Integrated Vehicle-Based Safety Systems

Heavy-Truck Field Operational Test

Methodology and Results Report

By

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This document presents the methodology and results 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 results 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.</td></tr>
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List of Acronyms

ACAS	Automotive Collision Avoidance System
ABS	Antilock Braking System
CAN	Controller Area Network
CDL	Commercial Drivers License
CWS	Crash Warning System
DAS	Data Acquisition System
DIU	Driver Interface Unit
DVI	Driver-Vehicle Interface
FCW	Forward Collision Warning
FOT	Field Operational Test
GUI	Graphical User Interface
HPMS	Highway Performance Monitoring System
HT	Heavy Truck
ISO	International Organization for Standardization
IVBSS	Integrated Vehicle-Based Safety Systems
LAM	Look-Ahead Module
LCM	Lane Change-Merge Warning
LDW	Lane Departure Warning
NHTSA	National Highway Traffic Safety Administration
NPTS	National Personal Transportation Survey
P&D	Pick-up and Delivery
RDCW	Road Departure Crash Warning
SHRP 2	Strategic Highway Research Program 2
TCP/IP	Transmission Control Protocol/Internet Protocol
TLX	Task Load Index
TTC	Time to Collision
U.S. DOT	United States Department of Transportation
UM	University of Michigan
UMTRI	University of Michigan Transportation Research Institute
VOC	Voice of the Customer
VORAD	Vehicle Onboard RADar

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 the methodology and results 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 fulltime 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 the 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 had 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 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. 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.
- 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 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 than0.2g [1.96 m/s2]), 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 less frequent. 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 ten heavy trucks in the IVBSS program: forward crash warning, lateral drift warning, and lane-change/merge 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 U.S. 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.

2. Methodology

2.1 Drivers

Ten FOT tractors were based at Con-way's Romulus, MI terminal. Based at this facility are over 100 drivers, 43 line-haul tractors, 33 daily-delivery tractors, 217 28-foot line-haul trailers, and 71 daily-delivery trailers ranging in size from 42 to 53 feet. Twenty drivers from the Romulus terminal were sought in order to run 10 tractors day and night over the course of the FOT.

The following is a breakdown of all drivers at the Romulus, MI terminal by age group:

- Age 20 to 29 (12%);
- Age 30 to 39 (28%);
- Age 40 to 49 (37%);
- Age 50 to 59 (19%); and
- Age 60 and older (4%).

A notice was posted at the terminal and two information sessions were held to inform potentially interested drivers what participation in the FOT entailed. At these sessions drivers were able to walk around an instrumented tractor and ask any questions they had about the program or the operation of the crash warning system.

The 10 FOT trucks were assigned to specific routes, and drivers who were interested in participating could sign up for those routes. Interested drivers were given detailed information regarding the requirements of their participation as well as a short video outlining the operation of the warning system.

Initially, 20 drivers were enlisted in the IVBSS FOT. Based on the population of drivers available, all drivers in the FOT were male. This set was composed of 10 Pick-up and Delivery (P&D) drivers who drove primarily during the day, making multiple stops at different locations to pick up or drop off freight. Also participating were 10 line-haul drivers, who drove primarily long distances during the night to move freight from one Con-way terminal to another. These drivers generally made only one stop per shift, to drop and load freight.

Over the course of the FOT, one driver was forced to withdraw from the study for personal reasons and another driver was unable to continue participating as the nature of his work at Con-way changed and he was no longer driving a truck. Because of the design of the study, with the beginning of each driver's experience taking place under the baseline condition, these drivers were not able to be replaced as by the time new drivers would be beginning, all 10 trucks were already operating in the treatment condition with the warning system active. Table 1 below presents descriptive statistics on the driving experience of the 18 drivers who completed the program.

Table 1: Descriptive statistics for driver population in IVBSS Heavy Truck FOT

	Average Age	Oldest	Youngest	Average Yrs. With CDL	Max. Yrs. With CDL	Min. Yrs. With CDL
P&D	48	62	33	19	33	10
Line-haul	50	55	41	26	35	18

At the completion of their experience in the FOT drivers were paid $300 in cash and awarded the equivalent of $150 in Con-way Safety Points.

2.2 Vehicles and Instrumentation

The Heavy Truck FOT was conducted with the assistance and cooperation of Con-way Freight. Con-way Freight is a regional and nationwide less-than-a-truckload (LTL) company that specializes in the transportation and delivery of palletized freight. Companywide, Con-way employs over 30,000 professional drivers and operates over 32,000 power units (tractors) and approximately 80,000 trailers. In addition to Con-way's willingness and commitment to participate in the FOT, the fleet also met a number of other criteria necessary for a successful FOT. These included a willingness to purchase the tractors, logistical and operational constraints, personnel considerations, and proximity of the fleet to the other program partners.

For the FOT, Con-way operated tractors from its Romulus, Michigan, service and distribution center. At this terminal, Con-way operates approximately 80 tractors in both line-haul and a local pick-up and delivery (P&D) operations. Each FOT tractor was assigned to a specific line-haul and P&D route. During the day, a tractor was employed on a P&D route, while at night the same tractor was used for a line-haul route. The drivers for these routes are bid out every year and are based on seniority. Con-way does not run a "slip-seat" operation; rather, drivers are assigned to tractors and aside from vacations and sick time (and any intentional rotation of tractors per the experimental design), the same drivers were driving the same tractors on the same routes for the entire FOT. This was confirmed by Con-way as part of the agreement with UMTRI. Tractors were in operation approximately 20 hours per day with two drivers assigned to each tractor. The valid data set collected for the 18 drivers who participated represented 601,844 miles, 22,724 trips, and 13,678 hours of driving.

There were exceptions, but in general Con-way used sets of 28-foot trailers for all line-haul operations. For P&D, Con-way typically used a 48-foot trailer but occasionally also used 28-, 40-, 45-, and 53-foot trailers. P&D trailer selection was a function of route and time of year, as the freight business varies during the year.

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. The tractors were equipped with the 3 subsystems comprising the heavy-truck warning system (forward collision warning, lane-change or merge warning, and lateral drift warning systems in an integrated safety system with a unified driver-vehicle interface).

2.2.1 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, the 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 2 describes the visual and audio elements of the warnings from 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 2: 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 LEDs. “Collision alert” graphic on LCD accompanied red LEDs
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

2.2.2 Objective Data Collection

This section covers both numeric and video data that constitutes the FOT database for the heavy-truck platform. This data is objective in the sense that it is undistorted by emotion or personal bias and is based on observable evidence.

2.2.2.1 The Objective Dataset

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

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

2.2.2.2 Data Types

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

Source: Most data collected by the DAS were from a dedicated Controller Area Network (CAN) bus (or set of CAN buses) implemented, programmed, and structured specifically for this project. However, other data came from the original equipment vehicle bus (J1939). UMTRI also installed its own set of sensors. These sensors provide researchers at UMTRI with additional measures of vehicle and driver performance, which are independent of the warning system. Finally, a category classified as "other" includes objective data that were linked to the onboard DAS data but were culled from external data sources such as the National Weather Service, the Highway Performance Monitoring System, and Con-way's logistical databases.

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

- **Custom:** Specifically this category applies to the radar and video cameras. For all radar units, the DAS recorded all radar targets and their associated data with the exception of the forward radar. In this case the signals for the primary forward target were recorded at 10 Hz while the signals for up to six secondary targets were recorded at 2 Hz. Video on both platforms was recorded at the highest frequency possible given the storage and compression considerations for the DAS. All video measures were also triggered at at least 10 Hz with a pre- and post-event window to capture and save the visual content of the scene surrounding a warning.
- **10 Hz Series:** Most objective data from the vehicle were saved in a time-history format with a 10 Hz resolution.
- **Triggered Event:** Many objective data signals were event-logged by the DAS. That is, when a signal transitioned beyond a threshold or there was a warning, the start and end times of that event were saved along with other relevant signals. These triggered events are the building blocks of more complex analysis methodologies that are used to address specific questions related to how the system and vehicle performed and, more critically, how the driver might have changed their driving behavior. Also, since these summaries are relatively small in size, they could be downloaded to UMTRI after each trip and used to monitor the health of the system and the experience of the driver.
- **Transitional: Logged** events contained the same content as time history events, but required less space and were often easier to summarize in large datasets.

- **Aggregated:** This general classification nearly always involved performing some type of operation on a specific signal and resulted in a number or set of numbers that reflect an overall summary of the measure. Examples include distance traveled, which is the integration of the speed signal over the time resolution of that signal, and the count of brake applications by the driver. Another important aggregation is histograms or the categorization of a signal into predefined bins to produce a time-weighted distribution of a signal. In some cases, two-dimensional histograms were created showing the relationship between two signals such as road type and speed.

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

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

2.2.2.3 Heavy-Truck Dedicated Instrumentation

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

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

2.2.3 Camera Positioning for Video Collection

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

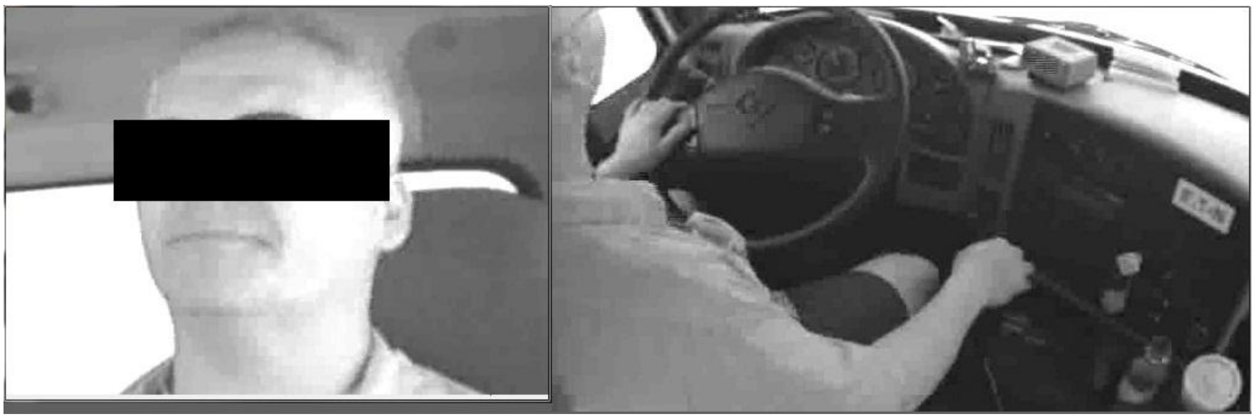

Figure 2: Sample driver face and cabin camera images

Figure 3: Sample forward image

Figure 4: Sample left-side rear-looking image

The major reasons for capturing the video data were to:

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

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

2.2.3.1 Video Data Compression and Sampling Rates

The video data from the FOT consumed a large amount of memory, comprising 71 percent of the data collected by the DAS. For this FOT, all video data were compressed both spatially and temporally using H.264 (MPEG-4) video compression.

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

2.2.4 Audio Data Collection

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

2.2.5 Data Acquisition System

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

2.2.5.1 DAS Main Module

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

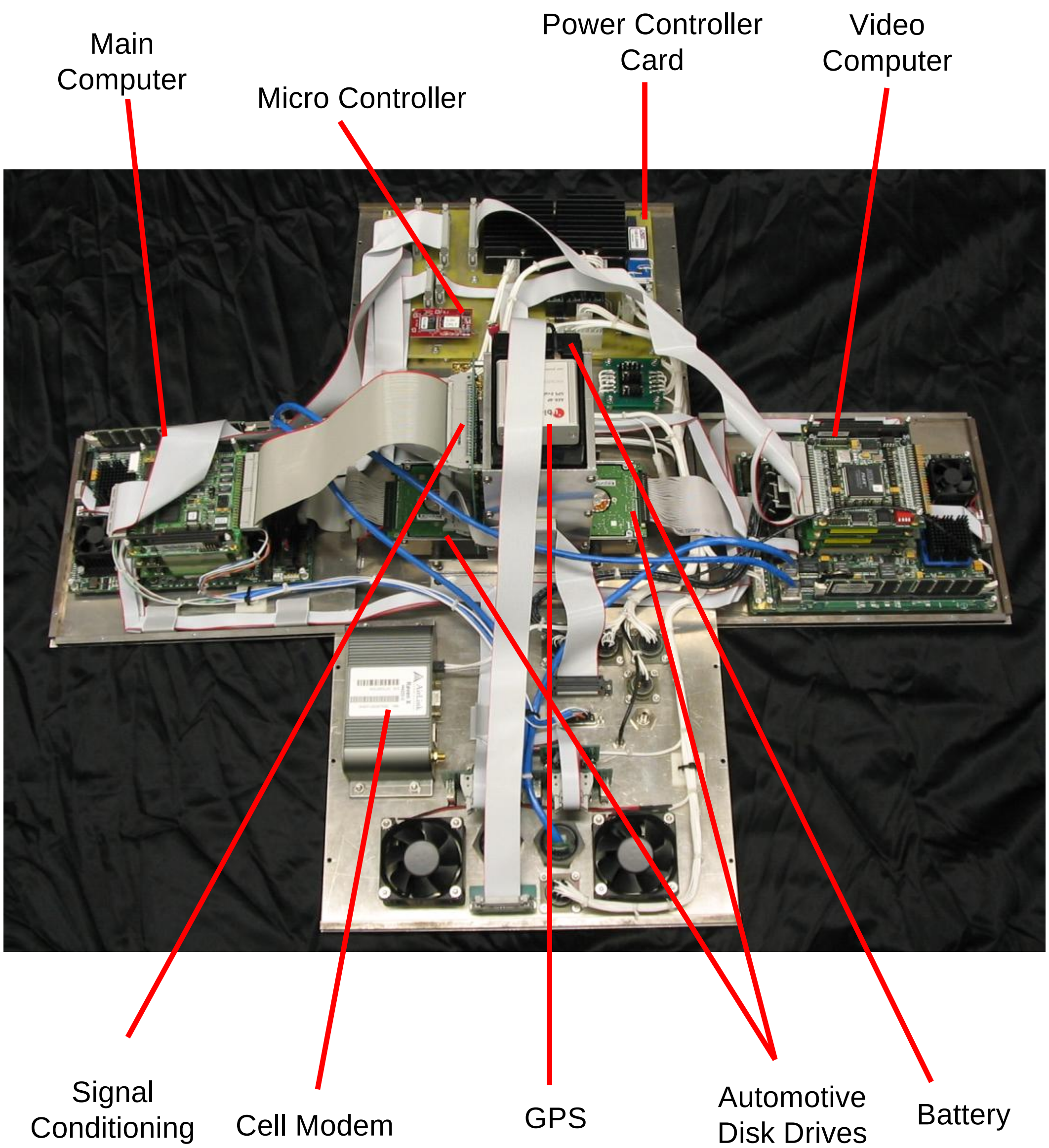

Figure 5: Major DAS components

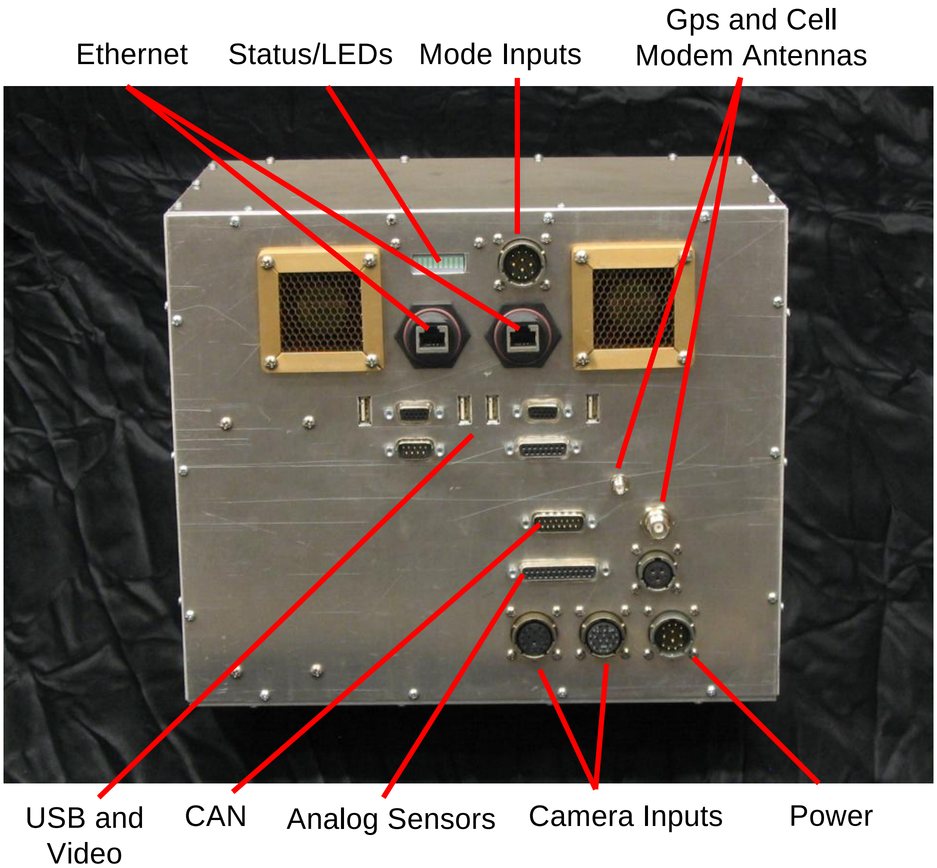

Figure 6: DAS, vehicle, and user interface

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

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

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

2.2.5.2 Modes of System Operation

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

Figure 7: DAS mode control box

2.2.5.3 FOT DAS Mode

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

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

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

2.2.5.4 Upload Mode

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

2.2.5.5 GUI DAS Mode

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

2.3 System Maintenance and Reliability

2.3.1 Scheduled Maintenance and Monitoring

Due to modifications and installation of sensors and other specialized equipment on the 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 performed by Con-way staff or an authorized International Truck dealer.

2.3.2 System Performance Monitoring

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

During the field test, the system performance data was monitored using files that UMTRI received via the cellular phone at the end of each ignition cycle. These files included histograms, counts, averages, first and last values, and diagnostic codes. UMTRI built routines to automatically scan the server for these files, and load them into the database for immediate processing by data validation routines. These routines, which also ran automatically, queried the data to generate summary reports that were broadcast by a Web-based server for viewing over the Internet. To the extent possible, these data provided validation that the integrated crash warning system was working as intended. 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.

2.3.3 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.

2.4 System Repairs

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.

2.4.1 System Repairs and Adjustments

Table 3 lists the nine critical integrated system sensor and component maintenance issues addressed during the field test. Each of these items is discussed below:

Table 3: System Maintenance Issues

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. It is unlikely to be the same in a production system, because 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 to 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.

2.5 Procedure

2.5.1 Participant Recruitment

The recruitment process for the FOT drivers began with a general meeting for all drivers at the Romulus, MI terminal. Two UMTRI researchers spoke with drivers about the nature of the program, the general requirements for participation and the compensation package. At the end of the talk, a 15 minute video was played presenting more detailed information about the functionality of the warning system. Finally, drivers went outside and were given the opportunity to walk around and climb inside an instrumented tractor which was brought to the terminal specifically for this presentation.

Initially, the 10 FOT tractors were assigned to specific routes which would likely produce the largest and most variable data set in terms of diversity of destinations. Had more drivers expressed interest in the program than could participate, seniority at the terminal would have determined which drivers got the routes with the FOT tractors. As it was, only 20 drivers signed up to participate.

2.5.2 Participant Orientation and Instruction

Customized training was necessary for drivers, mechanics, and fleet management personnel involved in this FOT. This training was conducted in one-on-one sessions with an UMTRI researcher. In previous FOT work, UMTRI has learned that frequent personal interaction and progress updates are important motivators for the drivers and mechanics at the fleet. In part, the success of the FOT relies on their input, so UMTRI worked actively to keep them involved in the ongoing FOT.

Training was an important element toward this goal. To the extent possible, training was integrated into the normal operations of the fleet, which served two purposes. First, it ensured that the people in charge of the day-to-day fleet operation knew the expectations placed upon the drivers and mechanics. Furthermore, their knowledge of the operation provided valuable input as to the most efficient way to get the work done. Second, fleet management personnel needed to become knowledgeable about the various system components involved in the study. Since most questions and problems would come first to these professionals, it was important that they had the necessary instruction and FOT contact information. In short, the supervisors needed to be ready to play their front-line roles in the FOT.

Driver training began with an introduction to the research vehicle and instruction on how the warning system operated with an opportunity to ask specific questions of a researcher. As the drivers' experience would begin with the system in the baseline condition, at this point the training and orientation focused more on the higher-level aspects of the program such as UMTRI's expectations for the drivers and information on the data that would be collected. Drivers were also shown the additional equipment that was installed on the tractor and briefed on its function. During these initial sessions drivers were not given an in-depth explanation of the crash warning system itself as they would not begin to experience warnings for two months.

Just before the system became enabled, or during the first shift in which the system became enabled, drivers took a 30-minute accompanied test drive with an UMTRI researcher. This drive was done in their tractor, with the integrated system in the treatment condition. Before and throughout this test drive the researcher was carefully explaining the functionality of the system and the operation of the driver-vehicle interface to the driver. This included an explanation about what each subsystem did, how they worked, and how to identify any operational problems.

Drivers were given the opportunity to experiment with the system and to ask the researchers any questions they may have had in the environment in which they would be working with the system for the duration of their participation. At the conclusion of this test drive, drivers were given an instructional DVD that they could watch at their leisure to help improve their understanding of the integrated system.

Each driver was given the means by which they could contact researchers as necessary. Two UMTRI researchers carried pagers, having one common number, at all times during the FOT. Drivers were assured of contacting a researcher, if the need arose, on a 24- hour-a-day basis.

Additionally, UMTRI researchers maintained a presence around the Romulus terminal in order to be available to the drivers allowing them to casually ask questions about the integrated system, or comment on system functionality or the FOT procedure. This proved valuable in identifying and addressing system issues that came up over the course of the FOT.

2.5.3 Conduct of the Field Operational Test

The heavy-truck FOT spanned a total period of 12 months (52 weeks) with a staggered introduction of equipped vehicles at the start of the FOT. The 10-truck fleet was deployed over a 4-month period. In mid-January the first four trucks were given to the fleet to initiate the FOT. One month later, a second set of three trucks was deployed. One more truck was deployed in mid-March. The final two trucks were given to the fleet in mid-April. The deployment schedule was developed to put as many trucks into service as possible, while minimizing carrying costs for trucks owned by the fleet but not used in normal operations.

Con-way Freight's operation consisted of two types of routes for five days a week out of the Detroit terminal; pickup 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 included 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.

Once in service, each truck was assigned to both a line-haul and P&D route and was driven by the same two drivers on a daily basis for the duration of the FOT. Drivers occasionally switched trucks, but all data was carefully attributed to the correct driver regardless of which truck he may have been driving.

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.

2.5.4 Post-Drive Debriefs

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

Debriefs were performed by an UMTRI researcher at the Romulus terminal. Care was taken to find a location within the terminal where drivers could speak freely without fear of being overheard by their superiors, ideally allowing a more free flow of information and potentially more honestly about situations where the system may have been important in avoiding critical situations.

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

The video review portion of the debrief asked drivers to watch video of warnings they received and to comment on the situation. Twelve warnings for each driver were selected in advance of the debrief by the researcher. Based on the overall frequency of the warnings an ideal set of 12 warning video clips would contain 3 FCWs, 2 LCMs, and 7 LDWs (4 cautionary, 3 imminent.) Included in the set of 12 warnings, each driver was shown at least one warning deemed by the researcher to be invalid.

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

At the completion of the driver debrief, the driver was paid $300 in cash and the paper work was completed to arrange the additional payment in Con-way Safety Points.

2.6 Heavy-Truck Data Retrieval

Retrieval of heavy-truck data was done through manual data retrieval, as initial estimates in excess of 500 MB per hour for both video and objective data was beyond the capacity of a current wireless area network given the allowable time for the download to occur. That is, since the video files were significant, there was a distinct possibility that a typical download would not finish within the allowable time window. An on-site server and data download mechanism was arranged with Con-way. The equipped tractors had designated parking spots located alongside Conway’s trailer maintenance facility and adjacent to the tractor parking area. These spots were equipped with data retrieval "umbilical" cords that needed only to be plugged in to initiate data transfer. Con-way agreed to assist UMTRI in this process to ensure that individual tractor units were downloaded on a regular basis. For data and system quality monitoring, UMTRI used an on-board cell modem, which sent data back to UMTRI after each ignition cycle. After the download, data from the fleet was then uploaded into the appropriate database and backed-up for archiving.

2.6.1 Procedures for Downloading Data from the Heavy-Truck Fleet

Data from each tractor were downloaded roughly every three weeks on a rotating basis by manually connecting a power/download cable to each DAS while it was parked at the distribution facilities on Monday mornings. An outline of the procedure for downloading is shown below:

- Drive to the fleet on Monday morning.
- Move the candidate tractors to a dedicated outdoor-download location at the fleet and connect power and the download cable to the DAS on each tractor.
- Connect an external large-capacity hard drive to a dedicated project server located at the fleet.
- Start the download process on each tractor to automatically move the data from each DAS to the local server and the external hard drive.
- Shut down and disconnect the dedicated download cables from each DAS.
- Return the vehicles to their designated parking spots.
- Disconnect the external hard drive and return with it to UMTRI.
- At UMTRI upload the files from the hard drive to the project server and load the database.
- Flag files that have been successfully loaded and backed-up for deletion.

To minimize the risk of losing data, files were not deleted from each DAS during the download process but were be managed remotely during the periodic cell modem calls from each truck to UMTRI during the FOT.

2.6.2 Ensuring System Functionality and Integrity of Retrieved Data for Heavy Trucks

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

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

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

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

2.6.3 DAS Remote Monitoring

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

2.6.4 Data Validation

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

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

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

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

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

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

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

2.6.5 Creation of Databases

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

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

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

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

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

2.6.6 Distribution of FOT data

This project generated a tremendous amount of data that was to be shared with the program partners and independent evaluator. Roughly 3 Tb of data was transferred to Volpe. The collection rate for the video data was 131 MB per hour and for the objective data was 53MB per hour for a total collection rate of 184 MB per hour. UMTRI performed the following processes before delivery of the data:

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

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

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

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

2.6.7 Tools for Data Analysis

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

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

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

Figure 8: The UMTRI data viewer

3. Results

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

3.1 Vehicle Exposure

This section characterizes the range of driving conditions encountered by the 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 9 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 4. Approximately 21.5 percent of the mileage was accumulated in the baseline condition, and 78.5 percent took place in the treatment condition.

Table 4: 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

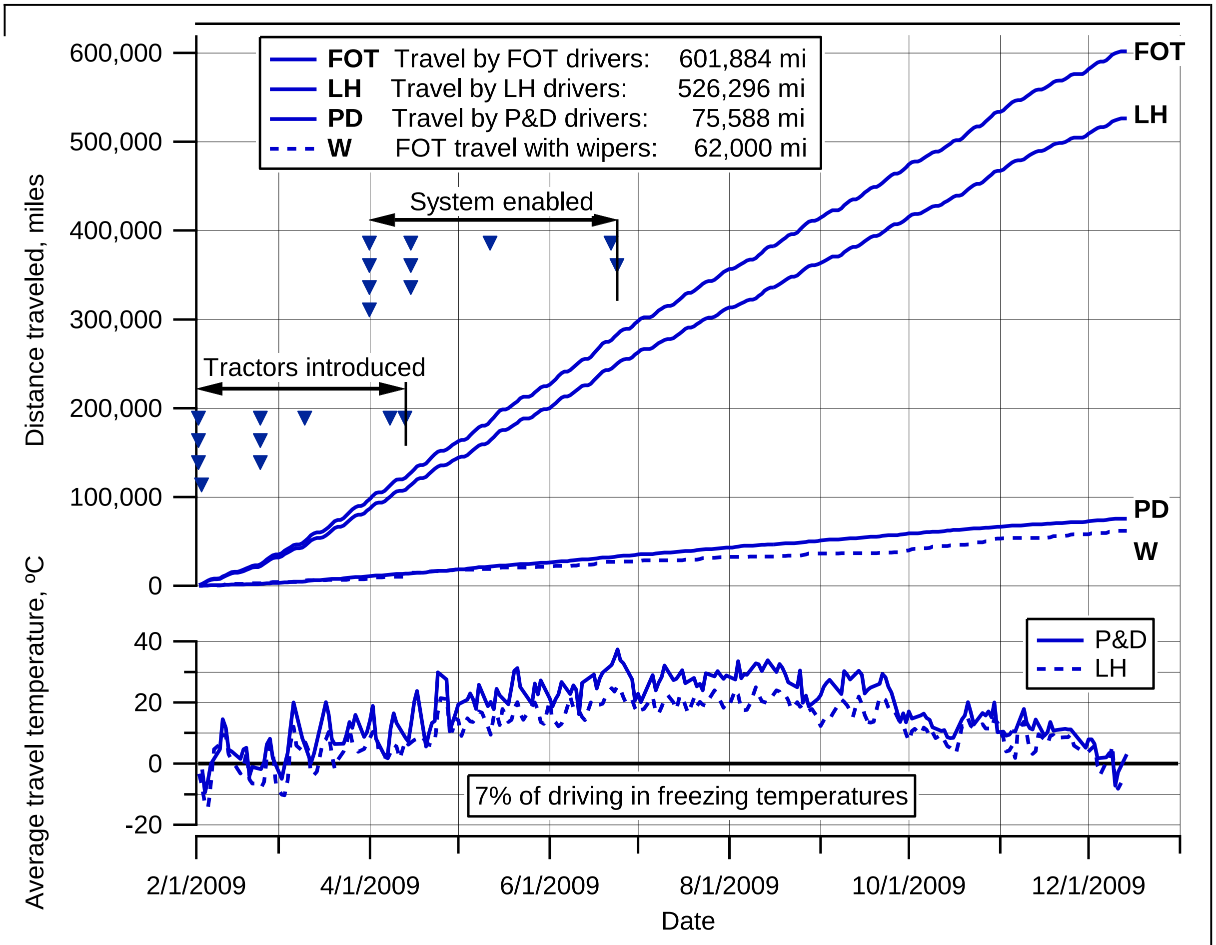

Figure 9: Distance accumulations during the heavy-truck field test

3.1.1 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%). Figure 10 and Figure 11 show the geographical ranges of driving by the P&D and line-haul drivers, respectively. As shown in Figure 10, 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 11) 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.

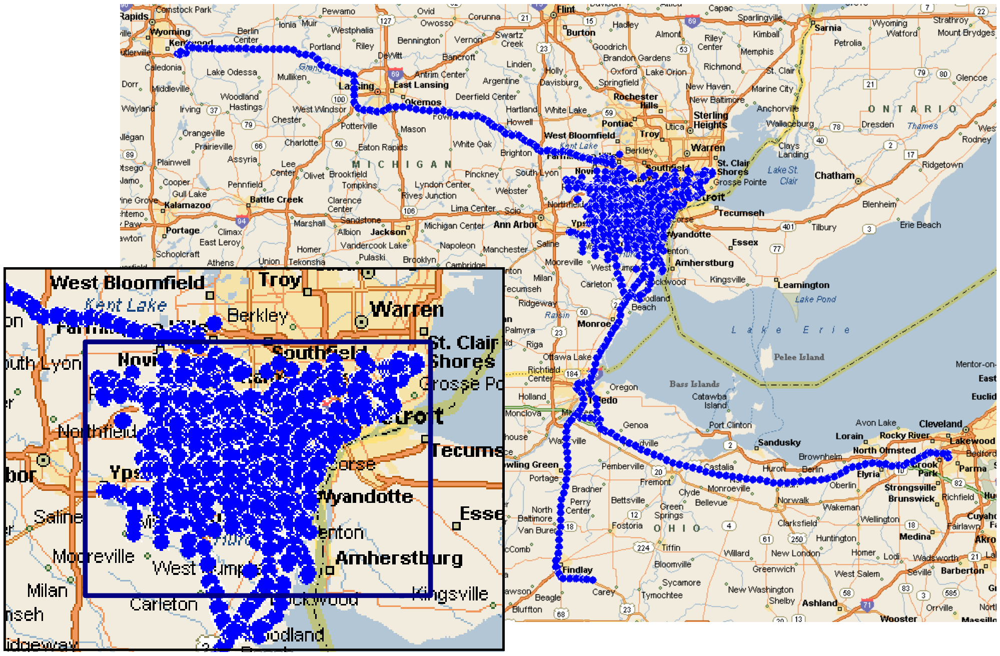

Figure 10: Geographical range of driving by P&D drivers, with insert of area of the most driving

Figure 11: Geographical range of driving by line-haul drivers

3.1.2 Trips and Travel Segments

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

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 5 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.

Table 5: Very short trips by the FOT drivers

	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 6). 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 6: 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

3.1.3 Roadway Variables

Some of the analyses that follow distinguish between travel on limited-access roadways, surface streets and highway ramps. Figure 12 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.

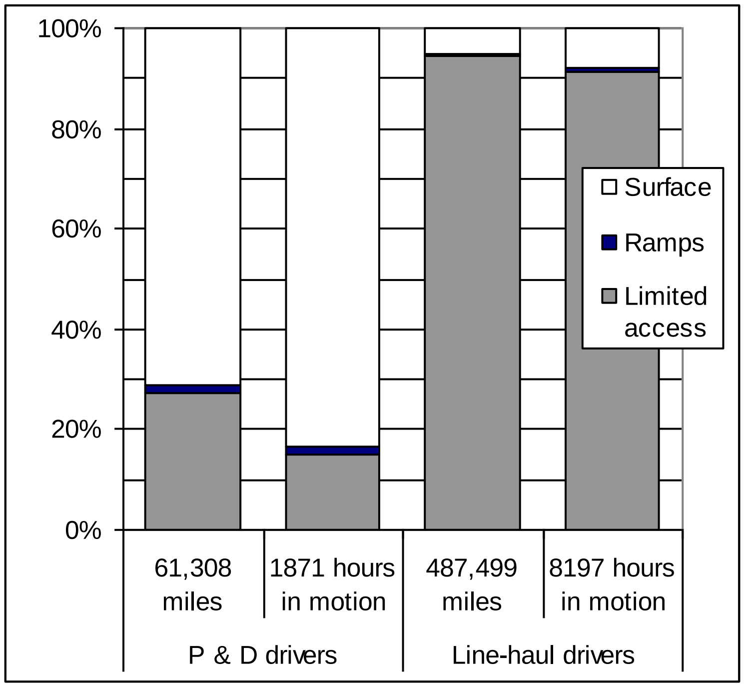

Figure 12: Portions of distance traveled and time in motion of each driver group by road type

3.1.4 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 13 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.

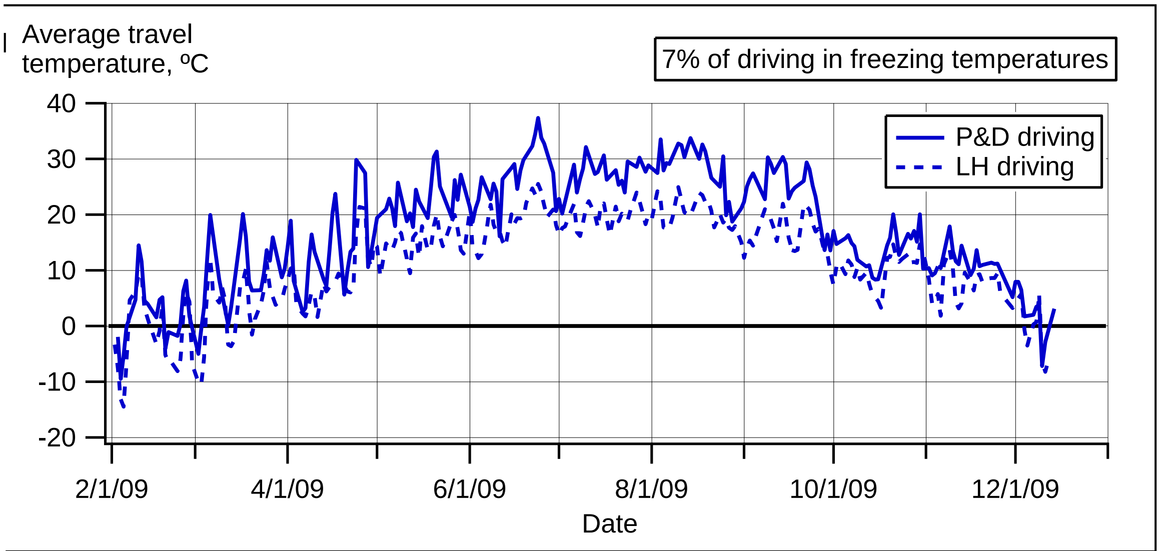

Figure 13: Average travel temperature

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 (28-32 feet), single-axle trailer or a longer (45-53 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 had 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 14 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.

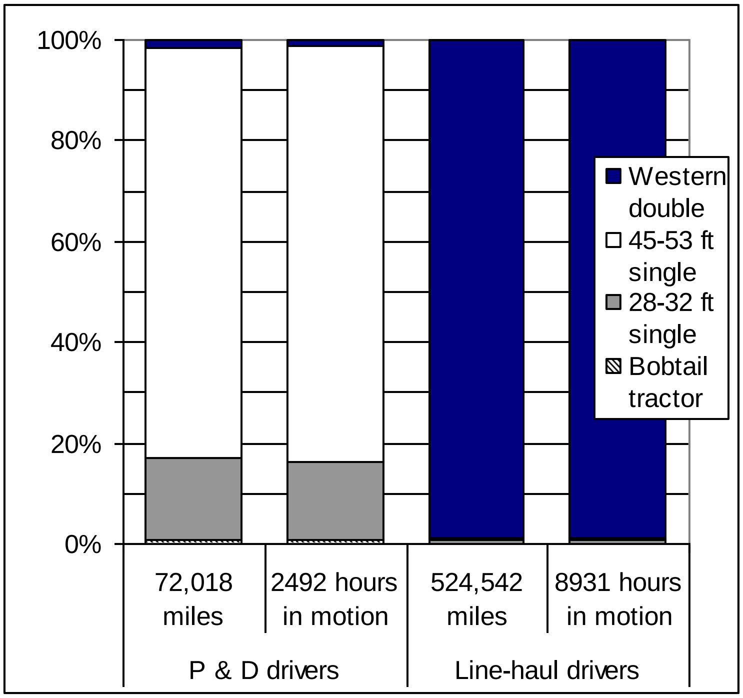

Figure 14: Portions of distance traveled and time in motion of each driver group by vehicle configuration

3.2 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 15 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.

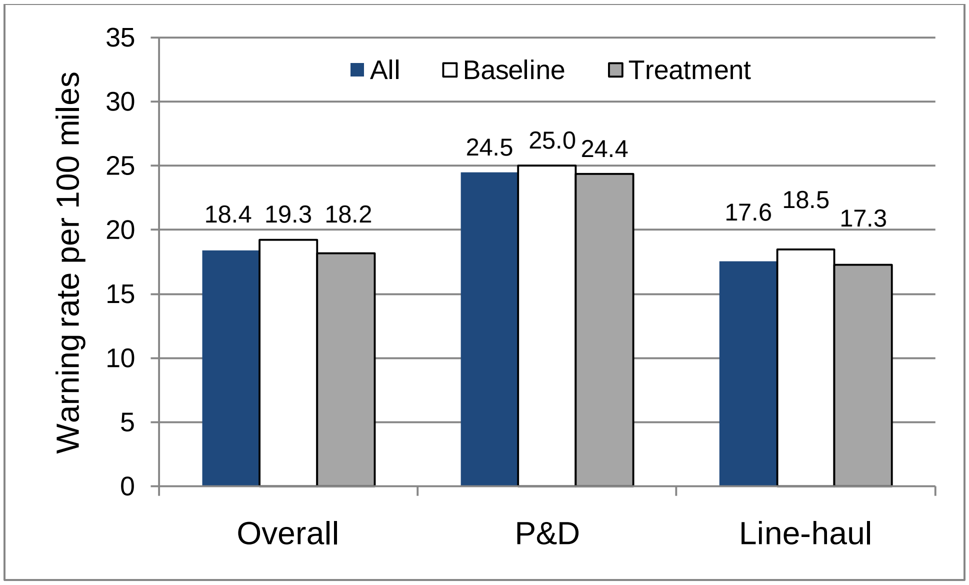

Figure 15: Warning rates during FOT

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 16.

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.

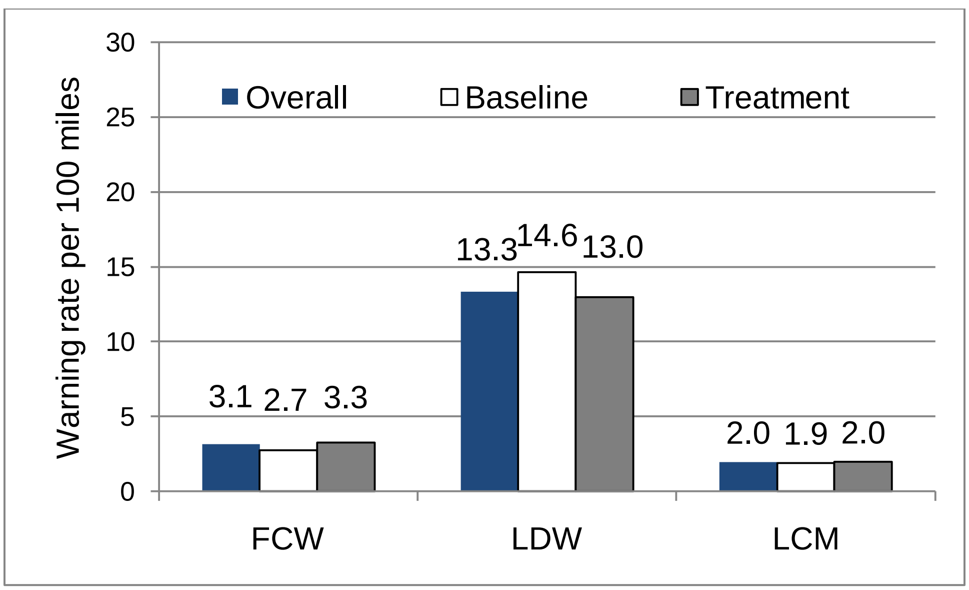

Figure 16: Warning rates by subsystem during the FOT

3.3 Driver Behavior Research Questions

3.3.1 Secondary Behaviors

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

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

A total of 1,980 five-second video clips were visually coded for the presence of secondary tasks. These video clips were chosen with the following criteria:

- The minimum speed for the 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 breakdown of the driving conditions for the 1980 clips is presented below in Table 7.

Table 7: Breakdown of clips reviewed for secondary tasks

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%
Ambient Light	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.

A list of potential secondary tasks along with the coded frequencies from the 1980 clips is displayed below in

(Note: 110 clips from the sample contained multiple secondary tasks; each individual task is uniquely represented in Table 8.)

