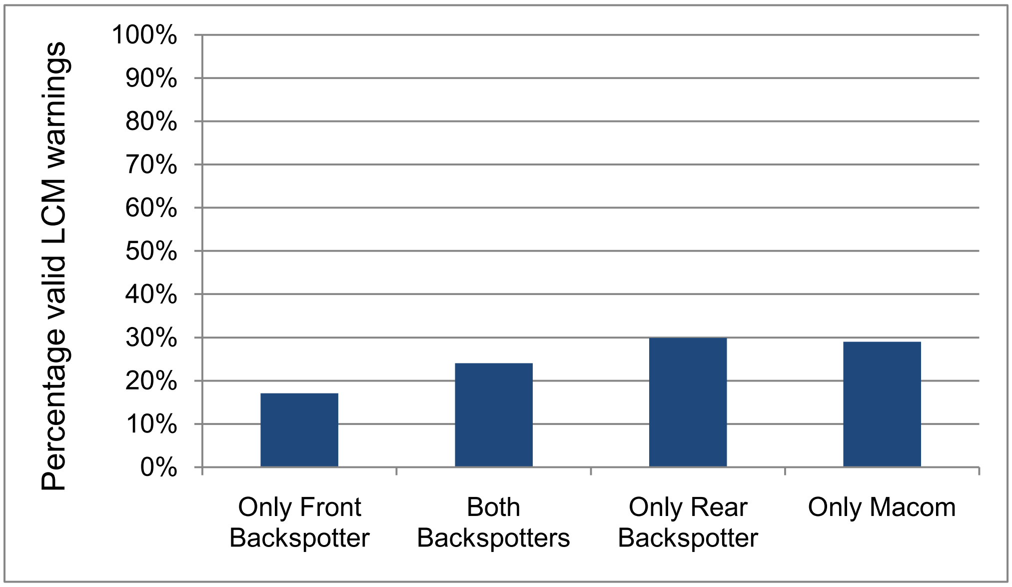

Figure 45. Summary of the distribution of valid LCM warnings

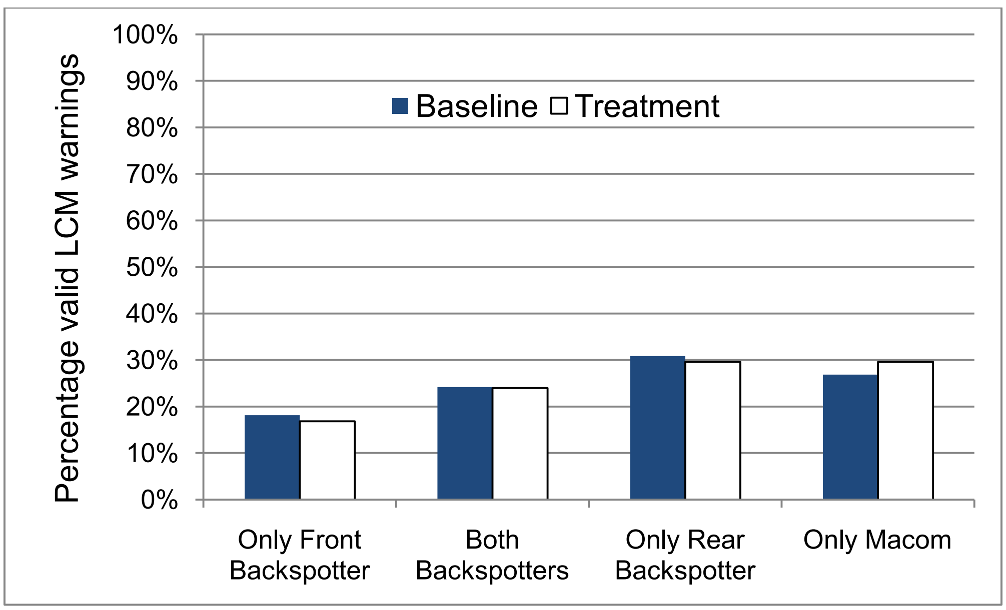

Figure 46. Summary of the distribution of valid LCM warnings as function of condition

The side on which the valid LCM warning was issued was statistically significant (χ^2 (3, N = 720) = 54.14, p = 0.0001). Figure 47 shows that of the 720 LCM warnings, 554 (77%) resulted from a POV on the left side of the SV. Of these 554 warnings, 77 percent occurred in the area covered by the BackSpotter radars, while only 23 percent happened with a POV adjacent to the trailer. However, for LCM warnings to the right of the SV, over half (51%) were issued with a vehicle in the zone adjacent to the trailer. Figure 48 illustrates the distribution of LCM warnings by zone on either side of the SV.

One reason for more occurrences of warnings to the right of the trailer arises from the SV signaling to change lanes to the right when it is passing a slower POV on the right. In this scenario, the SV driver may activate the turn signal and begin to drift to the right before the POV is outside of the M/A-COM zone. This is less likely to occur on the left, as it is relatively rare for the SV driver to pass a slower-moving vehicle on the left. As a result, LCM warnings to the left are much more likely to occur in the BackSpotter region, triggered by a passing, faster-moving POV. In this scenario, the SV driver activate a turn signal, and perhaps drifts a bit to the left, before the POV has cleared the BackSpotter zone, and hence an LCM warning is issued.

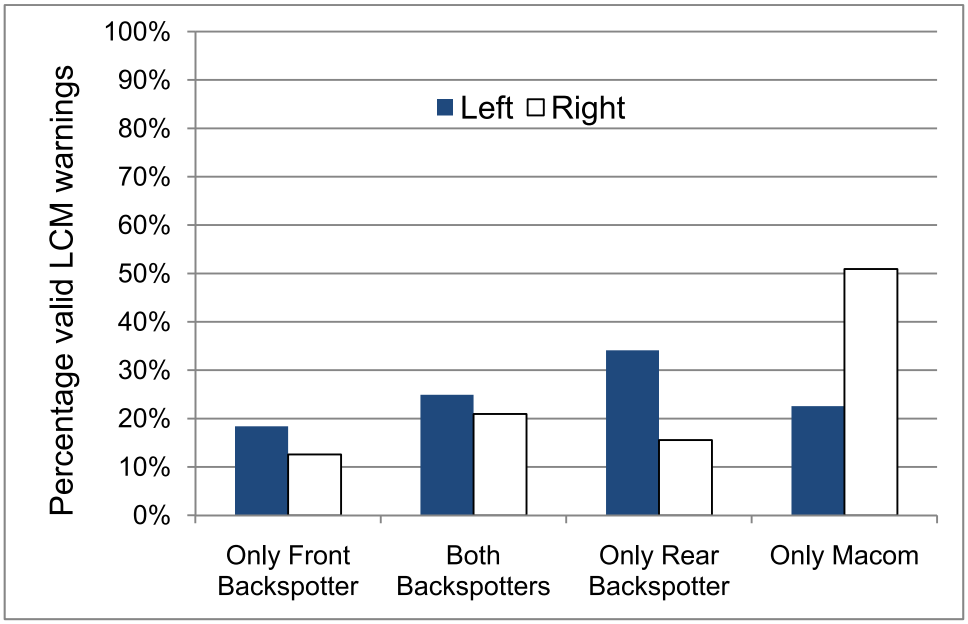

Figure 47. Effect of side on POV location during valid LCM warnings

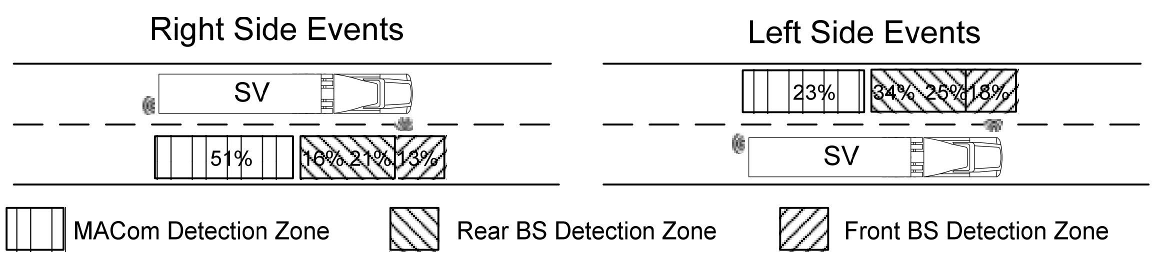

Figure 48. Effect of side on distribution of LCM warning by zone

The main effect of road type is shown in Figure 49. A total of 512 LCM warnings (71%) occurred on limited-access roads, and 208 on surface streets. Adjusted for exposure (miles driven) and assuming the distribution of this set is representative of all LCM warnings, LCM warnings are 3.3 times more likely to be issued on surface streets than on limited-access roads. Regarding the zone distribution by road type, the most likely location of the POV for a valid LCM warning is adjacent to the tractor and the forward portion of the trailer (individual and combined BackSpotter zones). These three zones account for the vast majority of valid LCM warnings on surface streets and limited-access roads, respectively. When normalized for exposure, valid LCM warnings are 4.2 times more likely to occur on surface streets than on limited-access roads adjacent to the trailer (only M/A-COM zone).

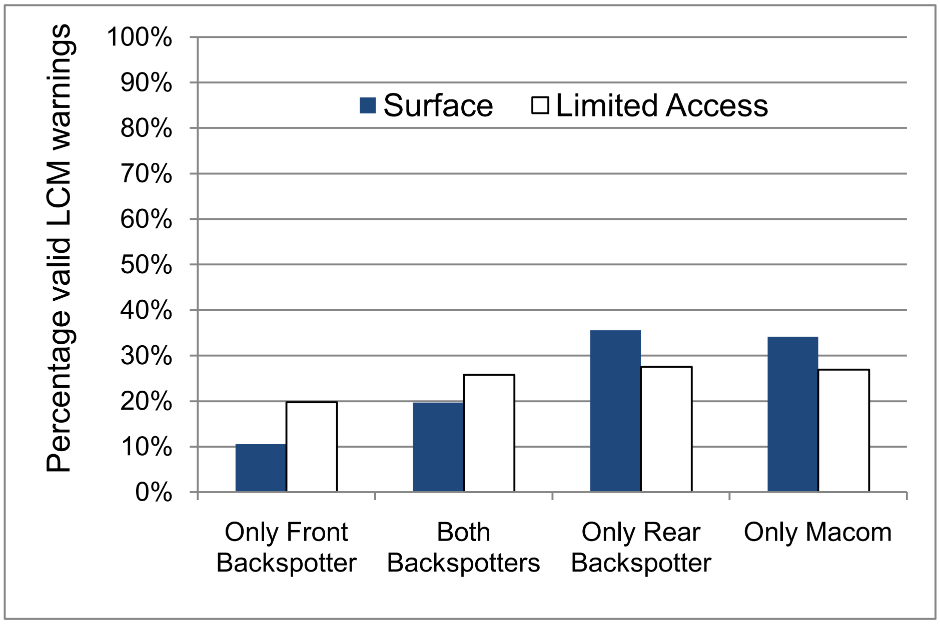

Figure 49. Main effect of road type on POV location during valid LCM warnings

Interpretation: The results show that the integrated system did not affect the location of valid LCM warnings on either side of the SV. That is, with or without the integrated system, drivers did not measurably change their lane-change behavior or timing in a manner that was influenced by the position of other vehicles during these events. The most statistically significant effect found was related to the side on which warnings occurred. The majority of warnings (77%) were issued on the left side of the SV, and the bulk of these occurred in the area adjacent to the tractor (BackSpotter zones). Twenty-three percent of the valid LCM warnings occurred with a POV adjacent to the trailer. However, for LCM warnings on the right of the SV, over half (51%) were issued with a vehicle in the zone adjacent to the trailer. This information may be beneficial for designers of crash warning systems in terms of understanding where to concentrate the sensing of vehicles in adjacent lanes, and perhaps the modification of warning thresholds as a function of the side of the vehicle.

QL7: Will the condition (baseline versus treatment) affect the frequency of lane changes?

Method: The investigation into effects of the integrated system on the frequency of lane-changes is based on a subset of 49,241 identified lane-change events. A lane change is defined as the lateral movement of the SV relative to the roadway in which the SV starts in the center of a defined traffic lane with boundary markings and ends in the center of an adjacent traffic lane that also has defined boundary markings. The lane change is the exact time when the SV lateral centerline crosses the shared boundary between the two adjacent traffic lanes.

Lane changes are comparatively complex events that involve both infrastructure information, including lane boundary markings, and lateral performance information from the SV sensors. The set of lane changes used in this analysis was constrained using the rules stated in Table 16. These constraints ensure that the set of lane changes analyzed does not contain events that were not intended to be lane changes by the SV driver. For example, a driver may intentionally occupy part of an adjacent traffic lane while maneuvering away from a stationary vehicle on the shoulder, or may inadvertently drift laterally into an adjacent lane before returning to the center of the original lane, especially at night and in low traffic situations.

Table 16. Analysis constraints

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

Results: This analysis addresses changes in the frequency of lane changes by normalizing the number of lane-change events by miles driven under different conditions. A statistical analysis compared lane-change rates as a function of the integrated system. Principal findings are based on results of a mixed linear model and the conclusions were derived from the model, not from a direct analysis of the data per se. However, the marginal means and probabilities predicted by the model were checked against queries of the initial data set to substantiate the model.

The presence of the integrated system did not affect lane-change frequency ($F(1,17) = 1.31$; $p = 0.2684$). While the integrated system did not have a statistically significant effect on lane-change frequency, the trend over time appears to indicate a minimal reduction in lane changes with the integrated system (Figure 50).

Interpretation: The results showed no statistically significant effect of the integrated system on the frequency of lane changes, although the trend appeared toward a reduction in lane changes with time. Fewer lane changes reduce drivers' exposure to lane-change crashes, which the integrated system does not appear to influence. This may be that drivers already only make lane changes that are necessary, in which case, warnings from the LCM subsystem could prove more beneficial in reducing crashes than behavioral modifications in lane change behavior associated with the integrated system.

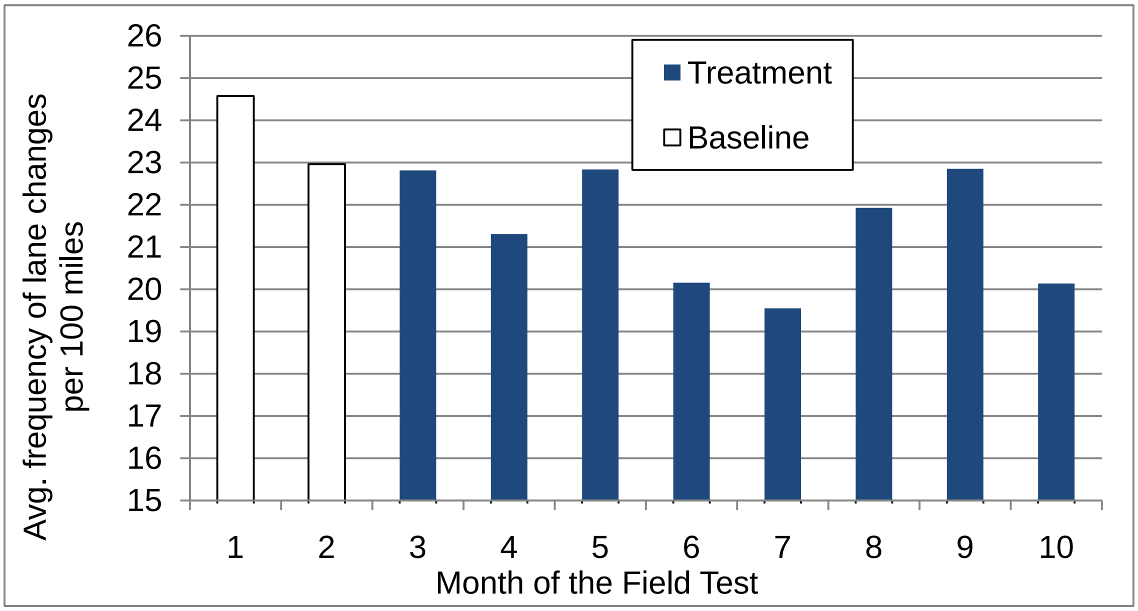

Figure 50. Lane change frequency over the duration of the field test for all conditions.