Table 8: Frequency of secondary tasks among 1980 five-second clips

Secondary Task Description	Number of clips with task
No secondary task	1132
Dialing Phone	8
Text messaging	34
Talking on/listening to hand-held phone	111
Talking on/listening (headset or hands-free)	195
Holding/Talking on CB radio	61
Singing/whistling	2
Talking to/looking at passengers	9
Adjusting Stereo controls	46
Adjusting HVAC controls,	6
Adjusting other controls on dash	4
Adjusting Satellite radio	0
Adjusting Navigation System	0
Adjusting other mounted aftermarket device	0
Holding/Manipulating in-hand device	16
Writing on manifest	1
Reading manifest	3
Eating: High involvement	14
Eating: Low involvement	119
Drinking: High involvement	20
Drinking: Low involvement	62
Grooming: High involvement	3
Grooming: Low involvement	67
Smoking: High involvement	2
Smoking: Low involvement	83
Reading	1
Writing	2
Searching interior	2
Reaching for object in vehicle	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.

Statistical Analysis: In order to best analyze the relationship between the introduction of the IVBSS system and secondary task frequency, some independent variables were transformed:

- Wiper speed was excluded, and the independent variable simply became "Wiper on" or "Wiper off"
- Different surface street categories were combined to yield only two categories of road type, "Highway," (representing all limited access roads) and "Surface".
- Day or night was determined using solar angle. Times with solar angles greater than 96 degrees were considered "Night."

Descriptive statistics from the sample of 1980 clips are presented below in Table 9:

Table 9: Descriptive statistics for secondary task performance by drivers

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

When the sample is broken down by driver, there appears to be no clear affect of treatment on secondary task frequency. A plot of each driver's secondary task frequency under both conditions is presented below in Figure 17. From the plot below, 8 drivers performed more secondary tasks under the baseline condition, while 10 drivers actually performed more secondary tasks under the treatment condition.

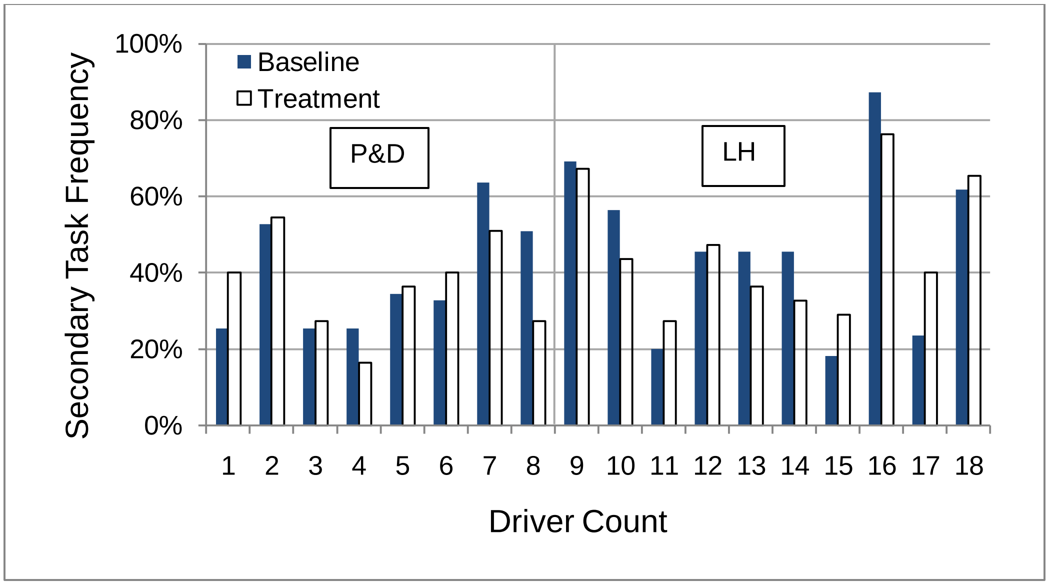

Figure 17: Secondary task frequency by condition for each driver

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. (Treatment (1, 17) F=.47, p=.5024) (Road type (1, 17) F=.45, p=.5141).

When the sample is broken down by driver and secondary task, the specific behaviors of each driver are apparent. Communication devices were the most common secondary task seen in the sample, with all but one driver seen at using a mobile phone at least once. Hand-held and Hands-free cell phone use by driver is presented below in Table 10. The one trend most apparent in the table below is the difference seen between P&D drivers and line-haul drivers. P&D drivers had almost no hands-free phone use, and were seen using a mobile phone in about 8 percent of clips, while line-haul drivers were seen using a phone in over 20 percent of clips. Line-haul drivers on the phone were seen using a hands-free device in 80 percent of mobile phone clips, while P&D drivers used a hands-free device in only 13 percent of mobile phone clips.

Table 10: Mobile phone use by route type (percentage of clips with phone use seen)

Route Type	Hand-Held Phone	Hands-free phone
P&D	7.0%	0.9%
Line-haul	4.2%	16.5%

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 considering the criteria listed below. 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 five video clips (out of 55) with windshield wiper use, five of the video clips for that driver's 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.

Results: A breakdown of the driving conditions for the 1980 clips is presented below in Table 11.

Table 11: Breakdown of clips reviewed for secondary tasks

Independent Variable	**Level**	**Preceding Warnings**	**Not Preceding Warnings**
Condition	Baseline	0	0
	Treatment	990	990
Road Type	Limited Access	541	546
	Surface	449	444
Ambient Light	Day	636	562
	Night	354	428
Weather	Wipers on	83	101
	Wipers off	907	889

A list of potential secondary tasks along with the coded frequencies from the 1980 clips is displayed below in Table 12.

Table 12: Frequency of secondary tasks among 1980 five-second clips

Secondary Task	Not associated with warnings	Preceding Warnings
No secondary task	573	602
Dialing Phone	4	11
Text messaging	18	21
Talking on/listening to hand-held phone	51	44
Talking on/listening (headset or hands-free)	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

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 Analysis: 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.

- Wiper speed was excluded, and the independent variable simply became "Wiper on" or "Wiper off"
- Different surface street categories were combined to yield only two categories of road type, "Highway," (representing all limited access roads) and "Surface".
- Day or night was determined using solar zenith angle. Times with solar zenith angles greater than 96 degrees were considered "Night."

Descriptive statistics from the 2 samples of 990 clips preceding warnings are presented below in Table 13 and Table 14.

Table 13: Descriptive statistics for secondary task performance by drivers in clips preceding warnings

Independent Variable	**Level**	**Secondary Task**	**No Secondary Task**	**Secondary Task %**
Route Type	P&D	176	264	40.0%
	Line-haul	212	338	38.5%
Road Type	Limited Access	207	334	38.3%
	Surface	181	268	40.3%
Ambient Light	Day	247	389	38.8%
	Night	141	213	39.8%
Weather	Wipers on	29	54	34.9%
	Wipers off	359	548	39.6%

Table 14: Descriptive statistics for secondary task performance by drivers in clips NOT preceding warnings

Independent Variable	Level	Secondary Task	No Secondary Task	Secondary Task %
Route Type	P&D	161	279	36.6%
	Line-haul	256	294	46.5%
Road Type	Limited Access	247	299	45.2%
	Surface	170	274	38.3%
Ambient Light	Day	223	339	39.7%
	Night	194	234	45.3%
Weather	Wipers on	38	63	37.6%
	Wipers off	379	510	42.6%

Overall, drivers were seen to be slightly less likely to be involved in a secondary task in the seconds preceding a warning than at some other randomly selected time. However, these two samples did not show a statistically significant difference in terms of secondary task frequency (Secondary task frequency, (1, 17) F=2.70, p=.1186).

When the data is examined by route type, P&D drivers actually were more likely to be involved in secondary tasks before warnings than at other times. The opposite trend was seen for line-haul drivers. This relationship is displayed in Figure 18 below. Across all independent variables, in clips preceding warnings, the variables associated with P&D drivers (day, surface streets) show a higher frequency of secondary tasks, while the conditions associated with line-haul drivers (night, highway) show a decrease.

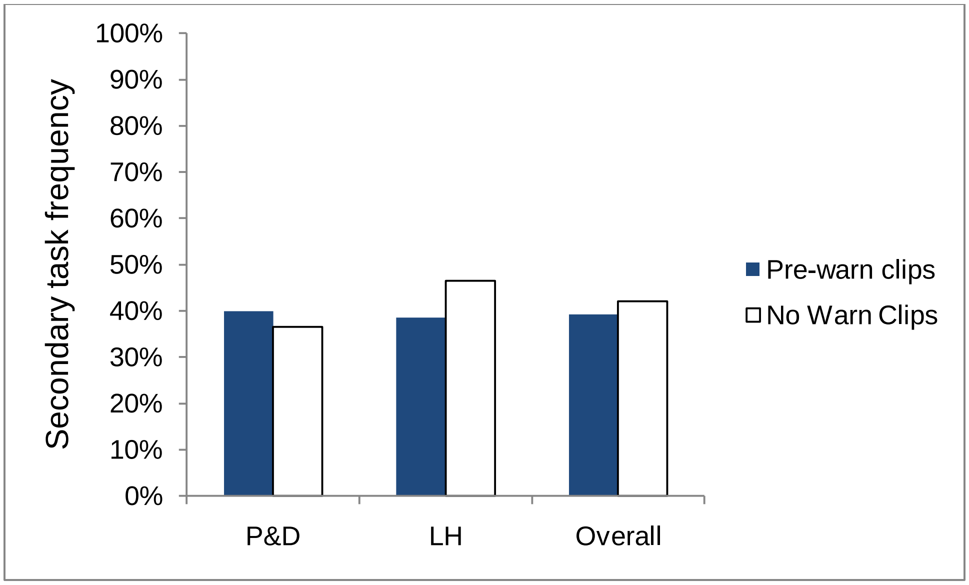

Figure 18: Relationship between secondary task frequency in Pre-warning clips and clips not associated with warnings.

A plot of each driver's secondary task frequency from both samples is presented below in Figure 19. The only trend visible in Figure 19 below is the slight tendency of P&D drivers to have a higher secondary task frequency in clips preceding warnings (to the left of the plot) versus line-haul drivers, most of whom had a higher frequency of secondary tasks in clips not associated with warnings (to the right of the plot).

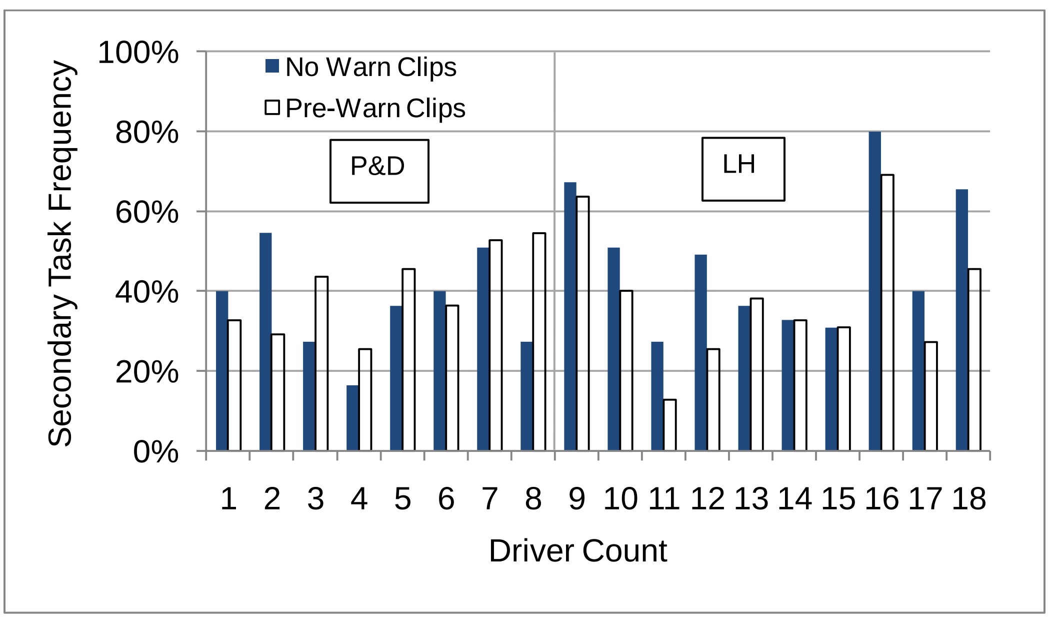

Figure 19: Secondary task frequency by condition for each driver

When the sample is broken down by driver and secondary task, the specific behaviors of each driver are apparent. Communication devices were the most common secondary task seen in the sample, with all but three drivers seen at using a mobile phone at least once. Hand-held and Hands-free cell phone use by driver is presented below in Table 15. The one trend most apparent in the table below is the difference seen between P&D drivers and line-haul drivers. P&D drivers had almost no hands-free phone use, and were seen using a mobile phone in about 7 percent of clips, while line-haul drivers were seen using a phone in about 10 percent of clips. Line-haul drivers on the phone were seen using a hands-free device in 80 percent of mobile phone clips, while P&D drivers used a hands-free device in only 3 percent of mobile phone clips.

Table 15: Mobile phone use by driver

Route Type	Hand-Held Phone	Hands-Free Phone
P&D	7.0%	0.2%
Line-haul	2.0%	7.8%

Discussion: In the interpretation of QC1, it was inferred that drivers were more willing perform secondary tasks when in situations with lower complexity (i.e. highways at night). The decrease in the proportion of clips with secondary tasks for line-haul drivers in the sample preceding warnings seems to support this. Line-haul drivers in areas where they were likely to receive warnings may have tended to avoid secondary tasks. Further, line-haul drivers may engage in secondary tasks (specifically eating and phone use) during periods of low complexity in order to remain stimulated and alert.

Conversely, the increased frequency of secondary task performance in the sample of clips preceding warnings by P&D drivers seems to indicate P&D drivers do not follow the same pattern. For P&D drivers, it is possible that performing secondary tasks increased the likelihood of receiving a warning.

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.

3.3.2 Response to Multiple Threats

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

Method: 244 events were found where a driver received a valid lateral alert and a forward crash warning within 3 seconds of each other. Of these, 140 had forward crash warnings elicited by a legitimate on-road target. Of the remaining 140 events, in 35 the driver received a lateral warning and a forward warning but they were unrelated. For example, a driver may casually drift from their lane, and then within 3 seconds a turning POV in front of them elicits an FCW. These unrelated warning events were removed from this analysis set. When only events in valid trips under the treatment condition were considered, 83 legitimate multiple warning events were left to be analyzed. Of these warnings, 78 took place on highway and 5 took place on surface streets. Also, 21 warnings took place at night while 62 took place during the day. One reason for the small sample here could be the fact that drivers were not on the highway during the day as much as in other environments, and from this sample that appears to be the environment in which multiple warnings occurred.

The multiple-threat warnings observed in the field test can each be described by one of the following five scenarios: Figure 20 through Figure 24 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 which the system identifies as the principle threat when a warning is issued. In scenarios 1 through 4, drivers were generally aware of their driving environment and preparing to make a lane change.

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.

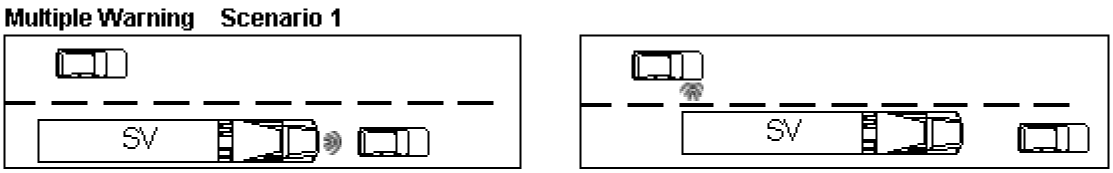

Figure 20: Illustration of Multiple Warning Scenario 1

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.

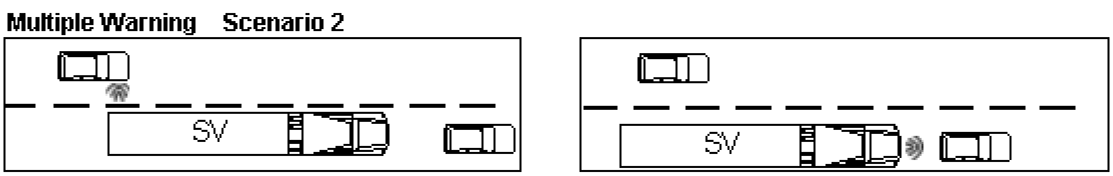

Figure 21: Illustration of Multiple Warning Scenario 2

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.

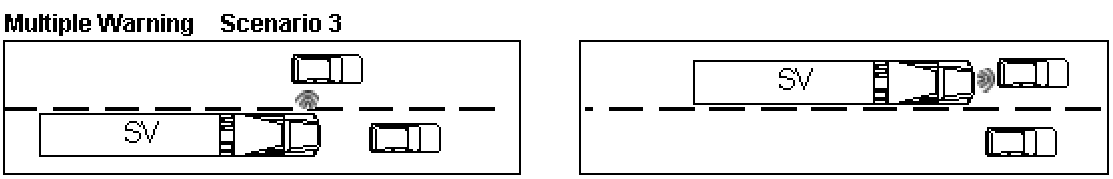

Figure 22: Illustration of Multiple Warning Scenario 3

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.

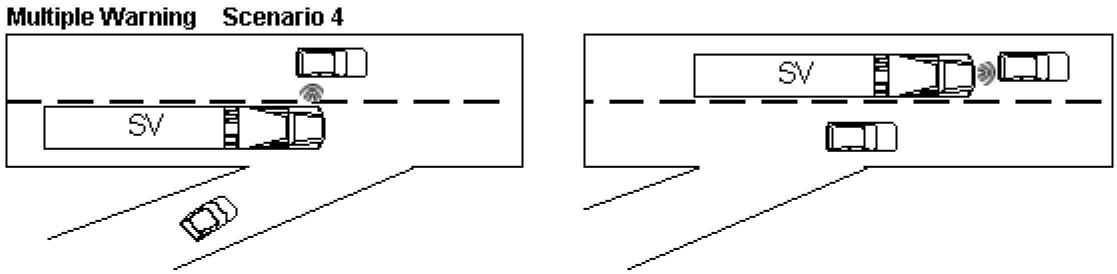

Figure 23: Illustration of Multiple Warning Scenario 4

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.

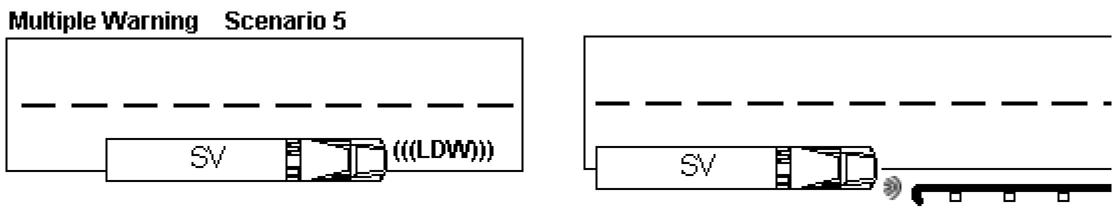

Figure 24: Illustration of Multiple Warning Scenario 5

Counts of the events falling under each of the above scenarios are displayed in Table 16 below.

Table 16: Counts for each category of multiple warnings

Scenario	Description	Count
1	FCW from slow lead POV, then Lateral alert	2
2	Lateral, then FCW from slower lead POV	30
3	Lateral, then FCW from new passing POV, No slower POV	27
4	Lateral, then FCW from new passing POV, initial slower lead POV	19
5	Sequential warnings into a roadside object	5
	TOTAL	83

Drivers' behaviors were different depending on which scenario they were involved in. The two events in scenario 1 were unusual. In one event, the driver changed lanes to move behind a faster POV, while the hazard lights were on, this caused an LCM warning as a car was passing on the right in the far right lane, and the system saw lateral movement (a relic of the initial lane change) in that direction with the turn signal (hazard lights) on. In the other scenario 1 event, the driver simply forgot to use the turn signal when changing lanes to go around a slower POV. Neither driver used the brakes to respond to the forward threat.

Under scenario 2, drivers were approaching a slower POV in their lane, and received a lateral warning when they began moving laterally to change lanes (with the turn signal on). As the drivers slowly moved laterally waiting for the faster-moving car in the adjacent lane to pass, they receive a Forward crash warning from the initial, slower moving lead vehicle. Drivers generally timed these maneuvers well enough to not require braking or even the release of the throttle. In 10 of the 30 events under scenario 2, the driver released the throttle, but in only 6 of these did the driver use the brake as well. In the events requiring a driver reaction to avoid the lead vehicle, the driver simply planned for the adjacent lane to clear in time to safely make the lane change, but it did not. The summary of responses to the multiple threats is presented in Table 17 below.

Table 17: Responses to multiple warnings

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

Scenarios 3 and 4 were more benign as the Forward crash warning was elicited by a lead POV that was moving faster than the subject vehicle. In only 7 events under scenario 3 or 4 (7 out of 46) did the driver need to release the throttle at all. In those 7 cases the speed of the truck dropped only 1 or 2 miles per hour, indicating only a small correction in speed was necessary to clear the situation. While the LCM warning and the subsequent forward crash warning were close in time, they were essentially unrelated as the driver had successfully made the lane change before the POV braked.

Interpretation: In general these drivers were very aware of the road environment around them. In none of the Scenario 1-4 multiple warning clips did the driver seem surprised by either of the warnings.

However, drivers in the scenario 5 events were fortunate to receive the warnings. In all cases the driver was distracted or drowsy and may have struck a roadside object had the system not warned when it did. While the initial warning was helpful, it did not appear that the second warning (in these cases a forward crash warning) was helpful. In all 5 cases the driver began to respond before the second of the multiple warnings.

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 four 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).

However, in one of these events, the driver was looking down at his phone and actually disregarded the drift warning for a full second before looking up and returning to the lane. Even in this case though, the driver reacted before getting the forward crash warning. This event does raise the issue of whether the number of drift warnings may cause drivers to begin paying less attention to them.

While the warnings would have been useful for a driver not careful about checking blind spots or too distracted to notice a slow lead POV, these drivers in these situations appeared to get little value from these multiple warnings. It appears one warning is enough to get the drivers attention back to the road environment. However, in none of these cases was the driver presented with two unexpected hazards simultaneously, in which case two warnings may be helpful. Also, because of the relatively slow speed of the trucks on the highways, these situations did not develop quickly. Often the driver was approaching a slower POV that was only going slightly slower than the subject vehicle. This gave the driver plenty of time to recognize the slower POV and plan a safe lane change.

3.3.3 Driver Acceptance Research Questions

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

Table 18: Compiled post-drive questionnaire results relating to changes in drivers' behavior

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q7	Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane. *1=strongly disagree, 7=strongly agree*	5.2	1.8	5.6	1.6	4.9	2
		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**"Yes"**	**"No"**	**"Yes"**	**"No"**	**"Yes"**	**"No"**
Q14	As a result of driving with the integrated system did you notice any changes in your driving behavior?	7	11	5	3	2	8
Q13	Did you rely on the integrated system?	5	13	1	7	4	6

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. Five of the ten P&D drivers responded affirmatively to this question, indicating that they were more likely to report a change in driving behavior. Among the ten line-haul drivers, only two responded that they changed their behavior as a result of driving with the integrated system. When allowed to provide open-ended responses, three drivers stated that the integrated system made them more alert, and two 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. Three drivers firmly disagreed with the statement (Drivers 1, 27, and 29). Figure 25 details these findings.

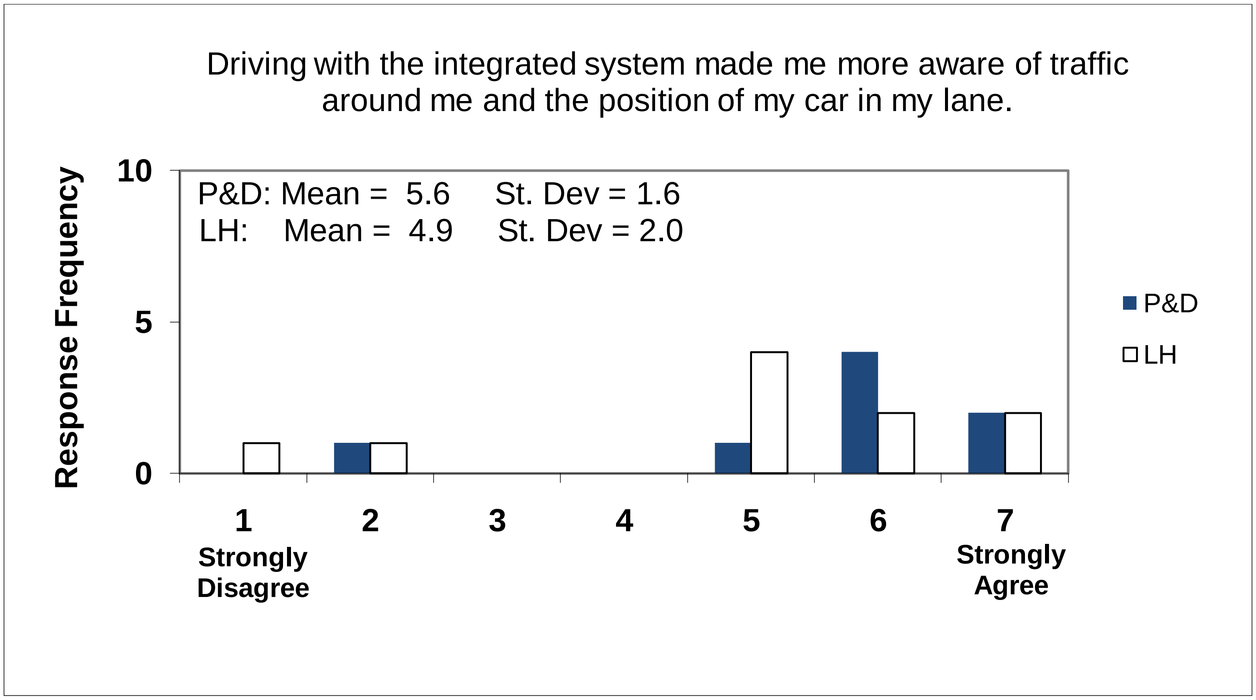

Figure 25: Responses to Post-drive Questionnaire Q7. "Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane"

As experienced professional drivers, it would not have been surprising if the drivers were hesitant to report relying on the integrated system. The fact that even 5 out of 18 drivers admitted to relying on the integrated system likely indicates that it helped them drive safely.

This set of drivers has been driving commercially for between 10 and 30 years. Line-haul drivers averaged 7 more years of experience than P&D drivers (information of driving experience is displayed below in Table 19.)

Table 19: Commercial driving experience (years with commercial drivers license)

	Average Years with CDL	**Std. Dev. Yrs with CDL**
P&D	18.9	7.5
LH	25.4	5.0

This difference in experience may account for more P&D drivers reporting changes in their behavior as they were less set in their behaviors when compared to the more experienced line-haul drivers. The two line-Haul drivers reporting that they did change their behavior as a result of driving with the integrated system were also the two least experienced line-Haul drivers.

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

Table 20: Compiled post-drive questionnaire results relating to drivers' acceptance

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q12	Overall, how satisfied were you with the integrated system? *1=very dissatisfied, 7=very satisfied*	4.9	1.5	5.1	1.6	4.8	1.4
		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**"Yes"**	**"No"**	**"Yes"**	**"No"**	**"Yes"**	**"No"**
Q39	Do you prefer to drive a truck equipped with the integrated system over a conventional truck?	15	3	6	2	9	1
Q40	Would you recommend that the company buy trucks equipped with the integrated system?	15	3	7	1	8	2

Responses from 3 questions relating to drivers' acceptance of the integrated warning system are presented above in Table 20. In terms of driver acceptance, there was very little difference between responses from P&D drivers and responses from line-haul drivers. For Q12, both groups were fairly satisfied with the system overall, with P&D drivers giving it a slightly higher mean score. The spread of drivers' responses to Q12 are displayed below in Figure 26. From the figure, 2 drivers responded that they were fairly dissatisfied with the system (Drivers 1 and 29.) Most drivers were neutral, with 10 of 18 drivers scoring the question either a 4 or 5.

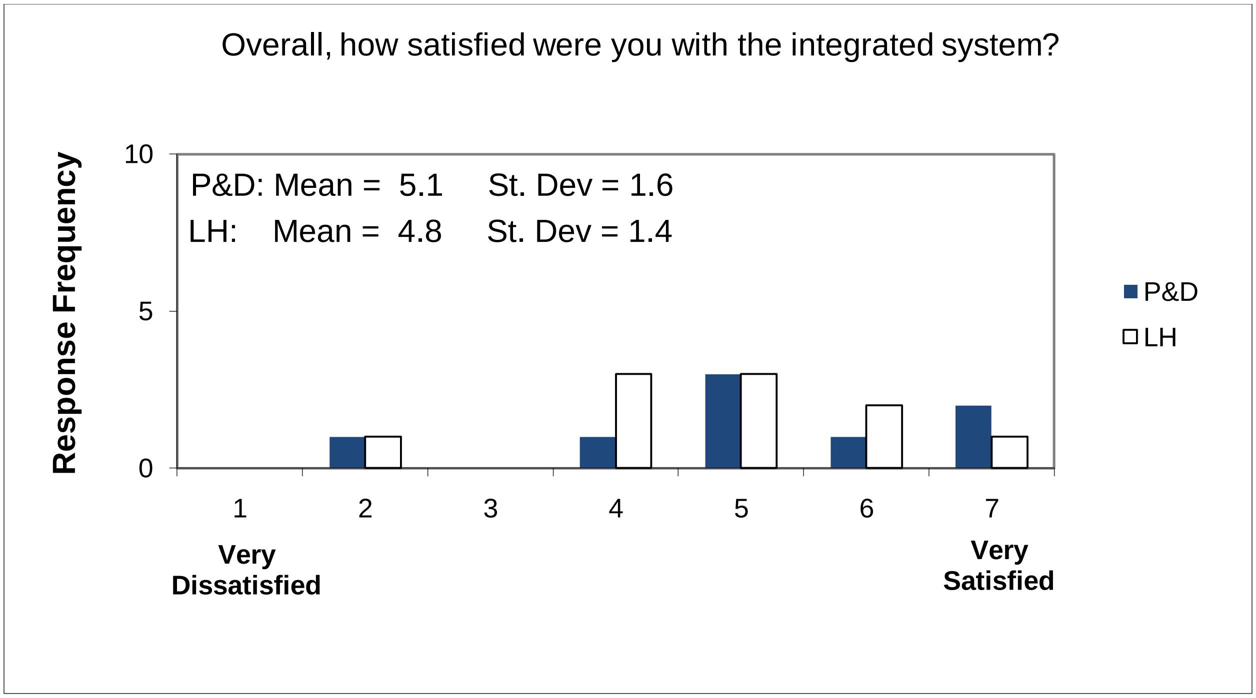

Figure 26: Responses to, "Overall, how satisfied were you with the integrated system?

When asked specifically if they preferred a truck with the integrated system in Q39, almost all drivers responded that they would prefer it over their conventional truck. This was consistent across both route types. Only three drivers responded that they wouldn't prefer a truck with the system, drivers 1, 10 and 29, two of whom also were negative in terms of their satisfaction in Q12 above. Driver 10 remarked that it would be useful to line-haul drivers, but not as useful for city (P&D) drivers. Five drivers remarked that they felt the system made them more alert. Driver 29, who preferred his conventional truck, remarked that "the system made too much a noise and gave me too many false warnings"

In Q40, drivers were asked if they would recommend that their company buy trucks equipped with the integrated system. Again, similar to Q39, drivers overwhelmingly responded that they felt the company should buy trucks equipped with the integrated system. Comments from these drivers recommending purchase generally referred to a likely increase in safety. Four drivers specifically commented that they thought the integrated system would reduce accidents. Of the drivers who responded that they would not recommend the integrated system to their company (Drivers 1, 25 and 29), two cited the number of false alerts as the reason behind their response.

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. While a few drivers felt that the annoyance of the false alarms outweighed the safety benefit provided by the system, the majority of drivers were willing to accept the imperfections of the system because they felt it made them safer drivers.

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

Table 21: Compiled post-drive questionnaire results relating to the salience of the warnings

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q11	I was not distracted by the warnings. *1=strongly disagree, 7=strongly agree*	4	1.4	4.4	1.4	3.7	1.3
Q17	The auditory warnings got my attention. *1=strongly disagree, 7=strongly agree*	5.8	0.9	5.8	1.3	5.9	0.6
Q18	The auditory warnings were not annoying. *1=strongly disagree, 7=strongly agree*	3.9	2	4.4	2.1	3.6	1.9
Q19	The yellow lights mounted near the exterior mirrors got my attention *1=strongly disagree, 7=strongly agree*	4.3	2.1	4.4	2.3	4.3	2
Q20	The yellow lights mounted near the exterior mirrors were not annoying *1=strongly disagree, 7=strongly agree*	5.7	1.5	6.1	1.4	5.3	1.5
Q35	The two lane change/merge warning displays mounted near the exterior mirrors were useful. *1=strongly disagree, 7=strongly agree*	4.8	1.9	4.8	2.2	4.8	1.8
Q36	The lane change/merge warnings are displayed in a convenient way. *1=strongly disagree, 7=strongly agree*	4.6	2	4.9	1.9	4.3	2.2

Responses from 7 questions relating to drivers' opinions of the warning modalities are presented above in Table 21. In general, overall responses regarding the salience of the warnings were mostly neutral. Line-haul drivers as a group did find the auditory warnings somewhat distracting and annoying (responses to Q11 are presented in Figure 27 below.) Otherwise, drivers seemed largely comfortable with the manner in which warnings were presented. While the means for both Q11 and Q18 regarding drivers' opinions of the auditory warnings were neutral, the spread of responses was quite large. Responses to Q11 and Q18 regarding the auditory warnings are presented in Figure 27 and Figure 28 below, respectively.

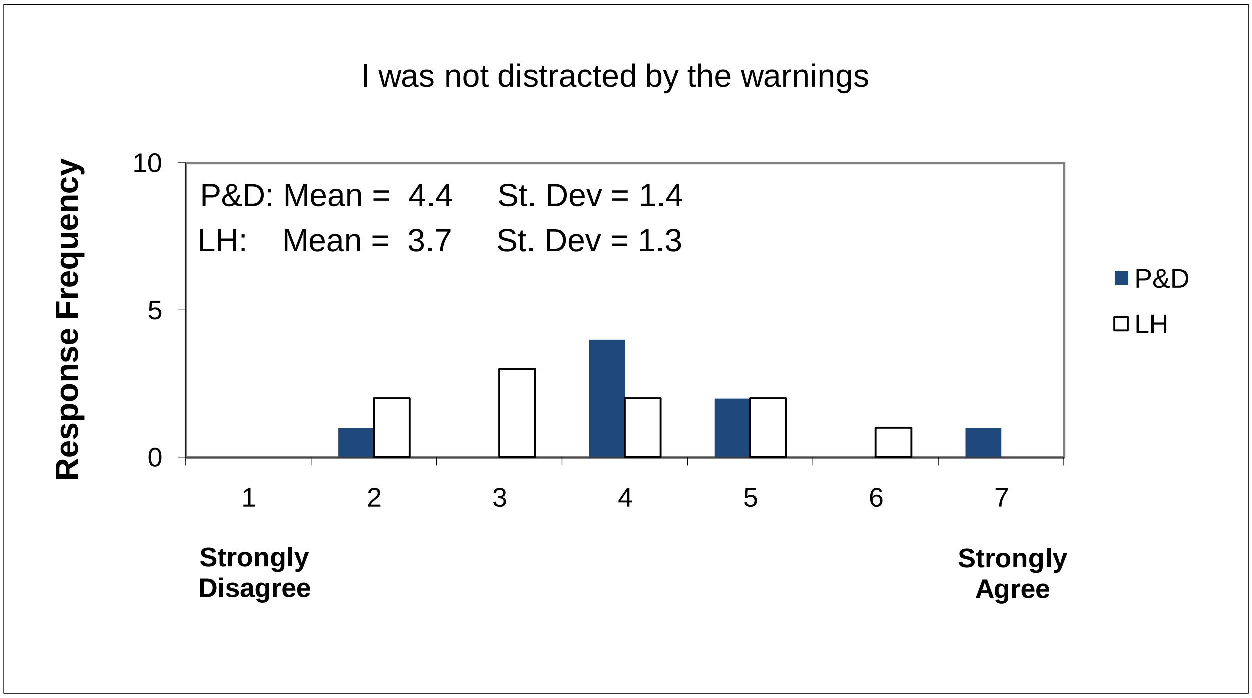

Figure 27: Responses to, "I was not distracted by the warnings"

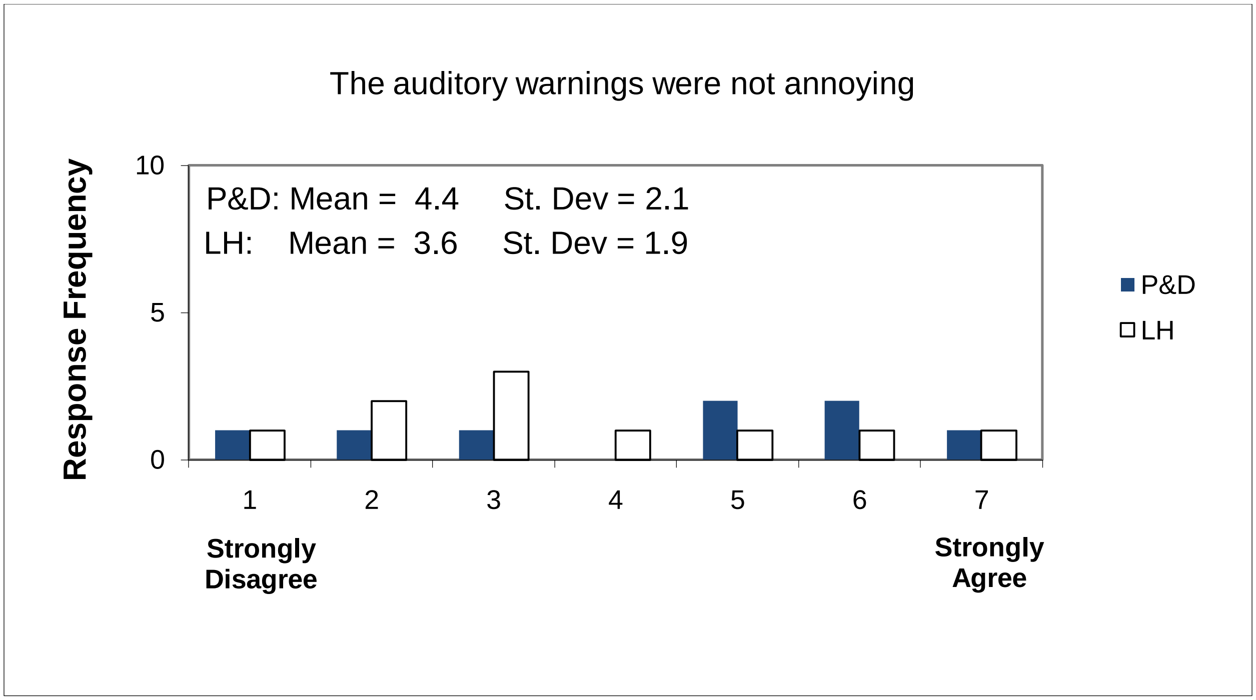

Figure 28: Responses to, “The auditory warnings were not annoying"

Based on these responses, 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 likely considered more than simply the warning tone and volume. Drivers who felt the system provided them with too many warnings they did not need would be more apt to find the warnings annoying regardless of the salience.

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 ten times as many of these invalid warnings as P&D drivers, with 72 percent of all FCWs issued for line-haul drivers being invalid warnings due to fixed roadside objects, overpasses and bridges. (The count of these warnings is presented below in Table 22.)

Table 22: Fraction of FCWs resulting from "stopped object"

Line-haul Stopped Object FCW	Total Line-haul FCW	Fraction
8041	11198	72%

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 (Figure 29).

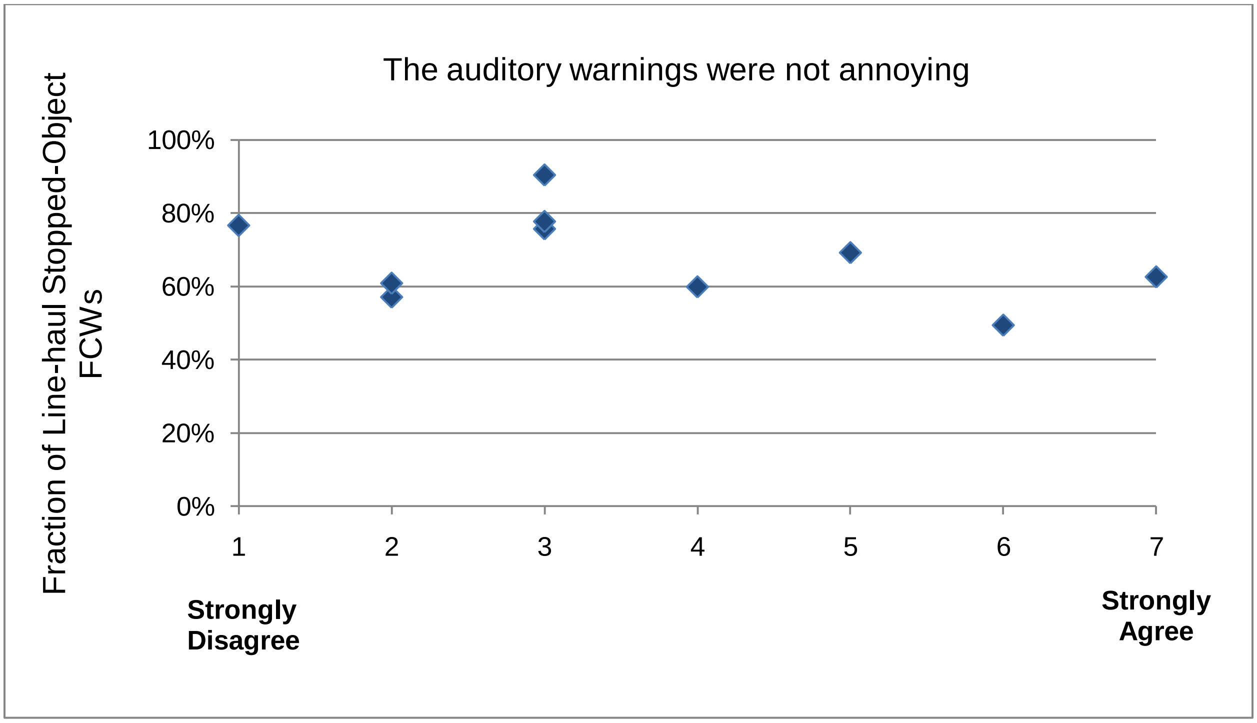

Figure 29: Fraction of "stopped object" Forward collision warnings versus line-haul drivers' responses to Q18.

Responses to Q35 indicate that drivers found the presence of the BSD side-warning lights useful; however, based on responses to Q19 and Q36, the lights could potentially be located in a more convenient way to catch drivers' attention more effectively. Currently drivers responded that the BSD side-warning lights were not annoying, however if the lights were repositioned to make them more salient to the drivers, care must be taken to ensure they do not become an 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.

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

Table 23: Compiled post-drive questionnaire results relating to drivers' perceived safety benefit

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q4	How helpful were the integrated system's warnings? *1=Not all Helpful, 7=Very Helpful*	5.0	1.4	4.9	1.5	5.1	1.4
Q6	Overall, I think that the integrated system is going to increase my driving safety. *1=strongly disagree, 7=strongly agree*	5.0	1.7	5.1	1.6	4.9	1.8
Q7	Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane. *1=strongly disagree, 7=strongly agree*	5.2	1.8	5.6	1.6	4.9	2
		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**"Yes"**	**"No"**	**"Yes"**	**"No"**	**"Yes"**	**"No"**
Q10	Did the integrated system prevent you from getting into a crash or near a crash?	8	10	4	4	4	6

Responses from 4 questions regarding drivers' opinions on the safety benefit of the integrated system are presented above in Table 23. Q6 provides the clearest picture into drivers' opinions about the safety benefit of the integrated system. Overall drivers felt that the system would somewhat increase their driving safety, with P&D drivers feeling slightly stronger about this than their line-haul counterparts. Figure 30 below displays the drivers' responses to Q6. From Figure 30 below, most individual drivers did feel that their driving safety was at least somewhat increased with the integrated system, however, Drivers 1, 27 and 29, who have previously scored the system more negatively than other drivers did not feel they received a safety benefit.

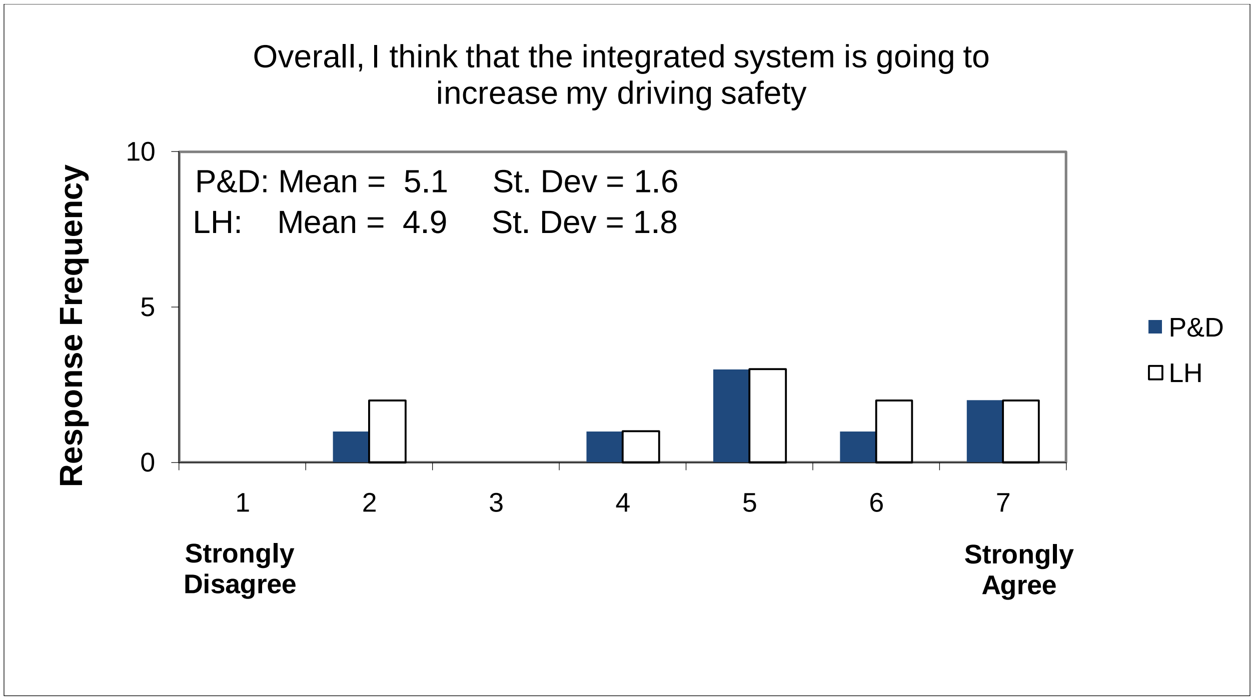

Figure 30: Responses to, "Overall, I think the integrated system is going to increase my driving safety"

Other questions in this group follow a similar pattern. Q4, regarding the helpfulness of warnings also received slightly better than neutral response. Only Driver 1, 27 and 29 scored the integrated system's warnings on the "not at all helpful" side of the scale.

Again, when asked whether the system made the drivers more aware of the traffic environment around them, the same pattern emerges. The plot of Q7 from the QC4 section also shows the same distribution, with only Drivers 1, 27 and 29 disagreeing that they received increased situational awareness from the integrated system.

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 four (3 P&D, 1 line-haul) drivers commented that it helped them avoid some type of forward crash. Interestingly, two 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 31. 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.

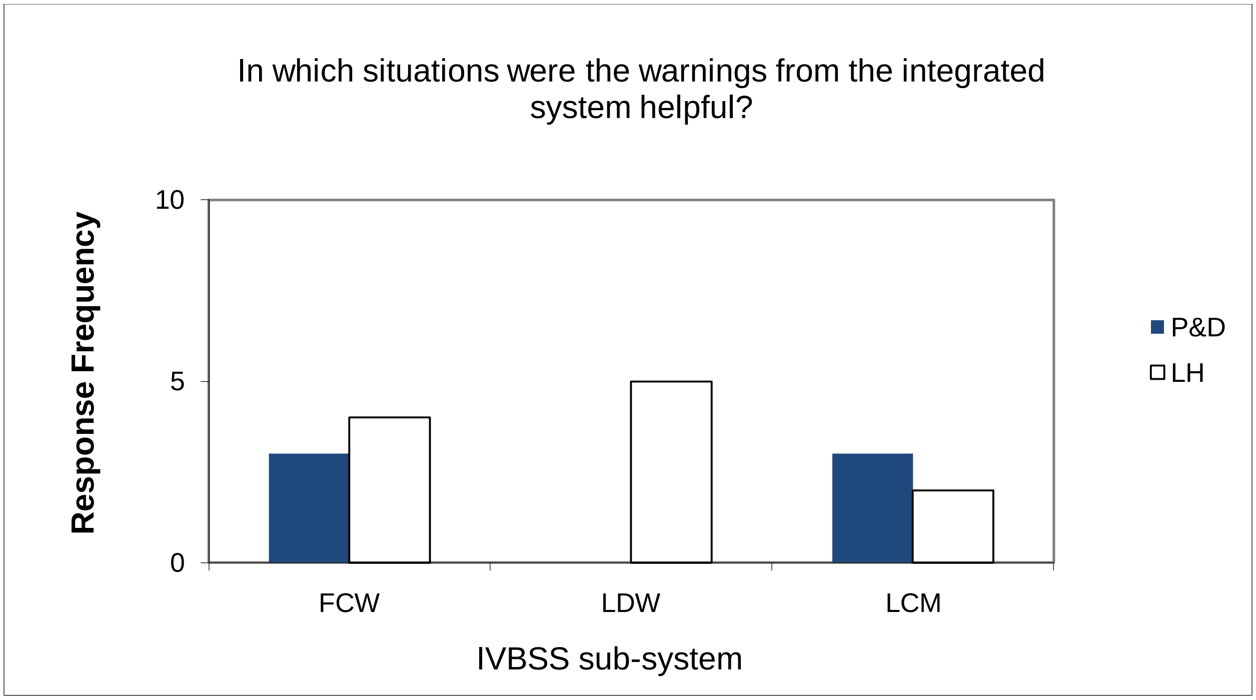

Figure 31: Aggregated summary of responses by warning type to Q5. "In which situations were the warnings from the integrated system helpful?"

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?

Table 24: Compiled post-drive questionnaire results relating to the convenience of use of the integrated system

		Overall		P&D		Line-haul	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q9	The integrated system made my job easier. *1=strongly disagree, 7=strongly agree*	4.3	1.8	4.3	2.2	4.3	1.6
Q16	I could easily distinguish among the auditory warnings? *1=strongly disagree, 7=strongly agree*	5.7	1.0	5.8	0.9	5.7	1.1
Q23	The number of false warnings caused me to begin to ignore the integrated system's warnings. *1=strongly disagree, 7=strongly agree*	3.6	1.9	2.5	1.7	4.4	1.6
Q24	The integrated system gave me warnings when I did not need them. *1=strongly disagree, 7=strongly agree*	5.9	1.5	5.9	1.1	5.9	1.7
Q31	The integrated system display was useful. *1=strongly disagree, 7=strongly agree*	5	1.2	5	1.2	5	1.3

When drivers were asked directly in Q9 whether driving with the integrated system made their jobs easier, responses from line-haul drivers were spread across the board, while P&D drivers basically fell into 3 groups. Four P&D drivers (Drivers 2, 4, 5, 6) scored the question a “6”, agreeing that the integrated system actually made their job easier. Three P&D drivers scored the questions a neutral “4”, and two drivers (Drivers 1 and 8) scored this question a “1”, indicating they strongly disagreed that the integrated system made their job easier. These drivers (1 and 8) consistently scored the system more negatively than the other P&D drivers.

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.

Too many false warnings would certainly affect the convenience of using the system. When asked in Q24 whether the system gave the drivers warnings which they did not need, all but one driver agreed that it did. Driver 21 scored the question a "2" implying that the system gave him few warnings which he felt he did not need.

False warnings affected different drivers' perceptions of the system differently. For Q23, line-haul drivers were much more likely to agree that the false warnings caused them to begin to ignore the integrated system. Responses to Q23 are displayed below in Figure 32. From Figure 32 it is apparent that line-haul drivers' responses are shifted to the right, while P&D drivers' responses are shifted to the left.

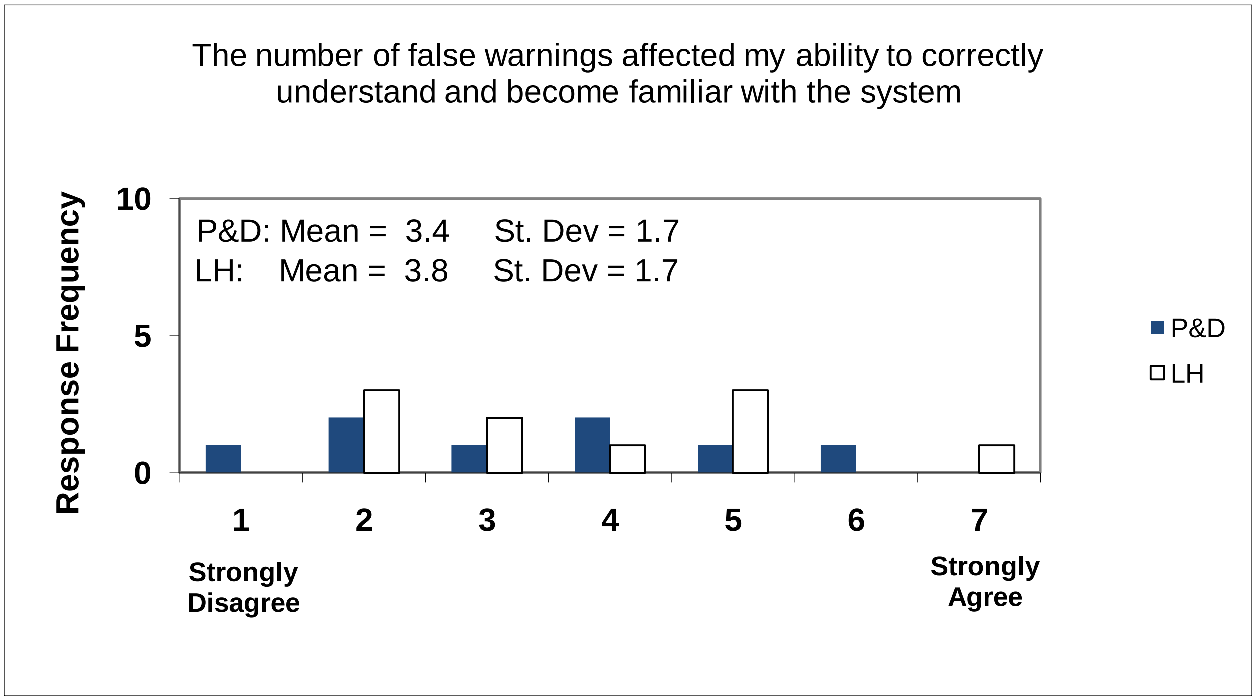

Figure 32: Responses to, "The number of false warnings caused me to begin to ignore the integrated system's warnings."

Interpretation: This is probably a result of a number of factors including the prevalence of false warnings by route type, the type of false warnings received and the situations in which the false warnings were received. Line-haul drivers were much more likely to receive false forward collision warnings in situations with relatively low traffic density (mainly limited access roads at night.) These warnings would be easy to ignore as a driver paying attention could clearly determine the warning was false by the absence of a vehicle in front of the truck. Also, line-haul drivers drove identical routes under very similar conditions night after night, so they began to expect certain false warnings resulting from specific pieces of infrastructure (overpasses, guardrails) at consistent locations on a nightly basis. For example, one line haul driver received the same false forward collision warning from the same overpass 205 times over the course of the FOT. Other drivers had similar experiences. Another line-haul driver received 972 false forward collision warnings over the course of the FOT from only 8 different overpasses. 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 much more likely to get false warnings in situations with more complexity, (surface streets, daytime). In these situations it would not be so easy to determine the validity of a warning quickly, especially when it was false. Cars cutting in front of the trucks or sneaking up into the lateral blind spots were much more common in P&D situations, so drivers receiving warnings in these situations understandably were less likely to dismiss warnings until they could mentally clear the area from which the warning originated.

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

Table 25: Compiled post-drive questionnaire results relating to driver's opinions on the usefulness of warnings

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q24	The integrated system gave me warnings when I did not need them. *1=strongly disagree, 7=strongly agree*	5.9	1.4	5.9	1.1	5.9	1.7
Q26	The integrated system gave me left/right hazard warnings when I did not need them. *1=strongly disagree, 7=strongly agree*	4.8	1.9	3.7	1.8	5.8	1.5
Q27	The integrated system gave me left/right drift warnings when I did not need them. *1=strongly disagree, 7=strongly agree*	4.4	1.9	3.7	1.8	5.1	1.8
Q28	The integrated system gave me hazard ahead warnings when I did not need them. *1=strongly disagree, 7=strongly agree*	4.9	1.7	4.6	1.7	5.2	1.8

Table 25 above presents means and standard deviations of drivers' responses to questions regarding the prevalence of warnings they felt that they did not need. 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 which they did not need, drivers of the different route types gave different responses, with line-haul drivers more strongly agreeing with the statements (that they received warnings they did not need).

Of the three warning subsystems, the 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 warning they did not need. For both route types, Q24, regarding the overall prevalence of unneeded warnings was more strongly agreed with than any question covering a specific warning type.

When comparing the actual warning rates to the drivers' responses, a slight trend can be seen. Figure 33 below presents invalid warning rates compared to drivers' responses to Q24. FCW's with threat level 8 were found to be over 99 percent invalid, and were considered invalid for this analysis. Also considered invalid here were Lane change/merge warnings with no adjacent vehicle present, and imminent drift warnings with no adjacent vehicle present where the driver did not drift far enough to elicit a cautionary drift warning. The two drivers with the highest rates of invalid warnings scored Q24 a 7, however two drivers with nearly the lowest rates of invalid warnings scored Q24 high. It does appear as invalid warning rates increased, so did drivers' responses to Q24.

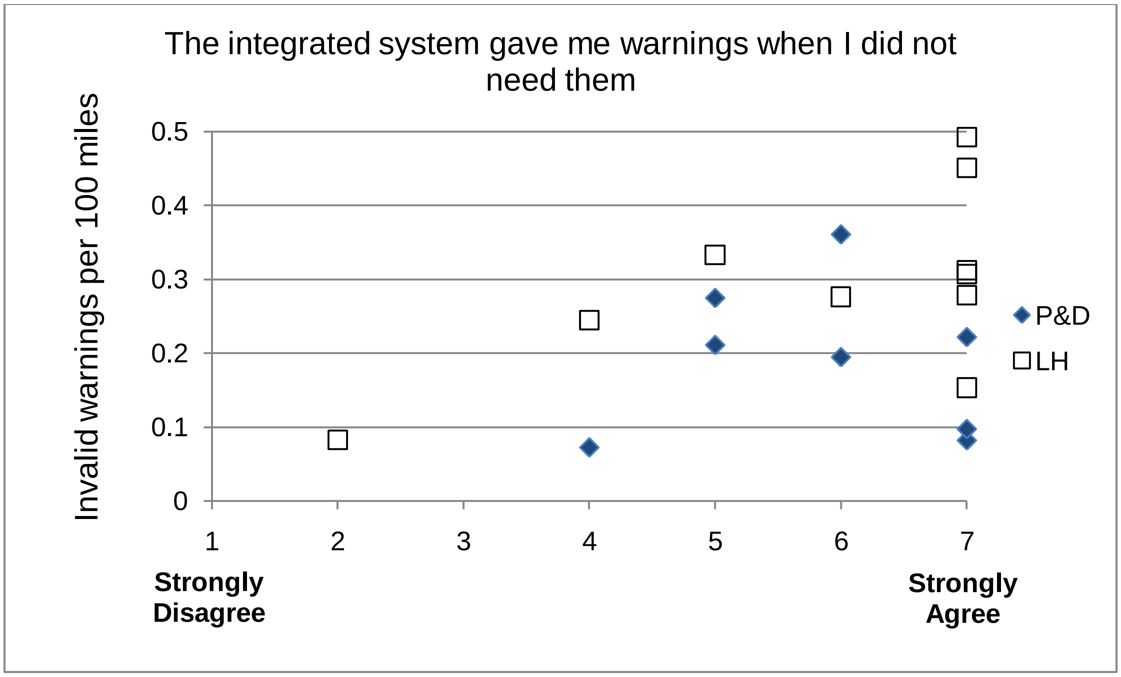

Figure 33: Invalid warning rate versus Drivers' responses to Q24 "The integrated system gave me warnings when I did not need them."

While half of the drivers strongly agreed with the statement in Q24, it appears drivers with lower invalid warning rates did not agree quite as strongly as drivers with higher warning rates.

When the sub-systems are examined individually, driver's responses do not mirror the objective warning rates closely. Figure 34 below presents valid warning percentages for each of the sub-systems.

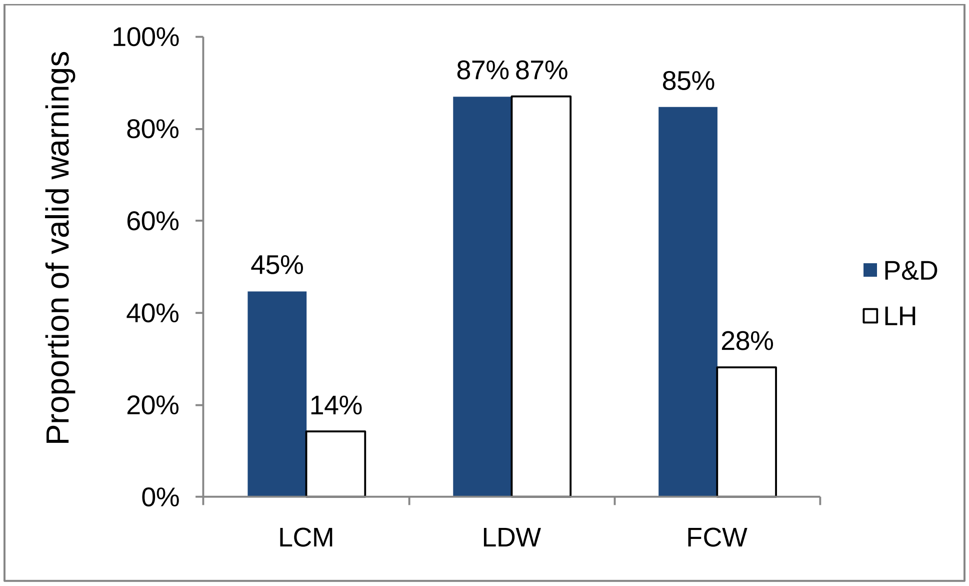

Figure 34: Proportion of valid warnings for each warning type

Drivers of both route types experienced a similar proportion of valid left and right lane departure warnings. P&D drivers had a higher proportion of valid LCM warnings, and a much higher proportion of valid FCW warnings.

Overall drivers' responses to Questions Q26, Q27 and Q28 did not closely mirror the proportions presented in Figure 34. Figure 35 below plots the drivers' mean responses to these questions (means and standard deviations can be seen above in Table 25).

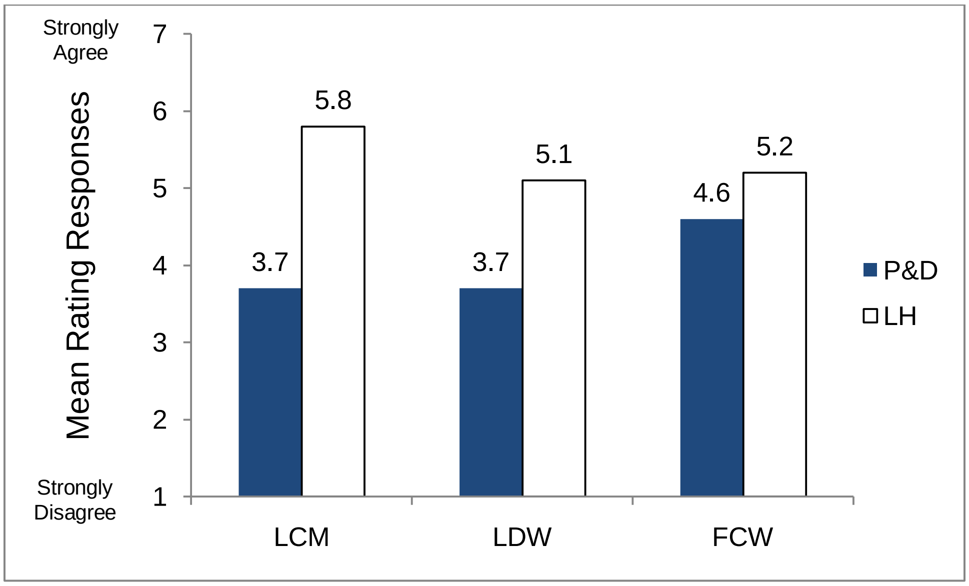

Figure 35: Mean responses to Q26, Q27 and Q28 by route type

The relationship of valid lateral drift warnings for LH drivers and valid forward crash warnings for P&D drivers as seen in Figure 34 was not reflected in drivers' opinions of the invalid warning rates presented in Figure 35. P&D drivers responded that they received the most forward crash warnings that they did not need, despite the fact that most of these warnings P&D drivers received (85%) should have been at least somewhat valid. Counts of the invalid warnings for each subsystem are presented below in Table 26 along with the corresponding proportion of all warnings for that route type.

Table 26: Counts of invalid warnings for each subsystem (percentage of all warnings received)

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 to Q26 that they received LCM warnings they did not need.

While line-haul and P&D drivers had roughly the same proportion of valid lane departure warnings, line-haul drivers received over 5 times more of these invalid warnings than the P&D drivers.

Interpretation: As discussed previously in other sections, drivers' opinions of invalid warnings likely depended on the situations in which they were received. While line-haul drivers grew accustomed to consistent invalid forward crash warnings from fixed objects on their fixed route, left/right hazard warnings occurred at much less predictable times. This may explain line-haul drivers responding that they received the most left/right hazard warnings that they did not need relative to the other sub-systems despite the higher actual proportion of forward crash warnings that 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 did have a much higher fraction of valid forward crash warnings than line-haul drivers, but the invalid warnings would have been much more startling as they were generally more unexpected and likely in areas where it was possible that another vehicle had quickly moved in front of the tractor. This salience of invalid forward crash warnings for P&D drivers may account for the relatively high mean score in Q28.

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

Table 27: Compiled post-drive questionnaire results relating to the ease of use of the integrated system

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q15	I always knew what to do when the integrated system provided a warning. *1=strongly disagree, 7=strongly agree*	5.7	1.2	6.1	0.6	5.3	1.4
Q23	The number of false warnings caused me to begin to ignore the integrated system's warnings. *1=strongly disagree, 7=strongly agree*	3.6	1.9	2.5	1.7	4.4	1.6
		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**"Yes"**	**"No"**	**"Yes"**	**"No"**	**"Yes"**	**"No"**
Q21	Did the integrated system perform as you expected? *Yes or No*	14	4	8	0	6	4

Table 27 above presents the results from 3 questions regarding the ease of use of the integrated system. Drivers of both route types found the integrated system to be easy to use. Responses to Q15 show drivers had a good understanding of the operation of the integrated system, with only one driver at all 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.

Drivers had varying opinions of the false warnings. Responses to Q23 show that line-haul drivers indicated that they somewhat began to ignore warnings, while P&D drivers did not. Responses to Q23 are broken down by route type and are displayed below in Figure 36.

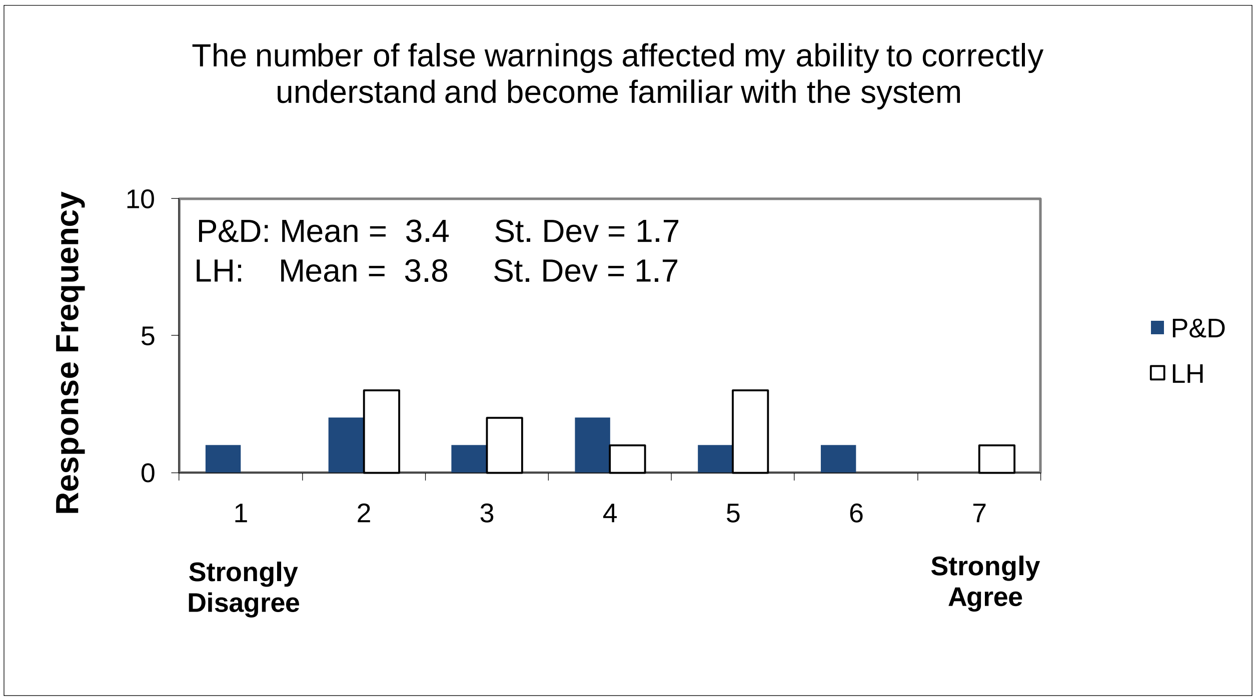

Figure 36: Responses to, “The number of false warnings caused me to begin to ignore the integrated system's warnings."

Interpretation: This was likely a result of the nature of the false warnings received by each route type. P&D drivers were much more likely to receive nuisance forward crash warnings at unpredictable times, which would be difficult to ignore as there was usually some lead vehicle present in the forward scene. Line-haul drivers on the other hand received many Forward crash warnings from overpasses and fixed objects in the same locations night after night on empty roads where it would be very unlikely for a forward hazard to appear quickly. Lane Change/Merge warnings were similar in that P&D drivers were in environments where any warning could be potentially legitimate. Line-haul drivers on the highway were less likely to have unexpected lateral threats appear.

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

Table 28: Compiled post-drive questionnaire results relating to the ease of understanding the integrated system

Q#	Question		1 day	2 days	1 week	1 month
Q8	How long after it became enabled did it take you to become familiar with the operation of the integrated system?	P&D	4	2	1	1
		Line-Haul	3	3	4	0

		Overall		P&D		Line-haul	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q16	I could easily distinguish among the auditory warnings? *1=strongly disagree, 7=strongly agree*	5.7	1.0	5.8	0.9	5.7	1.1
Q22	The number of false warnings affected my ability to correctly understand and become familiar with the system. *1=strongly disagree, 7=strongly agree*	3.6	1.6	3.4	1.7	3.8	1.7

Table 28 above presents the results from 3 questions regarding the ease of understanding the integrated system. Drivers of both route types found the integrated system to be easy to understand. Responses to Q8 show drivers quickly felt familiar with the integrated system after an accompanied test drive and just a few shifts with the integrated crash warning system enabled.

Most important in drivers' understanding of the system was their ability to correctly interpret the warnings that they received. When directly asked about this in Q16, drivers of both route types 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 warning over the course of the entire FOT, most drivers felt that these did not affect their understanding of the system. Driver responses to Q22 are plotted in Figure 37 below.

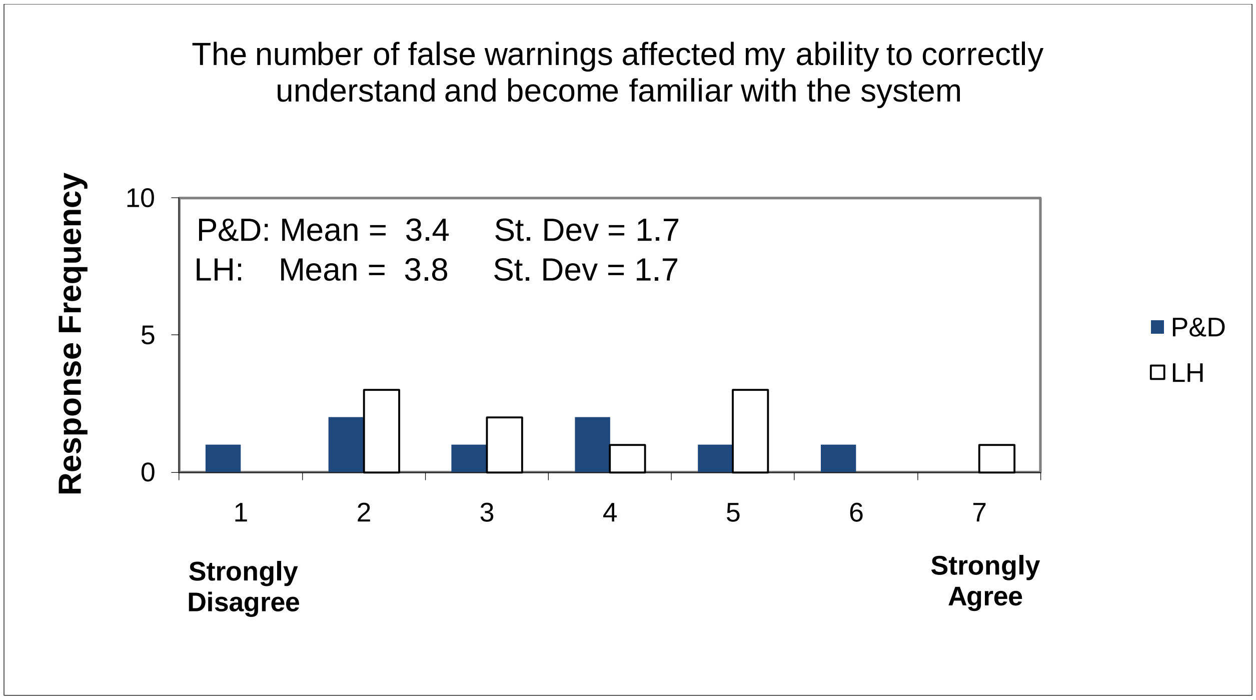

Figure 37: Responses to, "The number of false warnings affected my ability to correctly understand and become familiar with the system"

While the majority of the drivers disagreed with the statement "The number of false warnings affected my ability to correctly understand and become familiar with the system," the prevalence of false alarms was certainly an issue with many drivers' understanding of the system. Five drivers did feel that the false warnings affected their understanding, with two drivers (Drivers 2, and 30) strongly agreeing with the statement in Q22.

When considering the responses to Q8 and Q22 (both discussed above,) it appears that drivers did initially have some confusion about the operation of the system resulting from invalid warnings, but this was soon corrected for most of the drivers.

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.

3.4 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.

3.4.1 Vehicle Exposure and Warning Activity

This section describes the frequency of lateral drift and lane change/merge warnings in both baseline and treatment conditions. Key descriptive statistics are provided as a function of road class, route type, and exposure over time, along with brief descriptions of 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 29. 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 29: 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

3.4.2 Lateral Warning Classification and Validity

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

- **Valid**—warnings are helpful to the driver since they bring additional awareness to the driving task and can mitigate ignorance of an unrecognized conflict in the current driving situation. Warnings that are predictable and probable are also defined as valid. After a valid warning, the driver becomes more vigilant and makes an assessment of urgency. A valid warning may not be helpful in the immediate sense, but can be informative in that typically the driver is assuming normal driving behavior and actions will resolve the situation.
- **Invalid**—warnings are characterized by an incorrect or inaccurate assessment of the 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.

3.4.3 Lateral Warning Summary

In this section, the lateral warning exposure is presented using terms defining lateral warning type and validity. Figure 38 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 39 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.

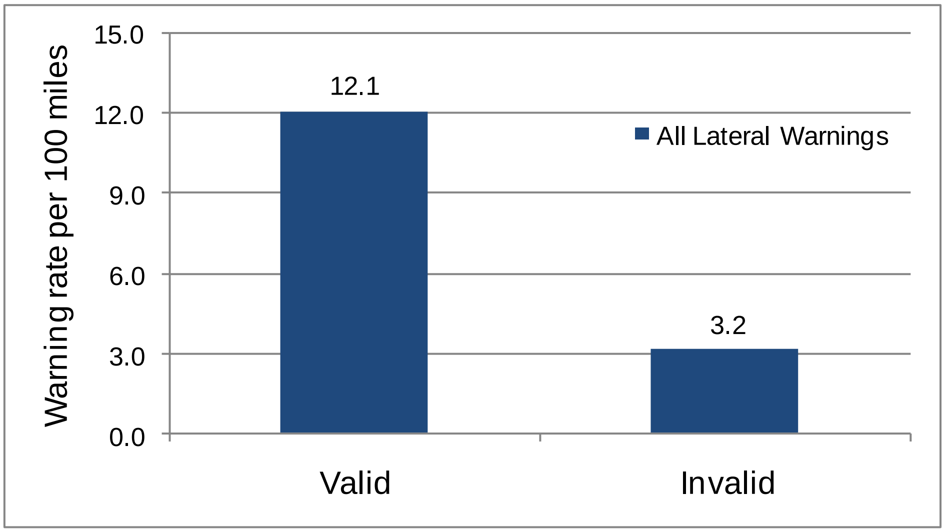

Figure 38: Overall lateral warning rate per 100 miles.

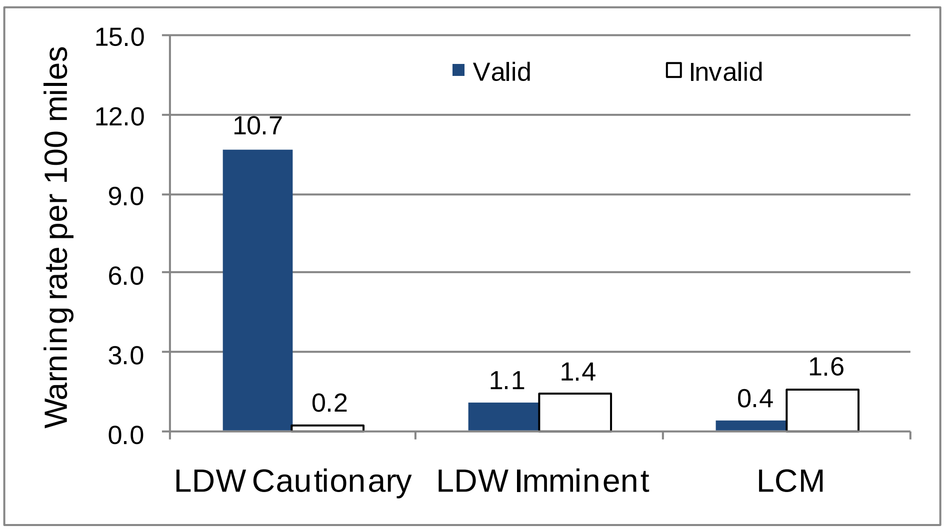

Figure 39: Overall lateral warning rate per 100 miles for each warning type.

Figure 40 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.

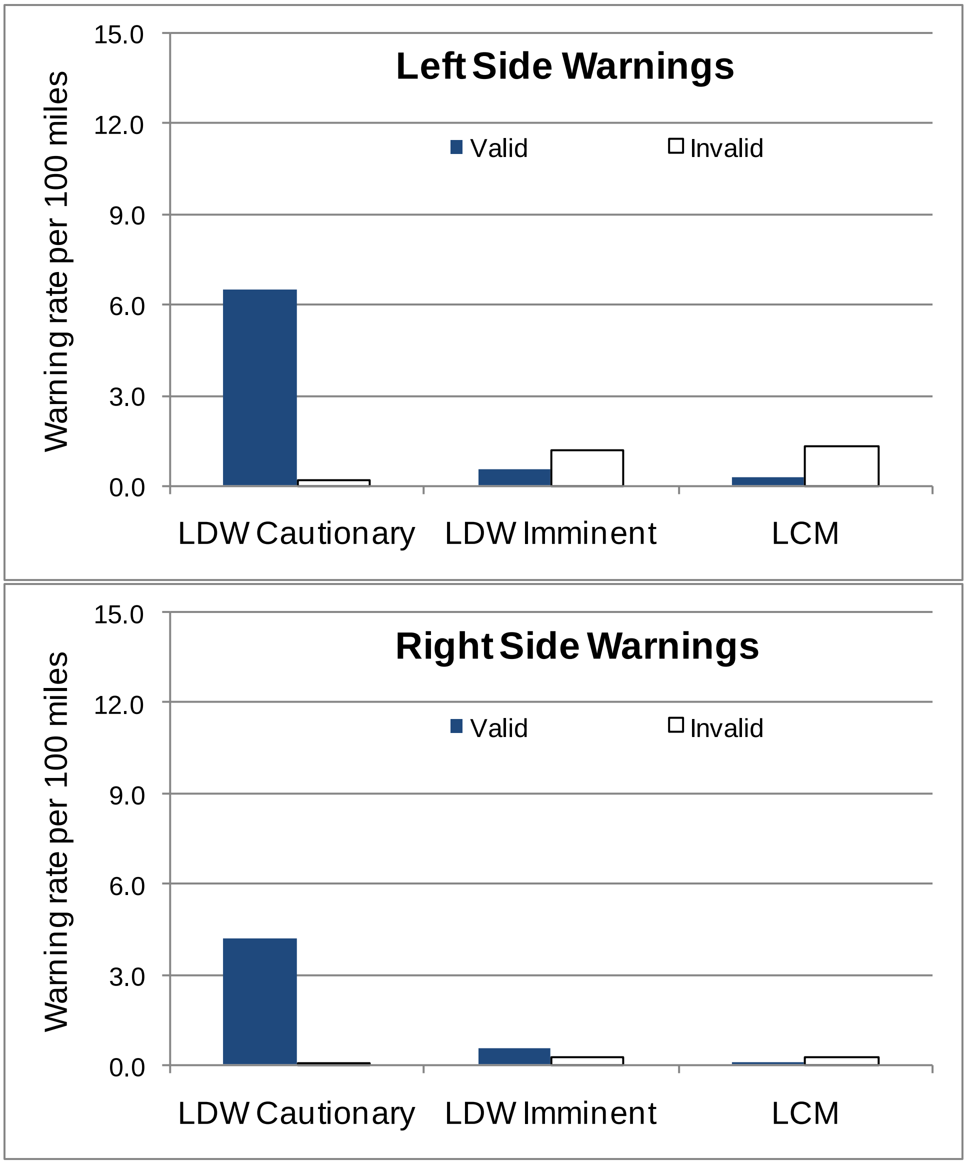

Figure 40: Overall lateral warning rate per 100 miles as a function of vehicle side and type.

In terms of the broader exposure variables of condition and route type, Table 30 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 30: 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

3.4.3.1 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.

3.4.4 Driver Behavior Research Questions

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

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

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

Method: The lateral offset is defined as the distance between the center line of the vehicle and the center line of the lane as shown in

Figure 41. If the vehicle is perfectly centered in the lane, lateral offset is zero.

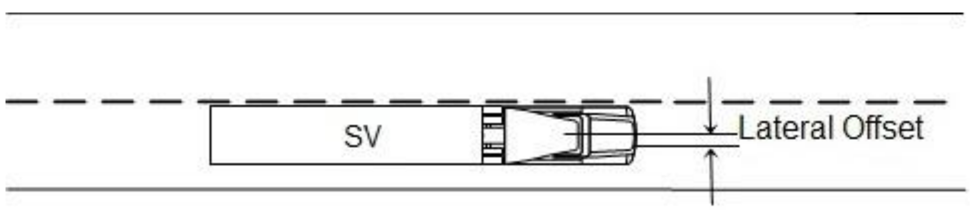

Figure 41: Conceptual diagram of lateral offset

This investigation is based on a subset of steady-state lane keeping events where the primary driving task is defined as maintaining a proper lateral offset. Intentional driving maneuvers such as lane changes and braking events were removed. When such a maneuver was performed, a buffer time of 5 seconds before and after was also removed to allow the driver to return to the lane keeping task. Each lane keeping event was required to last longer than 20 seconds to ensure that the driver settled into the driving task and eliminated short periods of driving where the driver was likely preparing for the next maneuver. Additional criteria required the lane tracking system to have known boundaries on both sides and the lane tracking status enabled to ensure good estimates of the lateral offset were used. A list of the constraints used in this analysis can be seen in Table 31 below.

Table 31: Analysis constraints

Constraints
1. Boundary types known and real (virtual boundaries not included)
2. Lane offset confidence 100 percent
3. Lane tracker enabled
4. No braking, lane changes or turn signal use
5. Buffer time of 5 seconds before and after any intentional maneuver
6. Event duration longer than 20 seconds (plus buffer)
7. Speed > 11.2 m/s (25 mph)
8. Valid trip and driver

Using the constraints listed in Table 31 a table of 213,500 events consisting of 4,481 hours (44.5% of driving when speeds greater than 25 mph) and 275,315 miles (47.3% of driving when speeds greater than 25 mph) of driving. The median duration was 49.0 seconds and the longest event was over 13 minutes. For each event the mean lateral offset was calculated from the raw FOT data and was used as the dependent variable. The list of independent variables shown in Table 32 was also recorded for each event. Figure 42 shows the hours of steady-state driving and lane tracking for the individual drivers. The steady-state driving occurs as a subset of the reliable lane tracking measurements.