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 SV approaches a lead vehicle in the same lane and makes a lane change behind a passing POV1 in an adjacent lane on the left (Figure 51). The range and range-rate to POV1 and POV2 were determined at the instant when the SV's left front tire crossed the boundary. It is assumed that lane changes to the right under similar circumstances are far less frequent, and therefore only lane changes to the left are considered. The constraints in Table 17 were used to ensure that the events are reliable and consistent with the scenario definition.

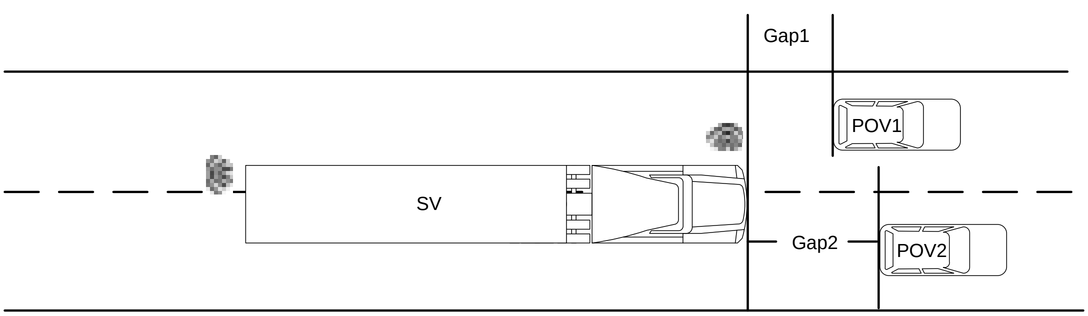

Figure 51. Gap between forward POVs and the SV during lane changes

Table 17. Analysis constraints

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

Results: The results are based on 2,862 events. The principal findings of this analysis are based on the results of a mixed linear model for the three dependent variables shown below. Analyses for each of the dependent variables were run independently.

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

POV2 Range: No effect of the integrated crash warning system was observed on the range to POV2. Statistically significant effects on the POV2 range included road type ($F(1,13)=20.79$; $p = 0.0005$) and speed ($F(1,16)=100.44$; $p < 0.0001$). On average, the range between the SV and POV2 just prior to the lane change was 17.7 meters on limited-access roads and 31.1 meters on surface streets. A shorter average range for limited-access roads suggests that drivers are less conservative on this road type as compared to surface streets and are willing to accept a much smaller time gap prior to the lane change. The results of the model suggest that for speeds less than 15 m/s (31 mph) drivers, on average, will allow a time gap (range/speed) of less than 1 second. For higher speeds, the model predicts that drivers on average will allow a time gap of between 1 and 1.4 seconds.

POV1 Range: There was no effect of the integrated crash warning system on the range to POV1. Statistically significant effects for range to POV1 were road type ($F(1,13)=27.21$; $p = 0.0002$) and hours of service ($F(1,16)=22.61$; $p = 0.0002$). For road type, the average range between the SV and POV1 just after the lane change was 10.7 meters for limited-access roads and 26.4 meters for surface streets. As observed with the range to POV2, the closer range for limited-access roads suggests that drivers are less conservative when changing lanes behind a passing vehicle on this road type. Video review showed that the SV driver waited for a faster moving POV1 to clear the adjacent lane prior to making the lane change in a larger number (67%) of events on limited-access roads, as compared to approximately 33 percent on surface streets.

Relative to the effect of hours of service, drivers reduced the distance to POV1 by 16 percent when comparing the first (20.2 m) to tenth (16.6 m) hour of service. Hours of service, a number between 0 and 10 that represents how many hours a driver has been working is independent of time-of-day. The model predicts time working has a linear effect on POV1 range with a slope of -0.4 meters per hour of service.

POV2 Range Rate: There was no effect of the integrated crash warning system on the range rate to POV2. Significant effects for POV2 range rate included ambient light ($T(1,12)=-3.85$; $p = 0.0023$) and speed ($T(1,16)=-4.38$; $p < 0.0005$). For ambient light, the average range rate between the SV and POV2 was 0.27 m/s less at night than in daytime. The model of the effect of speed showed that the range rate to POV2 is linearly related to speed by the following formula:

$$\text{POV2 Range-rate} = -0.0774(\text{Speed}) + 0.9982$$

Where: SV speed is m/s and POV2 range rate is m/s

This prediction shows that at 13 m/s (30 mph), the range rate between the SV and POV2 is very close to zero and linearly decreases to -1.8 (4 mph) at a speed of 28 m/s (62 mph), which is the governed speed of the tractors. Furthermore, this closing rate at higher speeds tends to get larger (faster closing speeds) at night than in the daytime.

Interpretation: The results show that while there was no significant effect of the integrated system on gap size when performing lane changes, and that the gap drivers chose is affected by the type of roadway environment, SV speed, hours of service, and time of day (ambient light).

2.2.3 Driver Acceptance Research Questions

This section reports key findings on driver acceptance of the lateral drift 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 subsystem (i.e., do drivers want LDW on their vehicles?)

Results: These results are based on questions included in the survey completed by drivers at the end of the study. In general, drivers accepted the LDW component of the integrated crash warning system, with P&D drivers slightly less satisfied than line-haul drivers. When asked what aspect(s) of the integrated system they liked most, 5 of the 18 drivers specifically mentioned the LDW subsystem. Two of the 18 drivers scored the LDW system negatively on the van der Laan scale for either usefulness or satisfaction (van der Laan et al., 1997).

The van der Laan Scale of Acceptance is a 5-point scale to assess nine different attributes of a technology. Each item on the scale is anchored by two polar adjectives, such as “good” and “bad,” and drivers are 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.”

Figure 52 shows the van der Laan scores for all integrated systems functions. LDW outperformed all other subsystems. The integrated system as a whole, in terms of driver satisfaction, was outperformed by the FCW subsystem in terms of usefulness.

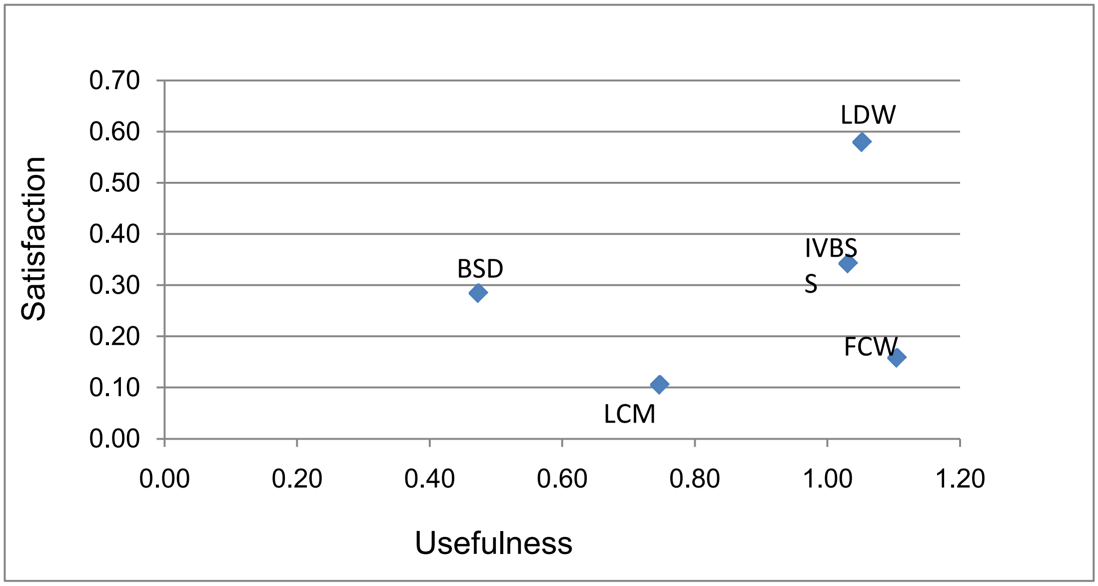

Figure 52. Van der Laan scores for the integrated system and subsystems

As shown in Figure 53, P&D drivers were more likely than line-haul drivers to say they received lateral drift warnings when they did not need them. P&D drivers often received lateral drift warnings in situations where they were fully aware that they were crossing a lane boundary, but were forced to do so by traffic conditions. On the other hand, line-haul drivers, who spend long hours predominantly on limited-access roadways, were more likely to need the lateral drift warnings to improve their situational awareness and alertness. When asked, 4 of the 10 line-haul drivers preferred the integrated system in their trucks, citing increased alertness.

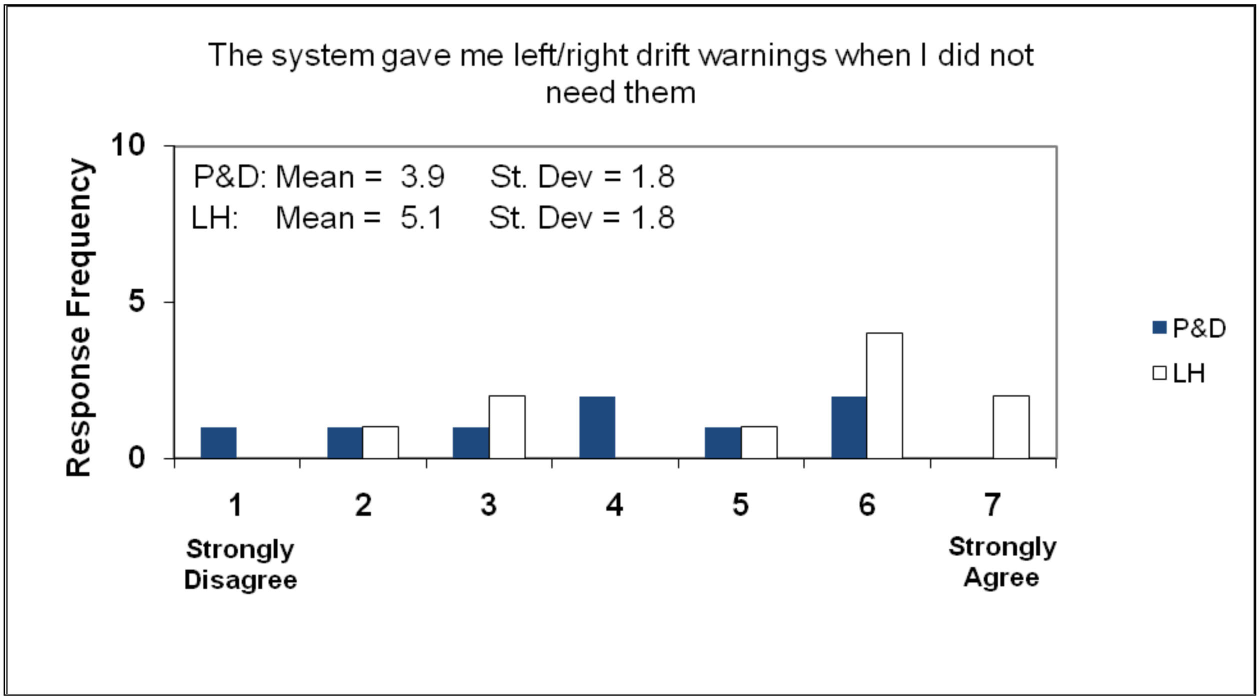

Figure 53. Responses to "The integrated system gave me left/right drift warnings when I did not need them."

Interpretation: Considering the integrated system as a whole and its individual subsystems, drivers rated LDW highest in terms of satisfaction. Additionally, it was rated only slightly lower than FCW in terms of perceived usefulness. LCM, as implemented in this FOT, was not well received by drivers. Some drivers, especially line-haul drivers on the road at night, occasionally become drowsy over the course of their exposure. It is in these situations where they likely received the most benefit from the LDW subsystem.

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

Results: These results are based on three questions in the survey completed by drivers at the end of the study.

Overall, drivers found the integrated system to be somewhat useful. P&D drivers rated the integrated system as more useful than did line-haul drivers. The benefit came primarily in terms of increased safety and awareness on the road. Seven of the drivers specifically stated that the integrated system prevented them from getting into a crash or near-crash, and drivers of both route types agreed with the statement "Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane." Three drivers did not find the integrated system to be useful.

Two open-ended questions asked drivers for specific situations in which they were aided by the warnings: “In which situations were the warnings from the integrated system helpful?” and “Did the integrated system prevent you from getting into a crash or a near crash?” Responses to these questions were aggregated and grouped by the subsystem the driver mentioned as being helpful. These responses are plotted in Figure 15. As discussed previously, P&D and line-haul drivers mentioned the FCW and LCM subsystems were roughly equal in terms of usefulness in specific situations. Line-haul drivers cited the LDW subsystem as useful more than did P&D drivers.

Figure 54 shows the van der Laan usefulness scores aggregated for three integrated crash warning subsystems.

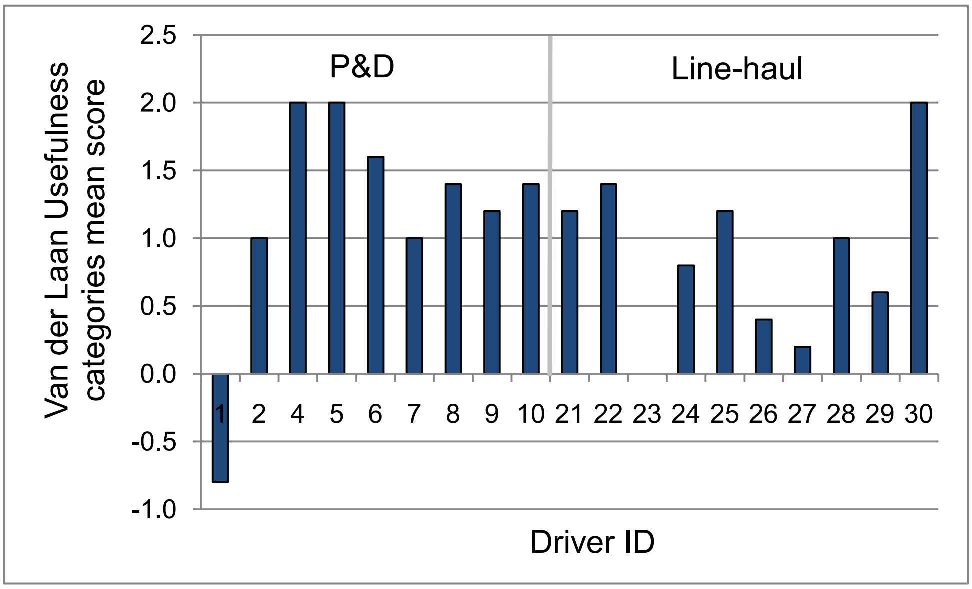

Figure 54. Van der Laan usefulness categories for three subsystems, compiled mean score by driver

Driver 1 was the only driver to give the subsystems a negative overall usefulness score. Driver 23 gave a mean score of zero; while drivers 24, 26, 27, and 29 gave the integrated system mean usefulness scores below 1. Drivers 4, 5, and 30 gave the integrated system a perfect usefulness score. It is worth noting that despite the spread of responses across route type, both P&D and line-haul drivers found the system to be useful overall.