Table 32: Variables

Dependent Variables
1. Lateral offset within lane
Independent Variables
1. Average Speed (Continuous: m/s)
2. Treatment Condition (Binary: yes, no)
3. Wiper State (Binary: on, off)
4. Gross Vehicle Weight (Binary: < 20 metric ton, > 20 metric ton)
5. Ambient Light (Binary: day, night)
6. Hours of Service (Continuous: hours)
7. Road Type (Binary: Limited Access, Surface)

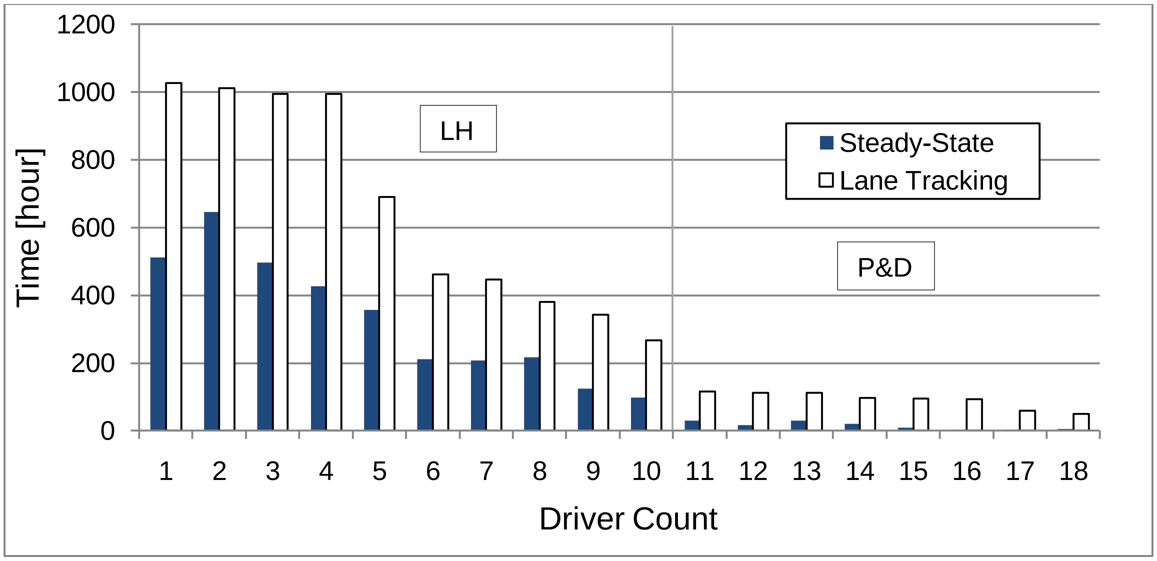

Figure 42: Steady-state and lane tracking durations for individual drivers, sorted by order of decreasing lane tracking durations.

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. The non-significant independent variables were removed from the analysis one at a time and the model was rerun until only the significant factors remained. The predictions generated by the model were also verified against the raw FOT data.

The condition of the integrated crash warning system did show significance on the lateral offset ($F(1,17) = 52.48$; $p < 0.0001$). For a majority of the steady-state lane keeping events, highway driving at night and high speeds, the model predicted a 1.7 cm move to the left due to the treatment condition (from 10.8 cm to 9.1 cm on the right of the lane's centerline). Figure 43 and Figure 44 below shows the lateral offset model predictions and FOT data as a function of average speed for surface streets and limited access roads respectively. The jump in the model values between 48 and 50 mph is due to the shift in road type from surface to limited access, since the lower speeds are rarely seen on the limited access and vice versa for surface streets. The overall effect of the integrated system across all conditions however is small, and represents a shift of only 0.9 cm to the right, away from the centerline, relative to the baseline condition

The FOT data confirms the model predictions regarding the lateral offset moving to the right with increasing speeds. Figure 45 shows the least square means predictions for the condition interaction on lateral offset.

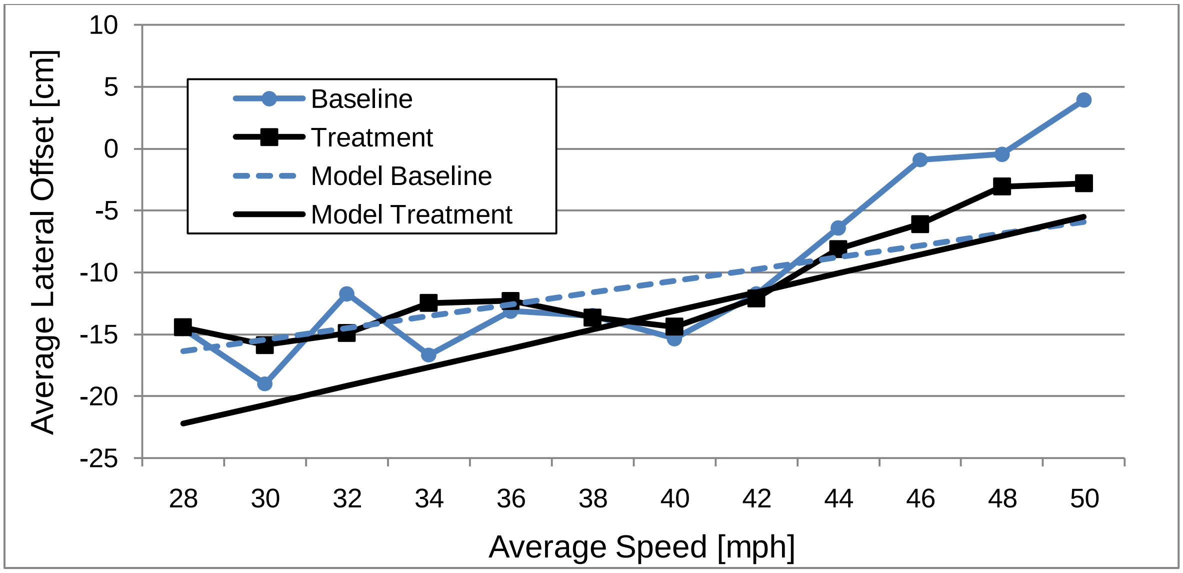

Figure 43: Average lateral offset for both experimental conditions versus the average speed during steady-state lane keeping for travel on surface streets.

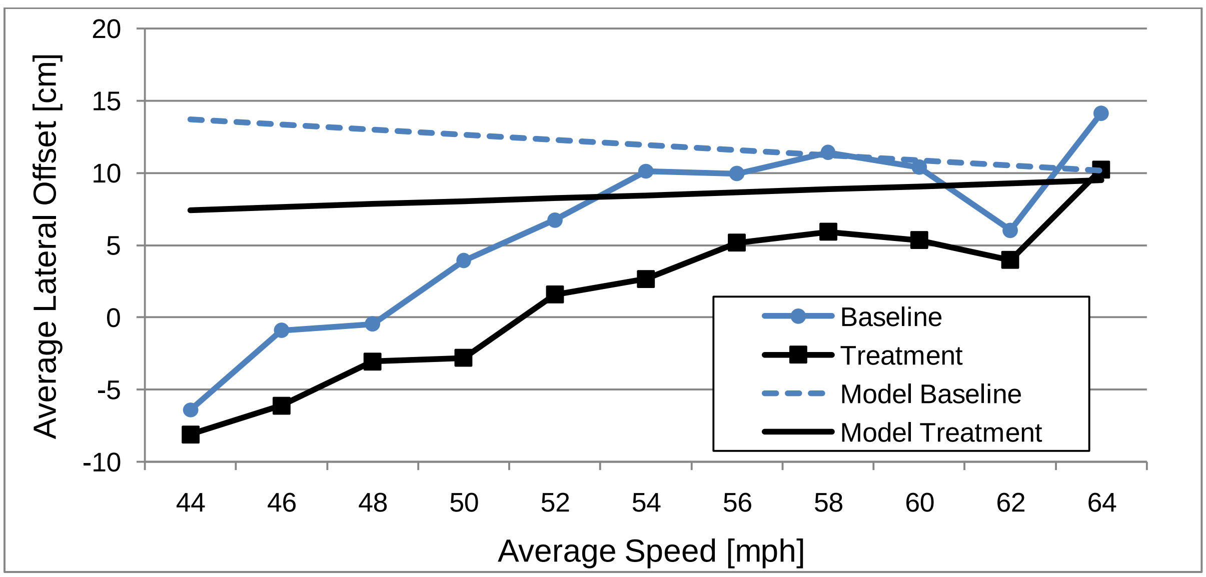

Figure 44: Average lateral offset for both experimental conditions versus the average speed during steady-state lane keeping for travel on limited access roads.

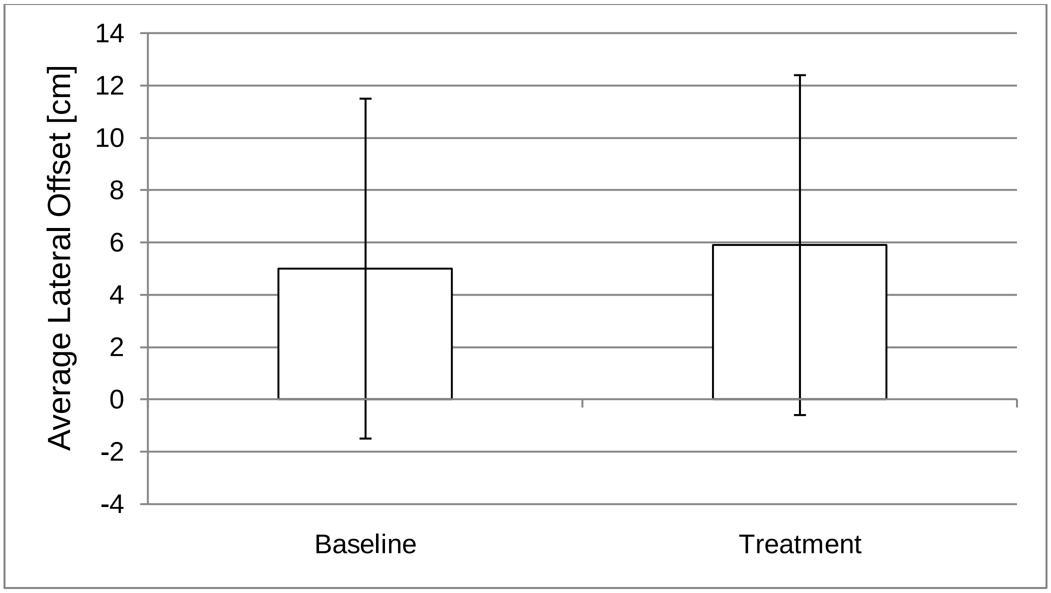

Figure 45: Least square means model predictions for lateral offset

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 significant effect on lateral position. The interactions for average speed can be seen in Figure 43 and Figure 44 above. The predicted marginal means for the two-way interaction of road type and condition can be seen below in Figure 46.

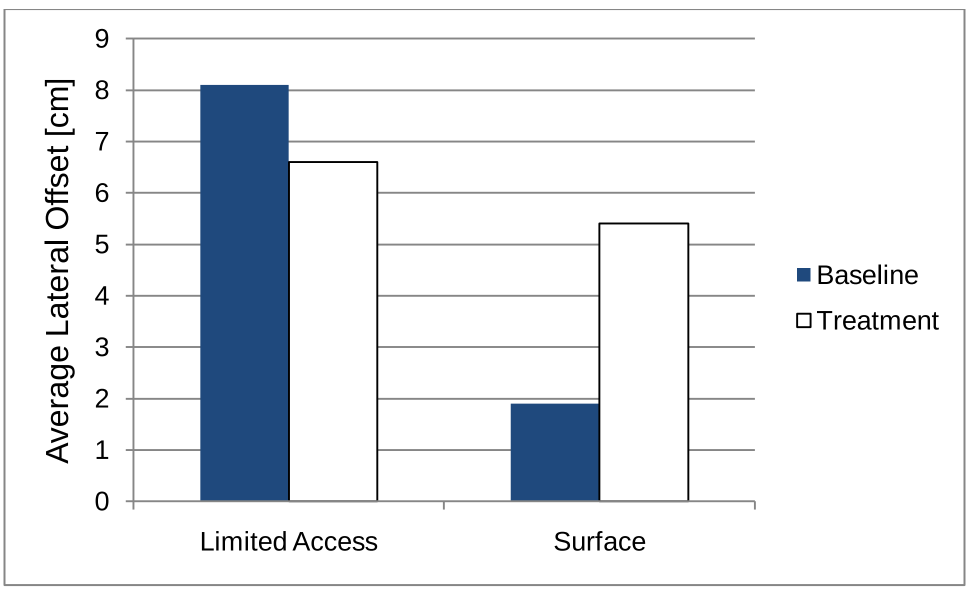

Figure 46: Least square means model predictions for road type and condition

The two-way interactions that showed statistical significance are summarized in Table 33. The variables that did not show any significant interactions were wiper state, load, and time working. These variables were removed from the final model.

Table 33: Summary of two-way interactions

Two-way interaction	Model Results
Condition * Road Type	$F(1,17) = 17.21$; $p = 0.0007$
Condition * Average Speed	$F(1,17) = 46.35$; $p < 0.0001$
Ambient Light * Road Type	$F(1,11) = 21.58$; $p = 0.0007$

Descriptive Statistics: The model predicted a slight shift in lateral offset with the treatment condition and this result can be demonstrated with the FOT data as well. Figure 47 shows the average lateral offset of the individual drivers for both experimental conditions. In the figure, the data is sorted by the baseline lateral offset in decreasing order. It is interesting to note the difference in lane position favored by the different drivers. The "Difference" line shows the difference between the baseline and treatment conditions, with a positive difference indicating a move to the center of the lane and a negative difference for a movement away from the center. A majority of the drivers (11 out of 18) moved to a more central location between the lane boundaries during the treatment condition.

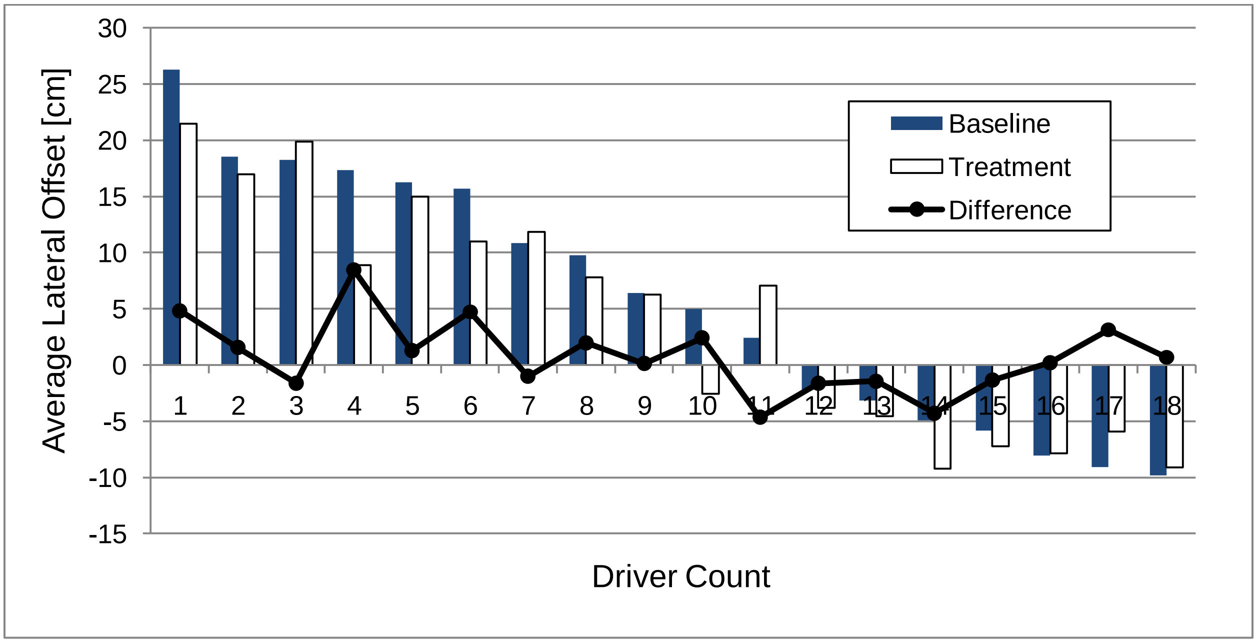

Figure 47: Average lateral offset for individual drivers for baseline and treatment conditions during steady-state lane keeping, sorted by order of decreasing baseline average lateral offset.

The model predicted significant interactions for the road type and condition. Figure 48 shows the average lateral offset for limited access and surface streets for both experimental conditions. The FOT data shows a preference for the right side of the lane for the baseline in both road types. The treatment condition shows a shift to the left for both road types, specifically a 2.5 cm shift for limited access and a 3.7cm shift for surface streets.

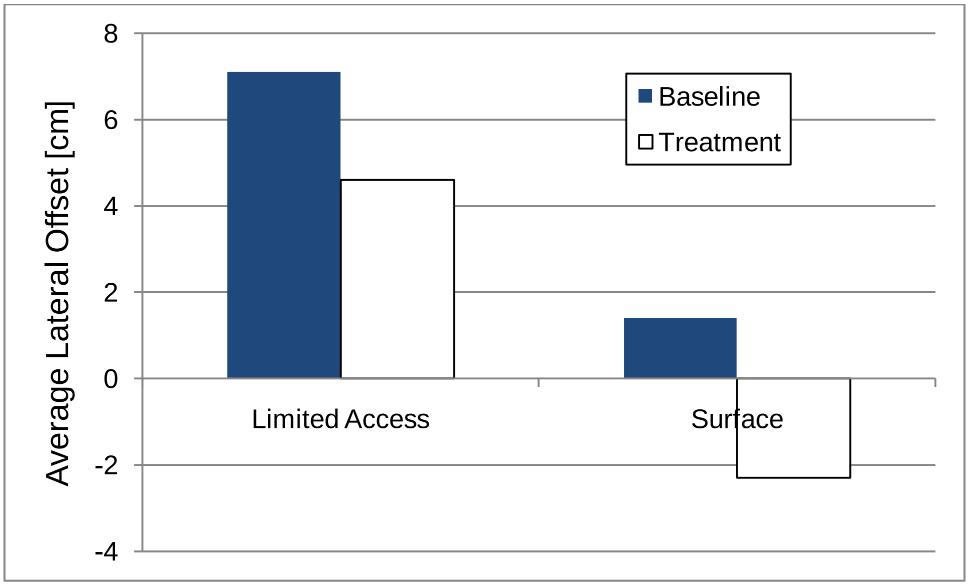

Figure 48: The average lateral offset for both experimental conditions and road types during steady-state lane keeping.

One of the difficulties of this analysis was the lack of steady-state lane keeping data for the P&D drivers specifically and low speeds for all drivers. Figure 49 shows a histogram of the fractional time versus average speed during the steady-state events. It can be seen that most of the data exists at high speeds. It can also be seen in Figure 42 above that most of the data comes from the LH drivers.

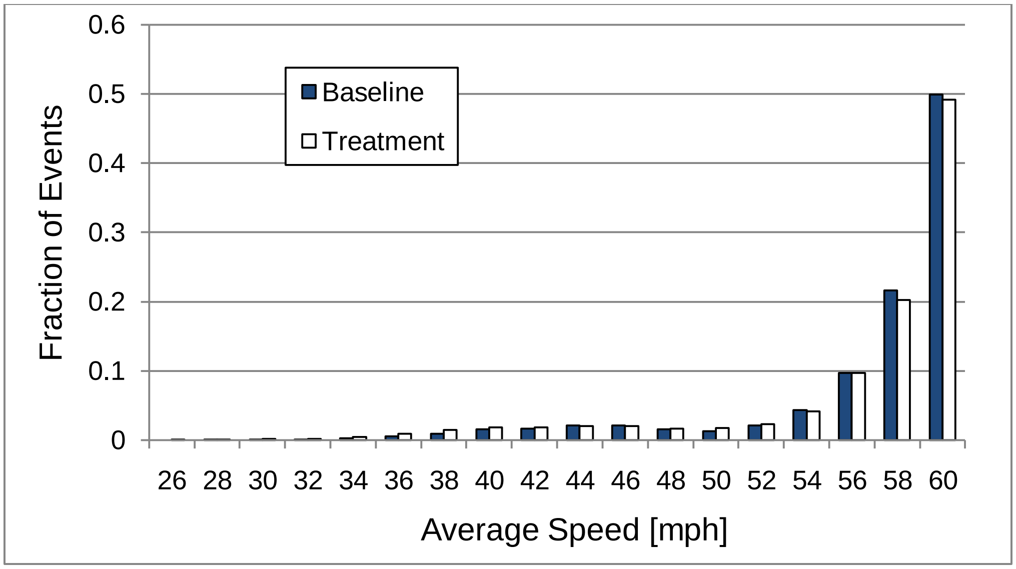

Figure 49: Histogram of average speeds for both experimental conditions for the steady-state lane keeping events.

Based on the nature of the FOT driving and the analysis constraints listed in Table 31, most of the data used by the model came from the LH driving. The predominance of long, continuous stretches of open road encountered by the LH drivers provided an excellent match between the numerical data and ideal lane-keeping event imagined by the investigators. On the other hand, the complex and diverse urban environment driven by the P&D drivers did not conform to the analysis constraints and represented a small fraction of the data examined. Further investigation on the lane keeping habits of P&D drivers would require relaxing these constraints while balancing the goals for useful filters.

Interpretation: The change in lateral offset is statistically changed by the presence of the integrated crash warning system ($p < 0.0001$). For the most prevalent driving condition in the steady-state lane keeping events (limited access at night and high speeds), the FOT data shows a change in average lateral offset of 5.1 cm to the left, from 10.4 cm to 5.3 cm to the right of the lane center. The FOT data also demonstrated a preference for driving to the right of the centerline on limited access and high speed driving, and a bias to the left of the centerline for surface streets and lower speeds. It appears that drivers favored different lane positions for the variety of situations encountered, and that could be based on experience or personal preference. These results were based on the steady-state lane keeping events that favored the conditions encountered by the LH drivers.

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

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

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

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

The previous research question (QL1) focused on periods of driving when maintaining the proper lane position was the primary task, and includes the unintentional lane departures of interest for this research question. Table 34 shows the constraints used to find the lane departures for this research question. A constraint on the maximum duration of the lane departure was implemented after video review determined that 76 percent of lane departure events over 20 seconds were not legitimate (due to inability to detect lane markings in high glare situations or construction zones).

Table 34: Analysis constraints

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

During the steady-state driving, there were 68,976 lane departure events which were used for this analysis. These events were grouped into each unique scenario represented by the independent variables listed in Table 35. The number of lane departures was then normalized by the number of 100 miles driven in that scenario to determine the lane departure frequency (lane departures per 100 miles). The normalized lane departures where then used for modeling the significant interactions.

Table 35: Variables

Dependent Variables
1. Lane departure frequency
Independent Variables
1. Average Speed (Continuous: m/s)
2. Treatment Condition (Binary: yes, no)
3. Wiper State (Binary: on, off)
4. Gross Vehicle Weight (Binary: < 22 metric tons, > 22 metric tons)
5. Presence of POV in closing zone or blind zone (Binary: yes, no)
6. Ambient Light (Binary: day, night)
7. Hours of Service (Continuous: hours)
8. Road type (Binary: Limited access, surface)

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

The presence of the integrated crash warning system did not show a statistically significance effect on the departure frequency ($F(1,17) = 0.39$; $p = 0.5385$), although the rate of departures did decrease for 13 of the 18 drivers. Figure 50 shows the least squares means of the lane departure rates for the baseline and treatment conditions (15.6 and 13.9 departures per 100 miles respectively).

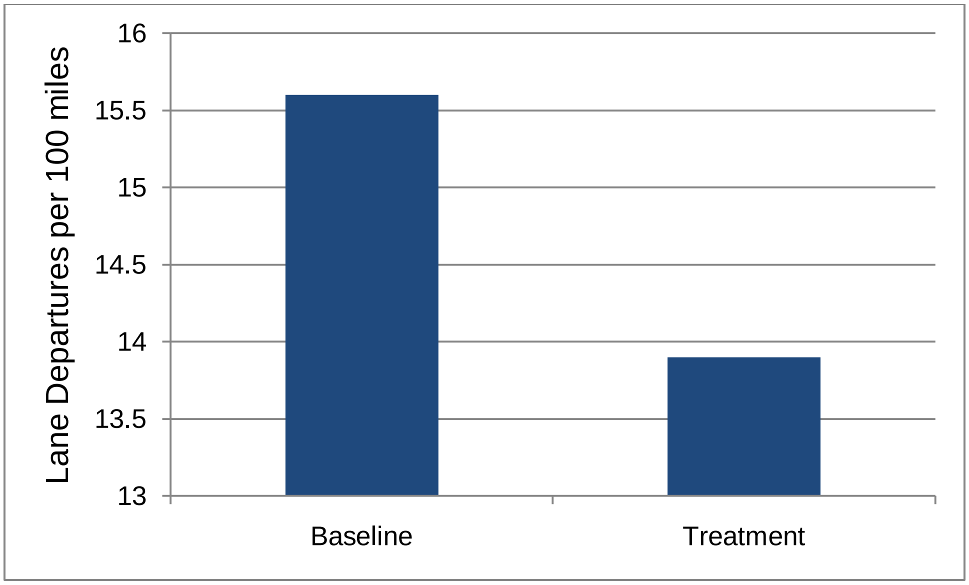

Figure 50: Least square means of lane departure rates for experimental condition during steady-state lane keeping.

The road type and wiper state were the only two variables in Table 35 to show significance on the lane departure frequency. The road type ($F(1,17) = 4.96$; $p = 0.0397$) predictions can be seen in Figure 51 where the limited access has a mean of 11.4 lane departures per 100 miles and the surface streets, with the increased maneuvering, had a mean of 18.1 lane departures per 100 miles. The predicted means for the wiper state ($F(1,17) = 5.86$; $p = 0.0270$) can be seen in Figure 52. For driving conditions with the wipers on, the model predicts a decrease in lane departure frequency from 16.9 to 12.6 departures per 100 miles.

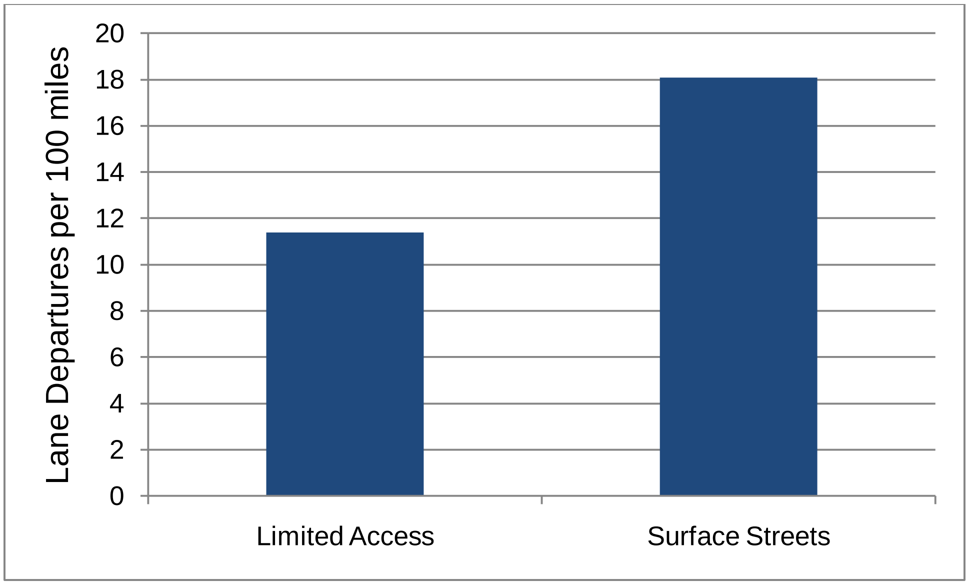

Figure 51: Least square means of lane departure rates for road type during steady-state lane keeping.

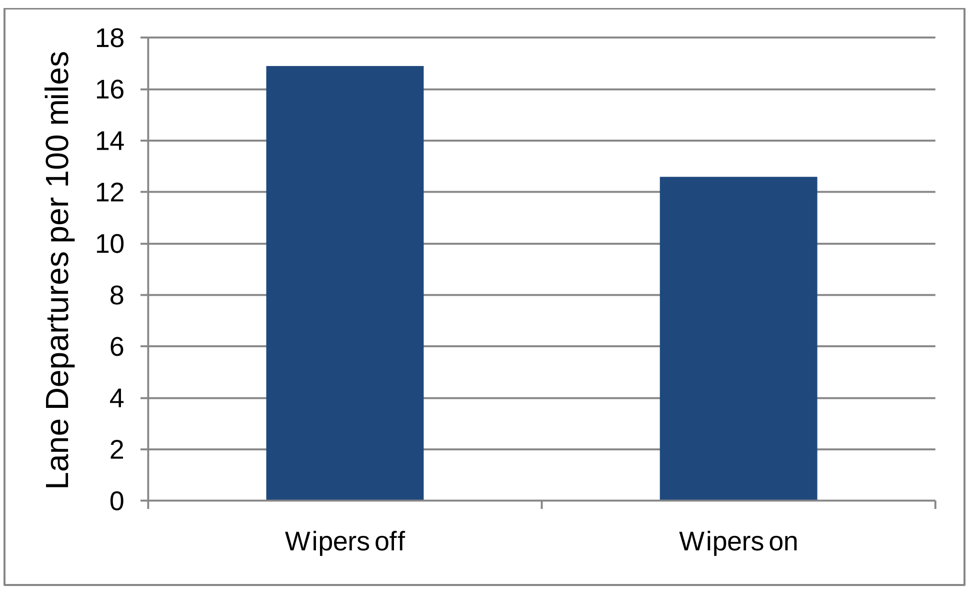

Figure 52: Least square means of lane departure rates for wiper state during steady-state lane keeping.

Descriptive Statistics: As stated above, this analysis was based on the 68,976 lane departures that occurred during the steady-state lane keeping. Figure 53 displays the lane departure count for the individual drivers, ordered by decreasing total lane departures. Note the difference in lane departure counts between individual drivers and the difference between LH and P&D route types.

The experimental condition did not have a statistically significant effect on the lane departure frequency, but the FOT data did show a decrease in lane departure rate for all but five of the drivers. Even though it was not significant, the presence of the integrated system decreased the alert rate by 19 percent from 7.9 to 6.4 alerts per 100 miles. Figure 54 shows the lane departure rate for the individual drivers for both experimental conditions, ordered by decreasing baseline lane departure frequency.

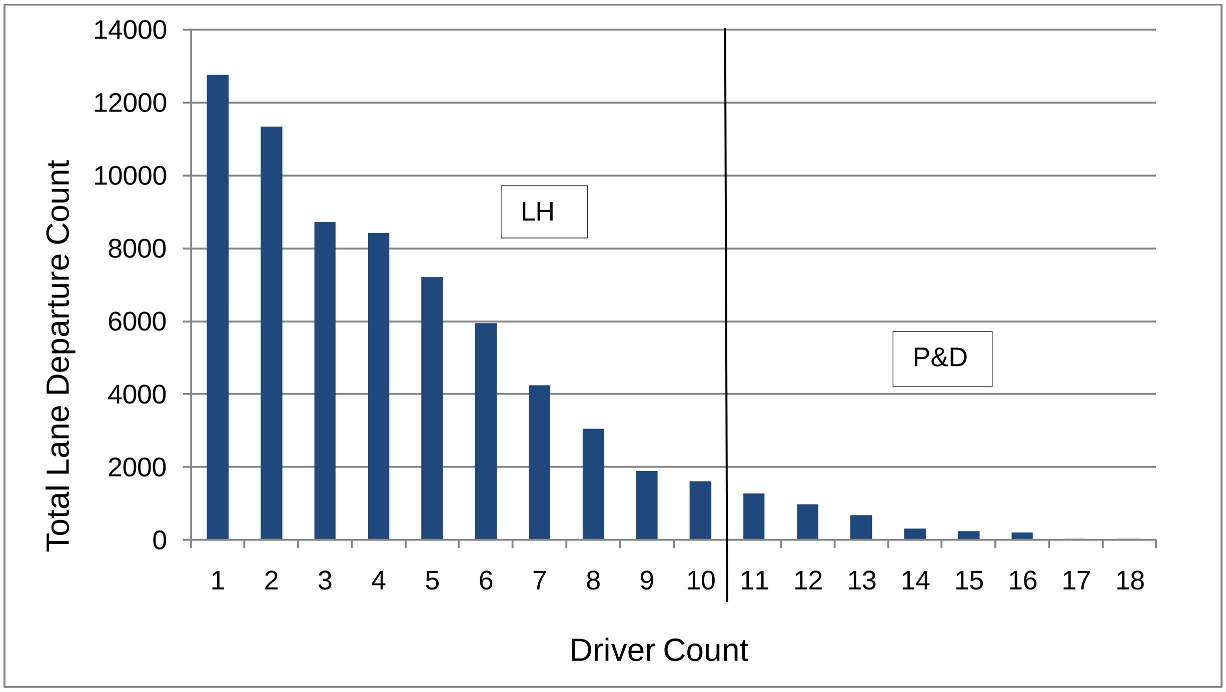

Figure 53: Total lane departure count for the individual drivers during steady-state lane-keeping.

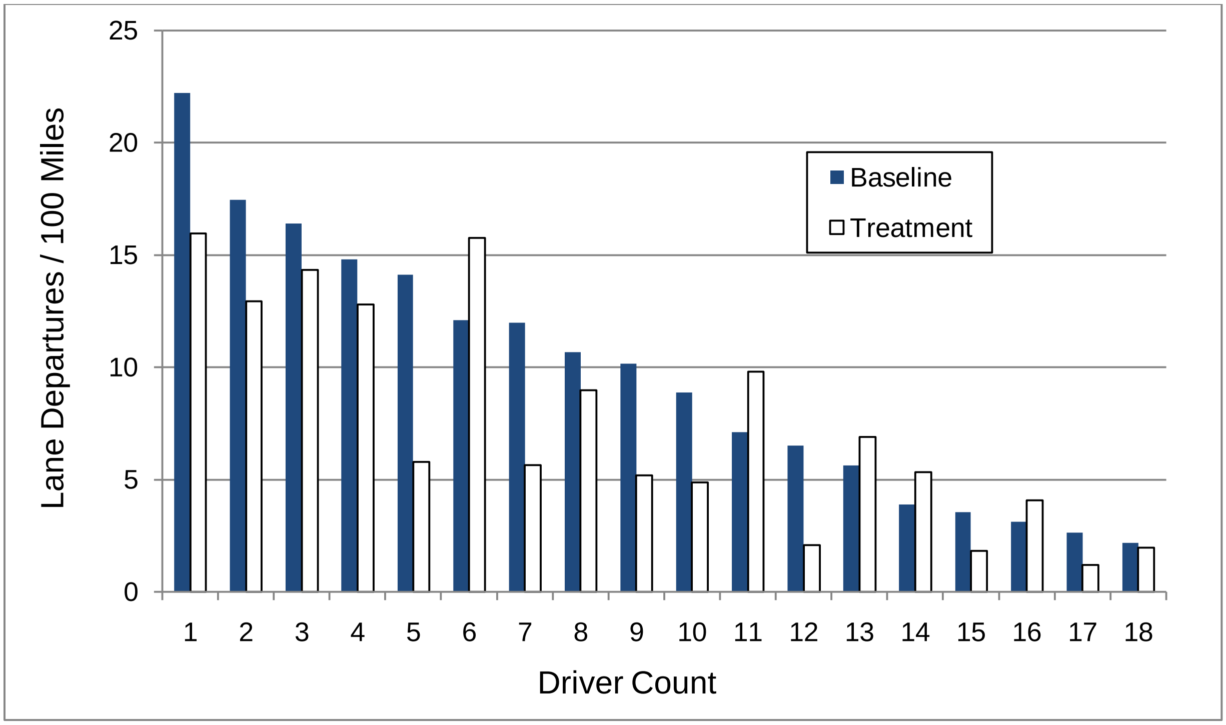

Figure 54: Lane departure rate for the individual drivers

The FOT data supports the model predictions for road type and wiper state, the independent variables with significant effects on the lane departure rates. Table 36 displays the lane departure rates for road types and the experimental condition. As predicted by the model, there is a large difference between the two road types. Table 37 displays the lane departure rates for wiper state along with the experimental condition.

Table 36: Lane departure rate for road type and condition from FOT data

Road Type	**Full FOT [departures/100 miles]**	**Baseline [departures/100 miles]**	**Treatment [departures/100 miles]**
Limited Access	6.49	7.65	6.20
Surface Streets	15.43	18.36	14.47

Table 37: Wiper state and condition from FOT data

Wiper State	**Full FOT [departures/100 miles]**	**Baseline [departures/100 miles]**	**Treatment [departures/100 miles]**
On	6.92	8.20	6.71
Off	6.67	7.93	6.34

Interpretation: The integrated crash warning system did not have a statistically significant effect on the lane departure frequency, although the normalized number of lane departures did decrease for all but five of the drivers (Figure 54). Overall the presence of the integrated system decreased the alert rate by 19 percent from 7.9 to 6.4 alerts per 100 miles.

The road type and wiper state were the two independent variables that did have a significant effect on the lane departure rate. The lane departure rate on limited access roads was less than the surface streets, 6.49 and 15.43 departures per 100 miles respectively. The lane departure rate also decreased when the wipers were in use from 6.92 to 6.67 lane departure per 100 miles. It is interesting to note, that the drivers were more careful in wiper on driving conditions.

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

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

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

The same lane departures used in research question QL2 were used in this analysis. The lane departures were pulled from the steady-state, lane keeping events and excluded active maneuvers. For each lane departure, the time from when the edge of the vehicle first crosses the lane boundary to when the entire vehicle is again in its own lane was determined. In addition, the maximum lane incursion distance into the adjacent lane was recorded for each event. All of the lane departure events in this analysis require the subject vehicle to return to its original lane in less than 20 seconds to exclude construction zones or poor lane tracking due to sun glare (see research question QL2). Table 38 summarizes the constraints used for this question.

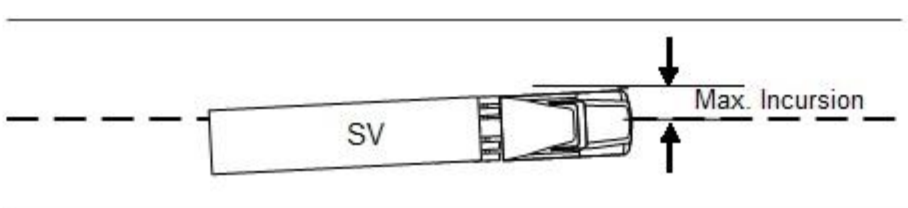

Figure 55: Conceptual drawing of lane departure.

Table 38: Analysis constraints

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

Table 39: Variables

Dependent Variables
1. Maximum lane incursion distance
2. Duration of incursion
Independent Variables
1. Average Speed (Continuous: m/s)
2. Treatment Condition (Binary: yes, no)
3. Wiper State (Binary: on, off)
4. Gross Vehicle Weight (Binary: < 20 metric tons, > 20 metric tons)
5. Presence of POV in closing zone or blind zone (Binary: yes, no)
6. Ambient Light (Binary: day, night)
7. Hours of Service (Continuous: hours)
8. Road type (Binary: Limited access, surface)
9. Lane departure direction (Binary: left, right)

Results: A Linear Mixed Model was used to determine if the trajectory of lane departure warnings varies with the independent variables (Table 39) for both the duration and incursion distance of the lane departure. Only the variables with a significant effect on the trajectory were left in the model. The results for the duration of the lane departure events will be discussed first, followed by the incursion distance.

The presence of the integrated system did not have a statistically significant effect on the duration of the lane departures ($F(1,17) = 2.78$; $p = 0.1139$). However, the model predicted a slight decrease in the lane departure duration in the treatment condition, from 1.89 to 1.81 seconds, shown in Figure 56. The FOT data also demonstrated a slight decrease in lane departure duration with the treatment condition, from 2.11 to 2.02 seconds.

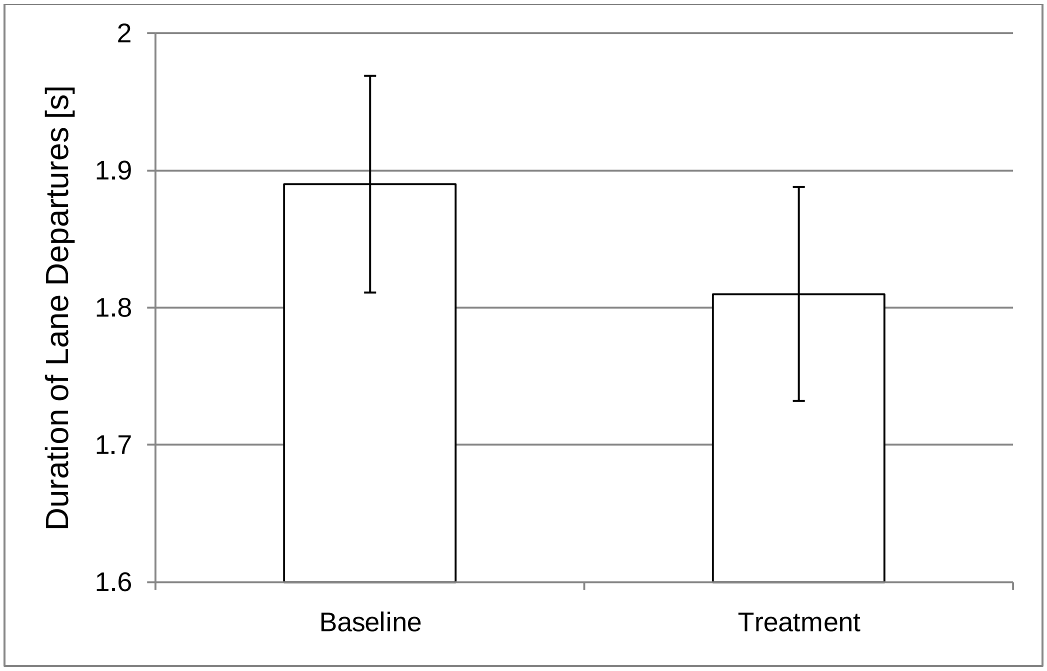

Figure 56: Duration least squares means for experimental condition during steady-state lane keeping.

The road type ($F(1,17) = 7.15$; $p = 0.0160$) and departure direction ($F(1,17) = 18.61$; $p = 0.005$) both had a significant effect on the departure duration. The model predicted longer departure durations on limited access roads compared to surface streets, as shown in Figure 57 below. The model also predicted a difference in the duration for departures to the right or left of the centerline, with departures to the right being slightly longer (see Figure 58).