Figure 55 shows the individual van der Laan usefulness mean scores for each subsystem, and the integrated crash warning system overall.

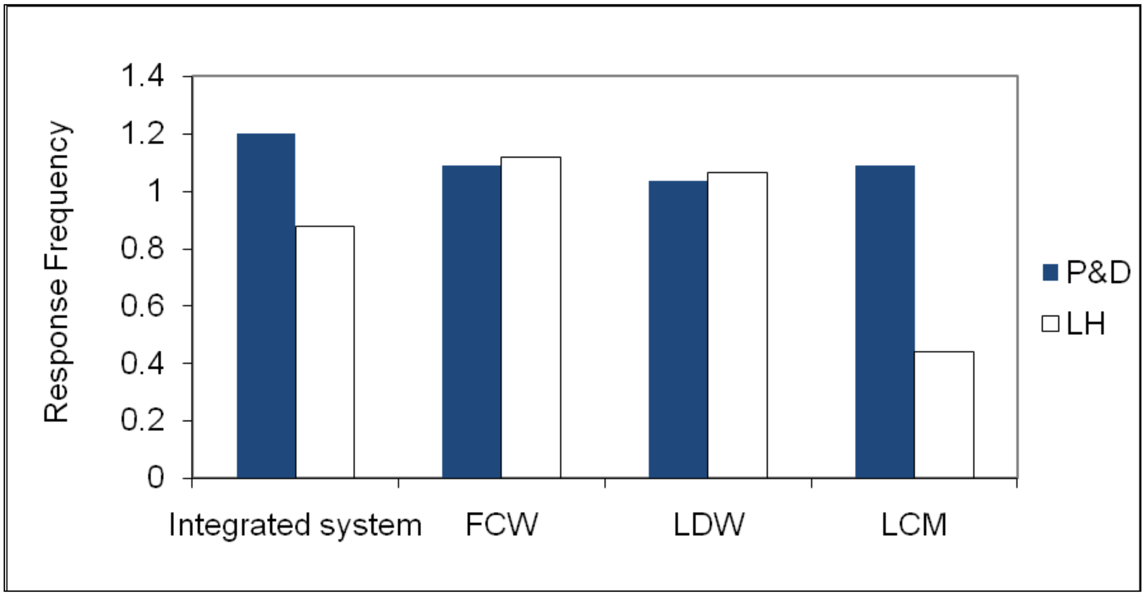

Figure 55. Mean van der Laan usefulness scores for integrated system, subsystems, and route type

P&D drivers gave the system an overall van der Laan usefulness score of 1.20, while line-haul drivers gave the system a 0.88. Line-haul drivers rated the LCM subsystem substantially less useful than any other subsystem, for either route type. While most drivers found some aspects of the system useful, line-haul drivers' opinions of the LCM subsystem were the lowest, although still positive overall. This is thought to be attributable to the different environments that P&D and line-haul drivers operate in – more specifically, differences in encountering other vehicles that will appear unexpectedly alongside of the vehicle. Based on the overall usefulness scores, these differences in driving environments may also contribute to drivers' opinions of the overall usefulness of the integrated system.

Interpretation: Drivers reported increased safety and heightened awareness. While line-haul drivers found the LDW subsystem to be more helpful than did the P&D drivers, both types of drivers specifically mentioned finding valid FCW warnings and the headway-time margin display to be helpful. The LDW subsystem was likely more useful to the line-haul drivers who were more at risk of becoming drowsy and drifting from their lane. The FCW was more useful to the P&D drivers who were constantly at risk of being cut-off by other drivers in heavy traffic, and potentially forced to respond quickly if the offending vehicle stopped or slowed abruptly in front of them.

QL11: Are drivers accepting of the LCM subsystem (i.e., do drivers want LCM on their vehicles)?

Results: These results are based on questions included in the survey completed by drivers at the end of the study.

In general, the LCM component was the least liked by drivers. When asked what aspect(s) of the integrated system they liked most, only 3 of the 18 drivers (1 P&D, 2 line-haul) specifically mentioned LCM. When asked what they liked least about the integrated system, 4 line-haul drivers mentioned the LCM subsystem.

Van der Laan scale responses shown in Figure 52 for Question QL9 indicate that LCM received the lowest usefulness and satisfaction scores relative to the other subsystems. Four drivers gave the LCM subsystem negative scores for both usefulness and satisfaction. Three other drivers scored the LCM subsystem negatively on one of the two van der Laan dimensions. P&D drivers rated the subsystem better than did line-haul drivers on both dimensions. These scores are presented in Figure 56 below.

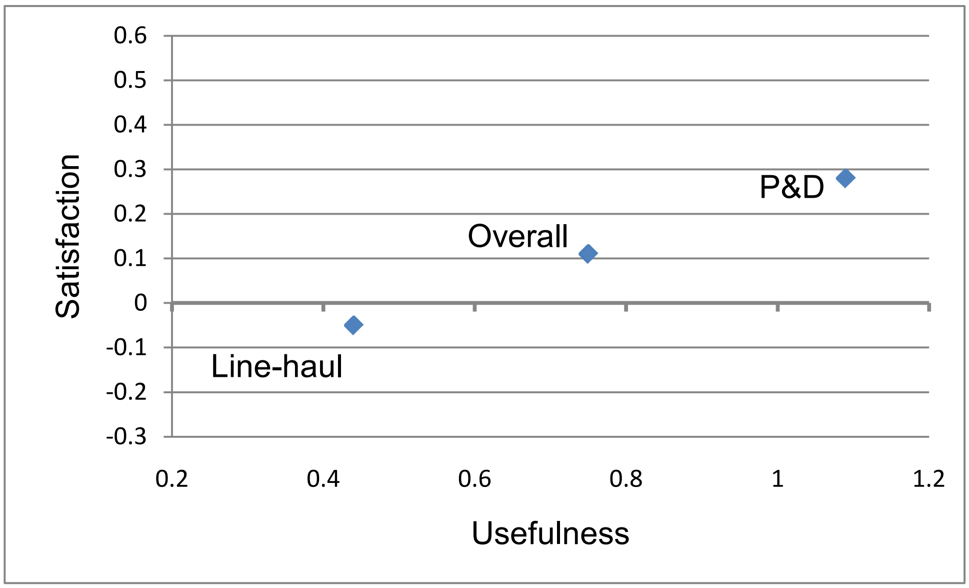

Figure 56: Mean van der Laan scores for the LCM subsystem by route type

Line-haul drivers were more likely than P&D drivers to say they received LCM warnings when they were not needed (Figure 57). This subjective response is consistent with the invalid warning rates observed for the P&D (55%) and line-haul drivers (86%).

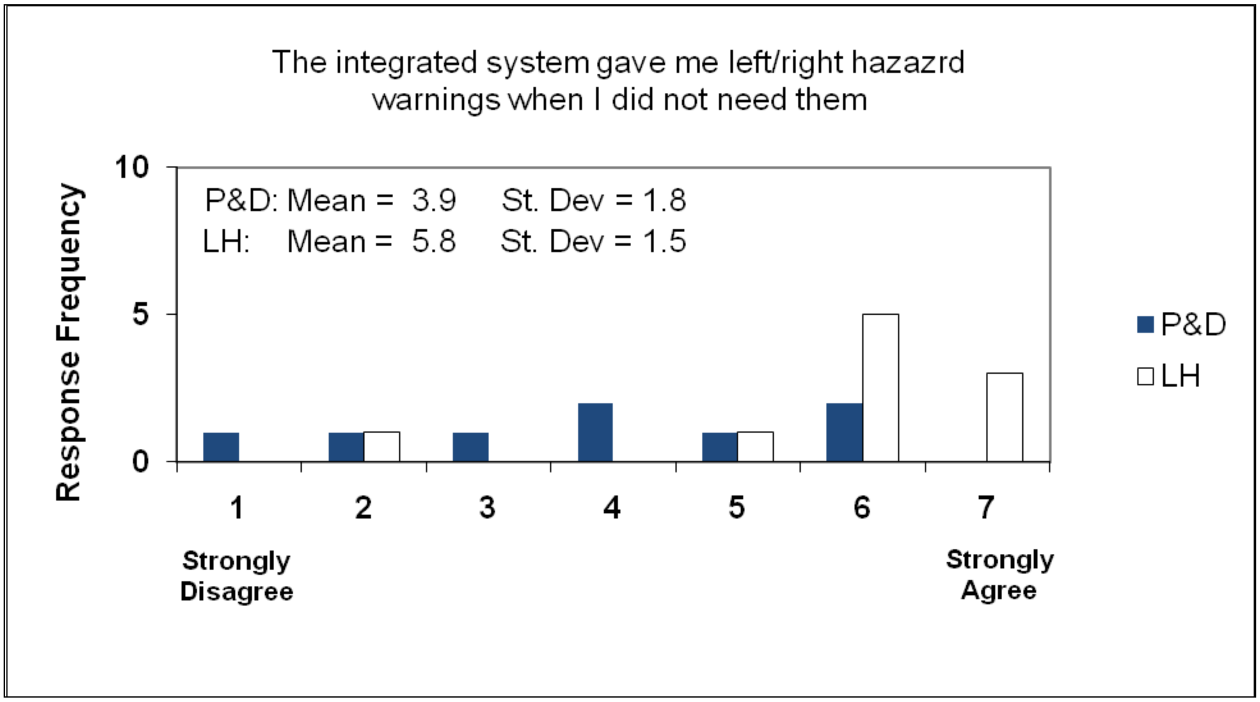

Figure 57. Responses to “The integrated system gave me left/right hazard warnings when I did not need them.”

Interpretation: Among the subsystems, drivers liked LCM the least due to the high percentage of invalid warnings that they received (86% for line-haul drivers). In contrast, the LDW and FCW subsystems were viewed as being more helpful; the LDW helped drivers when they were less alert while the FCW subsystem alerted drivers to sudden, unexpected maneuvers of other vehicles.

2.3 Longitudinal Control and Warnings Results

This section synthesizes the performance of the forward crash warning subsystem. This includes key descriptive data, results regarding the frequency of FCW 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 10-month FOT, a total of 21,159 forward crash warnings were recorded. This total includes all forward warning scenarios. Of this set, 18,918 warnings were attributed to the 18 participants. The overall warning rate across drivers, speeds, and all other conditions was 3.1 forward crash warnings per 100 miles of travel. A summary of the overall forward crash warning activity as function of condition, route type, and road type is given in Table 18. In general, the highest overall rate was on surface roads, followed by exit ramps. The lowest rate was on unknown road types, which include parking lots, staging areas, terminals, and other typically low speed areas. P&D drivers typically had a higher FCW rate than line-haul drivers did.

Table 18. Overall FCW activity by condition, route type, and road type

Condition	Route type	Road type	Count	Percent	Rate, per 100 miles
Baseline	P&D	Limited access	146	0.8	4.6
		Surface	772	4.1	8.3
		Ramps	11	0.1	3.5
		Unknown	39	0.2	1.9
	Line-Haul	Limited access	2259	11.9	2.3
		Surface	226	1.2	2.5
		Ramps	22	0.1	3.6
		Unknown	46	0.2	0.9
Treatment	P&D	Limited access	573	3.0	4.7
		Surface	3007	15.9	8.7
		Ramps	76	0.4	7.9
		Unknown	556	2.9	4.3
	Line-Haul	Limited access	9829	52.0	2.7
		Surface	581	3.1	3.8
		Ramps	77	0.4	3.8
		Unknown	698	3.7	2.2

2.3.1.1 Longitudinal Classification and Warning Summary

The analysis in the previous section considered all FCWs and gave an overall summary of the warning rate regardless of type of warning scenario or its validity and relevance. In this section, each type of warning will be considered separately in terms of both the assessed effectiveness of the warning and the driver's intention and reaction to the warning. The validity of longitudinal warnings was determined by whether or not there was a vehicle in the forward path of the subject vehicle at the time of the warning. UMTRI researchers examined a total 18,918 FCWs by reviewing the forward view of each FCW event. 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 knowledge and awareness to the driving task and can mitigate ignorance of an unrecognized conflict in the current driving situation. Warnings that are predictable and probable are also defined as valid. After a valid warning, the SV driver becomes vigilant to the driving task and makes an assessment of urgency in the current driving situation. A valid warning may not be helpful in the immediate sense, but can be informative in that typically the driver is assuming normal driving behavior and actions will resolve the situation.
- **Invalid**—warnings are characterized by an incorrect or inaccurate assessment of the driving environment by the warning system. They often appear to be spurious and random without any identifiable reason or model for their cause.

Figure 58 shows the overall FCW warning rate per 100 miles for valid and invalid warnings. Drivers had an invalid FCW rate of 1.84 per 100 miles. The high invalid rate for FCW is mostly associated with fixed roadside objects and overhead road structures 99 percent of which were invalid. Approximately 5 percent of the invalid FCWs were due to roadside objects, such as barrels in a construction zone or stopped vehicles on the side of the road, while the remaining 95 percent were associated with other overhead road structures, such as bridges.

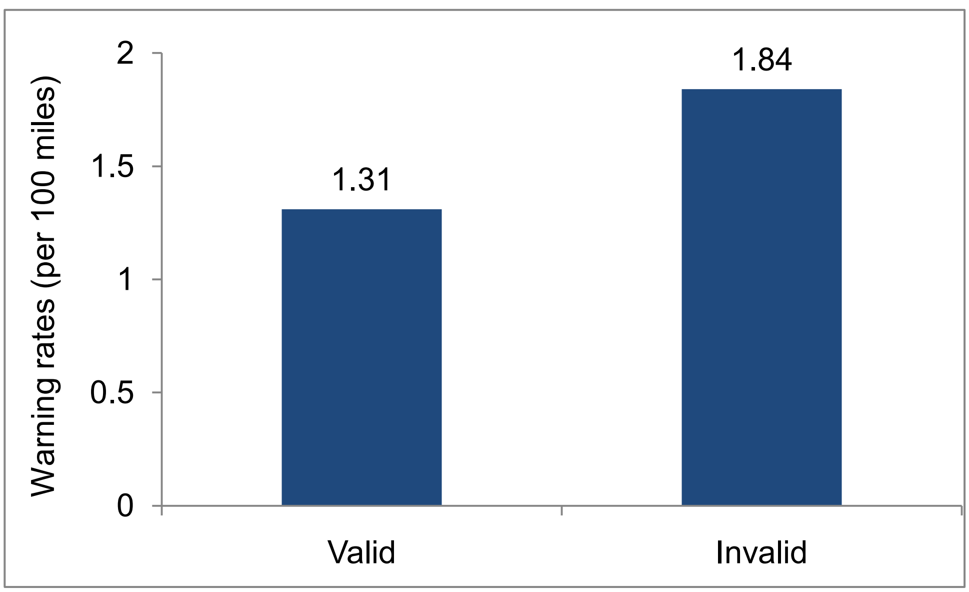

Figure 58. Overall longitudinal warning rate per 100 miles

Figure 59 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 and overhead road structures.

There were four FCW scenarios to consider:

- Fixed Roadside Objects—Stationary objects, including stopped vehicles, but often were caused by stationary roadside objects.
- Slowing POV—Lead vehicle decelerating, while the SV speed is effectively constant. A common example is a lead vehicle that decelerates to perform a turn.
- Closing on POV—Negative range rate, and within 0.5 second headway.
- Opening on POV—Positive range rate, and within 0.5 second headway.

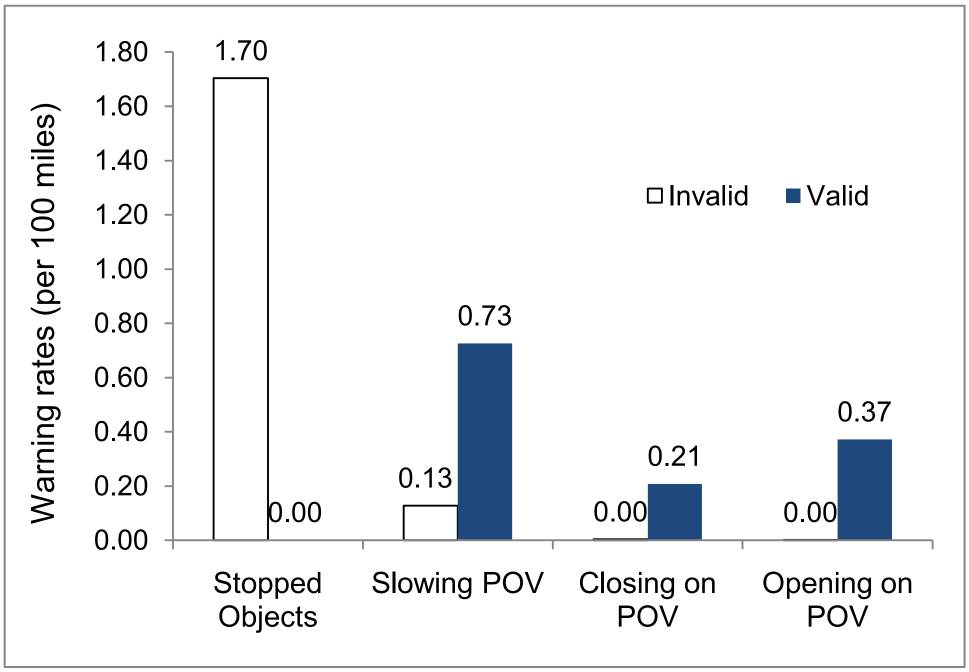

Figure 59. Overall longitudinal warning rate per 100 miles for each warning type

In terms of the broader exposure variables of condition and route type, Table 19 shows the number of warnings, percentage, and rate as a function of warning scenario and classification. The highest rate is for valid warnings for P&D drivers to slowing POVs at 2.69 warnings per 100 miles under the baseline condition. The warning rate for P&D drivers to slowing POVs in the treatment condition is 2.56 per 100 miles, the second highest warning rate.

Driver brake reactions within 5 seconds following an FCW warning were examined, with the results shown in Table 20. Drivers were more likely to brake in response to slowing POVs than for the closing or opening on POV scenarios, which are largely lane changes by the SV or a POV. Warnings for fixed roadside objects are not included in this analysis due to the low validity rate.

Table 19. Lateral warning rate by condition, route type, and classification

Condition	Route type	Warning type	Classification	Count	Percent	Rate, per 100 miles
Baseline	P&D	Fixed Object	Valid	1	0.01	0.00
			Invalid	90	0.48	0.38
		Slowing POV	Valid	643	3.40	2.69
			Invalid	50	0.26	0.21
		Opening on POV	Valid	116	0.61	0.48
			Invalid	0	0.00	0.00
		Closing on POV	Valid	67	0.35	0.28
			Invalid	1	0.01	0.00
	Line-Haul	Fixed Object	Valid	0	0.00	0.00
			Invalid	1478	7.81	0.80
		Slowing POV	Valid	299	1.58	0.16
			Invalid	123	0.65	0.07
		Opening on POV	Valid	421	2.23	0.23
			Invalid	2	0.01	0.00
		Closing on POV	Valid	216	1.14	0.12
			Invalid	14	0.07	0.01
Treatment	P&D	Fixed Object	Valid	6	0.03	0.01
			Invalid	640	3.38	0.65
		Slowing POV	Valid	2506	13.25	2.56
			Invalid	312	1.65	0.32
		Opening on POV	Valid	444	2.35	0.45
			Invalid	0	0.00	0.00
		Closing on POV	Valid	303	1.60	0.31
			Invalid	1	0.01	0.00
	Line-Haul	Fixed Object	Valid	0	0.00	0.00
			Invalid	8041	42.50	1.22
		Slowing POV	Valid	921	4.87	0.14
			Invalid	285	1.51	0.04
		Opening on POV	Valid	1257	6.64	0.19
			Invalid	7	0.04	0.00
		Closing on POV	Valid	668	3.53	0.10
			Invalid	6	0.03	0.00

Table 20. Percentages of braking events within 5 seconds from onset of FCW

Warning types	Condition		Road Type		Route Type	
	Baseline	Treatment	Limited Access	Surface Street	P&D	Line-Haul
Slowing POV	0.18	0.73	0.11	0.70	0.74	0.17
Closing on POV	0.01	0.07	0.04	0.03	0.05	0.02
Opening on POV	0.00	0.01	0.01	0.01	0.01	0.01

2.3.2 Driver Behavior Research Questions

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

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

Method: This analysis examines headway keeping (i.e., following events). Time headway or time headway margin refers to the time that it would take a following vehicle (SV) to reach the position of the vehicle being followed (POV) in the following vehicle's lane of travel. This is illustrated in Figure 60. Periods of extended following behavior, with durations of 5 seconds or longer, were only considered. This excluded major forward conflicts, lane changes, turns, or other maneuvers by either the following or the lead vehicle (the vehicle being followed). Constraints used in defining the following events are summarized in Table 21. A total of 96,356 following events were identified. Of those, approximately 96 percent had durations between 5 and 180 seconds (See Figure 61). The longest duration following the event was 55 minutes.

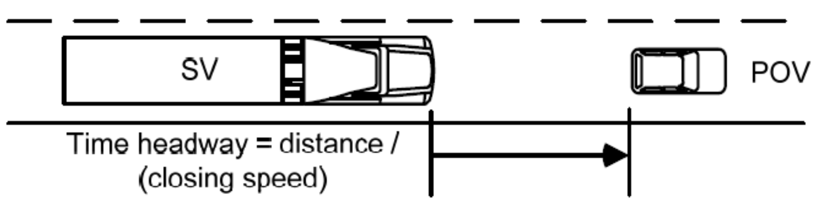

Figure 60. Time-headway margin during following events

Table 21. Constraints used in defining following events

Constraints
1. Range rate to the vehicle ahead in the range of -2m/s, 2m/s (45 mph),
2. Headway time margin falls in the range of 0 seconds to 3 seconds
3. Traveling speed of the SV is 11.2 m/s (25mph) or greater
4. Event durations is 5 seconds or longer

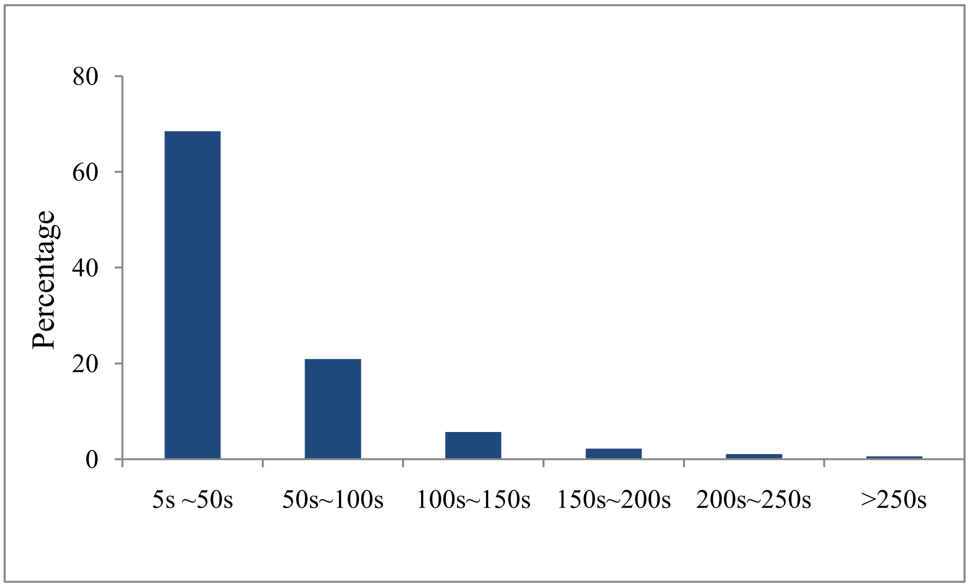

Figure 61. Percentages of the following event durations

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

The effect of treatment condition was found to be statistically significant ($F(1,17)=13.39$, $p<0.002$) with a longer mean headway time observed under treatment condition. Drivers maintained marginally longer average time headways under the treatment condition (mean=2.11s) than observed in the baseline condition (mean=2.04s) by 0.05 seconds (Figure 62). However, the difference is small and may be of limited practical significance.

Interpretation: The results show that while the integrated system had a statistically significant effect on the time headway that drivers maintained during following events, however, this effect is of little practical significance. Drivers maintained marginally longer average time headways with the integrated crash warning system than in the baseline condition. Drivers did report that they liked having the headway time displayed to them on the DVI, nonetheless the mean headways observed are not as long as might have been anticipated for a Class 8 tractor-trailer combination.

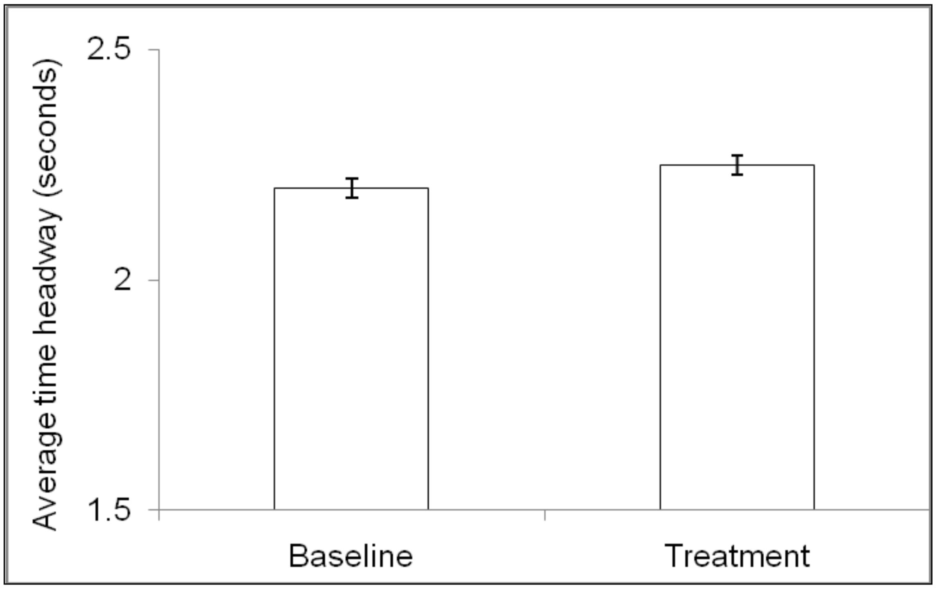

Figure 62. Average time headway under the baseline and treatment conditions, including standard error

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

Method: This analysis addresses forward conflicts in 13,504 events to determine whether the integrated system had an effect on the magnitude of forward conflicts. Two measures of forward conflict were used: the minimum time-to-collision during conflict events, and the maximum level of required deceleration. Time-to-collision is defined as the range (distance) divided by the closing speed between an SV and a POV. The required deceleration is defined as the constant level of SV braking needed to simultaneously reduce 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. One caveat about this type of required deceleration is that it is computed for each sample of field data, assuming that the POV will continue to decelerate at that level. The 13,504 events are identified by searching through the data for episodes in which the SV is traveling faster than 11.2 m/s (25 mph) and the POV is moving. In addition, the time-to-collision had to fall below 10 seconds and the required deceleration is less than +0.5 m/sec^2. Alternatively, a required deceleration below -1 m/sec^2 had to occur. These rules were used because the resulting events are ones in which the driver usually slows the vehicle, whether through braking or backing off the throttle.

For each of these 13,504 events, the minimum time-to-collision and the minimum required deceleration were identified. The driving scenario for each event was characterized as either shared-lane or multiple-lanes (Figure 63). In shared-lane scenarios, the SV and the POV are in the same lane, and continue to share that lane at least 5 seconds after a conflict ends. A multiple-lane scenario involves one or both vehicles changing lanes or turning during the conflict period, or within 3 seconds before the conflict begins or within 5 seconds after the conflict ends. The shared- and multiple-lane scenarios must be distinguished, as the latter is associated with higher conflict measures as drivers often anticipate that the lateral motion of the POV will resolve the conflict. Constraints that were used in defining the following events are summarized in Table 22.

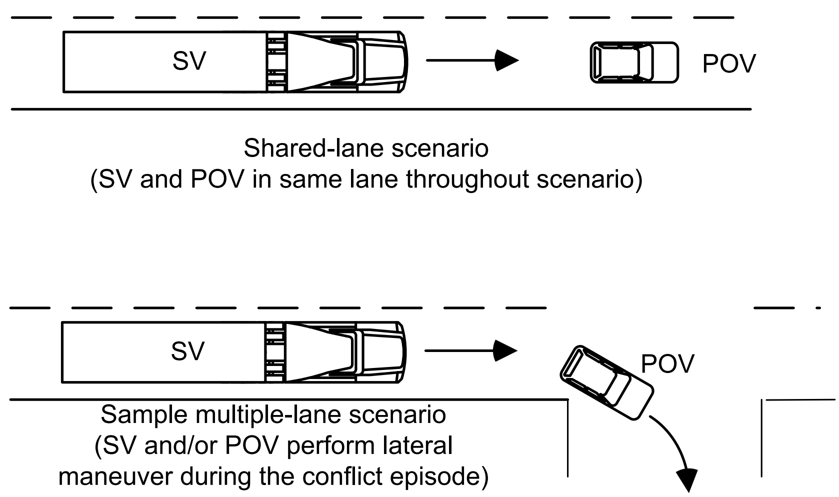

Figure 63. Forward conflicts in shared-lane and multiple-lane scenarios

Table 22. Constraints used in defining following events

Constraints
1. Speed greater than 11.2 m/s (25 mph)
2. Moving POVs only

Results: The principal findings of this analysis are based on the results of a mixed linear model.