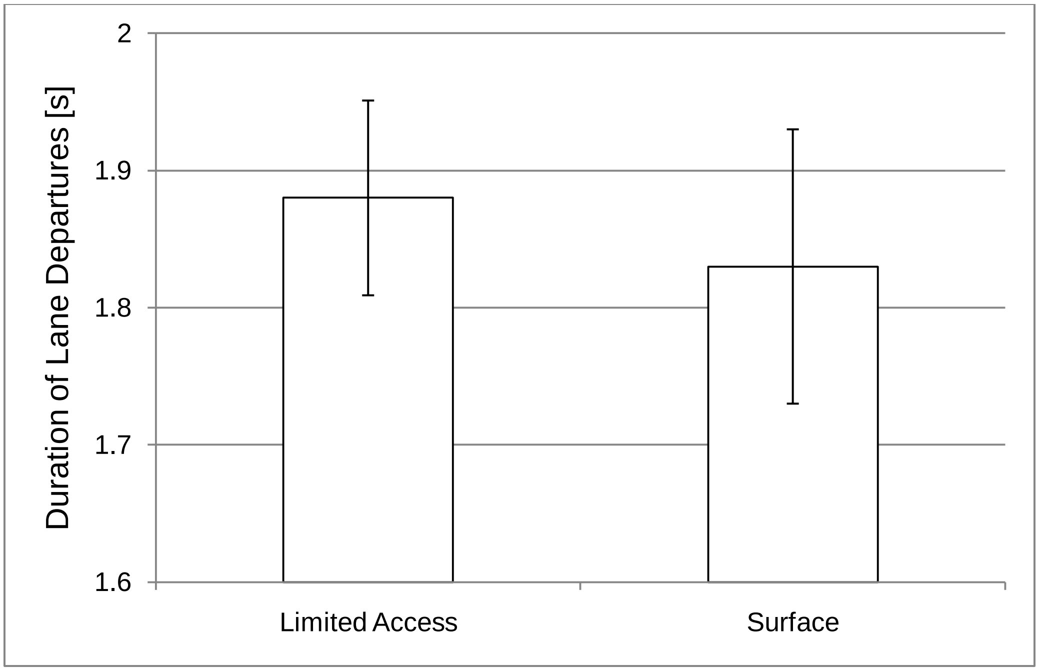

Figure 57: Duration least squares means for road type during steady-state lane keeping.

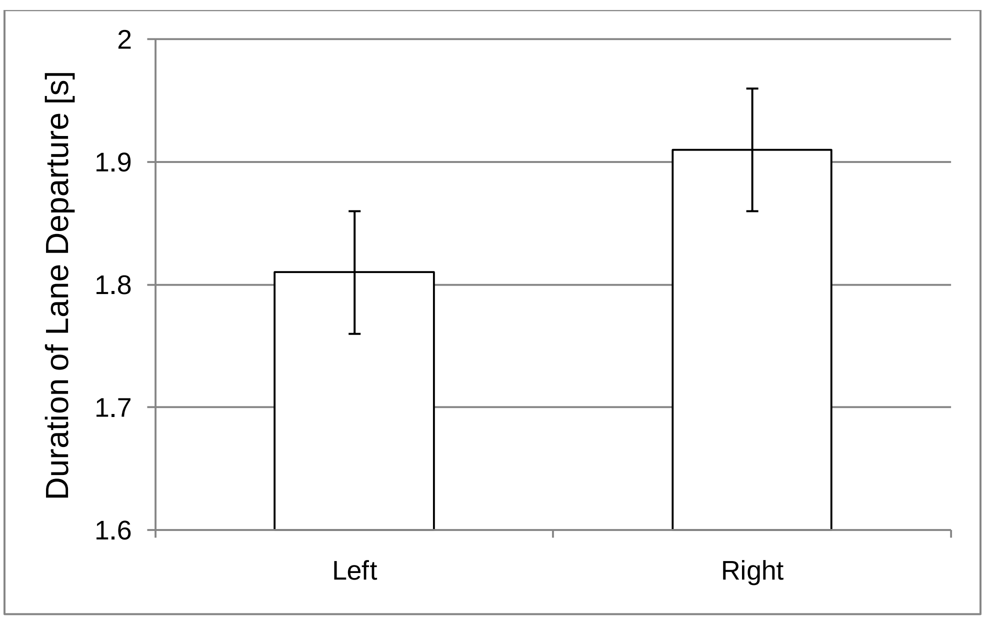

Figure 58: Duration least squares means for lane departure direction during steady-state lane keeping.

The hours of service also had a significant effect ($F(1,17) = 4.68$; $p = 0.0451$) on the departure duration during steady-state lane keeping. As the hours of service increased, the model predicted the departure duration to increase also. Figure 59 shows the departure duration as a function of hours of service based on the model predictions and FOT data. The figure shows left lane departure because the model parameters require one direction to be specified. The plot for the lane departure to the right has a similar slope, but is higher by about 0.1 seconds (see Figure 58 above). Note the presence of the integrated safety system reduces the departure duration at the end of the shift to that of the first hour during baseline.

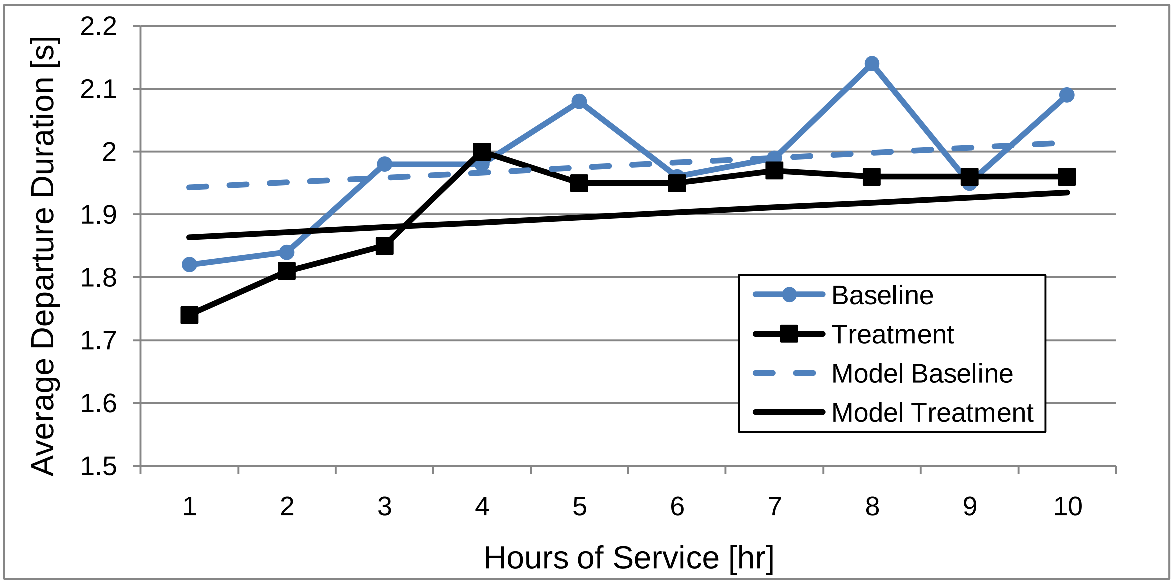

Figure 59: Lane departure duration for both experimental conditions versus hours of service for the steady-state left lane departure events on limited access.

The average speed was also found to have a significant effect on the departure duration ($F(1,17) = 44.24$; $p < 0.0001$). Figure 60 shows the model predictions along with the FOT data for departures to the left on limited access roads. As before, the model required these parameters to be specified, but for this case the average speed also had a two-way interaction with departure direction ($F(1,18) = 15.31$; $p = 0.001$) and road type ($F(1,17) = 5.12$; $p = 0.0370$). The data for lane departures to the right is similar, but the two-way interaction of speed and direction predicted a slightly smaller duration (0.09 seconds per each mph increase) for the lane departures to the right when compared to lane departures to the left at a given speed.

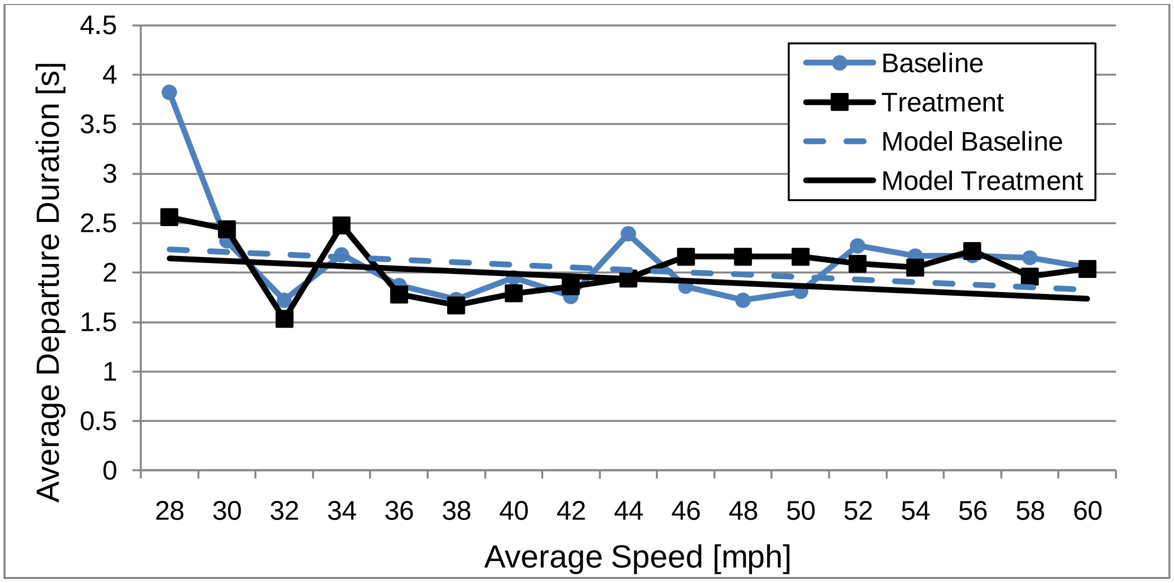

Figure 60: Lane departure duration for both experimental conditions versus speed for the steady-state left lane departure events on limited access roads.

That concludes the results for the departure duration, now the results for the incursion distance will be explained. Again, the presence of the integrated system alone did not have a statistically significant effect on the maximum distance of the lane departure ($F(1,17) = 0.72$; $p = 0.409$). In this case, the model predicted a small increase in distance for the treatment condition, from 13.4 to 13.6 cm (Figure 61). The FOT data also showed a small increase in the maximum departure incursion distance with the treatment condition from 13.9 to 14.5 cm.

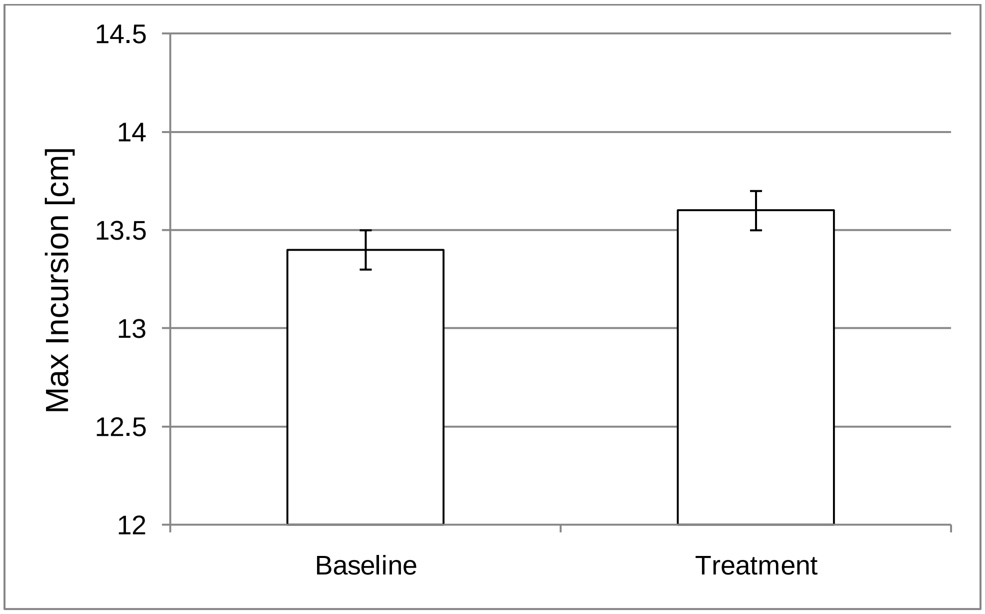

Figure 61: Maximum incursion distance least squares means for experimental condition during steady-state lane keeping.

The direction of the lane departure had a significant effect on the incursion distance ($F(1,17) = 9.22$; $p = 0.0074$). The model predicted departures to the left to be 0.06 cm larger than the departures to the right (Figure 62), while the FOT data showed incursions to the right to be 1.4 cm. larger than the left lane departure. The average maximum excursion for the FOT to the left was 13.5 cm compared to 14.9 cm to the right.

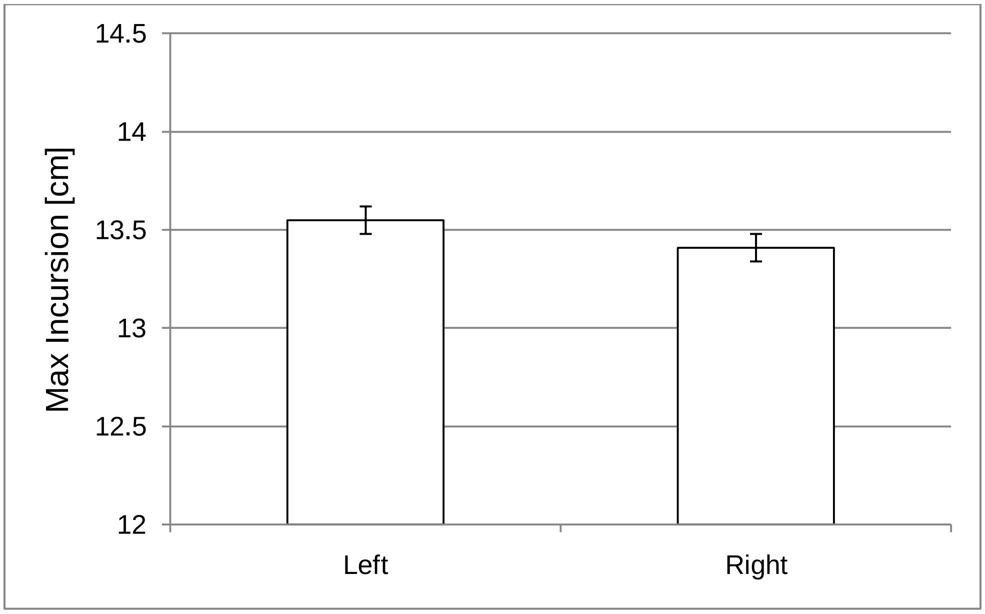

Figure 62: Maximum incursion distance least squares means for departure direction.

Another significant effect on the maximum incursion distance is the hours of service ($F(1,17) = 13.00$; $p = 0.0022$). Like the lane departure duration, the model predicts an increase in maximum departure duration with increasing hours of service. Figure 63 shows the model predictions and FOT data for both experimental conditions. The figure shows the results for left lane departure events for specification of model parameters. The difference between the right and left lane departure distance was discussed above and still holds (see Figure 62). The model predicts a slight increase in distance for the treatment condition, but that was not observed in the FOT data for driving less than five hours.

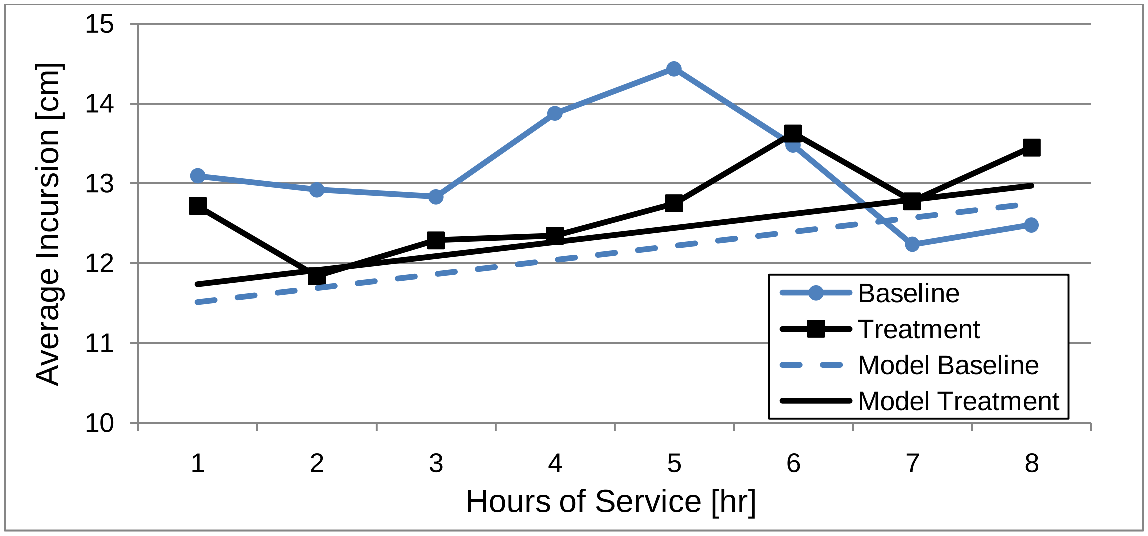

Figure 63: Average maximum incursion for both experimental conditions versus hours of service for the steady-state left lane departure events.

Finally, the average speed also had a significant effect on the lane incursion distance ($F(1,17) = 12.64$; $p = 0.0024$). The model predicts, and the FOT data confirms, a decrease in maximum incursion distance with increasing speed, as shown in Figure 64 for departures to the left. This decrease is similar to the decrease in duration discussed above, see Figure 60. There is also a two-way significant interaction for the average speed and lane departure direction on the incursion distance ($F(1,18) = 8.39$; $p = 0.0096$). For lane departure to the right, the two-way relationship would predict a slightly smaller decrease in maximum incursion with higher speeds, in other words, the model predictions in Figure 64 would not decrease as much with the increasing speeds.

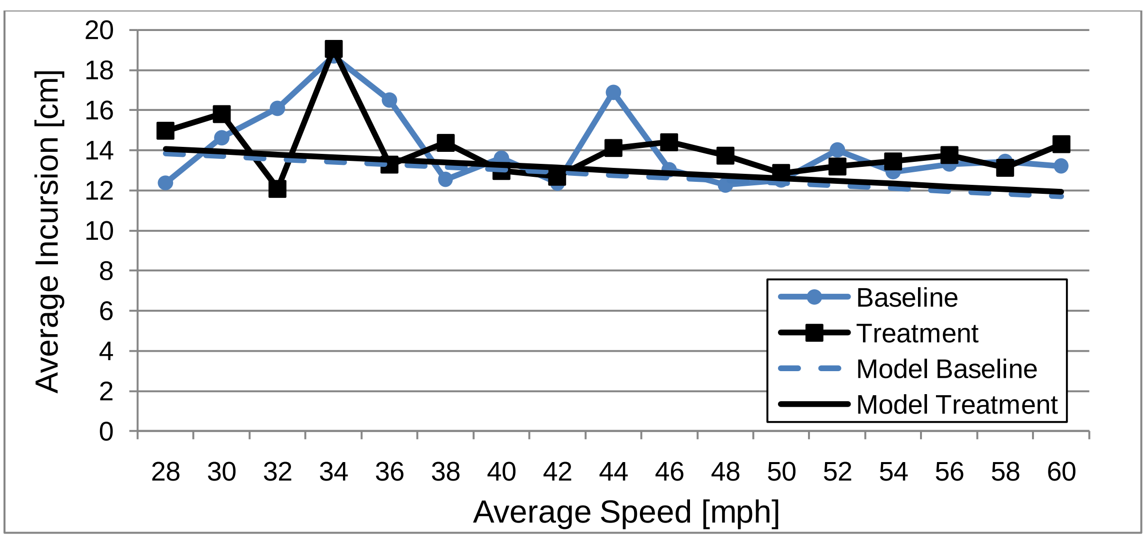

Figure 64: Average maximum incursion for both experimental conditions versus speed for the steady-state left lane departure events.

Descriptive Statistics: Figure 65 and Figure 66 present histograms for the lane departure duration and maximum incursion for the steady-state lane keeping lane departure events.

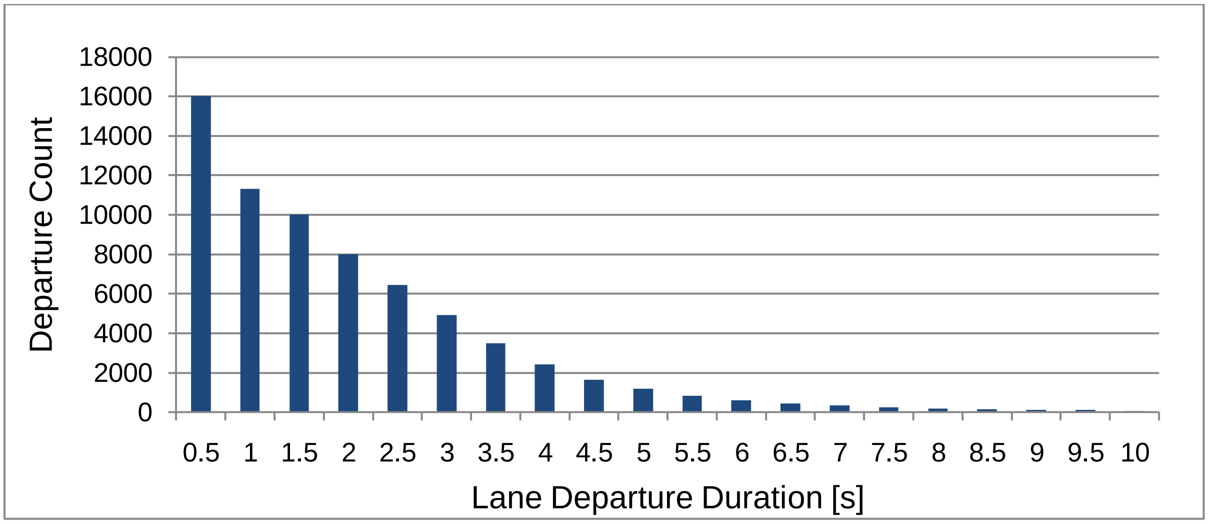

Figure 65: Histogram of lane departure duration during steady-state lane keeping events.

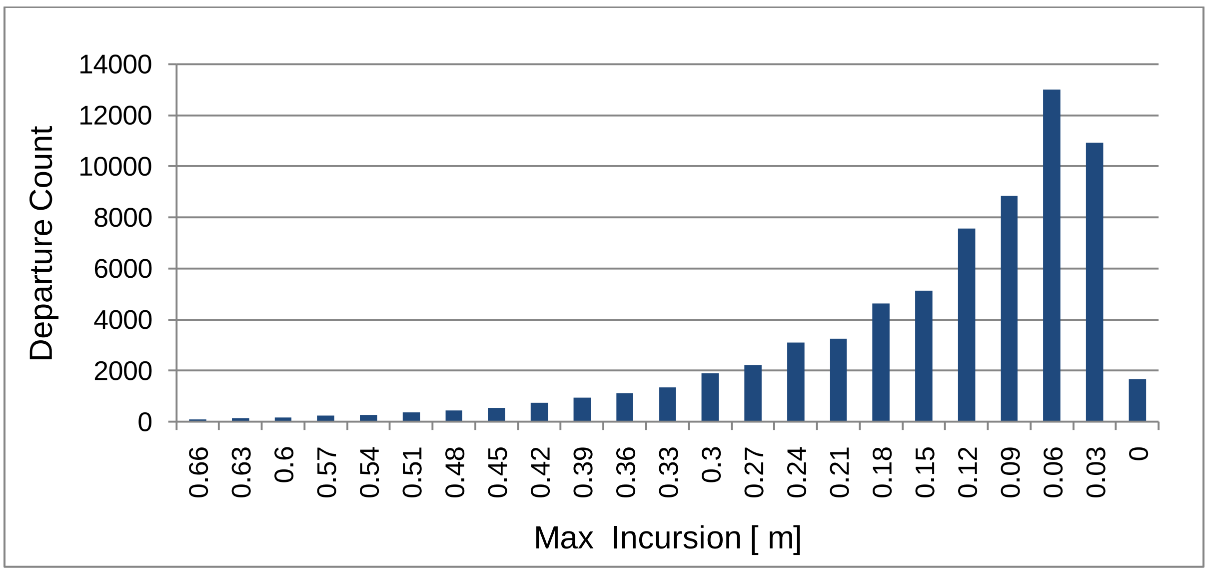

Figure 66: Histogram of maximum incursion during steady-state lane keeping events (zero represents the lane boundary).

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 usage during lane changes differ between the baseline and treatment conditions?

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

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

Method: Identify a set of left and right lane-change events to determine if the corresponding lateral-direction indicator (turn signal) is used differently when the integrated system is enabled as compared to the baseline period as show in Figure 67. Fundamentally, this analysis will address changes in the frequency of turn signal use for lane changes, that is, it will compare lane-changes with and without the use of a turn signal for both baseline and treatment periods.

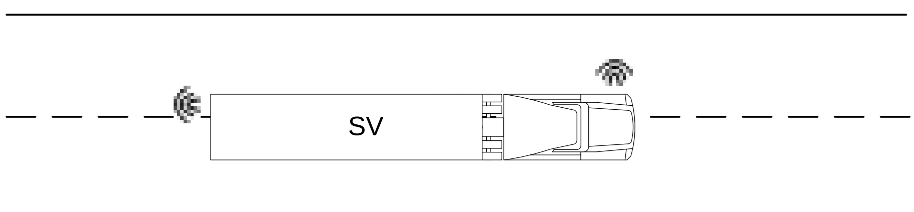

Figure 67: Turn signal usage during lane changes.

The investigation into possible changes in turn-signal usage during the FOT is based on a sub-set of 53,221 lane-change events. For the purpose of this report a lane-change is defined as the lateral movement of the SV relative to the roadway in which the SV 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. The explicit instant in time of the lane-change is defined as the moment when the SV lateral centerline crosses the shared boundary between the two adjacent traffic lanes. Lane-changes are comparatively complex events that involve both infrastructure information, primarily lane boundary demarcation, as well as lateral performance information from the sensors onboard the vehicle. At one extreme they occur on poorly marked roads but can be identified by patterns in the lateral kinematic variables that when integrated show a lateral translation of approximately 3.6 m (11.8 feet), a typical lane width, within a defined period. At the other extreme, they occur on well-marked roads but without any noticeable difference in vehicle lateral performance, as is the case when the lane-change occurs at the entry or exit to curves. At this extreme the road changes laterally relative to the path of the vehicle. In this case, without precise knowledge both the vehicle and road location, detecting a lane change using a numerical approach is very difficult.

To further address possible changes in turn-signal use during the FOT, lane-changes were also constrained using the rules stated in Table 40. The purpose of these constraints is to ensure that the final analysis set of lane-changes is not contaminated with events that may have been flagged as lane-changes but were actually not intended to be lane-changes by the SV driver. An example of this is when a driver intentionally occupies part of an adjacent traffic lane while maneuvering away from a stationary vehicle on the shoulder, or in an adjacent emergency lane. In other circumstances, especially at night and in low traffic situations, drivers may inadvertently drift laterally into an adjacent lane before returning to the center of their original lane. There are numerous examples in the data set of lane-deviation events like the ones mentioned above and in fact, the data set as a whole contains 226,886 events in which the LDW lane-change measure was set to true.

Table 40: Analysis Constraints

Constraints
1. Boundary types known and lane offset confidence 100 percent
2. Lane change is across a dashed boundary type
3. Lane change is performed on a straight segment of roadway
4. Speed > 17.9 m/s (40 mph)
5. No intentional lateral maneuvers by the SV driver in a five second window prior to the lane change (i.e., the SV is in a steady state condition within its lane).

Shown in Table 41 is the dependent variable for the analysis and a list of independent variables that were included to investigate the relationship between use of the turn signal, and other aspects of the vehicle environment, during lane changes.

Table 41: Variables

Dependent Variables
1. Use of turn signal during a lane-change event to the left or right
Independent Variables
1. Condition (Binary: baseline, treatment)
2. Lane change (Binary: left or right)
3. Wiper state (binary: on, off)
4. Load (binary: light, heavy)
5. Trailer (binary: single, double)
6. Ambient light (binary: day, night)
7. Road type (binary: limited access, surface)
8. Hours of service (continuous; units hours)
9. Exposure (continuous; units month)

Results: The principal findings of this analysis are based on the results of a mixed linear model and the conclusions shown below were derived from the model, and not 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.

In terms of integrated system, the model predicts that treatment alone was not found to have a significant effect on turn-signal use during lane-changes ($F(1,17) = 2.67$; $p = 0.1208$). Drivers failed to use their turn signals when performing lane changes 6 percent of the time in the baseline period, and slightly more than 4 percent of the time in the treatment condition.

The principal main effects that showed significance were the direction of the lane change and road type and are shown in Figure 68. Regarding the direction of the lane change, the model predicts that drivers are 2.2 times more likely to make an unsignaled lane change to the left compared to the right ($F(1,17) = 10.56$; $p = 0.0047$). The model predicts that drivers failed to use a turn signal in 6.4 percent of the lane-changes to the left and 2.9 percent of lane-changes to right.

Road type was found to have a significant effect ($F(1,17) = 16.12$; $p = 0.0009$). The model predicts that drivers 3.3 times more likely to not use a turn signal during a lane-change on surface roads compared to limited access roads. The model predicts that drivers failed to use a turn signal in 7.9 percent of the lane-changes on surface roads and 2.3 percent of lane-changes on limited access highways.

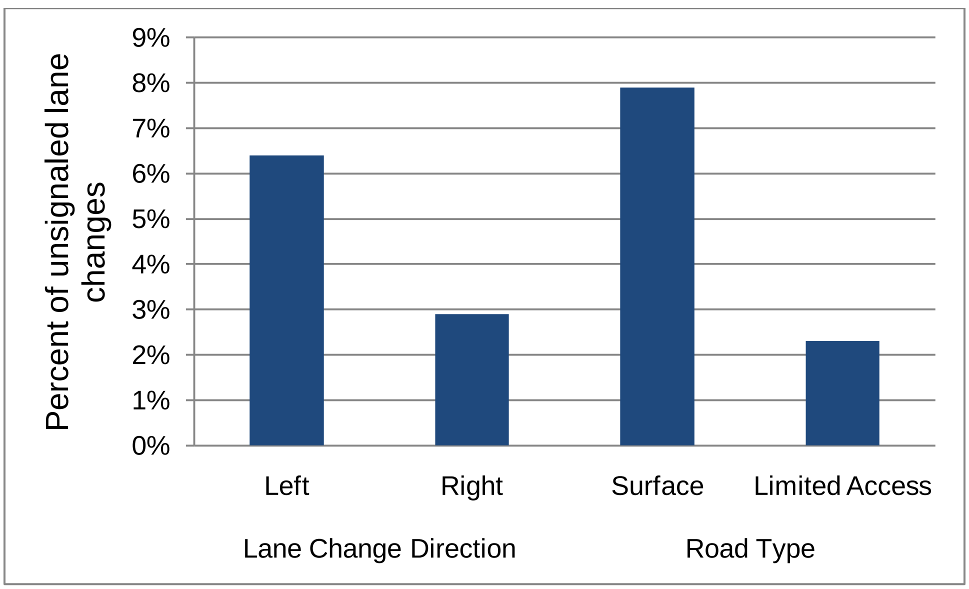

Figure 68: Main effects of lane change and road type on unsignaled lane changes

One two-way interaction that showed significance was Treatment condition by Road type ($F(1,17) = 2.67$; $p = 0.0503$). These results are shown in Figure 69. The model predicts that on surface roads, drivers are 1.8 times more likely to not use a turn signal during a lane-change in the baseline period as compared to the treatment period. The model predicts that on surface roads drivers failed to use a turn signal in 11 percent of lane changes in the baseline period and 6 percent of lane changes in the treatment period. For limited access roads the model predicts that drivers are 1.25 more likely to not use a turn signal in baseline compared to treatment. On this road type the drivers failed to use their turn signal 2.6 percent of the time in baseline and 2.1 percent of the time in treatment.

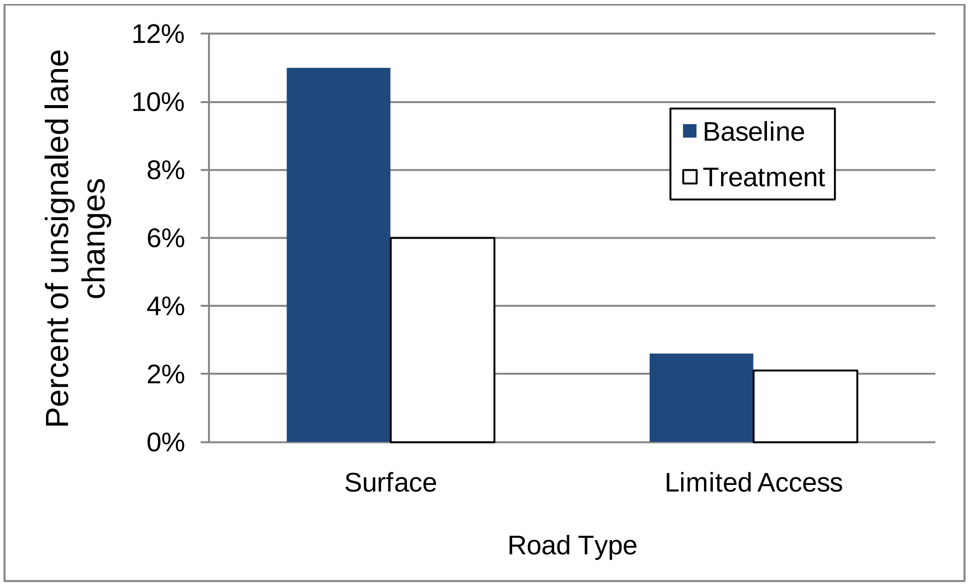

Figure 69: Interaction between phase and road type.

Descriptive Statistics: The general distribution of lane-changes and unsignaled lane changes for this analysis is summarized in Table 42. This table shows the count of all lane changes and the count of unsignaled lane changes for each of the dependent variables used in the statistical analysis for this research question. In terms of lane-change direction, the data set was balanced between left and right with only 485 more lane-changes to the left (less than a one percent difference). Similarly, the number of lane-changes as a function of time is evenly distributed with a Mean of 5,322 (St. Dev. = 884) per Month across all ten months of the FOT. Although no significance difference was found in signal usage as function of Month it is worth noting the two highest fractions of unsignaled lane-changes did occur in the Months 1 and 2, (the baseline months), at 0.055 and 0.065, respectively. Figure 70 shows the fraction of unsignaled lane changes as function of Month for all 18 drivers (Mean = 0.046; St. Dev. = 0.009).

Table 42: Count of lane-changes and percent of unsignaled lane changes for different dependent variables

Independent Variable	Level	% No Turn Signal	Lane Change Count
Direction	Left	6%	26853
	Right	3%	26368
Route Type	LH	4%	48550
	P&D	15%	4671
Condition	Baseline	6%	12360
	Treatment	4%	40861
Wiper state	Off	5%	50760
	On	5%	2461
Load	Light	11%	6043
	Heavy	4%	46818
Trailer	Double	4%	48214
	Single	14%	5007
Road type	Surface	12%	5418
	Limited Access	4%	47803

Independent Variable	Level	% No Turn Signal	Lane Change Count
Month	1	5%	7019
	2	6%	5341
	3	4%	6399
	4	4%	5440
	5	3%	5636
	6	4%	4387
	7	5%	4864
	8	4%	5275
	9	5%	4748
	10	4%	4112
Hours Service	1	4%	15596
	2	7%	4264
	3	7%	3458
	4	6%	2287
	5	15%	991
	6	10%	1618
	7	7%	3091
	8	5%	6987
	9	3%	7441
	10	2%	7488

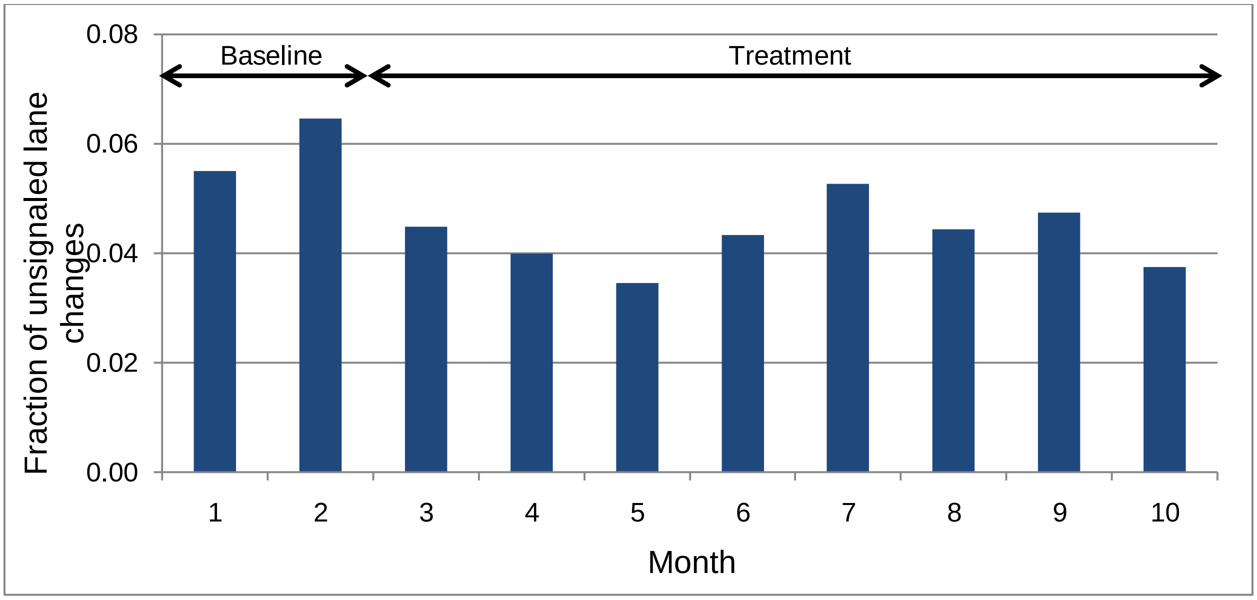

Figure 70: Fraction of unsignaled lane-changes as function of Month

Further investigation of unsignaled lane change events by individuals shows a wide variation across the driver population. Consider Figure 71 with the fraction of unsignaled lane changes for each driver in descending order. The figure shows two distinct groups of unsignaled lane change behavior, namely: a group of four drivers that have a proportionately higher fraction of unsignaled lane changes and a group of 14 drivers that routinely signal for lane-changes. In fact, the first group of four drivers constitutes over 54 percent of all unsignaled lane changes -with the most egregious driver not using the turn signal in almost 45 percent of lane-changes. The figure also labels the route type for each fraction and shows that there is no discernable pattern related to this variable. One interpretation is that regardless of this distinct division in driving task (That is: P&D is dominated by short, daytime trips on a variety of roads and predominantly in an urban-high traffic environment, whereas, LH is mostly long nighttime trips on rural, limited-access highways) the practice of making unsignaled lane changes appears to be based on the individual driver. To better understand the reasons why a driver would make unsignaled lane changes (i.e., handedness, distraction or engagement in secondary tasks, awareness of the surrounding traffic, indolence, etc.) further research is needed.

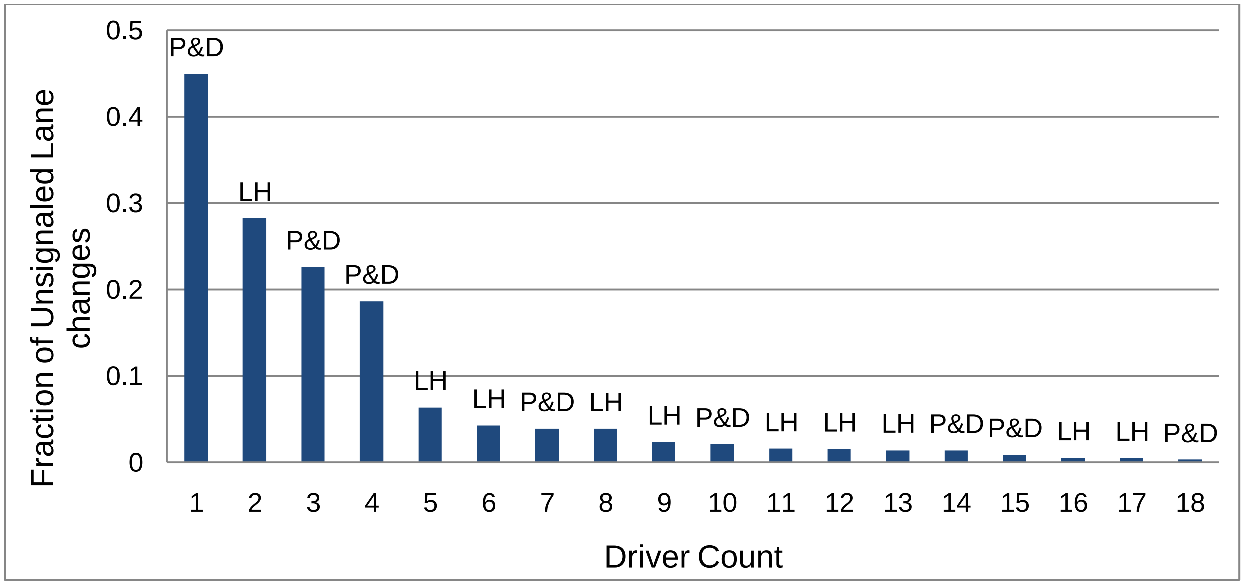

Figure 71: Fraction of unsignaled lane-changes as function of Driver Count

Based on Figure 71, and the assumption that any change in unsignaled lane change rate as a result of the integrated system would be found in drivers that have the greatest fraction of unsignaled lane changes, an analysis of their use as function of time was performed. (Further rationale for dividing the driver set is that drivers that routinely use their turn signal for lane changes before experiencing the integrated system had little opportunity to increase their use during the treatment period.)

Figure 72 shows how the fraction of unsignaled lane changes varied as function of Month for the four drivers with the greatest fraction of unsignaled lane changes. Three of the four drivers had a relatively constant rate of approximately 20 percent unsignaled lane changes per month, while the fourth driver showed a much greater variation in his unsignaled lane change rate. None of the drivers showed a pronounced decrease in their unsignaled lane change rate as function of exposure to the integrated system, and at least one driver showed a increase in unsignaled lane changes as a function of time and exposure to the integrated system.