The integrated system did not have a statistically significant effect on time-to-collision or required deceleration. The average minimum time-to-collision was 7.92 seconds in the baseline condition and 7.95 seconds in the treatment condition, with standard errors of 0.24 seconds. The average required deceleration values were -0.79 and -0.80 m/sec^2 for the baseline and treatment conditions respectively, with standard errors of 0.03 m/s^2 for both.

Scenario class (shared-lane versus multiple-lane) and road type were the variables that had the greatest impact on the occurrence and severity of conflicts. Shared-lane scenarios were associated with lesser conflicts, as expected, with the mean values shown in Figure 64. Limited access roads were also associated with lesser conflicts (also shown in Figure 64). For the required deceleration dependent variable, travel speed had a statistically significant effect with higher speeds associated with lower conflict levels (Figure 65). Note that there is a strong relationship between travel speed and road type in this study, so this finding is not surprising.

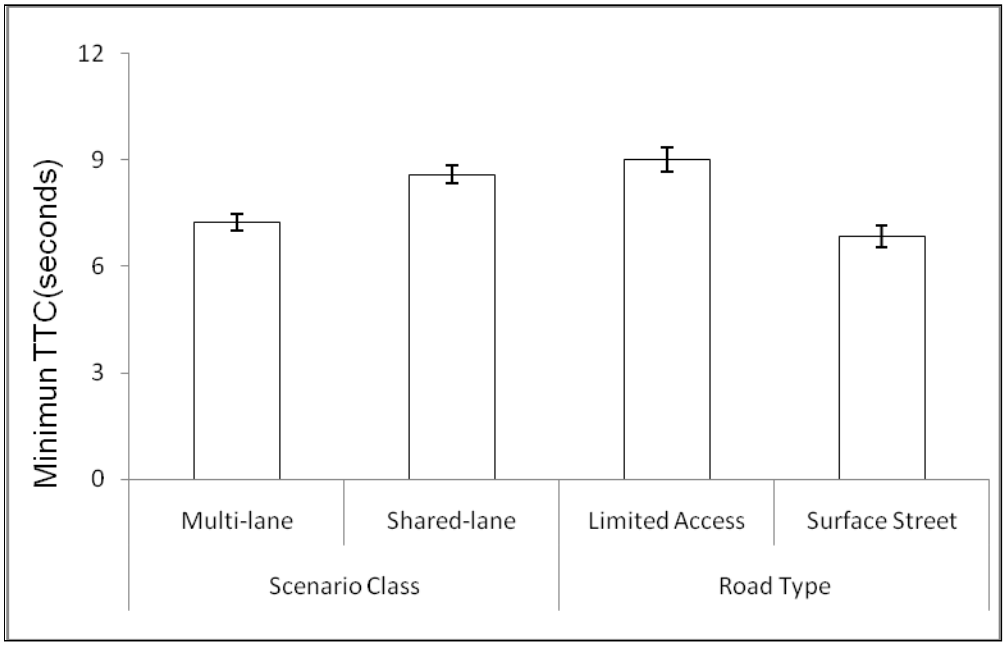

Figure 64. Effects of scenario class and road type on minimum time-to-collision, including standard error

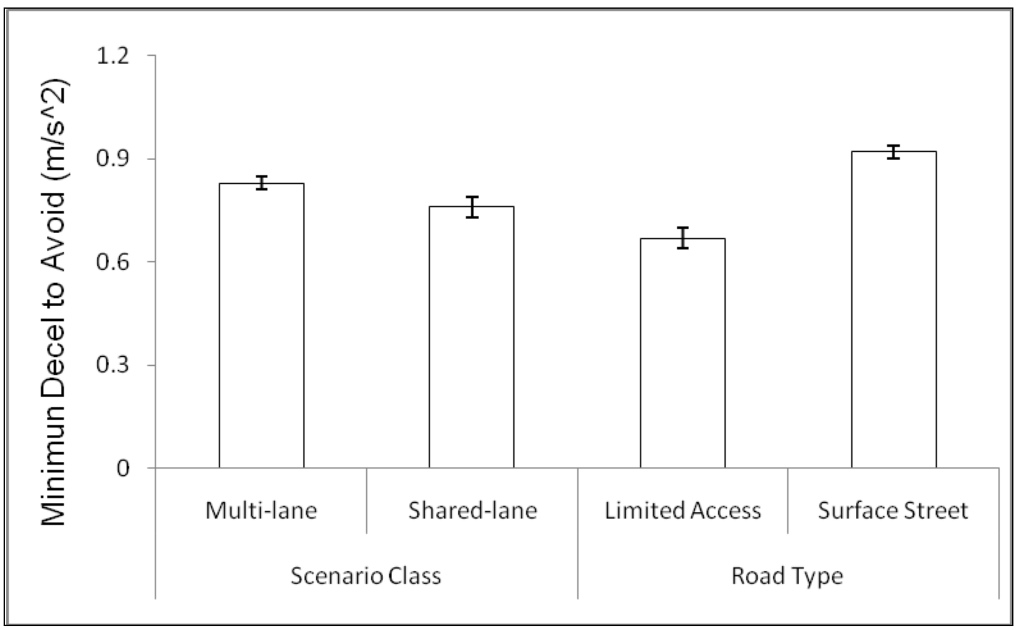

Figure 65. Effects of scenario class and road type on deceleration to avoid collision, including standard error

Interpretation: The results showed that there was no statistically significant effect of the integrated crash warning system on forward conflict levels during approaches to preceding vehicles. However, there was a statistically significant effect on conflict levels by the type of driving scenario and road type.

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

Method: The consideration of actual braking levels recognizes that hard-braking, whether required or not, may contribute to crash risk for heavy trucks because of their unique vehicle dynamics. Only those events in which a POV contributed to the driver's use of hard-braking were considered. The data selected for analysis was constrained by the conditions listed in Table 23. Two dependent measures of hard-braking were examined: the frequency per mile of hard-braking events and the maximum deceleration during hard-braking events. A histogram of maximum deceleration levels during hard braking events is presented below in Figure 66.

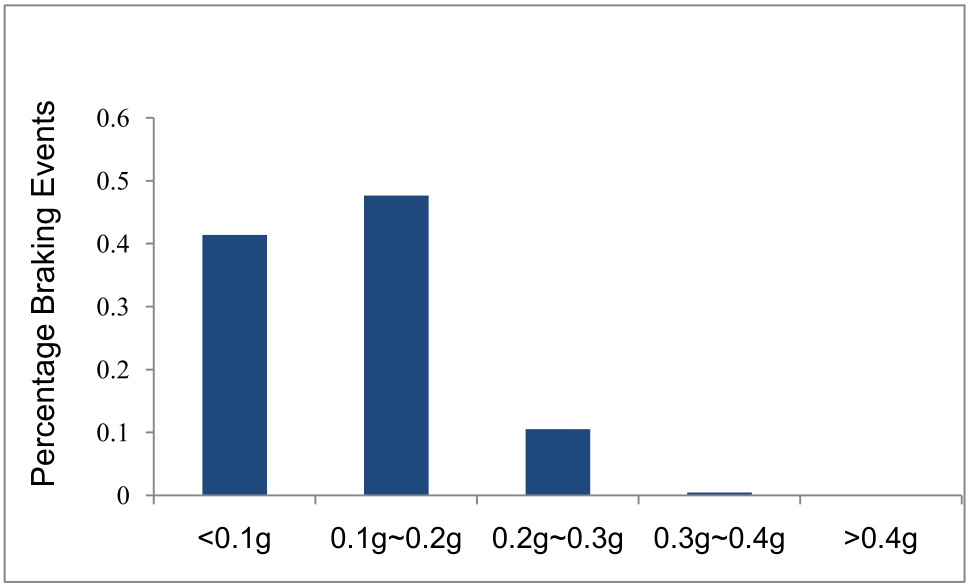

Figure 66. Histograms of maximum deceleration level for all braking events

Table 23. Constraints used in defining hard braking events

Constraints
1. Traveling speed of the SV is 11.2 m/s (25mph) or greater
2. Maximum deceleration of at least 0.2g
3. There is a leading vehicle in front of the subject vehicle

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

The integrated crash warning system did not have a statistically significant effect on the frequency of hard braking events. The frequency rate of hard braking events per mile under treatment condition (mean 0.914 per 100 miles) is only slightly less than under baseline condition (mean 0.915 per 100 miles). The effect of roadway type was statistically significant ($F(1,17) = 24.2$, $p < 0.001$). Drivers performed more hard braking events on surface streets (mean 1.74 per 100 miles) than on limited-access roadways (mean of 0.09 per 100 miles) as shown in Figure 67.

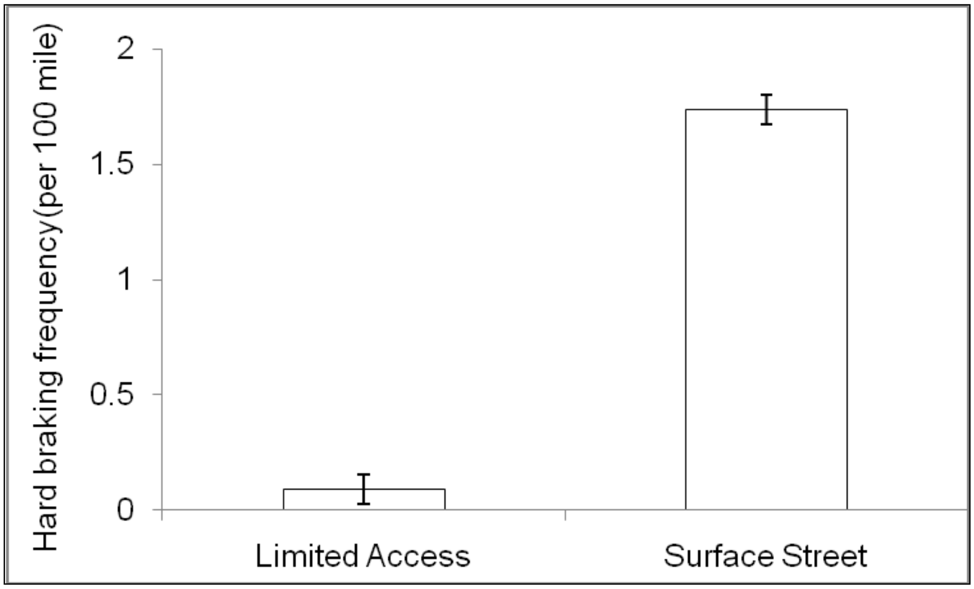

Figure 67. Means of hard braking frequency by road type, including standard error

Maximum Deceleration: The integrated crash warning system did not have a statistically significant effect on the maximum deceleration of hard-braking events. The average maximum deceleration increased by 6 percent between the baseline and treatment conditions, from a mean of 2.59 m/s^2 to a mean of 2.74 m/s^2. The road type did have a statistically significant, but minor effect on maximum deceleration of hard-braking events ($F(1, 17) = 24.63$, $p < 0.001$). Higher mean maximum decelerations were observed on surface streets (mean of 2.89 m/s^2) than on limited-access roadways (mean of 2.44 m/s^2), an increase of 18 percent (Figure 68).

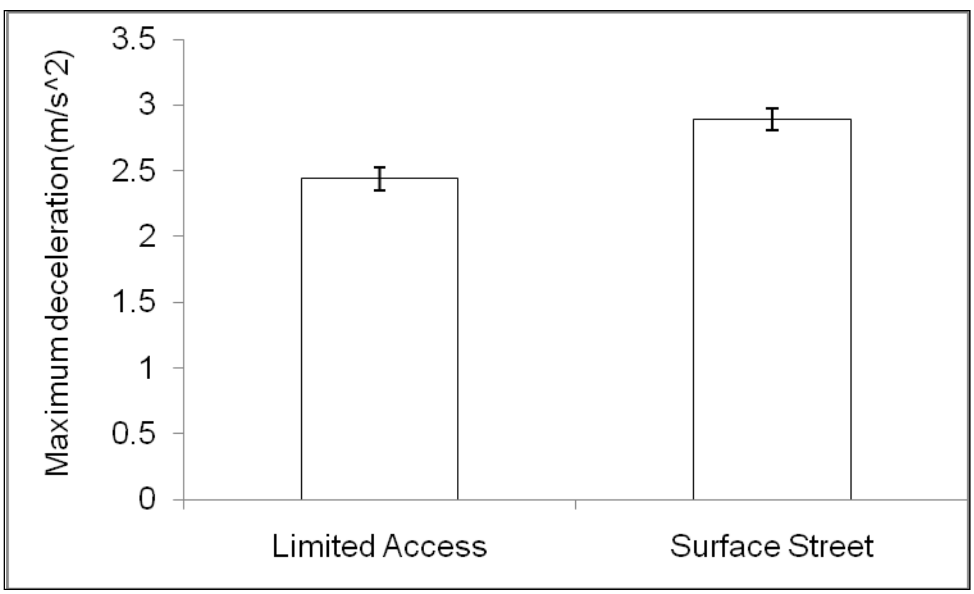

Figure 68. Means of maximum deceleration by road type, including standard error

Interpretation: The results showed no significant effect of the integrated warning system on hard-braking event frequency. The integrated crash warning system did not have a statistically significant effect on the maximum deceleration values, but mean maximum decelerations increased slightly between the baseline and treatment conditions—perhaps in response to the sense of urgency conveyed by the auditory warnings. These results appear to suggest that drivers did not become overly reliant on the FCW subsystem, as there is no evidence drivers were "caught off guard" and subsequently required to brake harder, with any greater frequency in the treatment condition than was observed in the baseline period.

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

Method: For this analysis, data from two types of closing-conflict events were examined: slowing object warnings and closing half-second warnings. Warnings due to fixed roadside objects and overhead road structures were excluded from this analysis, as fewer than 5 percent of these warnings were considered valid. Three dependent measures (listed below) regarding driver response to those warnings events were calculated and analyses for each were run independently. The data selected for analysis was confined to situations in which the traveling speed of the SV was 11.2 m/s (25mph) or higher, there was a lead POV, the driver's foot was on the accelerator pedal at the onset of the warning, and the driver responded to the forward conflict within 5 seconds. These constraints are listed below in Table 24.

The dependent measures used to assess hard-braking maneuvers include:

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

Table 24. Constraints used in the analysis

Constraints
1. Speed is greater than 11.2 m/s (25 mph).
2. Presence of a leading vehicle
3. A closing conflict (FCW warning type 9, 11)
4. Driver's foot on acceleration pedal at the time point of the warning started
5. Driver's response time within 5 seconds (to consider only responses to the current conflict)
6. Driving on limited access highway or surface road

Results: A total of 1,260 closing-conflict FCW events were identified. Those events that occurred on unknown road types or exit ramps were excluded. The remaining 982 events were used in the analyses.

Driver Reaction Time: The driver reaction-time analysis was performed using a linear mixed model approach. The integrated crash warning system had a statistically significant effect on driver reaction time ($F(1, 17) = 4.61$, $p = < 0.05$). As shown in Figure 69, driver reaction time to a developing forward conflict, the time between the warning and the release of the acceleration pedal, is 0.22 seconds (14%) less under the treatment condition (mean of 1.35 seconds) than the baseline condition (mean of 1.56 seconds).

The difference in reaction time was also statistically significant by road type (Figure 70). Reaction times to closing conflicts on limited access roadways (mean 1.61 seconds) were 0.31 seconds (19%) longer, on average, than on surface streets ($F(1, 17) = 7.32$, $p < 0.02$).

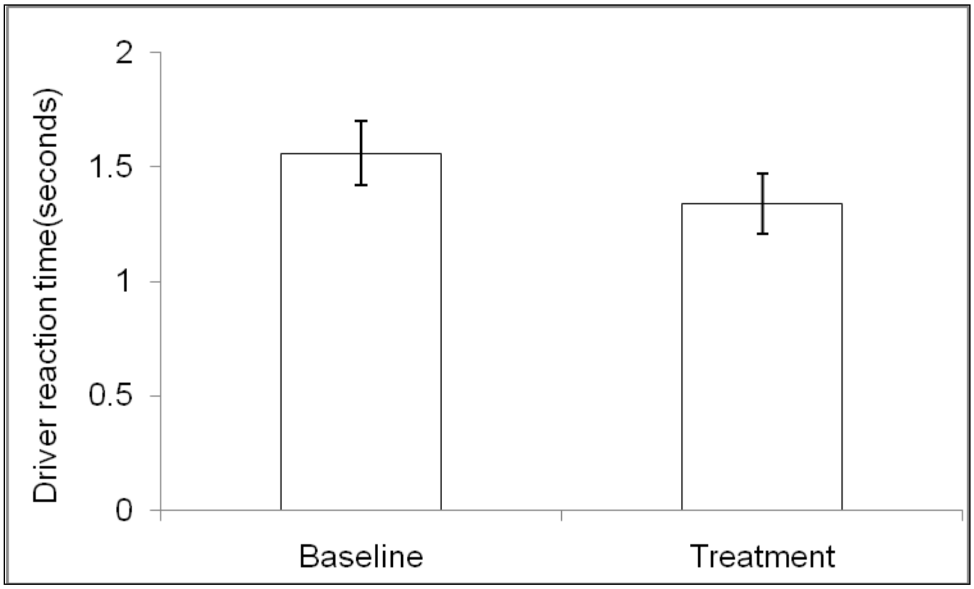

Figure 69. Mean driver reaction time by condition, including standard error

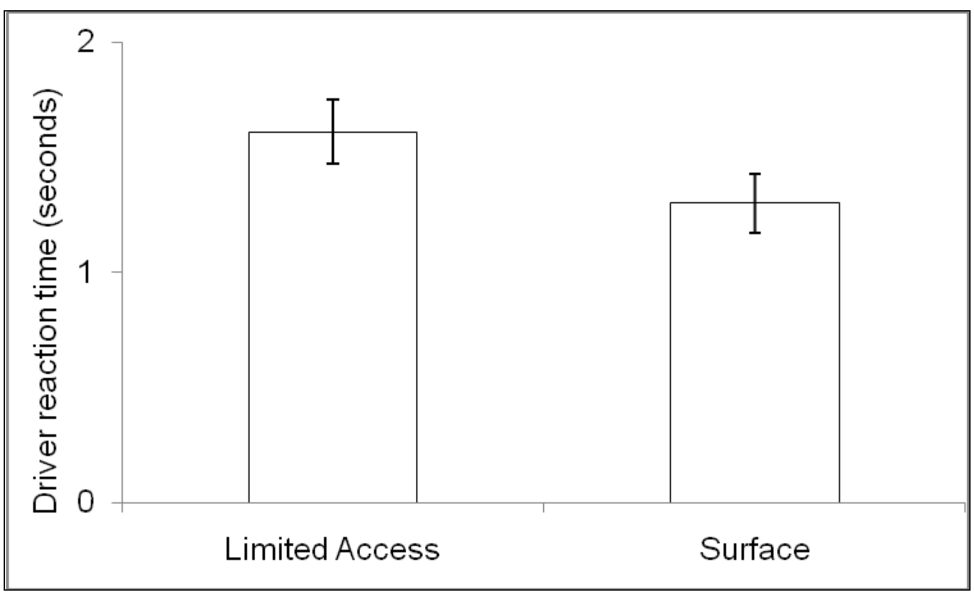

Figure 70. Mean driver reaction time by road type, including standard error

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 76.1%) was higher than in the baseline condition (mean of 70.8%). Roadway type was a statistically significant factor on the likelihood of the applying the brake during closing-conflict events (χ^2 (1) = 6.91, p = 0.009). Driving on surface streets was 61 percent more likely to result in braking during a closing conflict (mean of 80.4%) than was driving on limited-access roads (mean of 49.7%).

Brake Reaction Time: The brake reaction time analysis was performed using a linear mixed model approach. The integrated system was found to have a statistically significant effect on brake reaction time ($F(1, 17) = 5.21$, $p < 0.05$). As shown in Figure 71, time between the onset of the warning (whether it was heard by the driver under the treatment condition or not heard under the baseline condition) and when the driver began use of the brake pedal is 0.29 seconds (34%) shorter in the treatment condition than in the baseline condition (mean of 1.89 seconds).

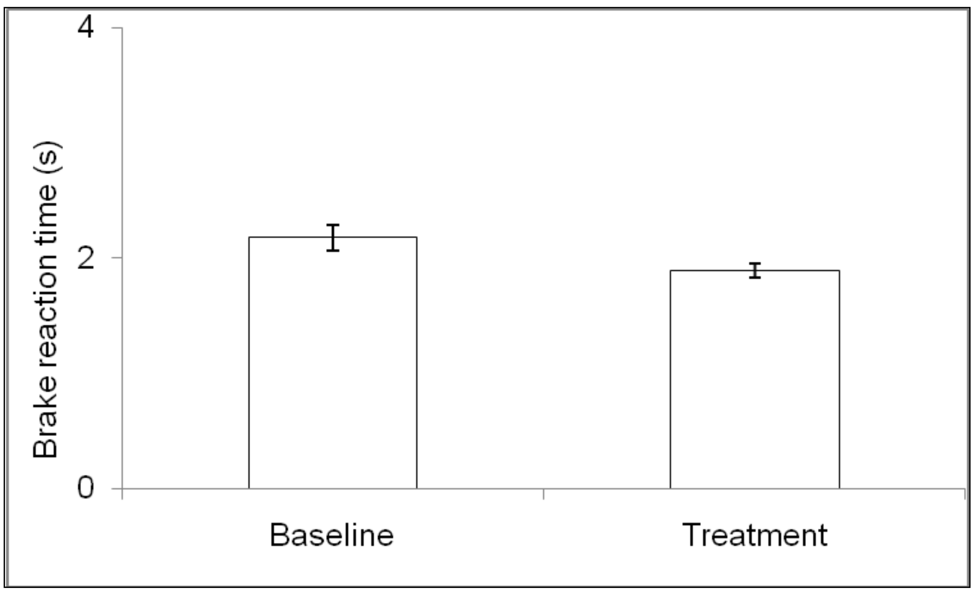

Figure 71. Mean brake reaction times by condition, including standard error

Interpretation: The results showed that truck drivers responded differently to forward closing conflicts with the integrated crash warning system. Specifically, drivers responded to closing-conflict events (e.g., slowing leading vehicle), with shorter driver reaction times and brake reaction times, in the treatment condition as compared to the baseline condition. These results suggest that drivers were more conscious of closing conflicts, and were more prepared to respond to these conflicts with the integrated system.

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 regarding 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)?

In general, drivers accepted the FCW subsystem conceptually, but many had reservations due to the frequency of invalid warnings, particularly in response to fixed roadside objects or overhead road structures. When asked directly in the post-drive questionnaire (Q2) "What did you like least about the integrated system?" 7 drivers specifically mentioned invalid forward crash warnings. When the van der Laan scores for the FCW subsystem are compared to the scores given to the other subsystems, FCW does very well among line-haul drivers, but poorly among P&D drivers, especially in terms of driver satisfaction. Figure 72 presents the van der Laan ratings broken down by route type for the FCW subsystem.

When asked what aspects of the integrated system drivers liked most, 2 drivers mentioned the FCW subsystem. However, 5 drivers mentioned specifically that they liked the FCW feature that displayed their time-headway at, or below, 3 seconds.

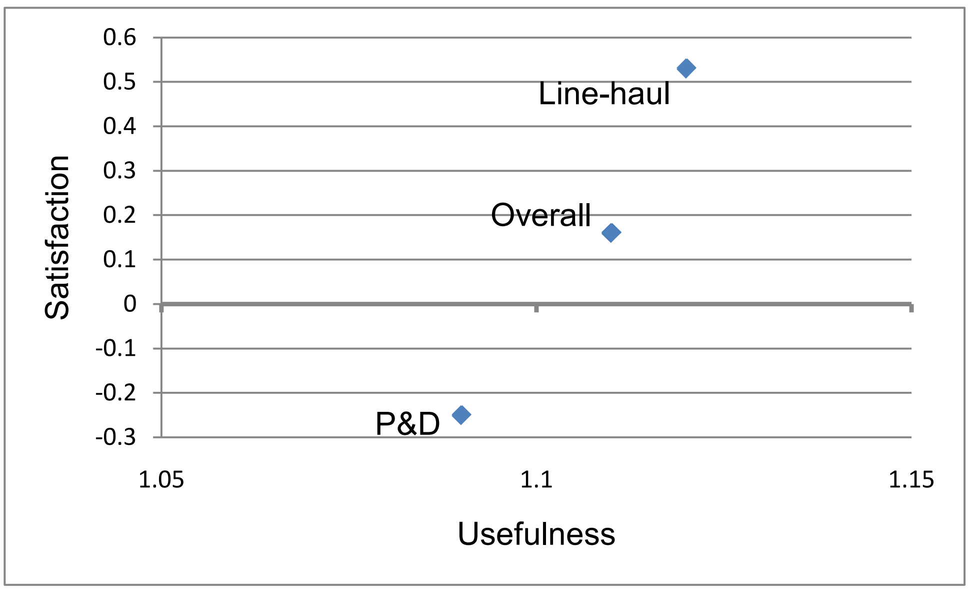

Figure 72: Mean van der Laan scores for the FCW subsystem by route type

P&D drivers scored the FCW subsystem negatively in terms of the van der Laan measure of satisfaction. This was the lowest score given to any subsystem for the integrated crash warning system for either van der Laan category. The discrepancy between P&D drivers' scores for usefulness and satisfaction seems to indicate that drivers liked the idea of the FCW subsystem based on the benefits it provided (perhaps such as better awareness of the forward area), but were not satisfied with the actual operation of the system due to the frequency of invalid warnings.

P&D and line-haul drivers responded similarly to the statement "The integrated system gave me hazard ahead warnings when I did not need them," but P&D drivers were slightly more likely to disagree than were line-haul drivers (Figure 73).

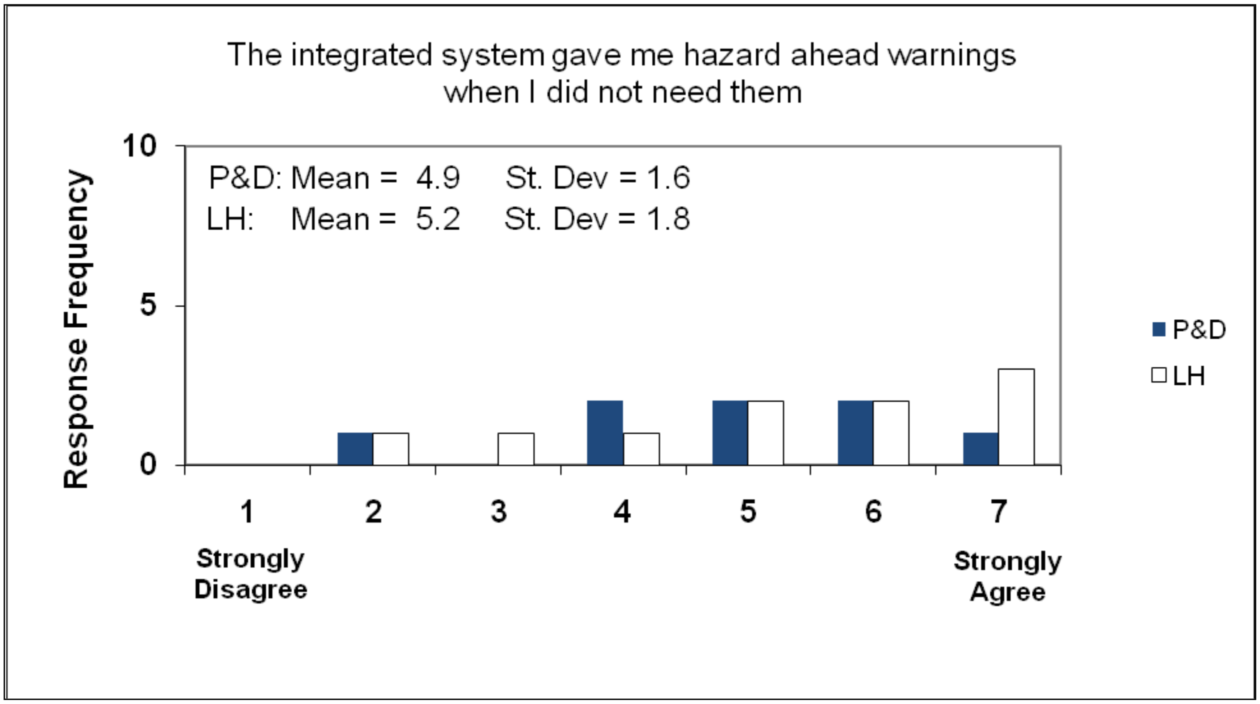

Figure 73. Responses to "The integrated system gave me hazard ahead warnings when I did not need them."

When examining forward crash warning events, it was found that line-haul drivers experienced considerably more warnings (in particular invalid warnings for fixed roadside objects and overhead road structures) than their P&D counterparts. Table 25 lists counts of forward crash warnings, excluding these warning events.

Table 25. Counts and associated invalid FCWs by route type

Drivers	Invalid FCW	Total FCW	% Invalid
P&D	646	4,212	15.3%
Line-haul	8,041	11,185	71.9%

While both sets of drivers received invalid FCWs, FCW events were mostly invalid for line-haul drivers. Many of these warnings were a result of highway overpasses or permanent roadway features. A full 55 percent of all FCW events for line-haul drivers came at a location where they received multiple FCWs over the course of the FOT. Conversely, only 9 percent of the FCWs that P&D drivers received were repeated at a particular location.

Interpretation: The different nature of the invalid alarms across the two route types may help explain the discrepancy in van der Laan satisfaction ratings. While line-haul drivers received a higher fraction of invalid forward crash warnings, these were often the result of fixed objects, and to some degree predictable by the drivers. Some line-haul drivers received the same set of invalid warnings night after night. In addition, in the road environment common among line-haul drivers (generally limited access roads at night), forward threats are less likely to appear suddenly. Both these factors may have contributed to the predictability of FCWs, making them somewhat less of a nuisance to line-haul drivers.

P&D drivers, on the other hand, received a lower fraction of invalid warnings, but the FCWs they did receive were likely less predictable given the environment they tend to operate in (surface streets with high traffic densities). For P&D drivers, every FCW was probably viewed as a potential threat that needed to be addressed.