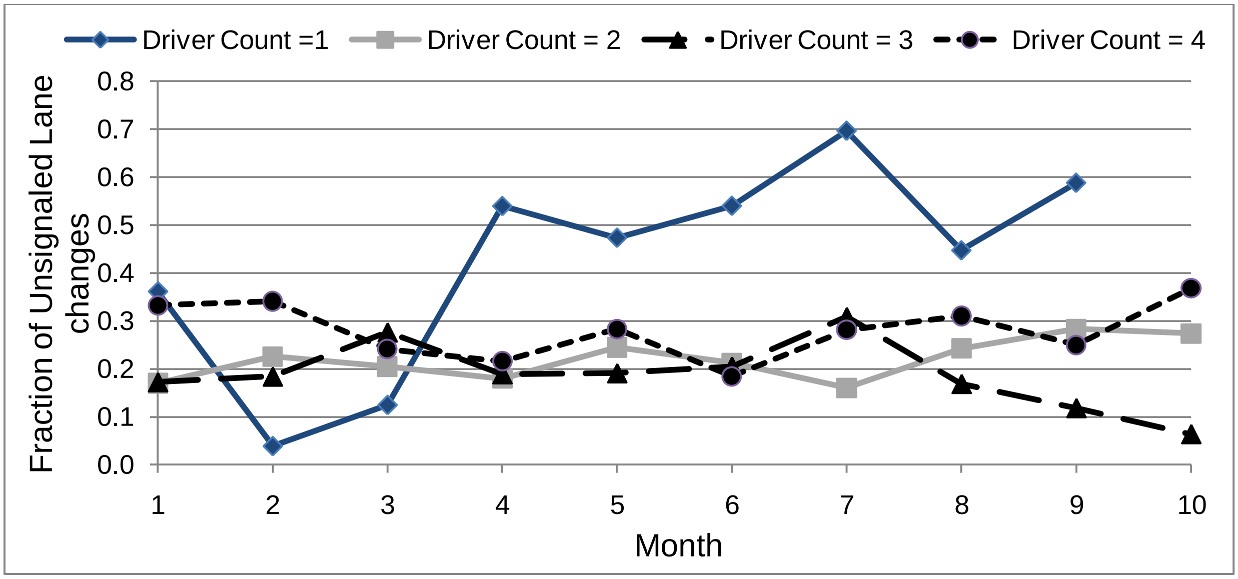

Figure 72: Fraction of unsignaled lane changes as function of Month for the four drivers with the greatest fraction of unsignaled lane changes.

Interpretation: The results showed that while there was no significant effect of the integrated system on turn signal use during lane changes, the overall trend was in a safety-positive direction. Namely, with the integrated system enabled drivers were more likely to use a turn signal when making a lane change relative to the baseline period. However one driver in particular, who was least likely of the 18 to use his turn signal when making lane changes, went in the opposite direction – using the turn signals even less when the integrated system was engaged.

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

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

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

Method: For this analysis, a set of 321,376 randomly sampled events of 5 seconds in duration were identified in the data set. For every event, a lateral position was calculated with respect to the lane boundary markers, within the lane. Additionally, each candidate event was characterized as being in an environment in which there is no object or vehicle occupying the opposite space adjacent to the vehicle, which may inhibit the driver from changing his lateral position away from a passing vehicle. This opposite space is shown in Figure 73 as a clear shoulder or unoccupied adjacent lane. The qualification of this 'empty' space will be determined by the side and rear sensing radar as showing the space as unoccupied. To reduce possible lane-position adjustments for other reasons, the constraints shown in Table 43 were implemented. These constraints required the event to occur on straight sections of road with good boundaries and no intentional lateral maneuvers temporally near each sample. Finally, each element in the set was analyzed to determine if a vehicle (or vehicles) was present in the adjacent lane for the entire 5 second window as shown by the crosshatched region in Figure 73. Similarly, events labeled unoccupied remained that way for the entire 5 second window.

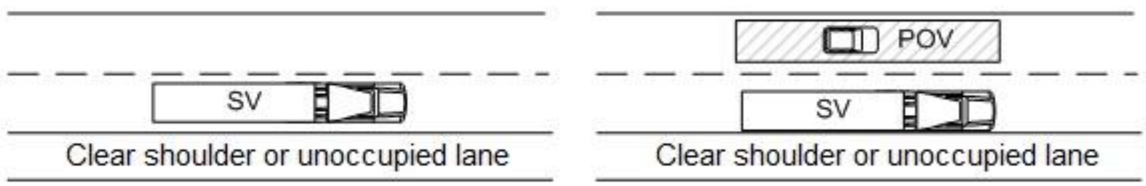

Figure 73: Lateral offset change away from an occupied space.

Table 43: Analysis Constraints

Constraints
1. Boundary types known and lane offset confidence 100 percent
2. Straight Road
3. Speed > 11.2 m/s (25 mph)
4. No intentional lateral maneuvers by the driver in near temporal proximity to each 5 second event

Shown in Table 44 are the dependent variables for the analysis and a list of independent variables that will be included in the analysis to investigate the relationship between lateral offset and other aspects of the vehicle environment and performance criteria.

Table 44: Variables

Dependent Variables
1. Average distance from the center of the lane
Independent Variables
1. Condition (Binary: baseline, treatment)
2. Wiper state (binary: on, off)
3. Load (binary: light, heavy)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road type (binary: limited access, surface)
7. AMR left (binary: unoccupied, occupied)
8. AMR Right (binary: unoccupied, occupied)
9. Time working (continuous; units hours of service)
10. Exposure (continuous; units month)

Results: The principal findings of this analysis are based on the results of a mixed linear model conducted for an adjacent lane on each side of the SV and the conclusions shown below were derived from the model and not 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 sign convention used for these results is a lateral offset from the center of the lane to the left is negative, to the right is positive. The predicted changes in lateral offset by the model for the main effects are shown in Figure 74 for an adjacent lane on the right and Figure 75 for an adjacent lane on the left. Both figures are oriented to show the practical direction and magnitude of the change relative to the available space between the outside of the front tire and the lane edge given a standard 12 foot (3.65 m) lane width and a measured track width of 2.54 m for the front tires of the FOT tractors.

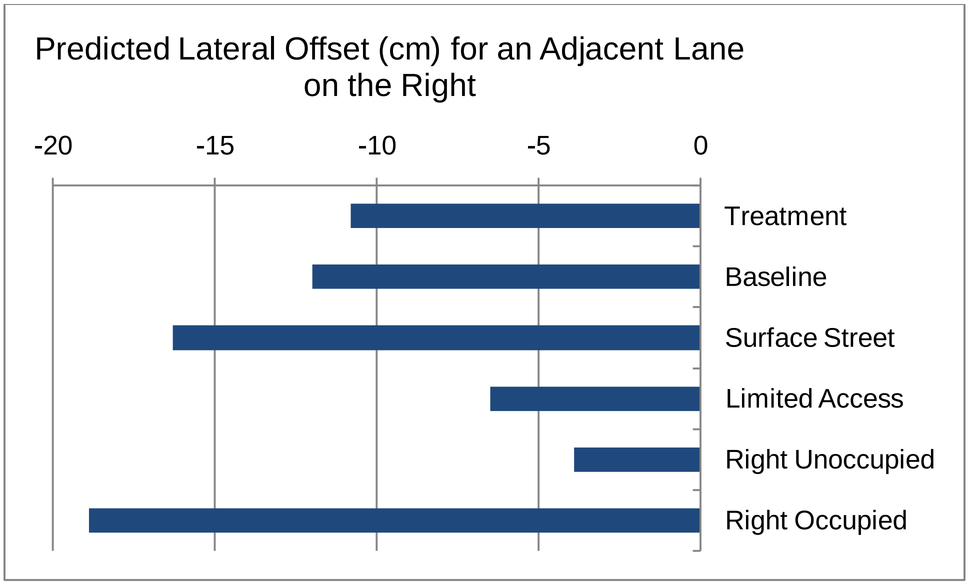

Figure 74: Predicted Lateral Offset for an Adjacent Lane on the Right

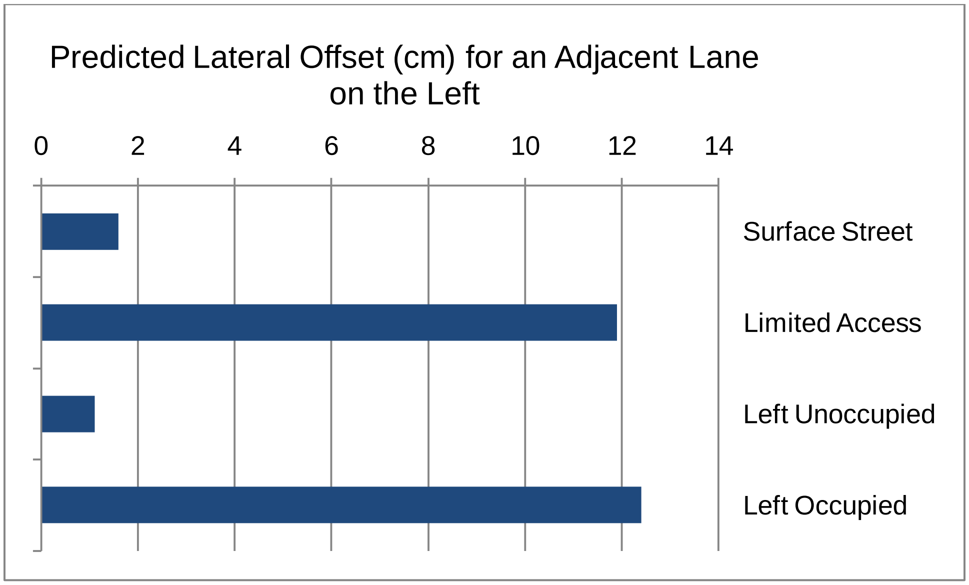

Figure 75: Predicted Lateral Offset for an Adjacent Lane on the Left

In terms of condition, the model finds the treatment condition (($F(1,17)=3.56$; $p = 0.0763$)) to be marginally significant in the model considering the available maneuvering room (AMR) on the right side. However, for the model considering AMR on the left side the model predicts that treatment condition alone was not significant. For both sides, however, the model predicts that change in lateral offset due to the condition is small and show that during treatment drivers stayed closer to the center of the lane by approximately 0.013 m (0.5 inches) for both cases. This finding supports the hypothesis that the integrated system does not cause drivers to change their lane position in a manner that increases their risk of a warning or crash due to lateral offset.

The other principal main effects that showed significance when considering an adjacent lane to the right were the adjacent lane state and road type. Regarding adjacent lane state, the model predicts that drivers move 0.15 m (6 inches) to the left (away) from an occupied adjacent lane on the right ($F(1,16)=178.26$; $p<0.0001$) as compared to an unoccupied lane on the right. For road type ($F(1,16)=33.34$; $p < 0.0001$) the model predicts that drivers move 0.098 m (3.9 inches) more to the left on surface roads as compared to limited access roads when there is an adjacent lane on the right.

The principal main effects that showed significance when considering an adjacent lane to the left were also adjacent lane state and road type. The largest effect predicted by the model is adjacent lane state ($F(1,17)=52.03$; $p<0.0001$) which showed that drivers move 0.12 m (4.3 inches) to the right when the adjacent lane on the left is occupied. For road type ($F(1,17)=28.61$ $p < 0.0001$) the model predicts that drivers move 0.10 m (3.9 inches) more to the right on limited access roads as compared to surface roads when there is an adjacent lane on the left (this effect is opposite of the main road type effect with adjacent lane on the right).

Table 45 shows the summary of analysis for two-way interactions that were significant for both an adjacent lane on the right and left.

Table 45: Two-way interaction summary of analysis

Two-way Interactions	Adjacent lane on right	Adjacent lane on the left
Road type by AMR	F(1,16)=26.59, p=<.0001	F(1,17)=5.98; p=0.0257

The average lateral offset changes as predicted by the model for the two-way interactions are given in Table 46.

Table 46: Predicted lateral offset from the interaction between road type and adjacent lane state.

		AMR Left	AMR Right
Road type	**Adjacent Lane**	**Lateral offset, m**	**Lateral offset, m**
Limited Access	Occupied	17.9	-15.6
Limited Access	Unoccupied	5.8	2.6
Surface	Occupied	6.7	-22.2
Surface	Unoccupied	-3.5	-10.4

These predicted averages are consistent with the discussion on main-effects. The two largest interactions both occur when there is an adjacent lane on the right and involve the state of that lane. For this condition the model predicts a change in lateral offset of 0.18 m (7.1 inches) for limited access roads

Descriptive Statistics: The general distribution of lateral offset events for this analysis is summarized in Table 47 for an adjacent lane on the left and Table 48 for an adjacent lane on the right. In total these events represent over 445 hours of driving. These data are heavily weighted toward events (95 percent) in which the adjacent lane is to the left of the SV lane meaning that this set of drivers spends about 95 percent of time in the right-most lane on multi-lane roads given that these event are representative of overall exposure at speeds above 11.2 m/s which is reasonable since they represent a random sampling of data for travel on straight sections of well-marked roads. When considering the events by route type, this ratio changes to 97 percent for LH and 64 percent for P&D. This change is consistent with the fact that the routes for P&D drivers are urban and on roads where sustained driving with an adjacent lane on the left is acceptable.

These data show that the percent of time that the adjacent lane to the SV is occupied is 6.6 and 28 percent for an adjacent lane to the left and right, respectively. Furthermore, limited access road type show an occupied lane on the right accounts for 41 percent of the driving time.

Table 47: Count of adjacent lane to the left events and occupied events for different dependent variables

Independent Variable	**Level**	**% Occupied**	**Count**	**Independent Variable**	**Level**	**% Occupied**	**Count**
AMR	Left	7%	304616	Month	1	6%	33576
Route Type	LH	6%	293155		2	6%	29682
	P&D	20%	11461		3	6%	35900
Condition	Baseline	6%	63258		4	7%	30403
	Treatment	7%	241358		5	6%	32355
Wiper state	Off	7%	293795		6	7%	26649
	On	7%	10821		7	8%	28807
Load	Light	10%	26170		8	7%	30591
	Heavy	6%	278446		9	7%	30380
Trailer	Double	6%	290566		10	7%	26273
	Single	16%	14050	Hours Service	1	6%	42251
Road type	Surface	6%	28287		2	5%	50616
	Limited Access	7%	276329		3	5%	39308
					4	4%	18470
					5	6%	7605
					6	5%	10261
					7	6%	10952
					8	6%	32328
					9	8%	44629
					10	11%	48196

Table 48: Count of adjacent lane to the right events and occupied events for different dependent variables.

Independent Variable	Level	% Occupied	Count
AMR	Right	28%	16760
Route Type	LH	34%	10269
	P&D	18%	6491
Condition	Baseline	34%	4065
	Treatment	26%	12695
Wiper state	Off	28%	15839
	On	24%	921
Load	Light	19%	5081
	Heavy	32%	11679
Trailer	Double	34%	10230
	Single	18%	6530
Road type	Surface	17%	9168
	Limited Access	41%	7592

Independent Variable	Level	% Occupied	Count
Month	1	33%	2370
	2	34%	1695
	3	26%	2163
	4	28%	1974
	5	28%	2060
	6	23%	1314
	7	25%	1412
	8	24%	1388
	9	27%	1264
	10	25%	1120
Hours Service	1	29%	3098
	2	28%	2208
	3	24%	1220
	4	24%	1058
	5	17%	737
	6	15%	713
	7	20%	979
	8	28%	1635
	9	34%	2031
	10	34%	3081

The statistical model above predicts that presence of a vehicle in an adjacent lane has the largest effect on lateral offset. Based on this fact, consider Figure 76 which shows the change in average lateral offset under these conditions (occupied/unoccupied) for an adjacent lane on the left. (A similar distribution, albeit with less change, occurs with an adjacent lane on the right). As the figure shows, the range in driver results related to this measure varies considerably from 0.27 m (10.6 inches) to 0.007 m (0.3 inches).

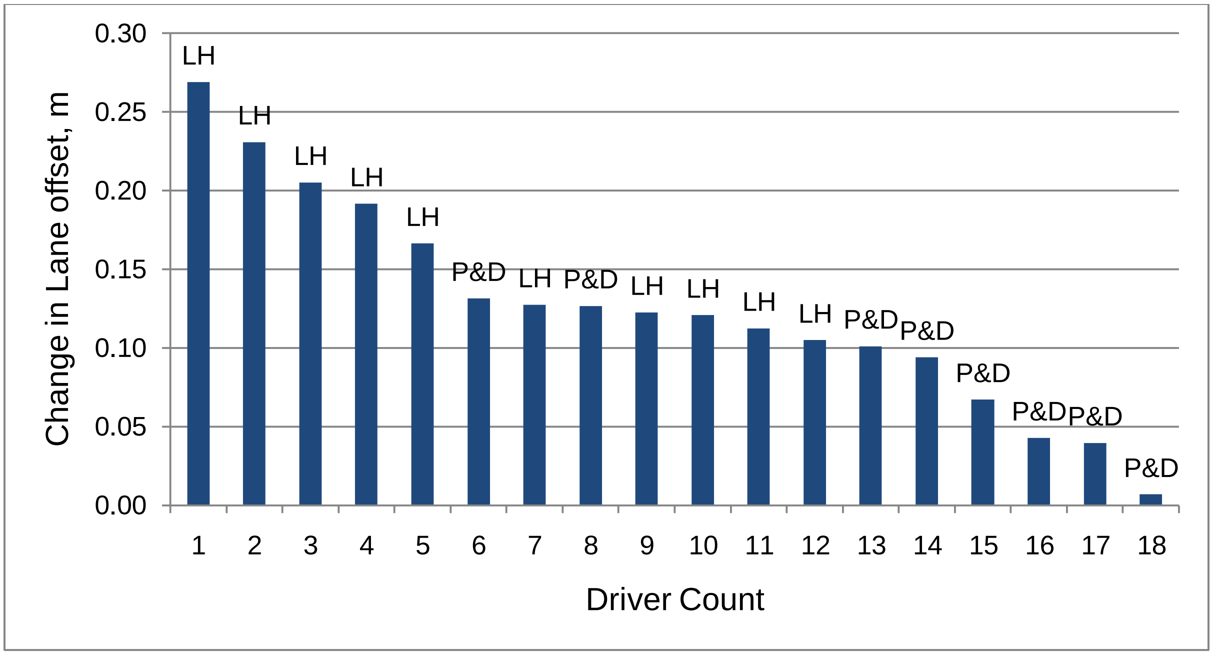

Figure 76: Change in lateral offset caused by an occupied vs. unoccupied adjacent lane on the left for each driver

For more perspective, consider Figure 77. This figure shows the change in lateral offset as function of the overall difference in driver (least vs. most conservative) performance for occupied vs. unoccupied lane position and other independent measures. The figure shows the overall range of these measures on lane offset emphasizing that individual drivers show the largest difference in performance when compared to the effect that road type, load, precipitation and phase have on lateral offset.

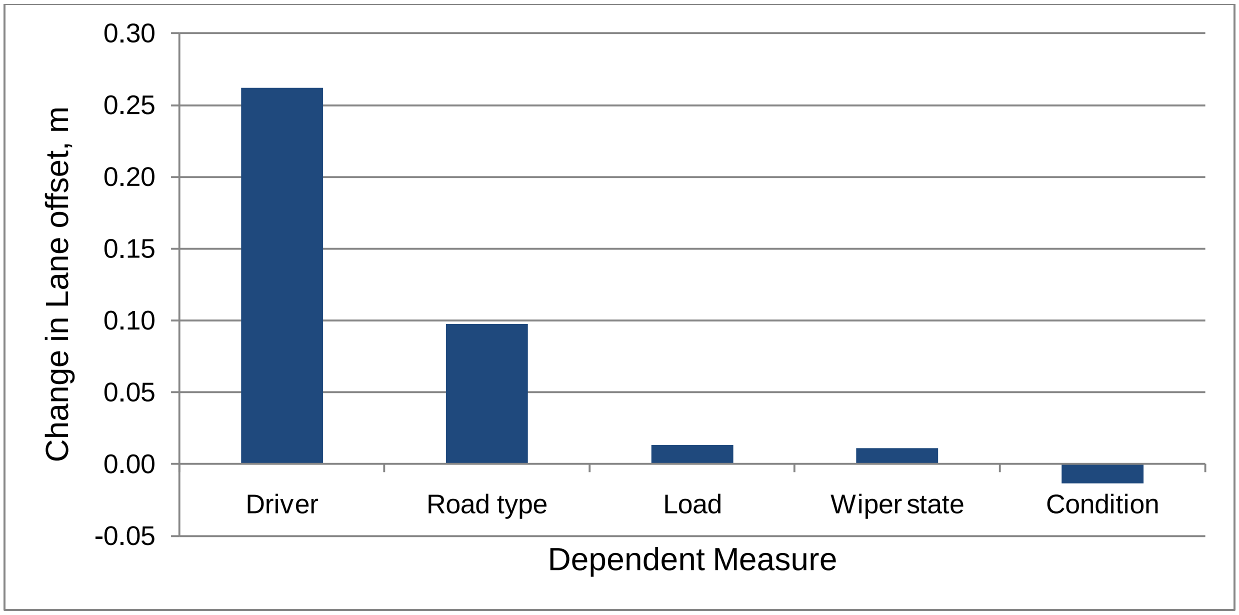

Figure 77: Relative change in lateral offset as function of driver and other dependent measures.

Interpretation: In terms of condition, the results show that treatment alone as a one-way interaction was found to be significant when considering an adjacent lane on the right and only marginally significant for an adjacent lane on the left. For both sides, however, the results show that the change in lane position due to the condition is small and that during treatment drivers stayed closer to the center of the lane by approximately 0.013 m (0.5 inches) for both left and right adjacent lanes. This finding supports the hypothesis that the integrated system does not cause drivers to change their lane position in a manner that increases their risk of a warning or crash due to lateral offset. In fact, the model predicts that drivers stay closer to the center of their lane in treatment as compared to baseline.

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

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

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

Method: First, the region adjacent to each side of the heavy truck was divided into three zones for the front and rear lateral proximity (BackSpotter) radar and the rear looking (trailer coverage) MACOM radar as shown in Figure 78. Next 720 LCM warnings were identified for conditions in which the space adjacent to the truck was occupied by a same-direction vehicle only. That is, the conditional statements operating on the objective data must exclude cases in which the space was occupied by a fixed roadside object such as a guardrail or barrier or cases in which the system mistakenly characterized a reflective object from the trailer as an adjacent vehicle. Next, for each LCM event, the zones on the corresponding side of the vehicle were characterized as being occupied or not. For those targets in the rear-looking radar zone the range and range-rate from the radar to the closest vehicle in that zone were identified. The analysis is performed using the constraints shown in Table 49. These rules will help establish a steady-state condition for the subject vehicle and dictate how long the turn signal and targets had to have persisted for the event to be considered a candidate for the analysis.

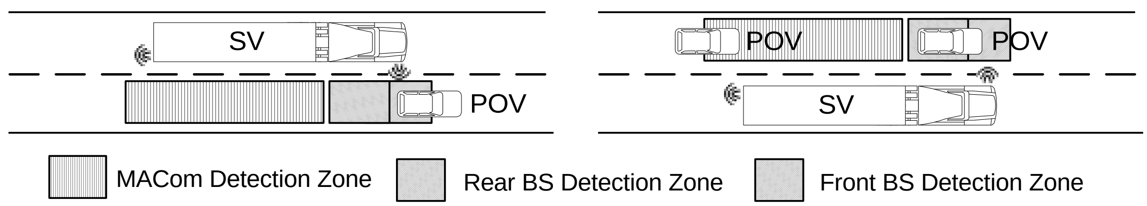

Figure 78: Location of adjacent vehicles relative for valid LCM warnings

Table 49: Analysis Constraints

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 s before LCM warning is issued
4. Speed > 11.2 m/s (25 mph)
5. For MACOM radar: target duration > 2 s and a non-zero range rate
6. For BackSpotter radar: the vehicle is present for at least 2 s at a range between 0 and 10 ft
7. No intentional lateral maneuvers by the SV driver in a five second window prior to the LCM (i.e., the SV is in a steady state condition within its lane)

Shown in Table 50 are the dependent variables for the analysis and a list of independent variables that will be included in the analysis to investigate the relationship between the location of the POV relative to the SV at the onset of an LCM warning and other aspects of the vehicle environment and performance criteria.

Table 50: Variables

Dependent Variables
1. Count and distribution of valid LCM warnings for the six zones around the vehicle
Independent Variables
1. Condition (Binary: baseline, treatment)
2. Wiper state (binary: on, off)
3. Load (binary: light, heavy)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road type (binary: limited access, surface)
7. Hours of service (continuous; units hours)
8. Exposure (continuous; units month)

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.

For the analysis, 720 valid LCM warnings were examined and four zones where considered. Figure 79 shows the percentage of alerts occurring as a function of zone. The most active zone was the area covered by the rear BackSpotter only in which 30 percent of the alerts occurred. The second most active zone at 29 percent is the Macom zone which covers the area adjacent to the trailer and aft of the landing gear. The front BackSpotter only and the overlap between both front and rear BackSpotter accounted for 17 and 24 percent of the LCM warnings, respectively.

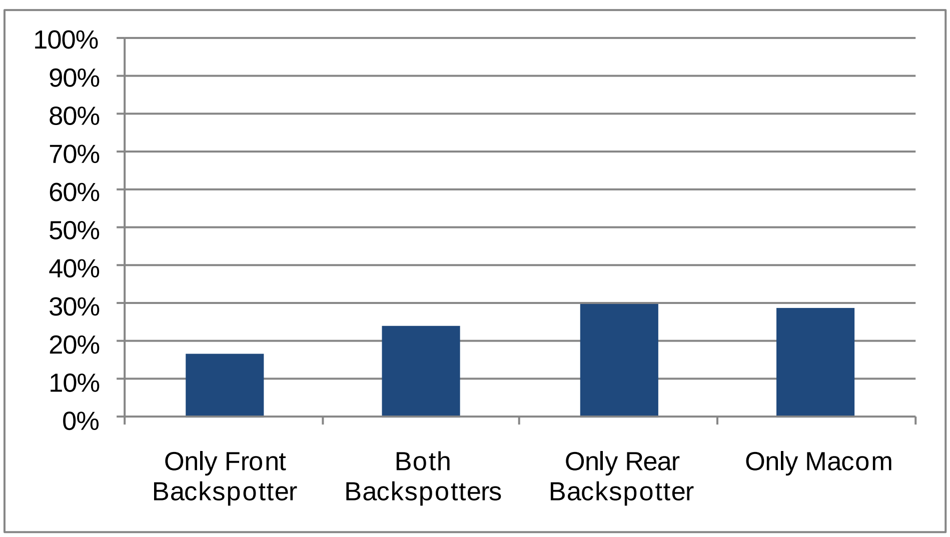

Figure 79: Summary of the distribution of LCM warnings.

The effect of condition was not found to be significant (χ^2 (3, N=720) = 0.4923, p = 0.9206) for the location of LCM warnings. Figure 80 shows the percentage distribution of LCM warnings for the baseline and treatment periods. For baseline there were 149 LCM warnings, for treatment 571. When exposure is considered, the alert rate is only marginally higher (5%) for treatment.

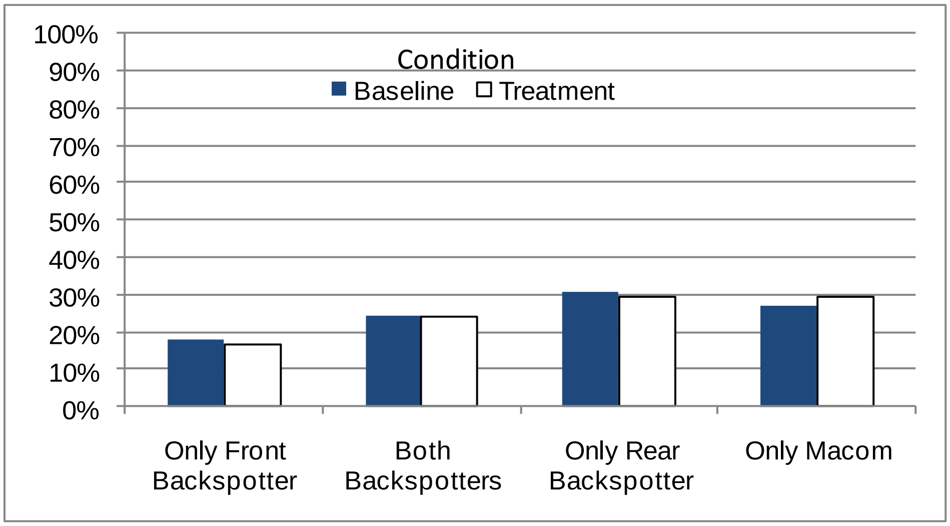

Figure 80: Summary of the distribution of LCM warnings as function of condition.

Several dependent variables were found to be significant. These results are summarized in Table 51.

Table 51: Significant findings using the Chi-square test for variance

Main Effect	**N**	**df**	χ^2	***p***
Side	720	3	54.1417	<.0001
Road type	720	3	15.3443	0.0015
Route type	720	3	22.1417	<.0001
Load	720	3	14.8989	0.0019

The results for POV side are shown in Figure 81. Of the 720 LCM warnings, 554 (77%) resulted from a POV on the left side of the SV. Of these 554 warnings, 429 (77%) occurred in the adjacent area covered by the BackSpotters while only 125 (23%) warnings 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 81 shows the effect of side on the distribution of LCM warnings by zone.

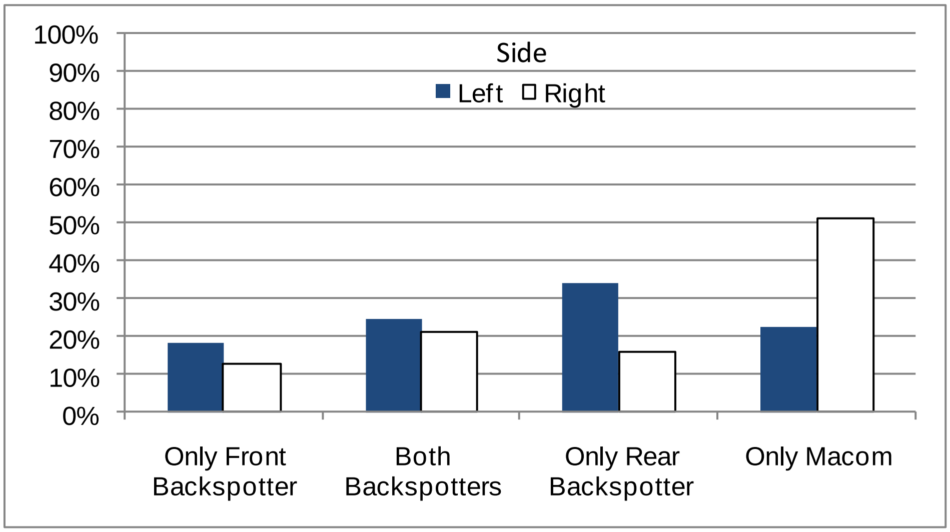

Figure 81: Main effect of side on POV location during LCM warnings

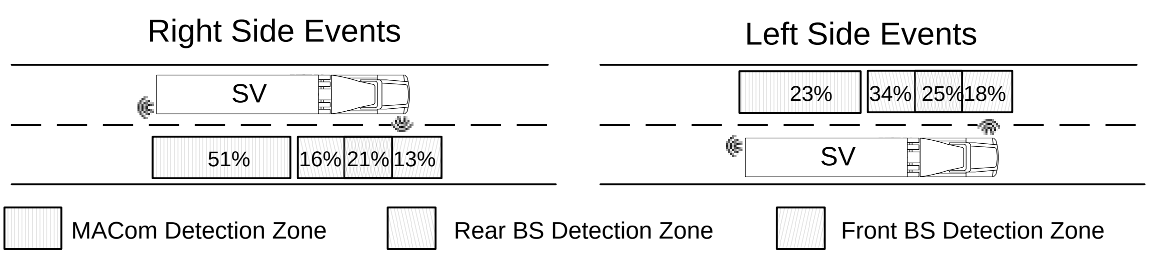

Figure 82: Effect of side on distribution of LCM warning by zone

The main effect of road type is shown in Figure 83. A total of 512 LCM warnings (71 percent) were on limited access and 208 on surface roads. Adjusted for exposure (i.e., miles driven) and assuming the distribution of this set is representative of all LCM warnings, LCM warnings are 3.3 times more likely to occur on surface streets as compared to limited access roads. Regarding the zone distribution on both road types, the most likely location of the POV for an LCM warning is adjacent to the tractor and the forward portion of the trailer. These three zones, account for 66 percent and 73 percent of the LCM warnings on surface and limited access roads, respectively. When normalized for exposure, trailer only (only Macom) LCM warnings are 4.2 time more likely to occur on surface as compared to limited access roads.

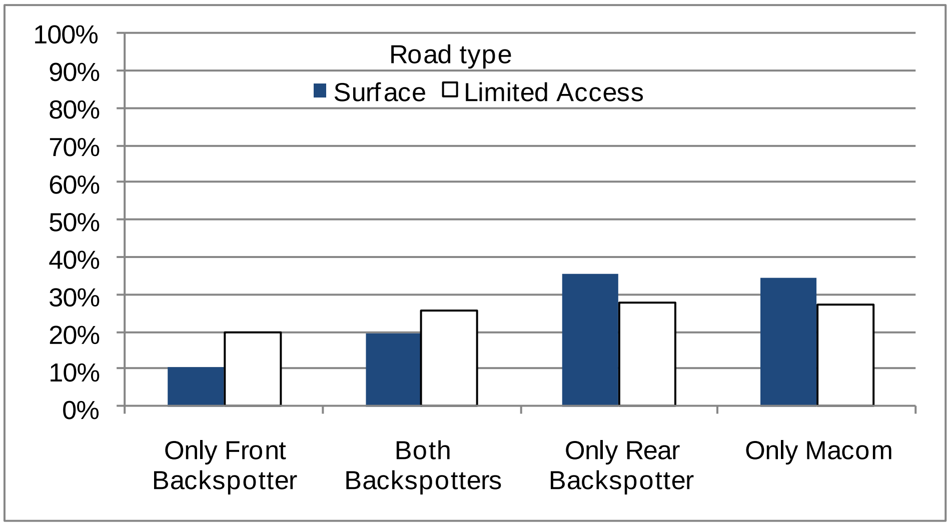

Figure 83: Main effect of road type on POV location during LCM warnings

The main effect of trailer and route type is shown in Figure 84. A total of 428 LCM warnings (59 percent) were with double/LH and 292 with single trailers/P&D drivers. Adjusted for exposure, LCM warnings are 5.4 times more likely on with single/P&D as compared to a double/LH trailer combination. Regarding the zone distribution, like road type, the most likely location of the POV for an LCM warning is adjacent to the tractor and the forward portion of the trailer. These three zones, account for 62 percent and 67 percent of the LCM warnings with single/P&D and double/LH trailers, respectively. When normalized for exposure, trailer only (only Macom) LCM warnings are 9.0 times more likely to occur with single/P&D as compared double/LH trailers.

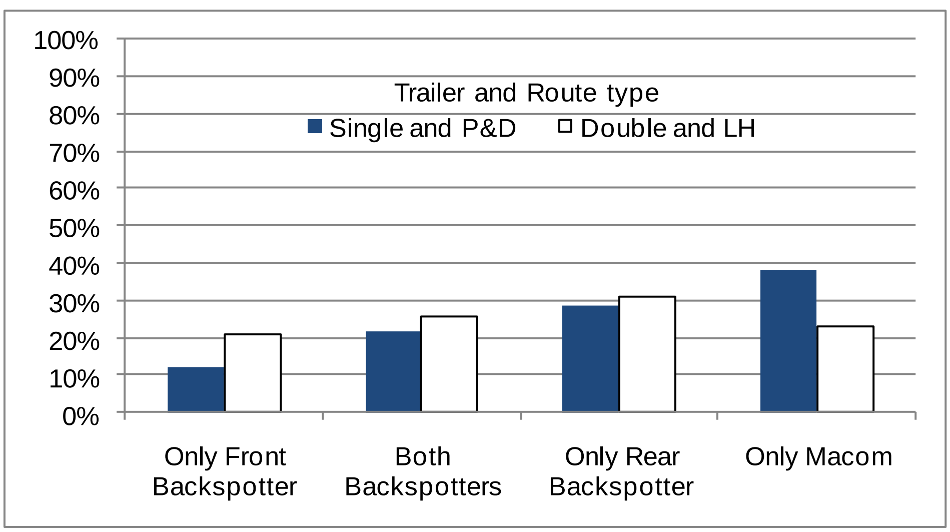

Figure 84: Main effect of trailer and route type on POV location during LCM warnings

The main effect of load is shown in Figure 85. A total of 424 LCM warnings (59 percent) were in the heavy and 296 were light condition. Adjusted for exposure, LCM warnings are 3.0 times more likely in the light as compared to the heavy condition. Regarding the zone distribution, the most likely location of the POV for an LCM warning is adjacent to the tractor and the forward portion of the trailer. These three zones, account for 65 percent and 75 percent of the LCM warnings in the light and heavy condition, respectively. When normalized for exposure, trailer only (only Macom) LCM warnings are 4.0 times more likely to occur in the light as compared to the heavy condition.

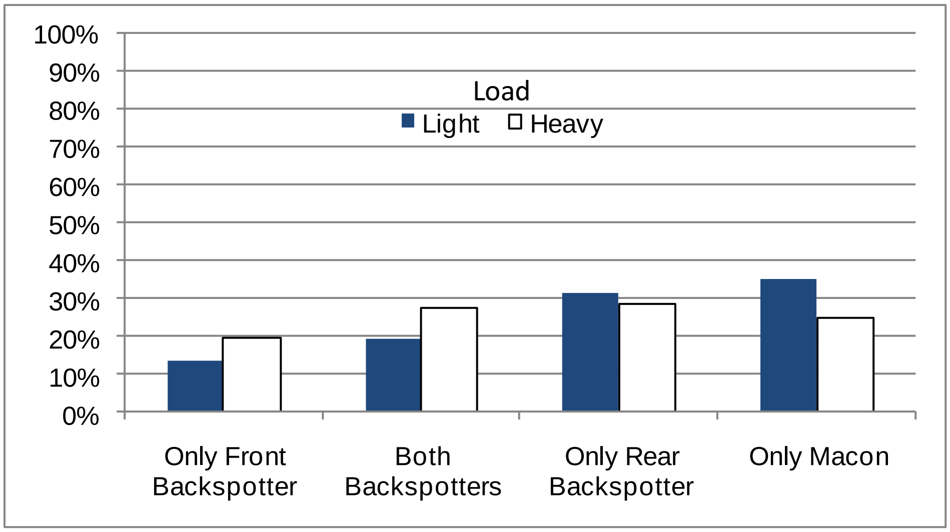

Figure 85: Main effect of load on POV location during LCM warnings

Interpretation: In terms of condition, the results show that treatment alone as a main effect was not found to be significant when considering the location of LCM warnings. The most significant effect found was side. Of the 720 LCM warnings, 554 (77 percent) resulted from a POV on the left side of the SV. Of these 554 warnings, 429 (77 percent) occurred in the adjacent area covered by the BackSpotters while only 125 (23 percent) warnings happened with a POV adjacent to the trailer.

One reason for the much larger occurrence of warnings to the right being triggered by the Macom radars adjacent to the trailer arises from the SV signaling to change lanes to the right when the SV is passing a slower POV on the right. In this scenario the SV driver may engage the turn signal and begin to drift toward the right before the POV is outside of the Macom coverage zone. This is less likely to occur on the left since it is relatively rare that the SV driver is passing a slower moving vehicle on the left. To the contrary, LCM warnings to the left are much more likely to occur in the BackSpotter region by a passing, faster-moving POV. In this scenario the SV driver will initiate a turn signal and perhaps a small drift to the left before the POV has cleared the BackSpotter zone on the left and hence an LCM warning is issued.

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

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

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

Method: Identify a set of valid (high confidence) left and right lane-change events as show in Figure 86. Fundamentally, this analysis will address changes in the frequency of lane changes by normalizing the number of lane change events by miles driven under different conditions. Then a statistical comparison will be made to compare lane-changes rate as a function of the integrated system.

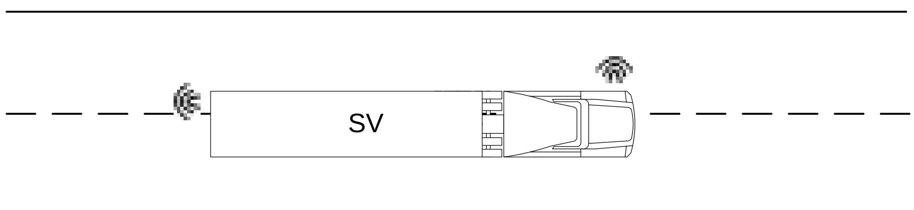

Figure 86: Lane change to the left.

The investigation into possible changes in lane-change rate during the FOT is based on a sub-set of 49,241lane-change events. For the purpose of this report a lane-change is defined as the lateral movement of the SV relative to the roadway in which the SV starts in the center of a defined traffic lane with boundary demarcations and ends in the center of an adjacent traffic lane that also has defined boundary demarcations. The explicit instant in time of the lane-change is defined as the moment when the SV lateral centerline crosses the shared boundary between the two adjacent traffic lanes. Lane-changes are comparatively complex events that involve both infrastructure information, primarily lane boundary demarcation, as well as lateral performance information from the sensors onboard the vehicle. At one extreme they occur on poorly marked roads but can be identified by patterns in the lateral kinematic variables that when integrated show a lateral translation of approximately 3.6 m (11.8 feet), a typical lane width, within a defined period. At the other extreme, they occur on well-marked roads but without any noticeable difference in vehicle lateral performance, as is the case when the lane-change occurs at the entry or exit to curves. At this extreme the road changes laterally relative to the path of the vehicle. In this case, without precise knowledge both the vehicle and road location, detecting a lane change using a numerical approach is very difficult.

The set of lane changes used in this analysis was constrained using the rules stated in Table 52. The purpose of these constraints is to ensure that the final analysis set of lane-changes is not contaminated with events that may have been flagged as lane-changes but were actually not intended to be lane-changes by the SV driver. An example of this is when a driver intentionally occupies part of an adjacent traffic lane while maneuvering away from a stationary vehicle on the shoulder, or in an adjacent emergency lane. In other circumstances, especially at night and in low traffic situations, drivers may inadvertently drift laterally into an adjacent lane before returning to the center of their original lane. There are numerous examples in the data set of lane-deviation events like the ones mentioned above and in fact, the data set as a whole contains 226,886 events in which the LDW lane-change measure was set to true.

Table 52: Analysis Constraints

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

Shown in Table 53 is the dependent variable for the analysis and a list of independent variables that were included to investigate the relationship between lane-change frequency and other aspects of the vehicle environment, during lane changes.

Table 53: Variables

Dependent Variables
1. Lane changes performed
Independent Variables
1. Condition (Binary: baseline, treatment)
2. Wiper state (binary: on, off)
3. Load (binary: light, heavy)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road type (binary: limited access, surface)
7. Traffic (discrete: sparse, moderate, dense)
8. Hours of service (continuous; units hours of service)
9. Exposure (continuous; units month)

Results: The principal findings of this analysis are based on the results of a mixed linear model and the conclusions shown below were derived from the model and not 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.

In terms of integrated system, the model predicts that treatment alone was not found to have a significant effect lane-change frequency ($F(1,17) = 1.31$; $p = 0.2684$).

The principal main effects that showed significance were traffic and wiper state and are shown in Figure 87. Regarding traffic ($F(2,32) = 27.97$; $p < 0.0001$) the model predicts that the frequency of lane changes increases by 1.77 times from sparse to moderate traffic and 2.5 times from moderate to heavy traffic. For wiper state ($F(1,17) = 7.57$; $p = 0.0136$) the model predicts that drivers increase the frequency of lane changes by 1.3 times when the wiper is on compared to off. No two-way interactions were found.