This outcome has implications for the development of crash warning systems that maintain records of the locations where repeated warnings are generated. Specifically, advanced systems could adjust the warning thresholds to be less sensitive at locations where repeated warnings have been recorded. This approach would likely have considerable impact in reducing the overall frequency of invalid warnings in response to fixed roadside objects and overhead road structures.

2.4 Driver-Vehicle Interface

This section synthesizes results regarding drivers' perception of and interaction with the integrated system's driver-vehicle interface (DVI). Key results regarding the DVI from the post-drive survey are included. Descriptive statistics regarding drivers' interactions with the DVI are provided as a function of road class, route type, and exposure over time.

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

Drivers largely rated the DVI for the integrated system favorably. Drivers responded that they clearly understood what the DVI conveyed when they received warnings, agreeing strongly with the statement "I always knew what to do when the integrated system provided a warning." P&D drivers expressed slightly more confidence in their understanding of the system's warnings (Figure 74).

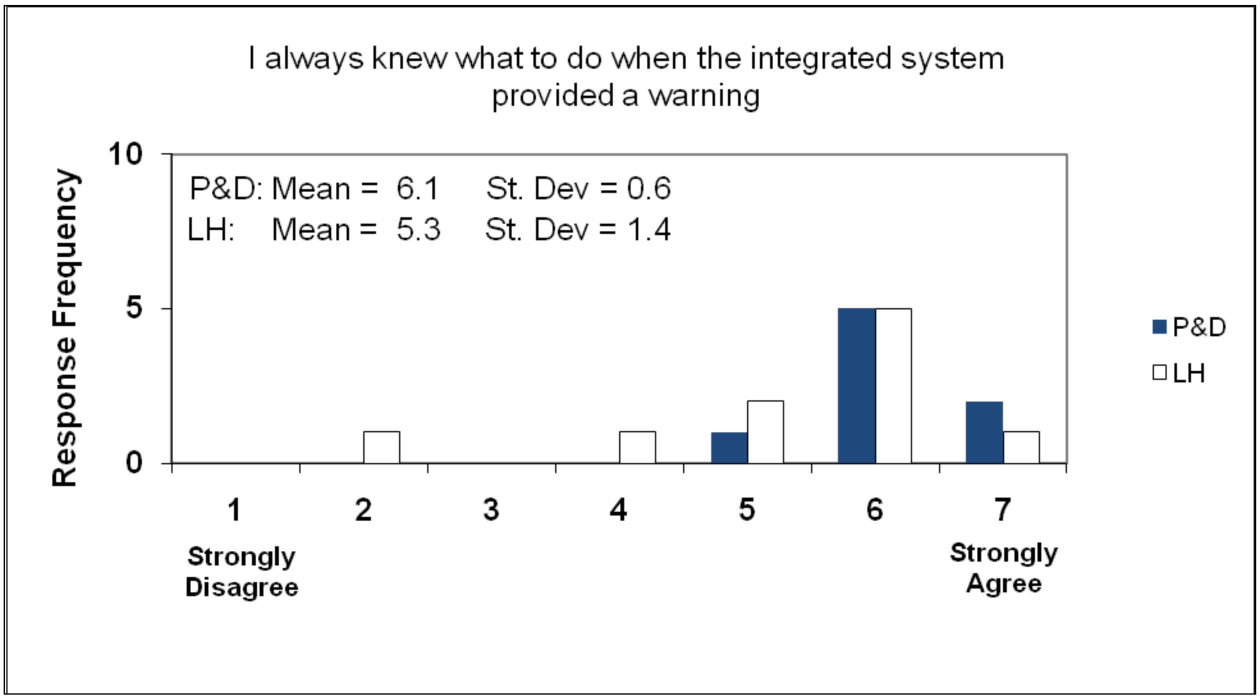

Figure 74. Responses to "I always knew what to do when the integrated system provided a warning."

These results may have been due to the larger relative number of invalid forward collision warnings and lane change/merge warnings experienced by line-haul drivers. As mentioned when addressing question QC9, line-haul drivers only braked in response to 2 percent of FCWs and only encountered a lateral hazard in 14 percent of LCM events. Both of these fractions were much larger for P&D drivers, making them more likely to feel they developed an adequate understanding of how the integrated crash warning system worked.

Drivers responded positively when asked whether the dash-mounted display was useful. When asked specifically about the half circle icons on the display (to indicate whether lane delineators were being tracked), drivers tended to agree that they helped them understand how the system operated. In the open-ended question portion of the survey, 4 drivers stated that they liked the visual cues on the display that presented the headway-time margin in relation to a lead vehicle.

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?

When asked about the controls for the driver-vehicle interface, specifically the auditory warnings, drivers gave a wide range of responses. This was evident in the large standard deviations of responses to the statements, "the mute button was useful" and "the volume control was useful." P&D drivers generally found both driver inputs to the DVI slightly more useful than did line-haul drivers (Figures 75 and 76).

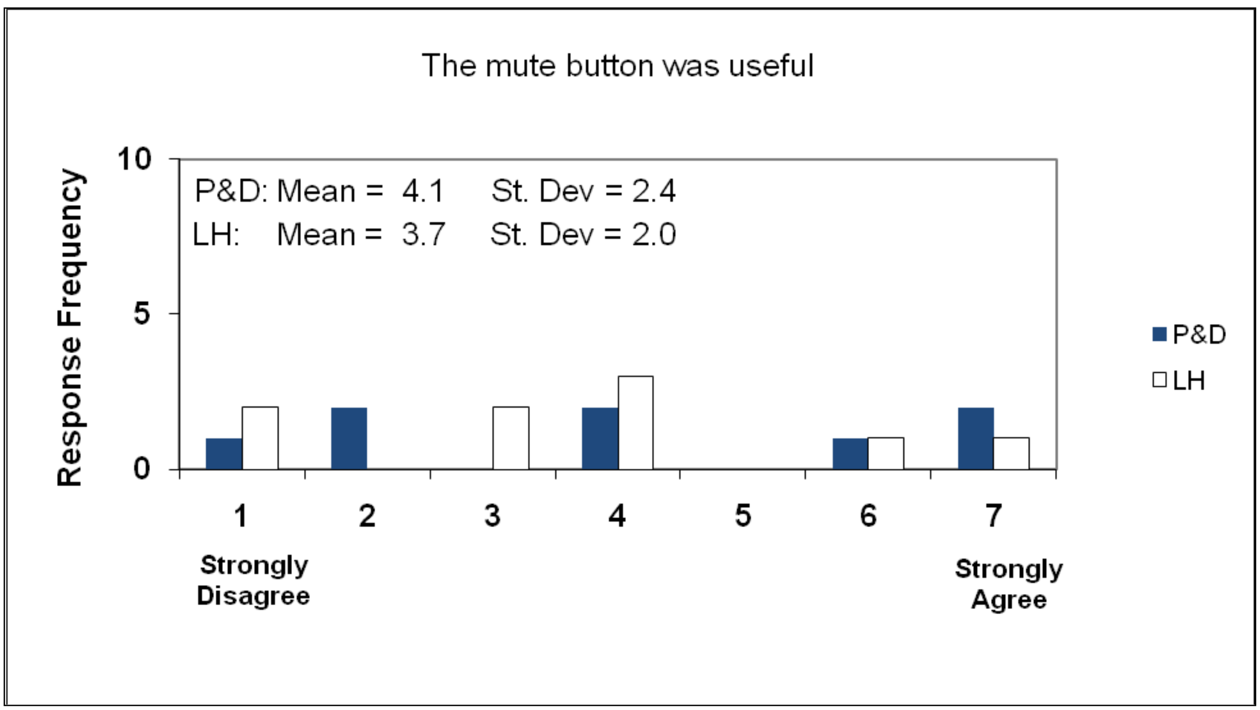

Figure 75. Responses to "The mute button was useful."

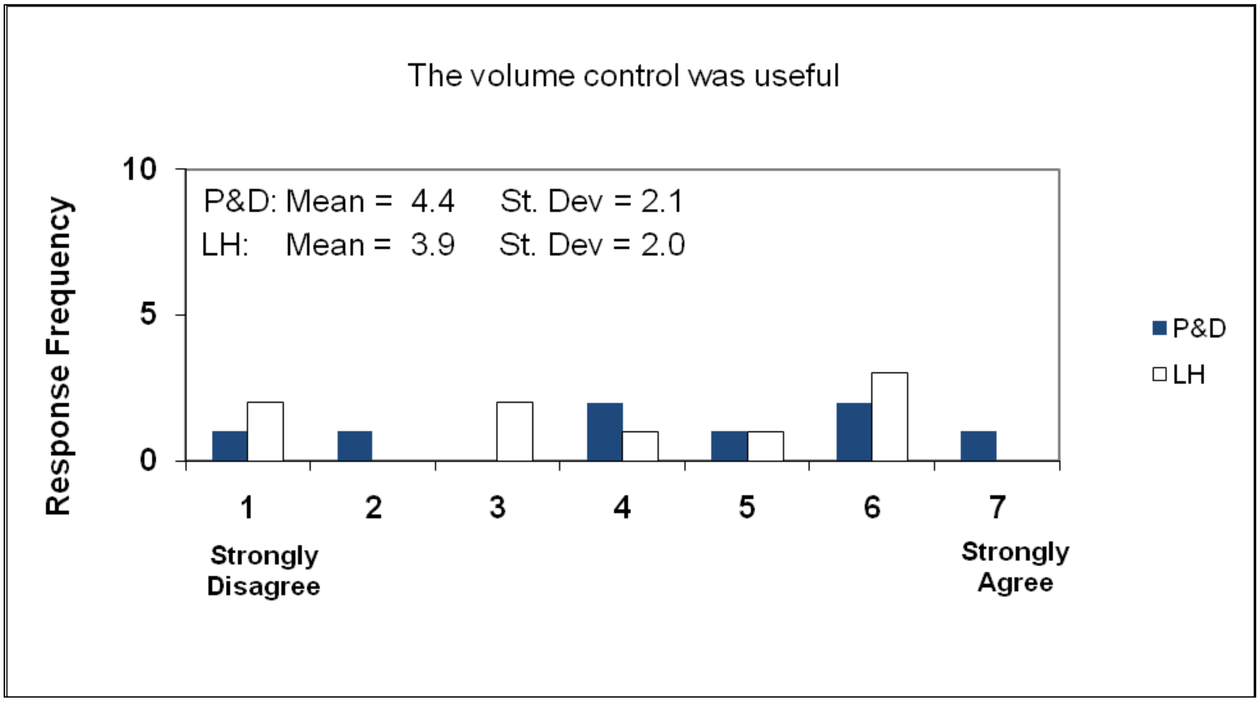

Figure 76. Responses to "The volume control was useful."

Three drivers responded that they never used either the mute or the volume controls. One driver said he never used the mute function, while another said he never used the volume control. Not surprisingly, drivers who rated the mute function favorably used it the most frequently. Only 2 drivers used the mute function more than twice. One of these drivers used the mute function 235 times and the other on 59 occasions. Both of these drivers stated that they used the mute function in construction zones, and both scored the mute favorably (either a 6 or a 7 on a 7-point scale). One additional driver who rated the mute function favorably stated that he used it during a period when the FCW radar was determined to be out of alignment, and likely was giving the driver an increased number of invalid forward collision warnings. Driver route type does not appear to affect the frequency with which the mute button was used.

Interpretation: While some drivers used the volume control and mute button, they used them very little over the 10-month period. Overall, these controls were not rated as particularly helpful. This suggests that an integrated warning system could be designed without these controls, potentially lowering costs.

3. System Maintenance and Reliability

3.1 Scheduled Maintenance and Monitoring

Due to modifications and installation of sensors and other specialized equipment on the trucks used during the field test, one member of Con-way's maintenance staff was selected and trained to assist UMTRI in the maintenance and repair of the trucks 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. Con-way was not expected to make adjustments to equipment added as part of the integrated crash warning system. Normal vehicle maintenance was to be performed by Con-way staff or an authorized International Truck dealer.

3.2 System Performance Monitoring

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

During the field test, the system performance data was monitored using files that UMTRI received via the cellular phone at the end of each ignition cycle. These files included histograms, counts, averages, first and last values, and diagnostic codes. UMTRI built routines to automatically scan the server for these files, and load them into the database for immediate processing by data validation routines. These routines, which also ran automatically, queried the data to generate summary reports that were broadcast by a Web-based server for viewing over the Internet. To the extent possible, these data provided validation that the integrated crash warning system was working as intended. Eaton also closely monitored system performance after receiving a copy of the data from UMTRI. When abnormal system behavior such as a significantly higher warning rate was observed, the team would look further into intermediate system performance signals in the data to identify the potential root cause and work with UMTRI and Con-way to schedule an on-site diagnosis and repair if necessary.

3.3 Scheduled Maintenance

The only scheduled maintenance on the fleet was the retrieval of data from the data acquisition systems. Data retrieval was performed for each vehicle on Monday mornings every third week, with 3 to 4 vehicles having data retrieved on 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 two crashes during the field test. The first was a line-haul driver striking a deer on a rural limited-access road. The FCW system did not issue a warning, as it is not intended to detect and respond to animals or humans. The result of the crash was the replacement of the AC20 radar on the front passenger side of the truck.

The second crash was at a low speed (below 25 mph, the minimum operating speed of the integrated system) in which the truck driver made a right-hand turn into a sport utility vehicle on the passenger side of the struck vehicle. The sport utility vehicle was attempting to pass the truck on the right, although there was not even a passable lane available. Again, no warning was issued, as the speed of the truck was below the operating speed of the integrated system.

3.5 System Repairs and Adjustments

Table 26 lists the nine critical integrated system sensor and component maintenance issues addressed during the field test. Each of these items is discussed below:

Table 26. Integrated system repairs and adjustments.

Item	System	Incident Description	Action taken	Hours	Date
1	LDW	Low Availability	Re-align headlights	0.5	8/28/2009
2	LCM	Observed rotated mud flaps on some tractors	Check and re-align all rear BackSpotter	3	8/31/2009
3	LCM	Failed BackSpotter	Replaced Rear BackSpotter	1	8/26/2009
4	LCM	Failed BackSpotter	Replaced Rear BackSpotter	1	9/11/2009
5	FCW	Too many FCW stopped warning	AC20 radar re-alignment	3	9/24/2009
6	LCM	Too many LCM warnings	M/A-COM radar re-align	1.5	9/24/2009
7	System	Fusion fault	Replace fusion engine	1	10/15/2009
8	FCW	Damaged sensor bracket; Too many FCW stopped Warnings	Replace AC20 radar due to deer strike	2	11/3/2009
9	FCW	Too many FCW stopped warnings	AC20 radar re-alignment	3	11/9/2009

Item 1 – Low availability of the LDW subsystem was found in the remote data checks conducted by UMTRI. The cause of the problem was identified as misaligned headlights, which was confirmed by the drivers of this unit. It is believed that the headlights were misaligned when the truck was delivered to Con-way, and Con-way does not regularly check headlight alignment unless an issue is reported by the driver. Apparently, the headlights were not so badly out of alignment that drivers noticed and reported the problem to the Con-way maintenance department; however, in the investigation of lower availability on this unit, the data collected showed trips at nighttime to have marginally lower system availability than trips during the daytime. When directly asked about the headlight alignment, drivers responded that the headlights of this tractor were different than those on other trucks. It is possible that this issue would have gone undetected in a normal fleet installation since it did not trigger any system level fault codes. This problem highlights the need for suppliers to have thorough maintenance protocols not only of the system itself, but other systems that the technology relies upon for proper functioning.

Item 2 — Rotated BackSpotter sensors: In order to optimize and cover the entire area adjacent to the equipped vehicle, two lateral proximity sensors (Eaton BackSpotter) were mounted as far apart as possible on each side of the tractor. The forward sensor was mounted on the upper fender above the corner of the bumper and clear of the "high-hit" area associated with the front of the vehicle. The rear sensor was mounted on the outward end of the main support arm of the rear splash-guard just forward of the drive axle and tire. Misalignment (rotation) of the rear sensors occurred when the splash-guards were unintentionally rotated by heavy road spray or physical contact with a trailer landing gear, causing the sensors to rotate, changing their detection cones. This problem was addressed by re-aligning the splash-guards arms and tightening the clamp that secures them to the frame. This problem was detected through visual inspection and was specific to this installation and not likely to be the same in a production system since either the sensor would be mounted in different location (less severe) or the rotation of the mounting arm would be better fixed in rotation.

Items 3, 4, and 7 – DVI faults: These items were detected by subsystem faults given to the driver through the DVI and identified through the remote data. In these cases, drivers would include the fault code in their equipment log at the end of their shift and either "tag" the vehicle for service or follow the maintenance reporting procedure of their fleet.

Items 5, 6, and 9 – Too many alerts: These problems were found by observing a change in the warning rate, particularly the number of FCW warnings issued in response to fixed roadside objects and overhead structures. In a production system, drivers would have to report alignment issues to their maintenance departments when they noticed degraded performance and increased alerts. It would be beneficial for suppliers to have an alignment feedback screen that would allow drivers to check the alignment of the sensor when they were on a flat straight road with a another vehicle in front of them—a similar feature also be used by maintenance personal to verify the system alignment following a repair or sensor replacement.

Item 8 – Deer strike: This problem was detected by both visual inspection (damage to the bumper due the deer strike) and a noticeable change in the warning rate following the crash.

Finally, most of the sensor alignment issues were unique to this installation and the result of inadequate physical tolerances (i.e., the bracket was too close to the bumper) and likely would not have occurred in a production installation. Nonetheless, alignment and calibration of these sensors is important and reasonable protocols are needed to ensure that they are adjusted and installed correctly.

4. Conclusions

Overall, the IVBSS Heavy-Truck 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 few system failures. In general, the overall system behavior and invalid alert rate was comparable to what had previously observed in extended pilot testing – the exception being a higher percentage of invalid FCW and LCM warnings was observed during the field test. The average rate of invalid warnings across all drivers for all warning types was 5 per 100 miles, which was still high enough that it did not meet many of the drivers' expectations.

4.1 Summary of Key Findings

Driver Behavior. Below are several key findings related to driver behavior:

- In multiple-threat scenarios, the warning presented to the driver first appeared to be sufficient to direct their attention to performing an appropriate corrective maneuver. This finding, in combination with the rarity of multiple-threat scenarios, may bring into question whether integrated systems for commercial trucks need to place much emphasis on addressing multiple-threat scenarios through warning arbitration.
- Even though the integrated system was present and could potentially warn drivers of developing crashes were they not paying sufficient attention, the commercial drivers in this field test did not appear to become overly reliant on the integrated system and did not increase the frequency with which they chose to engage in secondary tasks (eating, talking on a cellular telephone, etc.).
- Improvements in lane keeping and lane changing behaviors were limited with the integrated system. While the change in the rate of lane departures was not statistically significant, it did decrease for the majority of the drivers. Neither was there a statistically significant effect on how far, or how long, drivers were outside of the lane boundaries when driving with the integrated system. However, there was a statistically significant effect of the integrated system on drivers maintaining lane positions slightly closer to the center of the lane. The frequency of lane changes was no different with the integrated system, nor was the use of turn signals. Turn signal use when making a lane change was not modified by the integrated system, but the majority of the commercial drivers were already compliant in the use of their turn signal.
- Changes in driving behavior relative to forward conflicts were more pronounced than behavioral changes relative to lateral conflicts. Despite the frequent occurrence of invalid warnings associated with fixed roadside objects and overhead road structures, there were several changes in driver behavior attributable to the integrated system. This included a statistically significant, but negligible increase in following distances to lead vehicles. There were statistically significant differences in driver reaction time and time to apply the brake where both were reduced by the integrated system.

Driver Acceptance. Below are several key findings affecting driver acceptance:

- Fifteen of the 18 drivers stated that they would prefer driving a truck with an integrated crash warning system to one without, the same proportion of drivers also stated that they would recommend the purchase of trucks with integrated system.
- Fifteen out of the 18 drivers stated that they believed the integrated system will increase their driving safety. Drivers reported that the integrated system made them more aware of the traffic environment, particularly their position in the lane, and seven drivers stated that the integrated system potentially helped them avoid a crash.
- Despite the relatively high percentage of invalid warnings for fixed roadside objects, overhead road structures, and lane change/merge scenarios, drivers still stated that the system was convenient and easy to use. The driver-vehicle interface was easy to understand, and drivers claimed to know how to respond when a crash warning was presented.
- Of the three subsystems, drivers clearly preferred the LDW system, rating it the most satisfying of the three subsystems, with FCW being rated the most useful. LDW was a particular favorite for the line-haul drivers, given the long hours and great distances covered on limited access roadways. However, both P&D and line-haul drivers mentioned the headway time display of the FCW subsystem as being particularly helpful.

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 heavy truck field operational test findings:

- If FCW systems are expected to properly discriminate between stopped vehicles and fixed roadside objects and overhead road structures, the development of location-based data sets that identify the locations at which repeated warnings are received and there is no driver response, should be implemented. At least for the near future, performance of FCW systems that rely on autonomous, vehicle-based sensing will continue to be challenged with the reliable classification of stopped or fixed objects at the long ranges needed to provide sufficient time for commercial vehicles to avoid crashes. Virtually all of the FCWs in this field test were invalid, largely attributable to fixed roadside objects or overhead road structures that could be cataloged with repeated traversals where the driver did not respond to the initial warnings.
- The algorithm used in the LCM subsystem for detecting vehicles adjacent to the trailer of the tractor-trailer combination had difficulty discriminating returns from the trailer and adjacent objects when the tractor was towing a double trailer. This may be due to swaying of the towed trailers or the metal converter dolly on which the second trailer rides. Additional testing of the trailer reflection algorithms should be evaluated, specifically with the double-trailer configuration. The challenge here is inherent to the

nature of the radar and the tractor-only solution. In the future, a different type of radar or a different sensor suite design might be considered to address this challenge.

- For an integrated system, addressing multiple, simultaneous or near-simultaneous threats, might not be as critical as once thought. Multiple-threat scenarios are rare to begin with. When they did occur, drivers responded to the first warning presented, and their responses were appropriate for the indicated threat. For this commercial truck application with professional drivers, the effort and cost associated with the process of arbitrating warnings may not be justified.
- There was no evidence of driver over-reliance on crash warnings indicated in the results of this field operational test. Drivers reported that they did not overly rely on the integrated system, and the lack of a statistically significant difference in the frequency of secondary behaviors between the baseline and treatment periods supports this claim. While it can certainly be argued that the high percentage of invalid FCW and LCM warnings influenced drivers' sense of being able to rely on the integrated system, the lack of evidence for any signs of increased risk compensation or behavioral adaptation seems to suggest that if an effect exists it is relatively minor.
- FCW systems, or integrated crash warning systems, that include an FCW component should consider displaying a gross measure of headway time (i.e., perhaps with a resolution of 1 sec). A considerable portion of the drivers in this field study reported finding the display of headway time beneficial, and this display may have helped contribute to the slight increase in headway times maintained with the integrated system.
- As a group, line-haul drivers rated the integrated crash warning system as being more useful and satisfying than did their P&D counterparts. Given the increased exposure that line-haul drivers have in terms of miles driven, and the perceived benefits to be had from crash warning systems, carriers that are considering the purchase of crash warning systems might first consider their installation on tractors that are used most frequently for line-haul operations. This is particularly true when one considers the key findings related to increasing lane departure distance and duration that accompanies increasing hours of service.

In summary, the IVBSS Heavy-Truck 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 Heavy-Truck 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 autumn 2010 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?	Driving behavior was generally unaffected by the presence of the integrated warning system. However, drivers did report relying on the system for lane keeping assistance.
QC5	Are drivers accepting the integrated system (i.e., do drivers want the system on their vehicles)?	Drivers overwhelmingly responded that they prefer driving a truck equipped with the integrated warning system to a conventional truck. Furthermore, they recommend the purchase of such systems to increase safety.
QC6	Are the modalities used to convey warnings to drivers salient?	While the auditory warnings were attention-getting, the high invalid warning rate for LCMs and FCWs, particularly for line-haul drivers, resulted in drivers describing the warnings as "distracting" or "annoying." Reducing the invalid warning rate should result in drivers finding the warnings to be salient without being distracting or annoying.
QC7	Do drivers perceive a safety benefit from the integrated system?	Drivers perceived that the integrated warning system will increase driving safety, at least marginally. Forty percent of the drivers reported that the integrated system prevented them from having a crash.
QC8	Do drivers find the integrated system convenient to use?	Drivers found the system convenient to use. Drivers who received a high percentage of invalid warnings reported that they began to ignore the system.
QC9	Do drivers report a prevalence of false warnings that correspond with the objective false warning rate?	There is not a good correspondence between the subjective ratings of subsystems and the corresponding rates of invalid warnings. Drivers had varying opinions of the invalid warnings that appeared to be heavily dependent on the type of route they drove.
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?	The integrated system was fairly easy to understand. Reducing the number of invalid warnings will help to increase understanding of the integrated warning system as nearly one-third of the drivers reported that invalid warnings affected their understanding of the integrated system.
QL1	Does lateral offset vary between baseline and treatment conditions?	There is a statistically significant effect of the integrated crash warning system on lateral offset. The effect is most prevalent for steady-state lane-keeping events for travel on limited-access roadways, with drivers maintaining lane positions closer to the center of the lane in the treatment condition.
QL2	Does the lane departure warning frequency vary between baseline and treatment conditions?	The integrated crash warning system did not have a statistically significant effect on lane departure frequency, although the normalized number of lane departures did decrease. A decrease in lane departures was observed for 13 of the 18 drivers.
QL3	When vehicles depart the lane, does the vehicle trajectory, including the lane incursion and duration, change between the baseline and treatment conditions?	The change in duration and distance of lane incursions is not affected by the presence of the integrated crash warning system. However, hours of service had a statistically significant effect on incursion duration and distance.
QL4	Does turn signal use during lane changes differ between the baseline and treatment conditions?	The results show no statistically significant effect of the integrated system on turn-signal use during lane changes, but they did show an overall trend toward more frequent use of turn signals.
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 truck the adjacent vehicle is on.
QL6	What is the location of all adjacent vehicles relative to the subject vehicle for valid LCM warnings?	The results show that the integrated system did not affect the location of valid LCM warnings. The most statistically significant effect found was related to the side on which warnings occurred, 77 percent issued on the left side, and the majority of these occurred in the area adjacent to the tractor.
QL7	Will drivers change lanes less frequently in the treatment period, once the integrated system is enabled?	The results showed no statistically significant effect of the integrated system on the frequency of lane changes, although the trend appeared to head towards a reduction over time.
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 results show that while there was no statistically significant effect of the integrated system on gap size when performing lane changes, the gap is affected by the type of roadway environment, speed of the SV, hours of service, and time of day.
QL9	Are drivers accepting of the LDW subsystem (i.e., do drivers want LDW on their vehicles)?	Considering the integrated system as a whole, and its individual subsystems, drivers rated LDW highest in terms of satisfaction. Additionally, it was only slightly outperformed by FCW in terms of perceived usefulness.

Question Number	Research Question	Key Findings
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 found the integrated system to be somewhat useful. Drivers reported increased safety and heightened awareness. While line-haul drivers found the LDW subsystem to be more helpful than did P&D drivers, both types of drivers specifically mentioned finding valid FCW warnings and the headway-time margin display to be helpful.
QL11	Are drivers accepting of the LCM subsystem (i.e., do drivers want LCM on their vehicles)?	Among the subsystems, drivers liked LCM the least. This in part may be explained by the percentage of invalid warnings that drivers received (86% for line-haul drivers).
QF1	Does the presence of integrated system affect the following distances maintained by the heavy truck drivers?	The integrated system had a statistically significant effect on the time headway that drivers maintained during following events. Drivers maintained longer average time headways with the integrated crash warning system than in the baseline condition.
QF2	Will the frequency and/or magnitude of forward conflicts be reduced between the baseline and treatment conditions?	There was no statistically significant effect of the integrated crash warning system on forward conflict levels during approaches to preceding vehicles. However, the type of driving scenario and road type had a statistically significant effect on conflict level.
QF3	Does the integrated system affect the frequency of hard-braking maneuvers involving a stopped or slowing POV?	There was no statistically significant effect of the integrated crash warning system on hard-braking event frequency. The integrated crash warning system did not have a statistically significant effect on the maximum deceleration values, but mean maximum decelerations increased slightly between the baseline and treatment conditions.
QF4	Will the integrated system warnings improve drivers' responses to those forward conflicts in which closing-speed warnings occur?	The integrated system had a statistically significant effect on driver reaction time and brake reaction time. Drivers responded to closing-conflict events with shorter driver reaction times and brake reaction times with the integrated system.
QF5	Are drivers accepting of the FCW subsystem (i.e., do drivers want this system on their vehicles)?	Line-haul drivers received a considerably higher fraction of invalid forward crash warnings in response to fixed roadside objects and overhead road structures and they were less accepting of the FCW subsystem as a result.
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?	While some drivers used the volume control and mute button, they used them very little over the 10-month period. Overall, these controls were not rated as particularly helpful.

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)
Average Axle Load	Kg		GVW divided by number of axles. Although GVW has a strong influence on vehicle performance both laterally and longitudinally, average axle load is a more precise measure of a vehicle's stopping ability, since braking force is directly related to the number of braked wheels (i.e., tire/road surface area and friction material surface area).
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
Driver	-		Unique identification number that links each tractor and trip with a subject via manual coding of the face video
Gross Vehicle Weight	Kg		Estimated total vehicle weight using engine and state variables while the vehicle is accelerating
Hours of Service	hrs		Elapsed time since the start of a drivers tour, measured in hours
Lane Offset Confidence	%	0-100	Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem
Load	-	Heavy, Light	Total weight of the combined vehicle including cargo is greater than 22 metric ton (Heavy) or less than 22 metric tons (Light)

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

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

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

Other Terms	Units	Levels	Description
Lane Offset Confidence	%		Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem
Lateral Position			See Lane Offset
Lateral Speed	m/s		Vehicle speed lateral to lane direction from the LDW subsystem
Likert-Type Scale Value	-	1 to 7	A number between 1 and 7 indicating general agreement of a driver with a question included in the post-drive survey. Anchor terms are provided at the two ends of the extreme
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

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

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