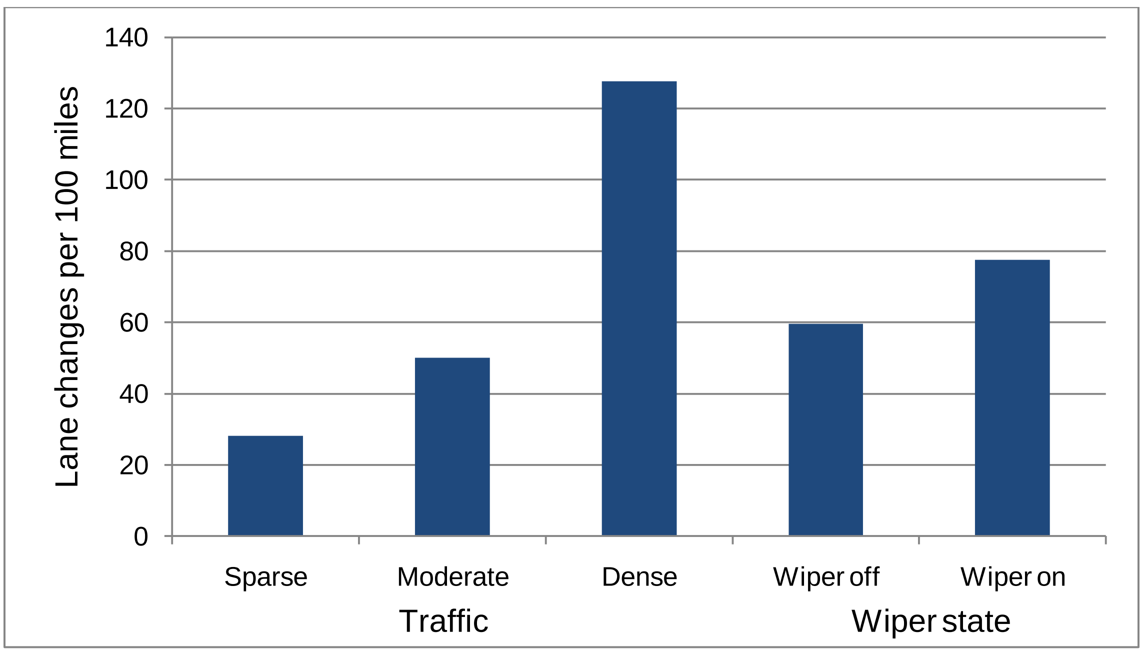

Figure 87: Main effects of traffic and wiper state on lane change frequency

Descriptive Statistics: The general distribution of lane-changes for this analysis is summarized in Table 53: Variables. This table shows the count of all lane changes for each of the dependent variables used in the statistical analysis for this research question. In terms of lane-change direction, the data set was balanced between left and right with only 236 more lane-changes to the left (less than a one percent difference). Similarly, the number of lane-changes as a function of time is evenly distributed with a Mean of 4966.8 (St. Dev. = 797) per Month across all ten months of the FOT. Although no significance difference was found in signal usage as function of Month it is worth noting the two highest rates of lane-changes did occur in the Months 1 and 2, the baseline months, at 24.57 and 22.96 lane changes per 100 miles, respectively. Figure 88 shows the average frequency of lane changes per 100 miles as function of Month for all 18 drivers (Mean = 21.9; St. Dev. = 1.59).

Table 54: Count of lane-changes for different dependent variables

Independent Variable	Level	Count	Independent Variable	Level	Count
Direction	Left	24952	Month	1	6413
	Right	24716		2	4781
Route Type	LH	44843		3	6027
	P&D	4825		4	5127
Condition	Baseline	11194		5	5375
	Treatment	38474		6	4100
Wiper state	Off	47350		7	4548
	On	2318		8	4918
Load	Light	6358		9	4458
	Heavy	43310		10	3921
Trailer	Double	44430	Hours Service	1	14606
	Single	5238		2	3945
Road type	Surface	5797		3	3207
	Limited Access	43871		4	2177
Traffic	Sparse	39775		5	939
	Moderate	9754		6	1572
	Heavy	139		7	2870
				8	6360
				9	6910
				10	7082

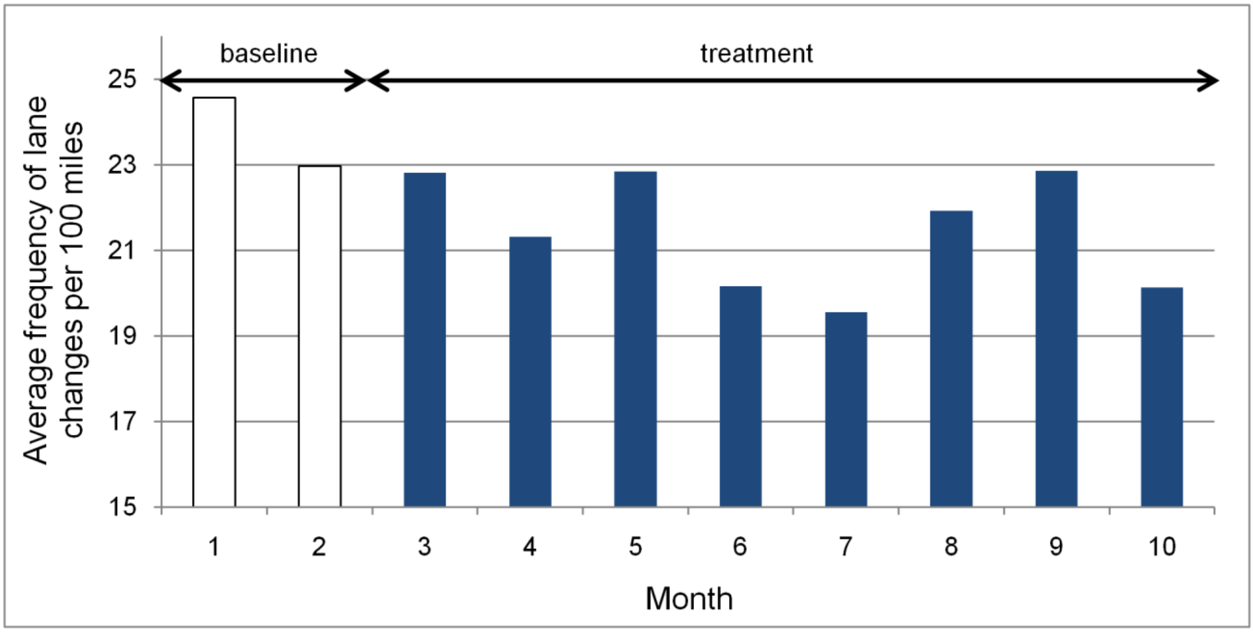

Figure 88: Average frequency of lane-changes as function of Month

Further investigation of lane change rates by individuals shows a wide variation across the driver population. Consider Figure 89 which shows the frequency of lane changes per 100 miles for each driver in descending order.

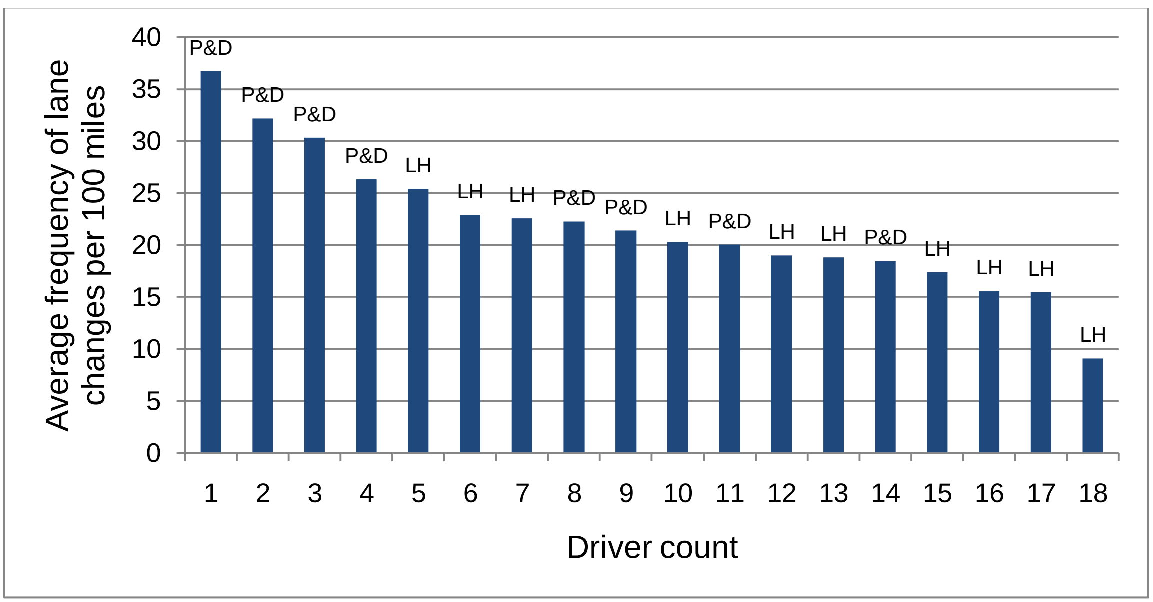

Figure 89: Average frequency of lane changes per 100 miles over 18 drivers

The figure shows no distinct groups of lane change rate behavior among the drivers with the exception of the last driver who has a markedly lower rate than others. The only possible distinction that can be drawn from the figure is that four drivers with the highest rate are P&D and the four with the lowest rate are LH.

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.

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

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

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

Method: Identify instances where the SV is approaching a lead vehicle in the same lane and makes a lane change behind a passing POV1 in an adjacent lane on the left as shown in Figure 90. For each event code the range and range-rate to POV2 at the instant when the SV left front tire crosses the boundary for the last reliable forward measure from the FCW radar. Also, upon changing lanes and when the SV right front tire crosses the boundary determine the range and range-rate of the SV to POV1. Quantitative data will be used to determine the position of the SV front tires when possible, and analysis of video will be used for the other cases when the boundaries are obscured by a lead vehicle. It is assumed that lane changes to the right under similar circumstances are rare, and therefore only lane changes to the left will be considered. The constraints identified in Table 55 will be used to ensure that the candidate set of events is reliable and consistent with the scenario definition.

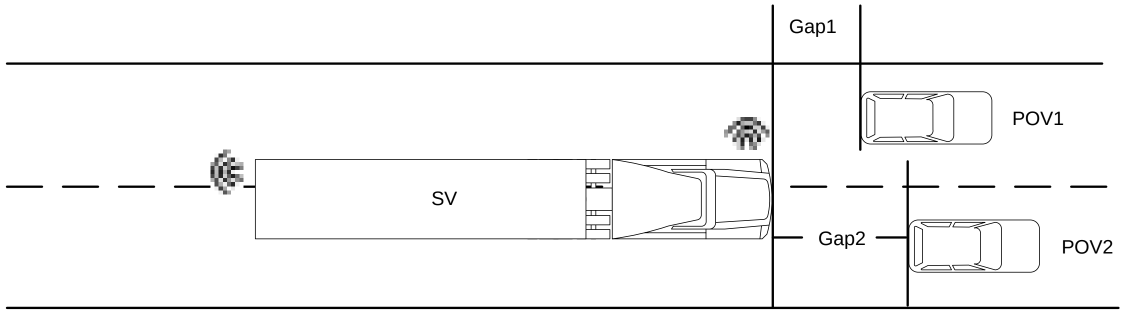

Figure 90: Location of adjacent and forward vehicles relative to the subject vehicle during lane-changes

Table 55: Analysis Constraints

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

Shown in Table 56 are the dependent variables for the analysis and a list of independent variables that will be included in the analysis to investigate the relationship between the gaps drivers are willing to accept during lane changes and other aspects of the environment and performance criteria.

Table 56: Variables

Dependent Variables
1. Range between the SV, POV1, and POV2 during lane changes and range-rate between SV and POV2
Independent Variables
1. Condition (binary: baseline, treatment)
2. Wiper state (binary: on, off)
3. Load (binary: light, heavy)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road type (binary: limited access, surface)
7. Exposure (continuous; hours of service)
8. Speed (continuous; units, m/s)
9. Exposure (continuous; units month)

Results: The results presented below are based on 2862 events that satisfied the analysis constraints given in Table 55. The principal findings of this analysis are based on the results of a mixed linear model for three dependent variables, namely:

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

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

POV2 Range Model: The main effects for the POV2 Range model were road type ($F(1,13)=20.79$; $p = 0.0005$) and speed ($F(1,16)=100.44$; $p < 0.0001$). No main effect of condition was observed. For road type alone the model predicts that on average the range between the SV and POV2 just prior to the lane change is 17.7 and 31.1 m on limited access and surface roads, respectively. The average shorter range for limited access roads suggests that drivers are less conservative on this road type and willing to accept a much smaller time-gap prior to the lane change than on surface roads. The exact reasons for this behavior are not clear from these data but may have to do with the predictability of other vehicles in the more controlled environment found on limited access roads. That is, drivers are willing to accept closer distances because they think the driver of the preceding vehicle will not perform an unanticipated high level of deceleration.

The results of the model suggest that at 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 allow a time-gap of between1 and 1.4 seconds.

Figure 91 displays the interaction of POV2 range as a function of speed for both road types. The model predicts greater range values as function of speed for surface as compared to limited access roads. If range is normalized by speed the difference in road type becomes even more pronounced.

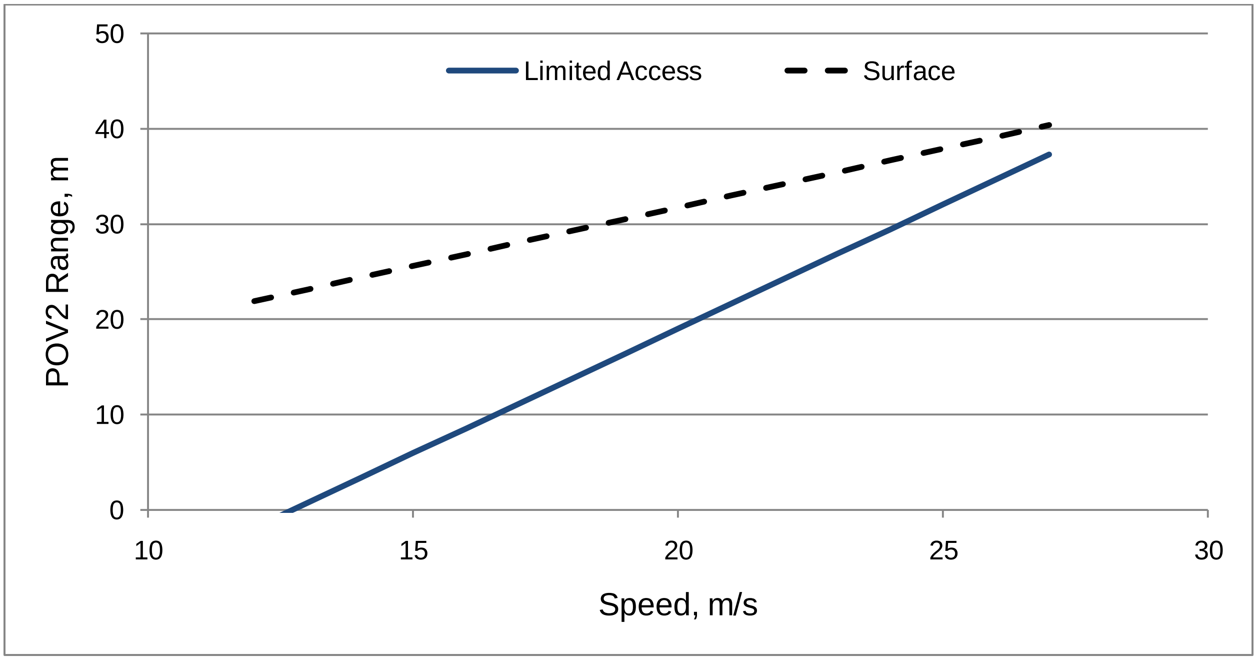

Figure 91: POV2 range as a function of speed for both road types

Figure 92 displays time-gap as a function of speed and road type. Regardless of speed the model predicts that on surface roads, drivers routinely use a gap of between 1.5 and 1.8 seconds, compared to limited access roads where time-gap has a non-linear relationship with speed. For limited access roads the model predicts increasing time-gaps with increasing exponentially from 0.4s at 15 m/s (34 mph) to 1.4s at 27 m/s (60 mph).

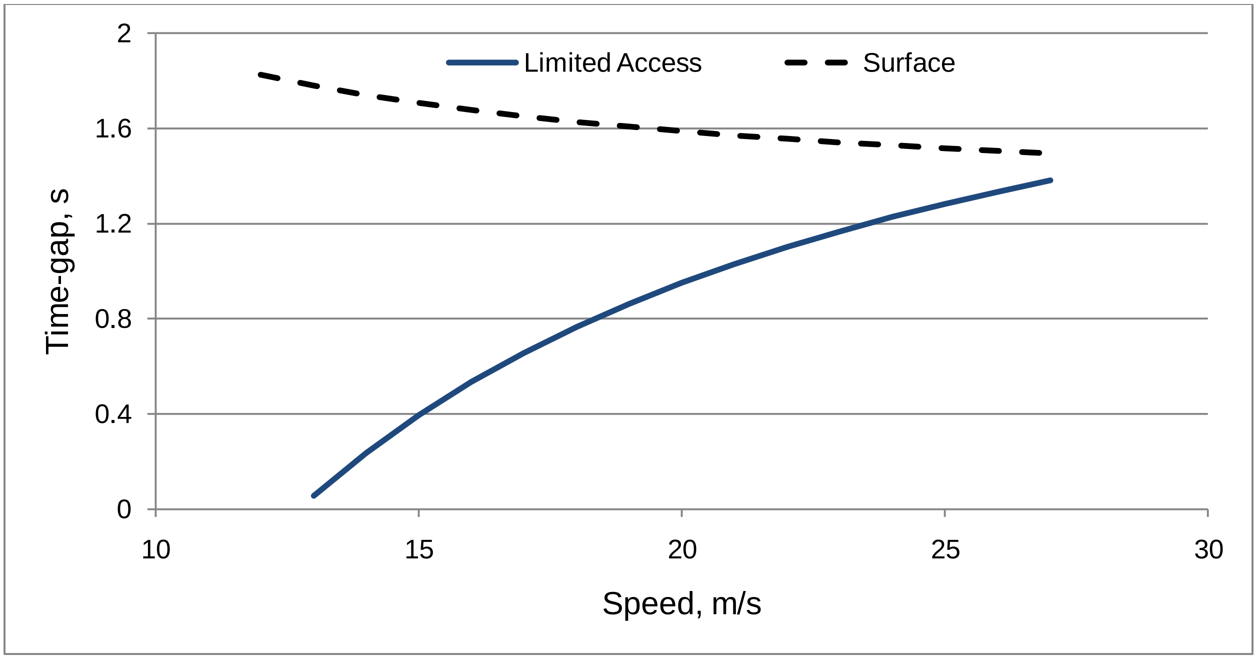

Figure 92: POV2 time-gap as a function of speed for both road types

POV1 Range Model: The main effects for the POV1 Range model were road type ($F(1,13)=27.21$; $p = 0.0002$), hours of service ($F(1,16)=22.61$; $p = 0.0002$), and speed ($F(1,15)=143.23$; $p <0.0001$). Also, the two-way interaction of speed and road type was found to significantly affect POV1 range ($F(1,11) = 21.54$, $p=.0007$). No main effect of treatment condition was observed. For road type alone the model predicts that on average the range between the SV and POV1 just after the lane change is 10.7 and 26.4 m on limited access and surface roads, respectively. As was observed with the POV2 Range model, 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 of these events shows a large number (67 percent) of events on limited access roads involve the SV driver waiting for a faster moving adjacent POV1 to clear the adjacent lane prior to making the lane change as compared to approximately 33 percent on surface roads. It is in these scenarios that the shorter range to POV1 is likely to occur.

For time working the model predicts that the drivers will reduce the distance to POV1 by around 16 percent when comparing the first (20.2 m) to tenth (16.6 m) hour of service. The model predicts time working has a linear effect on POV1 range with a slope of -.4 m. per hour of service.

As was the case with POV2 range, POV1 range has a significant two-way effect between speed and road type. For this effect the model predicts shorter POV1 range values for limited access as compared to surface roads and that for both road types the range is larger with increasing speed.

POV2 Range-rate Model: The main effects included in the POV2 Range-rate model were ambient light (F(1,12)=-3.85; p = 0.0023) and speed (F(1,16)=-4.38; p <0.0005). No main effect of treatment condition was observed. For ambient light the model predicts that the average range-rate between the SV and POV2 will be 0.27 m/s less at night as compared to the day. For the main effect of speed, the model predicts that the range-rate to POV2 is linearly related to speed by the following formula:

POV2 Range-rate = -0.0774(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 as compared to day.

Descriptive Statistics: To further explore the intra-vehicle kinematics in this lane-change scenario, consider Figure 93 and Figure 94 which show POV2 and POV1 distributions of range and range-rate, respectively, for the 2862 events identified in FOT dataset.

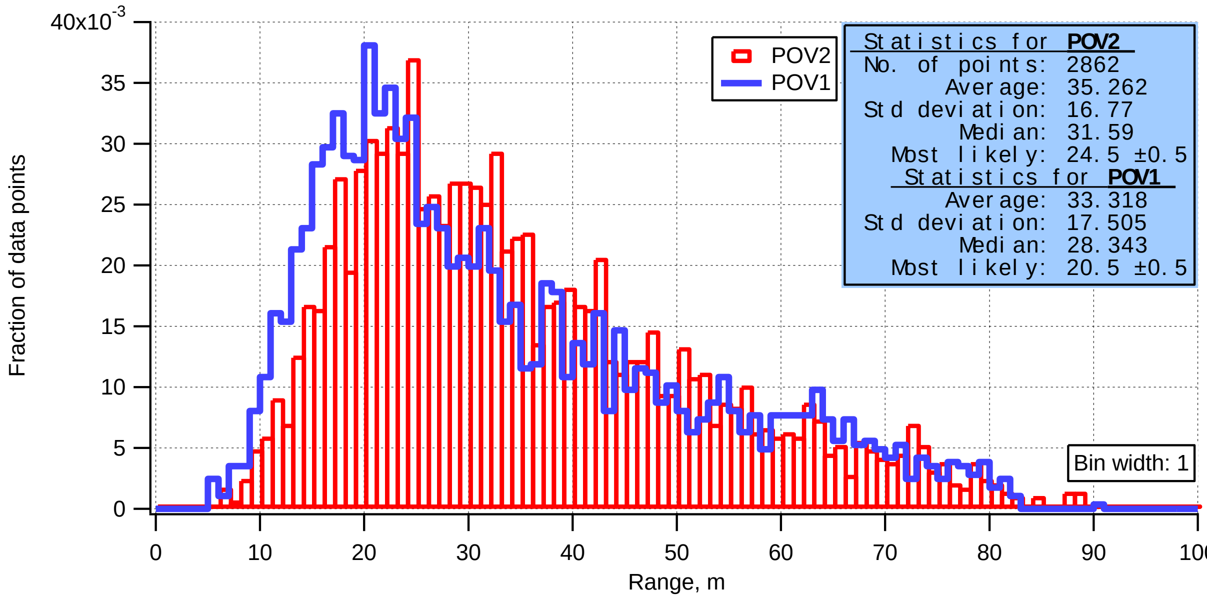

Figure 93: Distribution of range to POV2 and POV1

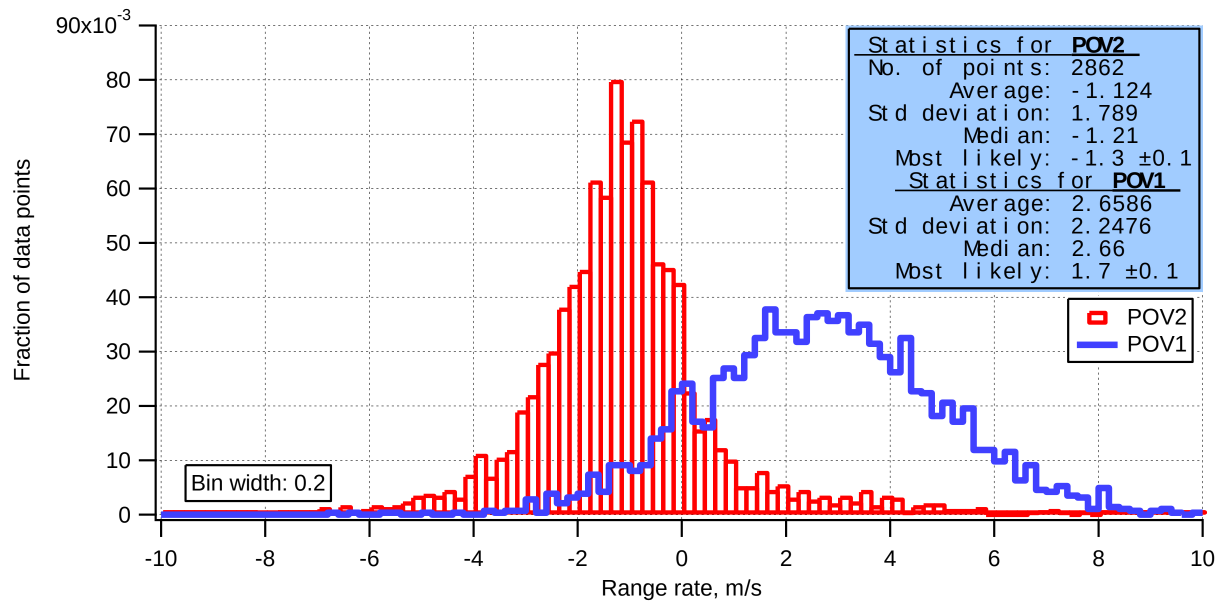

Figure 94: Distribution of range-rate to POV2 and POV1

As Figure 93 shows, the distribution of range for POV2 and POV1 has a similar shape with general statistics (average, standard deviation, median and mode) within about 4 m of each other. This is not true for POV2 and POV1 range-rate distributions as shown in Figure 94. In this figure the distributions are quite different with an average range-rate of -1.12 (2.5 mph) m for POV2 and 2.7 m/s (6 mph) for POV1. In many cases, this multiple threat scenario is benign since the proximity of all the vehicles and lack of other traffic allow the SV driver to change lanes and pass POV2 at a long range without much consideration of the faster-moving POV1. However, in a subset of these scenarios the SV driver is closing on a slower vehicle (POV2) while waiting for a faster moving vehicle to clear the adjacent lane (POV1) In this scenario, some drivers allow the range and time-gap to POV2 to become relatively short, sacrificing safe following behavior in order to time a lane change without losing forward speed.

To explore this case consider Figure 95 which shows the average distance travelled between time-gap events of 0.3 to 1.0 seconds. For this set of 18 drivers there was a closing scenario in which the time-gap between the SV and POV2 fell to 0.3s or less every 34,209 miles or in the case of .5 s or less every 3851 miles. As a reference, the average distance for this fleet was approximately 2000 miles per day so closing scenarios with a time-gap of less than 0.5 s occurred about every other day (151 events found in 315 days of the FOT). This relationship between rate of events and time-gap appears to take an exponential form as shown in Figure 96 which overlays an exponential fit to the data in Figure 95. Assuming that this set of 18 drivers is representative of truck drivers in general, and that other possible confounding influences found in this fleet are representative of general trucking fleet, the Figure suggests that situations resulting in no time-gap (zero range) would occurs about every 2.34 million miles of travel which is not far from an estimation of 3.45 million miles between rear-end crash types throughout the US with combination trucks (USDOT 2009). This estimate is based on an estimate of total annual miles driven in 2007 for combination truck is 145 billion and that annually there are approximately 42,000 rear-end crashes (GES USDOT 1999).

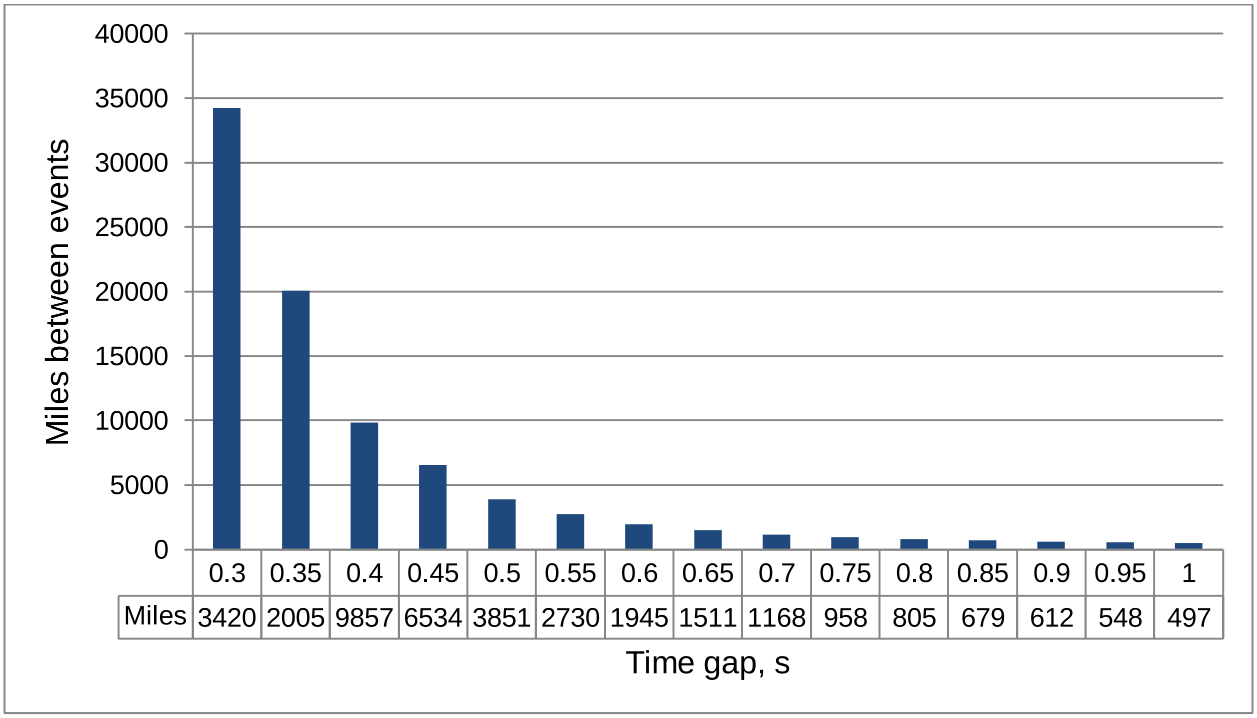

Figure 95: Average distance travelled between time-gap (Range/Speed) events of 0.3 to 1.0 seconds

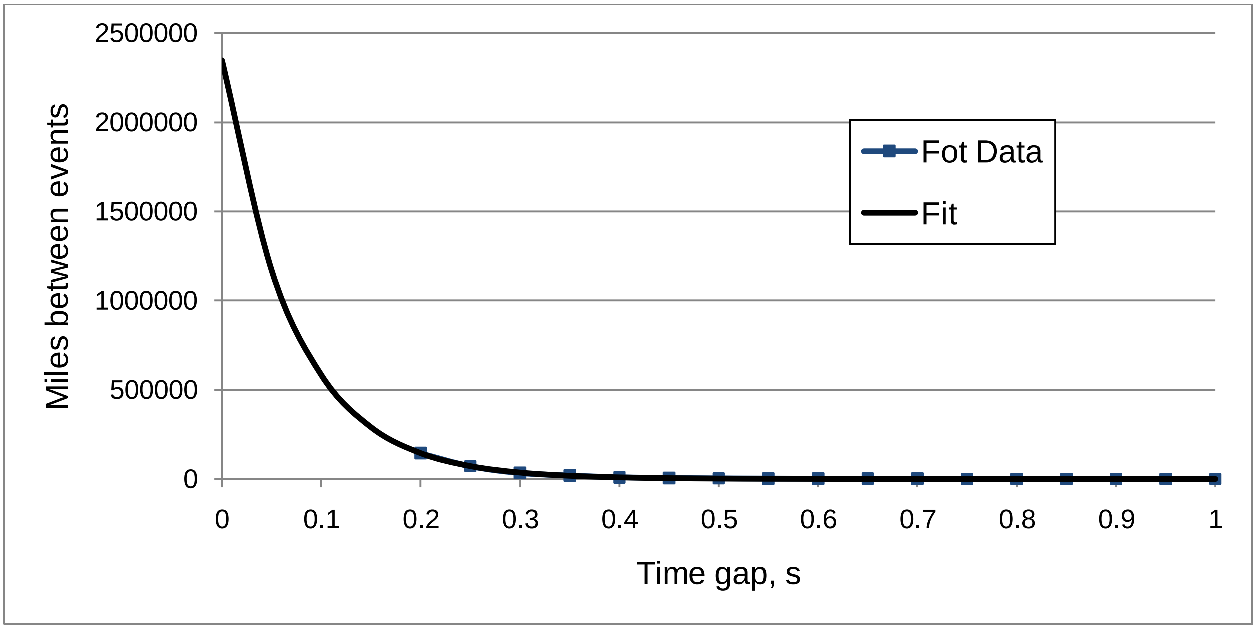

Figure 96: Exponential fit relating miles between events as function of time gap.

To further explore how these events are distributed among this set of drivers consider Figure 97. This figure shows the distribution of miles between events of a time-gap of less than 1s for the 12 drivers with 5 or more of these events during their exposure period. At one end of the distribution, a P&D driver had a time-gap of 1 s or less every 174 miles when changing lanes behind a POV1. Of the seven highest event drivers, three were LH and 4 were P&D which indicates that this behavior is not unique to route type and the dependencies that are implied by route type, namely: ambient light, road type, and trailer configuration.

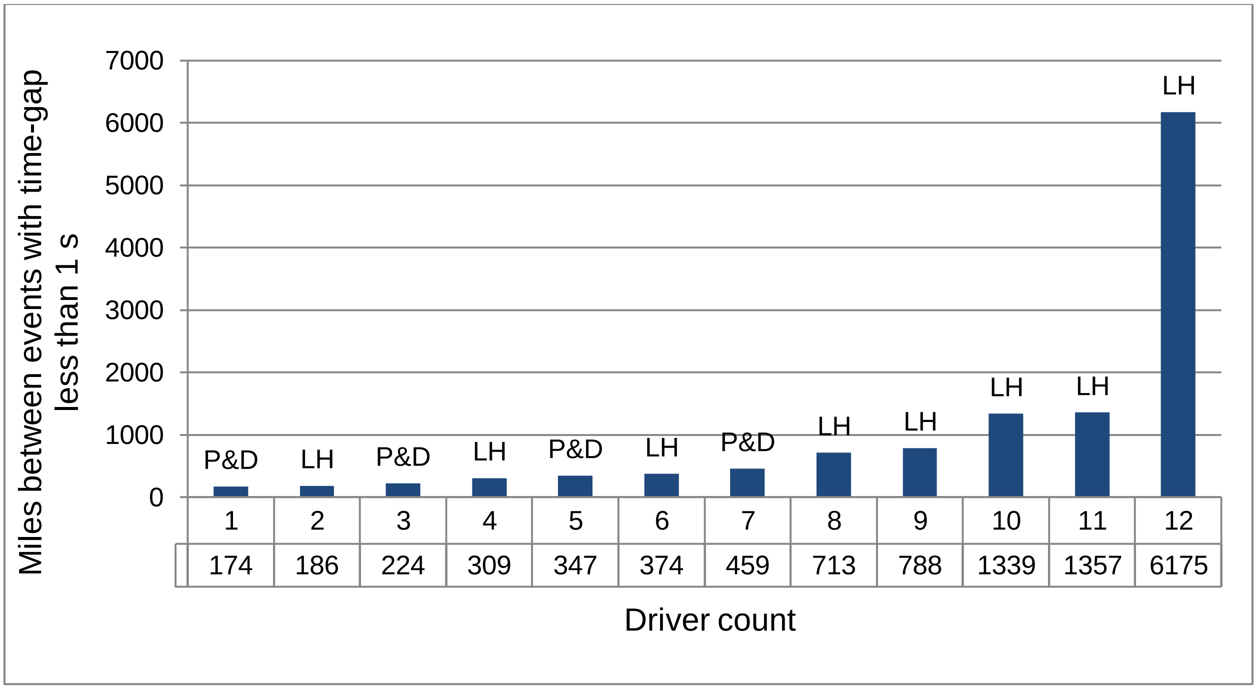

Figure 97: Miles between events with Time-gap of less than 1 second

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).

3.4.5 Driver Acceptance Research Questions

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

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, five 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 98 shows the Van der Laan scores for all integrated systems functions. LDW outperformed all other subsystems.

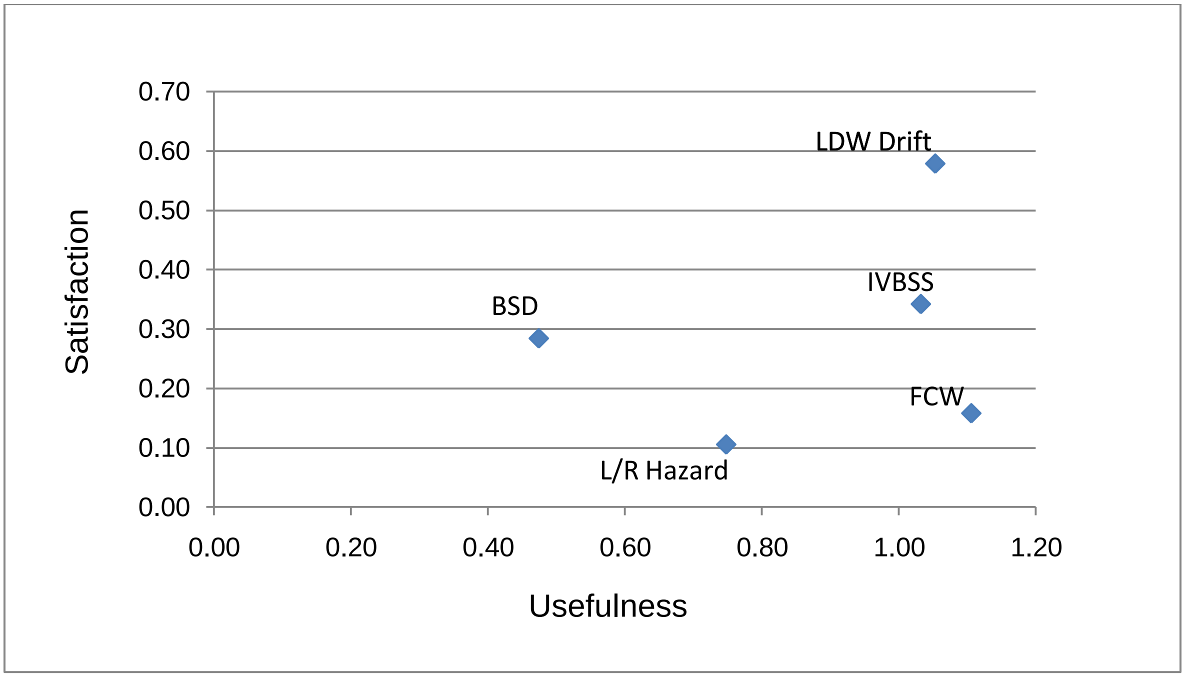

Figure 98: Van der Laan scores for IVBSS sub-systems

Specifically, only Drivers 1 and 29 scored the LDW system on the negative side of the Van der Laan scale for both measures (usefulness and satisfaction). One driver (Driver 23) scored the LDW system positively in terms of usefulness, but negatively in terms of satisfaction.

In Q27, when asked whether they received drift warnings when they did not need them, P&D and line-haul drivers disagreed. P&D drivers were much more likely to disagree with this statement than line-haul drivers (indicating line-haul drivers more strongly felt that they received warnings that they did not need). Responses to Q27 are presented below in Figure 99.

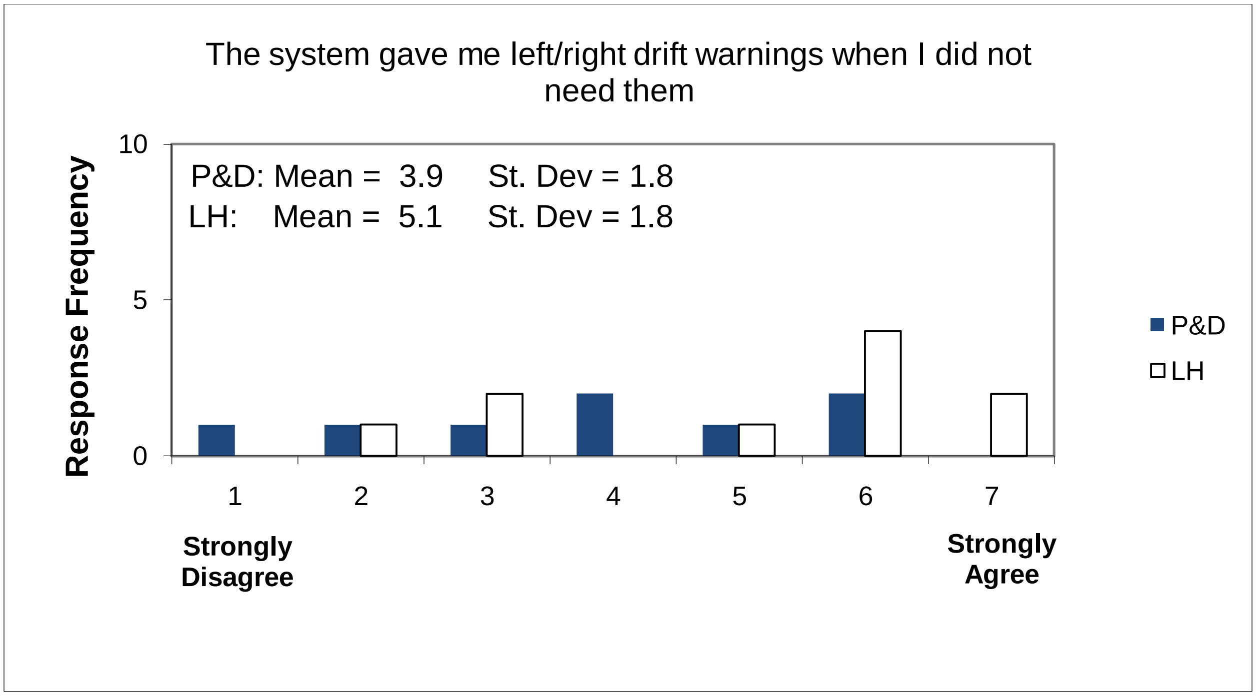

Figure 99: Q27 "The integrated system gave me left/right drift warnings when I did not need them"

Ultimately, when drivers were asked whether they would want the integrated system on their trucks, only 3 drivers said no. Three other drivers specifically mentioned the lane departure warnings as the main factor in their positive opinion of the system.

Interpretation: Drivers of the different route types experienced very different driving environments and likely received different benefits from each of the subsystems. Specific to the drift warnings, P&D drivers in the city often received lane departure warnings in situations where they were fully aware that they were crossing a lane line, but were forced to by the traffic situation. These types of situations likely resulted in their less favorable scores to Q27.

Line-haul drivers, spending long hours on highways, were much more likely to need the lane departure warnings to augment their alertness. A driver receiving a few very useful lane departure warnings when drowsy on the road would be more likely to accept a higher frequency of nuisance warnings. Four of the 10 line-haul drivers, when asked whether they preferred the integrated system in their truck cited increased alertness as the main reason behind their preference. With line-haul drivers receiving few useful forward crash warnings, this alertness benefit was almost certainly a result of the lane departure warning sub-system.

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

Responses from 3 questions regarding drivers' opinions on the usefulness of the integrated system are presented below in Table 57.

Table 57: Compiled Post-drive Questionnaire results relating to the usefulness of the integrated system

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q4	How helpful were the integrated system's warnings? *1=Not all Helpful, 7=Very Helpful*	5.0	1.4	4.9	1.5	5.1	1.4
Q6	Overall, I think that the integrated system is going to increase my driving safety. *1=strongly disagree, 7=strongly agree*	5.0	1.7	5.1	1.6	4.9	1.8
Q7	Driving with the integrated system made me more aware of traffic around me and the position of my car in my lane. *1=strongly disagree, 7=strongly agree*	5.2	1.8	5.6	1.6	4.9	2
Q9	The integrated system made my job easier. *1=strongly disagree, 7=strongly agree*	4.3	1.8	4.3	2.2	4.3	1.6

Drivers overall found the system to be useful. Primarily this benefit came in terms of increased safety and awareness on the road.

The perceived safety benefit of the system is discussed more in-depth in section QC7. Based on the responses to multiple questions, only Drivers 1, 27 and 29 did not find the system to be useful. These drivers gave the only negative response to Q4, Q6 and Q7 above. Also, these 3 drivers, (along with Drivers 8 and 24) scored Q9 negatively as well.

Two open-ended questions asked drivers for specific situations in which they were aided by the warnings. Q5 asked: "In which situations were the warnings from the integrated system helpful?" Q10 asked: "Did the integrated system prevent you from getting into a crash or near a crash?" Responses from these two questions were aggregated together and grouped by the system which the driver mentioned as helpful. These responses are plotted in Figure 31 in section QC7. As discussed previously, drivers mentioned the FCW and the LCM subsystems roughly equally across route types in terms of specific situations where the subsystems proved useful. Line-haul drivers cited the LDW system as useful substantially more than did P&D drivers.

The Van der Laan “Usefulness” scores aggregated for the 3 subsystems of the integrated system are presented below in Figure 100.

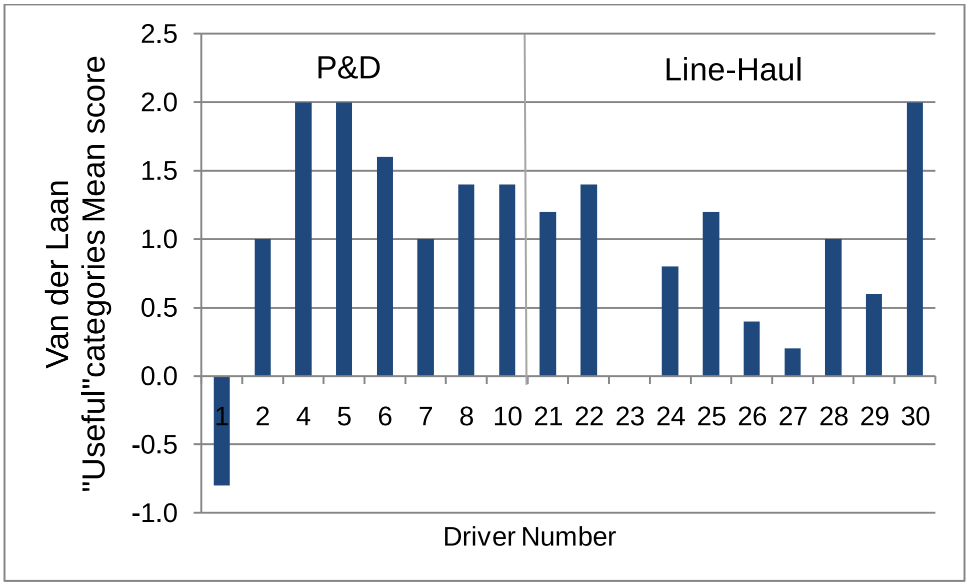

Figure 100: Van der Laan "Usefulness" categories for 3 subsystems compiled mean score by driver

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

Van der Laan “Usefulness” mean scores are displayed for each subsystem and the integrated system overall in Figure 101 below.

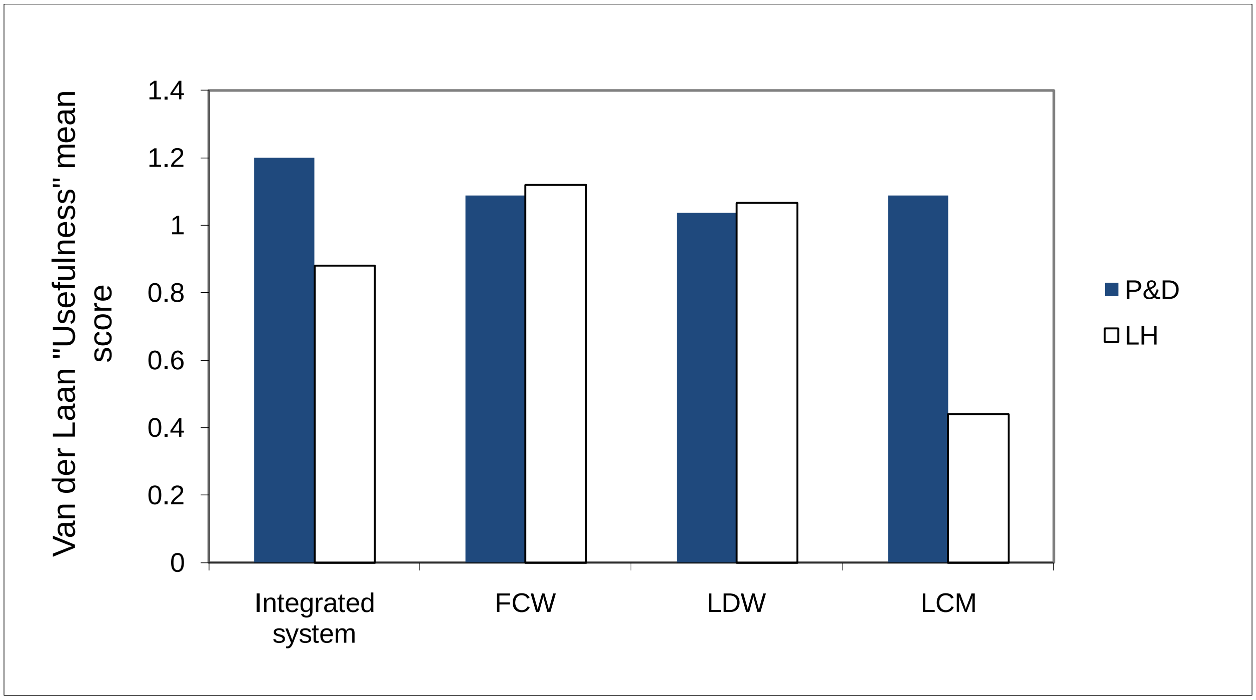

Figure 101: Mean Van der Laan "Usefulness" scores by subsystem and route type

Overall 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 across both route types.

Interpretation: While most drivers of both route types found some aspects of the system useful, line-haul drivers opinions of the Lane Change/Merge subsystem were clearly the lowest (although overall still positive). This is understandable as the environment where line-haul drivers operate (highways at night) is not an environment where unexpected threats are likely to quickly appear on the side of the vehicle. Based on the overall usefulness scores shown above, these different environments may also contribute to drivers' opinions of the overall usefulness of the integrated system as well.

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 three of the 18 drivers (1 P&D, 2 line-haul) specifically mentioned LCM. When asked what they liked least about the integrated system, four line-haul drivers mentioned the LCM subsystem.

Van der Laan scale responses shown in Figure 98 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 Figure 102 below.

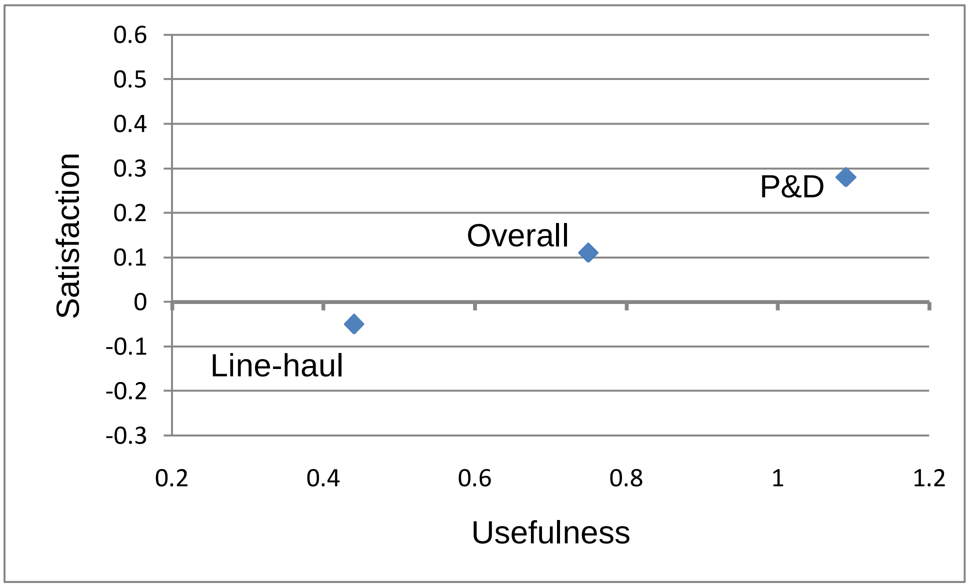

Figure 102: Mean Van der Laan scores for the LCM subsystem by route type

Line-haul drivers were more likely than P&D drivers to say they received LCM warnings when they were not needed (Figure 103). This subjective response is consistent with the invalid warning rates observed for the P&D (55%) and line-haul drivers (86%).

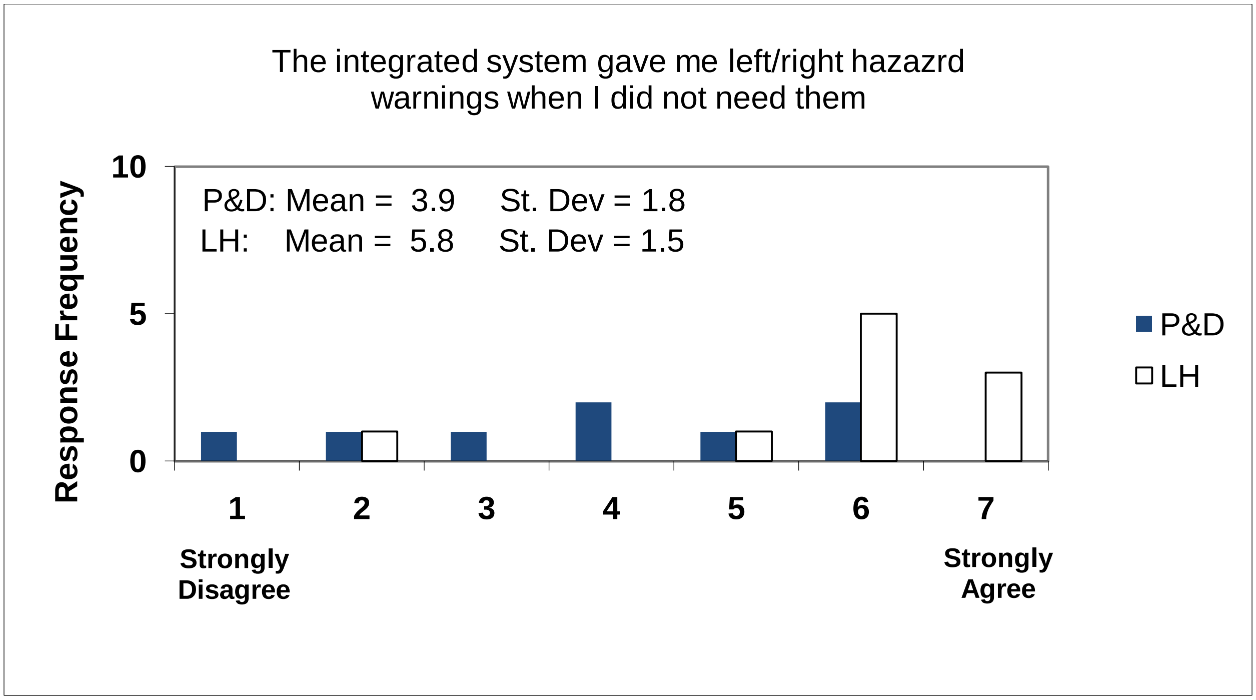

Figure 103: Responses to "The integrated system gave me left/right hazard warnings when I did not need them."

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.

3.4 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.

3.4.5 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 58. 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 58: 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

3.4.6 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 104 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.

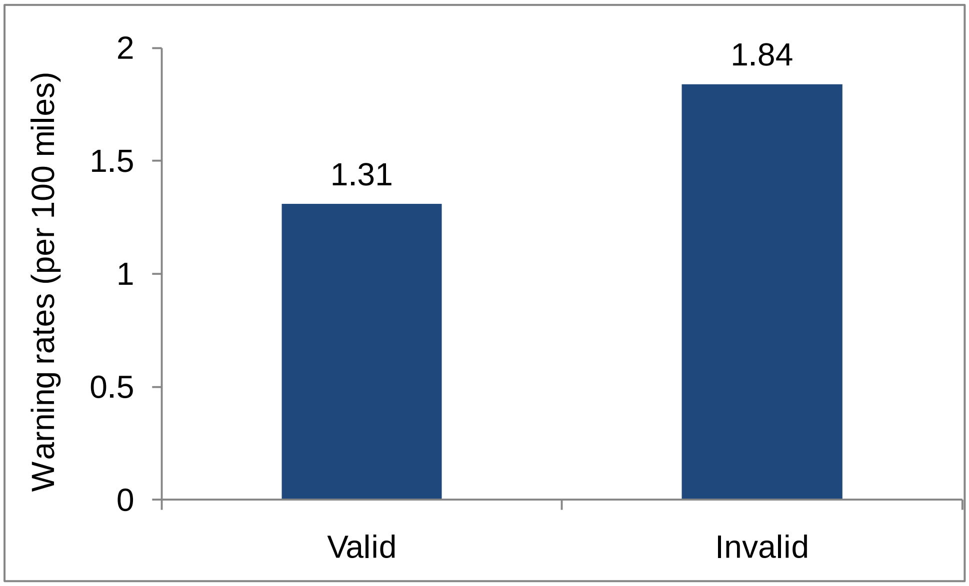

Figure 104: Overall longitudinal warning rate per 100 miles

Figure 105 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.

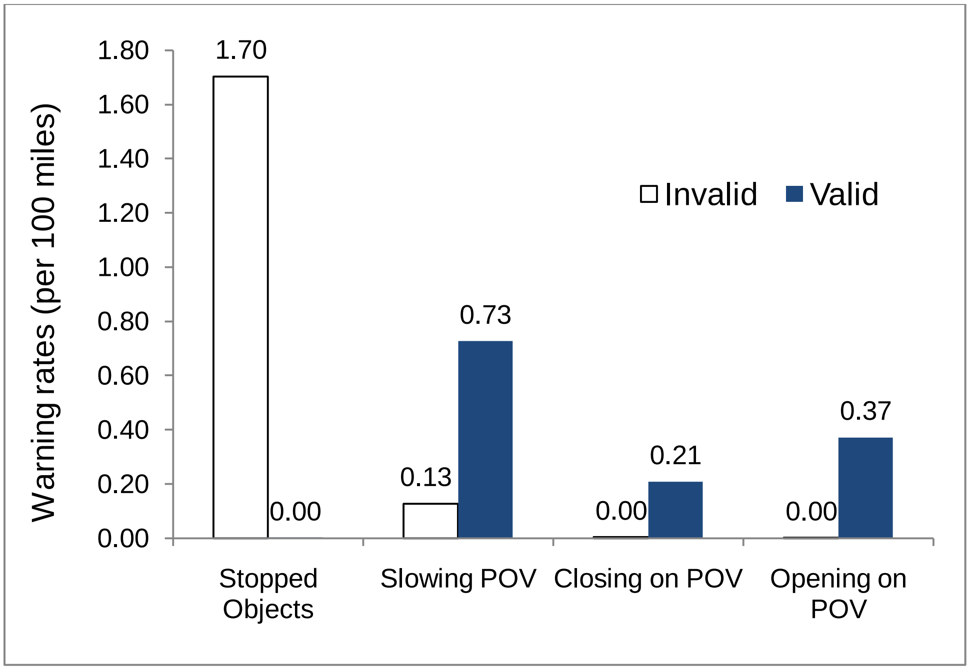

Figure 105: Overall longitudinal warning rate per 100 miles for each warning type

In terms of the broader exposure variables of condition and route type, Table 59 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.

Table 59: Longitudinal 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

Driver brake reactions within 5 seconds following an FCW warning were examined, with the results shown in Table 60. 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 60: 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

3.4.7 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?

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

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

Method: The purpose of this analysis is to evaluate whether the forward crash warning system would have an impact on truck drivers' behavior during following situations. Therefore, this analysis concentrates on headway-keeping events (following events). The definition of "following" was established in past projects for light vehicle (Ervin et al., 2005), and the specific thresholds was updated for heavy trucks here by using IVBSS FOT data. This definition is intended to consider only extended periods of following behavior, which exclude significant forward conflict (i.e., sizable closing speeds), lane changes, turns, or other maneuvers by either the preceding or the following vehicle that introduce confounding influences on the heavy truck driver's intentions or ability to maintain his or her preferred following distance. That is, the data selected for analysis was confined to situations during which (1) range rate to the vehicle ahead falls in the range of (-2m/s, 2m/s) (i.e., 4.5mph), (2) headway time margin falls in the range of 0 seconds to 3 seconds , and (3) traveling speed of subject vehicle at 11 m/s (i.e., 25mph) or greater. Furthermore, all analyses were restricted to only steady followings events with duration of 5 seconds and longer to eliminate rapid vehicle passing events. These constraints are listed below in Table 61.

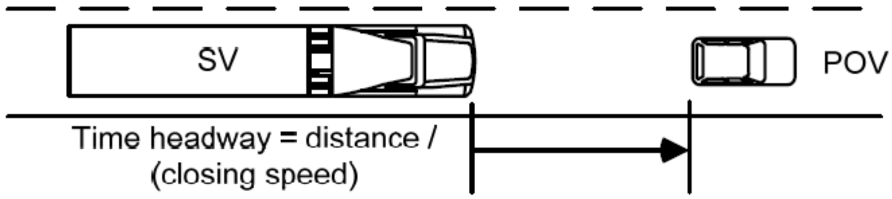

Figure 106: Diagram of time headway margin during followings event.

Table 61: Analysis Constraints

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

The measure regarding the following distance maintained by truck drivers under both treatment (with the presence of the FCW warning system) and baseline (without the presence of the FCW warning system) conditions was average time headway (in seconds). This measure was computed as the mean time headway duration during each following event and is used as one indication of time headway distribution comparison. A Linear Mixed Model was conducted using the statistical software package SAS 9.2 with the PROC MIXED procedure. Only the significant results were reported here.

Table 62: Independent variables used in statistical models

Dependent Variables
1. Following distance
Independent Variables
1. Treatment condition (binary: yes, no)
2. Wiper (binary: on, off)
3. Route type (binary: P&D, LH)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road Type (binary: limited access, surface)
7. Traffic (categorical: sparse, moderate, dense)
8. Hours of service (continuous; units hours)
9. Average axle load (binary: heavy, light)

Results: There were total 96,356 following events identified based on the four filter criterion. Of all the following events, around 96 percent of the data falls within the duration range of 3 minutes (i.e., ≤180seconds). The longest following event is 55 minutes long. Table 63 presents the counts of following events for different variables.

The effect of treatment condition was found to be statistically significant ($F(1, 17)=7.85$, $p=0.01$). As shown in Figure 107, drivers maintained a significantly longer average time headway under the treatment condition than under the baseline condition (differences of least square means: Δ=0.05 s, 95 percent confidence interval (CI): 0.01, 0.07). The Road type impact was also found significant ($F(1, 17) =71.18$, $p<0.001$). As shown in Figure 108, truck drivers maintained a longer headway distance from the leading vehicle on surface streets than on limited access highways (Δ=0.2 s, 95% CI: 0.16, 0.27).

Table 63: Count of steady-state following events for different variables

Independent Variable	Level	Count
Condition	Baseline	22338
	Treatment	74108
Ambient Light	Day	56379
	Night	39977
Wiper state	On	6257
	Off	90099
Load	Light	33233
	Heavy	63123
Road type	Surface	27327
	Limited Access	69029
Traffic	Sparse	55907
	Moderate	38866
	Heavy	1582
Trailer	Single	30824
	Double	65532

Independent Variable	Level	Count
Month	1	12953
	2	9385
	3	11710
	4	10062
	5	10759
	6	9379
	7	10545
	8	8936
	9	8017
	10	4610
Hours Service	1	25008
	2	7924
	3	6585
	4	5395
	5	3698
	6	4555
	7	7225
	8	11088
	9	11651
	10	13227

The average headway time of drivers driving at night was also significantly longer than driving in the day time ($t(16)= 6.03$, $p=0.09$, Δ=0.1 s, 95% CI: 0.06, 0.12, Figure 109). Traffic density was also found to be significant ($F (2, 34) =4.46$, $p<0.01$). Drivers maintained significantly shorter time headway when the traffic condition is moderate when compared to both sparse traffic condition ($t(34)= 2.39$, $p=0.02$, Δ=0.03 s, 95% CI: 0.01, 0.06, Figure 110) and dense traffic condition ($t(34)= 3.22$, $p=0.003$, $\Delta=0.07$ s, 95% CI: 0.03, 0.12). No difference between dense traffic condition and sparse condition was found. The truck load impact was found significant with a high load leading to a longer average time headway ($t(17)= 2.94$, $p=0.009$, $\Delta=0.03$ s, 95% CI: 0.01, 0.06, Figure 111). A higher mean headway time was also observed when the wiper was on then no wiper state ($t(17)= 5.28$, $p<0.001$, $\Delta=0.07$ s, 95% CI: 0.04, 0.1, Figure 112)

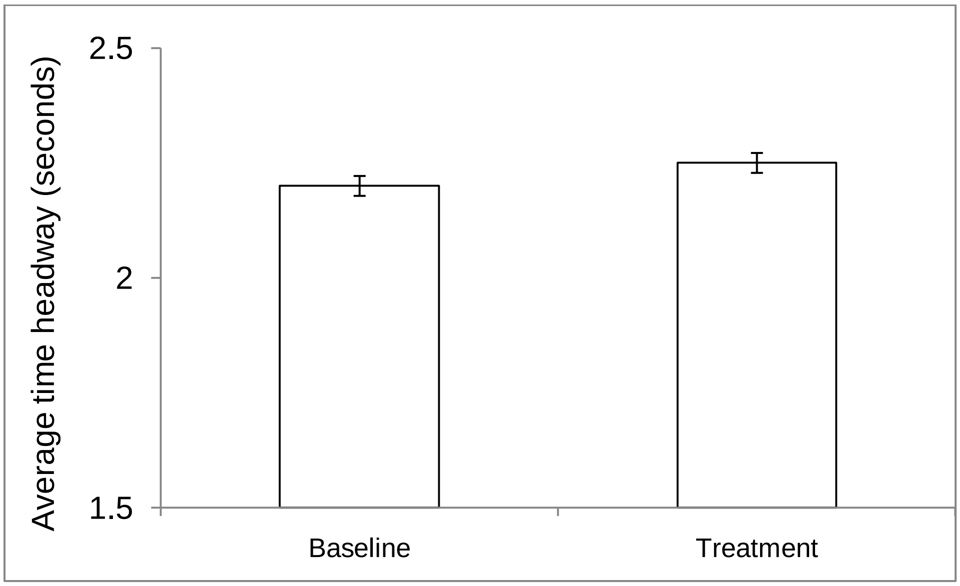

Figure 107: Least squares means of average time headway under two treatment conditions

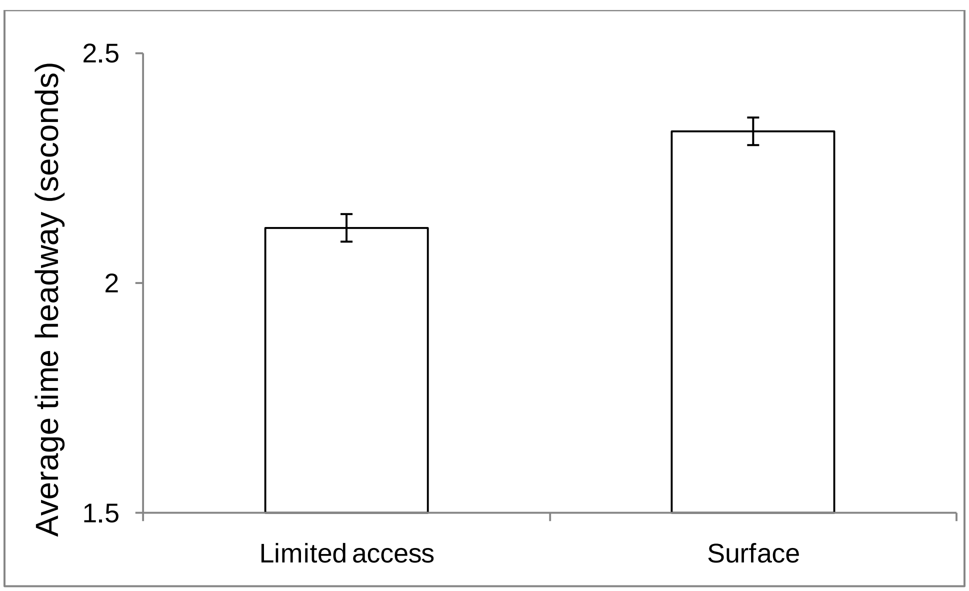

Figure 108: Least squares means of average time headway on different road segments

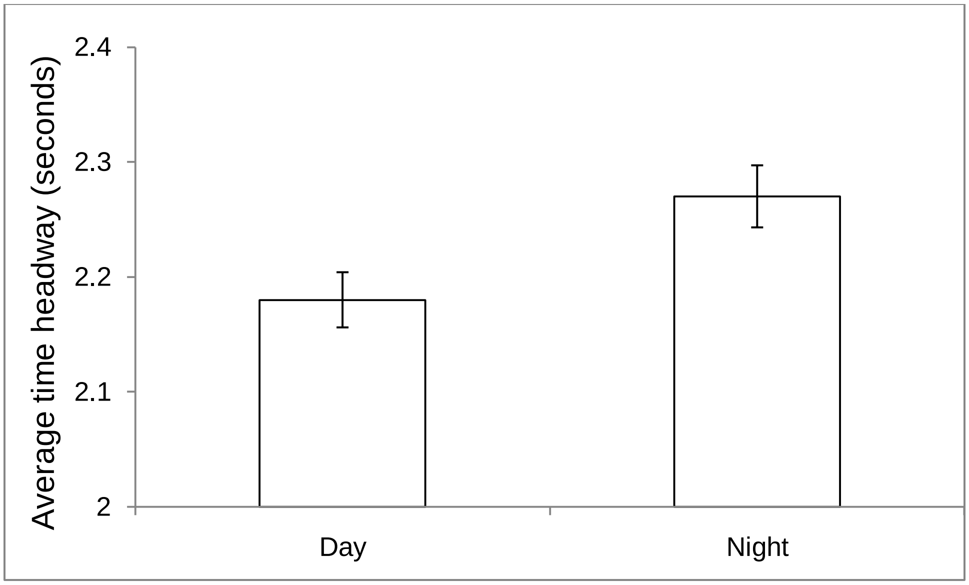

Figure 109: Least squares means of average headway time when driving at day/night

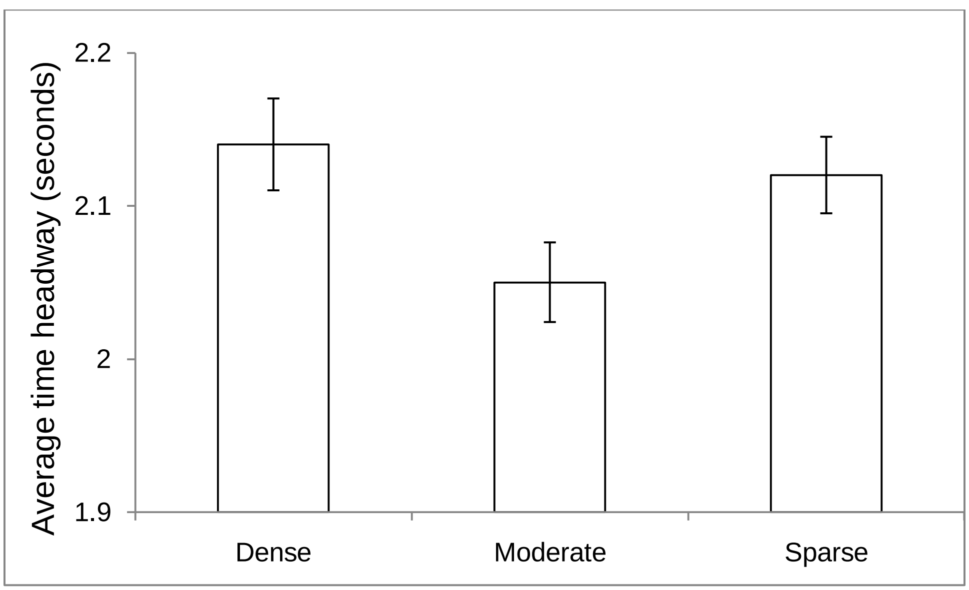

Figure 110: Least squares means of headway time under different traffic densities

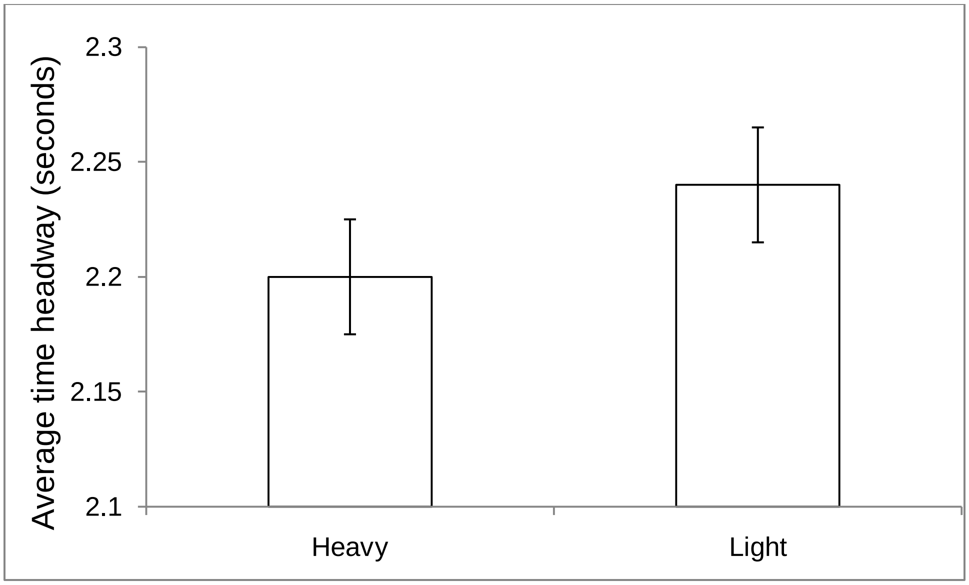

Figure 111: Least squares means of headway time under different loading levels

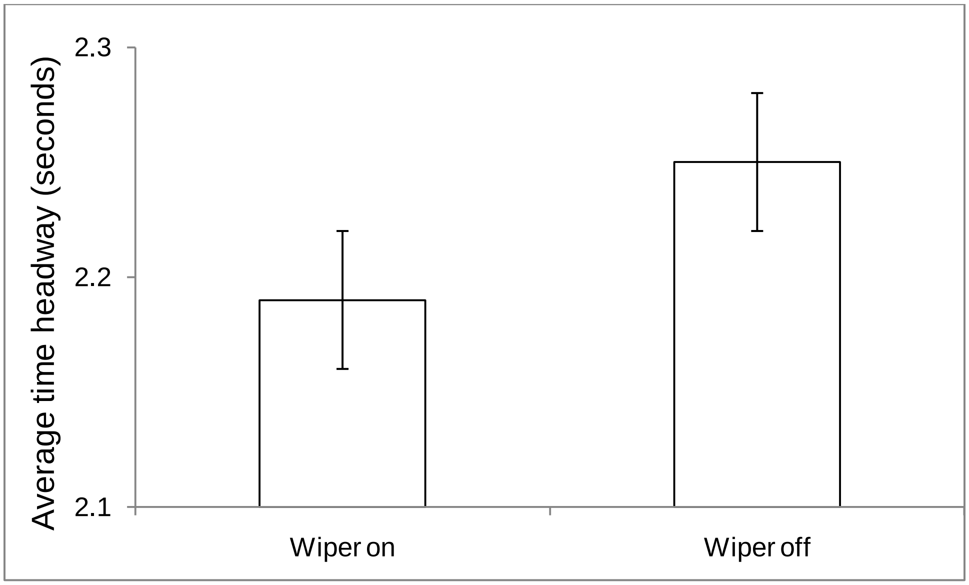

Figure 112: Least squares means of headway time with different wiper states

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.

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

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

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

Method: The analysis address forward conflict in 13,504 events, and uses a general linear mixed model approach to determining whether the integrated system has an effect on the conflict levels. Two measures of forward conflict are used: the minimum time to collision during the mild conflict events and the minimum level of required deceleration during the events. Time to collision is defined as the range (distance) divided by the closing speed between the SV and the POV. The required deceleration is defined as the constant level of SV braking needed to simultaneously bring range and closing speed to zero, i.e., to just avoid impact. Required deceleration is negative when braking is needed, so that the minimum value is the greatest magnitude of braking required. 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 constraints in Table 64 apply, and in which the following are also true:
- The time to collision falls below 10 seconds and the required deceleration is less than +0.5 m/sec^2, or
- The required deceleration falls below -1 m/sec^2.

These rules were used because the resulting events are ones in which the driver usually slows their vehicle, whether through braking or throttling off.

For each of these 13,504 events, the minimum time to collision and the minimum required deceleration were identified. Each event was also tagged with the values for seven independent variables, as shown in Table 65. After the driver, the next most important is the class of driving scenario, which is either “shared-lane” scenarios or “multiple-lane” scenarios. Figure 113 shows that shared-lane scenarios are ones in which the SV and the POV are in the same lane, and continue to share that lane at least 5 seconds after the mild conflict ends. Multiple-lane scenarios involve one or both vehicles changing lanes or turning during the conflict period, or within three seconds before the conflict begins or within 5 seconds of the conflict ending. The reason for distinguishing between shared- and multiple-lane scenarios is that the latter is associated with higher conflict measures as drivers anticipate that the lateral motion will resolve the conflict. This is known from the Automotive Collision Avoidance System (ACAS) Field Operational Test

– Methodology and Results Report (Ervin et al 2005). For this FOT, there are no shared-lane conflicts that meet the constraints of this analysis in which the required deceleration is less than -3 m/sec2. There are a few hundred multiple-lane conflicts in which the required deceleration exceeds that level.

Another independent variable is the average axle load for the combination of the tractor and trailers, which affects the braking and stability characteristics of the truck in heavy braking. Using the average axle load is a way to address variation in different trailer configurations and loading levels.

The surrogate measure of traffic density is similar to that used in the ACAS FOT program (Ervin et al., 2005) and is based upon observations of same-direction traffic in the SV's lane and, where appropriate, in adjacent lanes.

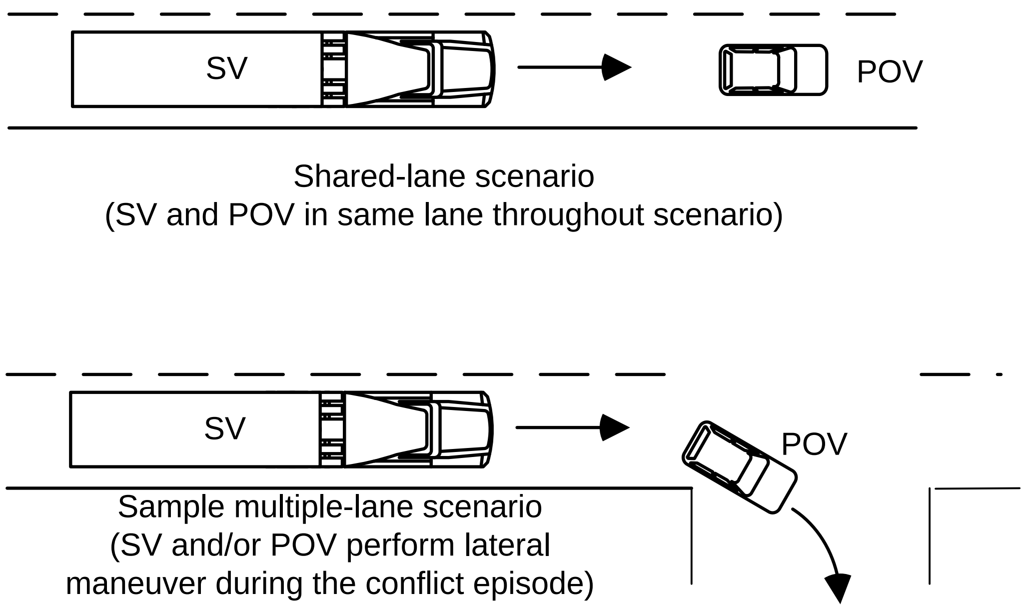

Figure 113: Forward conflict in shared-lane scenarios and multiple-lane scenarios

Table 64: Analysis Constraints

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

Table 65: Variables

Dependent Variables
1. Time-to-collision
2. Required deceleration
Independent Variables
1. Minimum time to collision values for each observed conflict
2. Minimum required deceleration for each observed conflict
3. Independent Variables
4. Treatment (Binary: Yes, No)
5. Driving scenario (Binary: Shared lane, Multiple lane)
6. Average axle load (Binary: < 5000 Kg, > 5000 Kg)
7. Traffic density (Binary: low, high)
8. Road Type (Binary: Limited Access, Surface)
9. Speed (Binary: Low (<23.3 m/s (52 mph)), High (> 23.3 m/s (52 mph))
10. Wipers (Binary: On, Off)

Results: The principal findings of this analysis are based on the results of a mixed linear model and the conclusions shown below were derived from the model and not a direct analysis of the data per se.

The main effects that did surface are shown in Table 66. In terms of the integrated system, the model concludes that treatment alone was not found to have a significant effect on forward conflict magnitude, either in time to collision ($p>0.05$) or in required deceleration ($p>0.05$). The average time to collision values during the baseline and treatment periods were 7.92 and 7.95 seconds, respectively, with standard errors of 0.24. The average required deceleration values were -0.79 and -0.80 m/sec^2, respectively, with standard errors of 0.03 m/sec^2 for both.

Table 66: Main effects for forward conflict magnitude

Independent Variable	Dependent variable	
	Time to collision	**Required deceleration**
Treatment	No main effect Least squares means: 7.91 sec baseline, 7.94 sec treatment.	No main effect Lease squares means : 0.79m/sec^2 baseline, 0.80m/sec^2 treatment
Scenario class	Main effect ($F(1,17)=56.9$, $p<0.0001$) Least squares means: 7.25 sec multi-lane; 8.59 sec shared-lane	Main effect $F(1,17)=4.92$, $p<0.05$) Lease squares means : 0.83m/sec^2 multi-lane; 0.76m/sec^2 shared-lane
Road type	Main effect ($F(1,16)=9.67$, $p<0.01$) Least squares means: 9.01 sec highway; 6.84 sec surface	Main effect ($F(1,16)=36.7$, $p<0.0001$) Least squares means: 0.67m/sec^2 highway; 0.92m/sec^2 surface
Travel speed	No main effect	Main effect ($F(1,15)=56.27$, $p<0.0001$) Least squares means: 0.94 m/s^2 low speed; 0.65 m/s^2 high speed

The principal main effects that showed significance for the minimum time to collision were the scenario class (shared-lane vs. multiple-lane), and the road type. Shared-lane scenarios were associated with lesser conflicts, as expected; with a model-predicted mean values shown in Table 66Table 66 and Figure 114. Limited access roads were also associated with lesser conflicts with means again shown in the table.

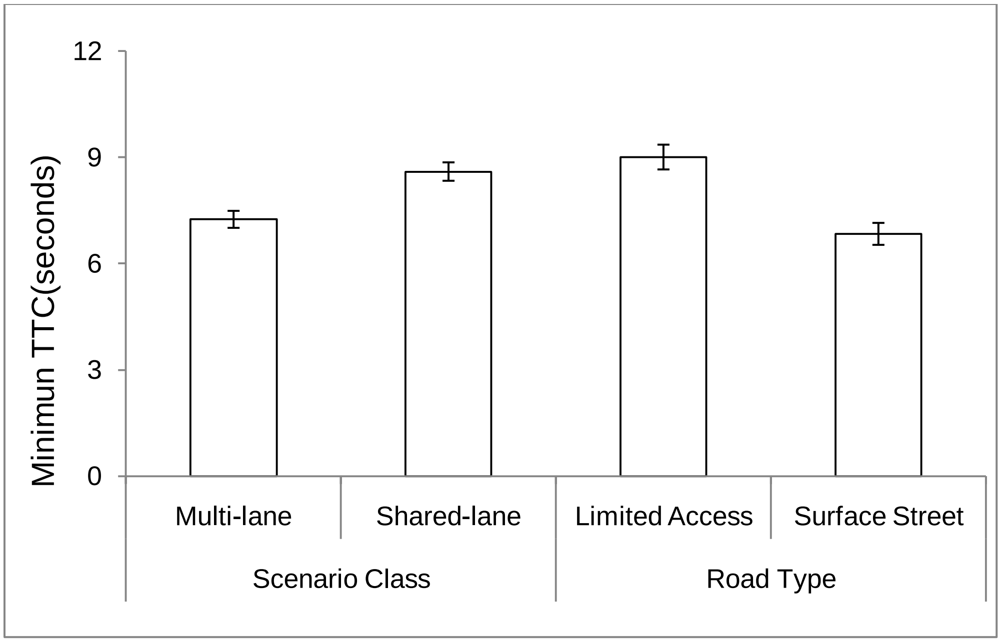

Figure 114: Effects of scenario class and road type on minimum time to collision

For the required deceleration dependent variable, the scenario, the road type and the travel speed had a significant effect with higher speeds associated with lower conflict levels. Note that travel speed and road type are highly correlated in this study, so this finding is not surprising. This data is presented in Table 66 above and Figure 115 below.

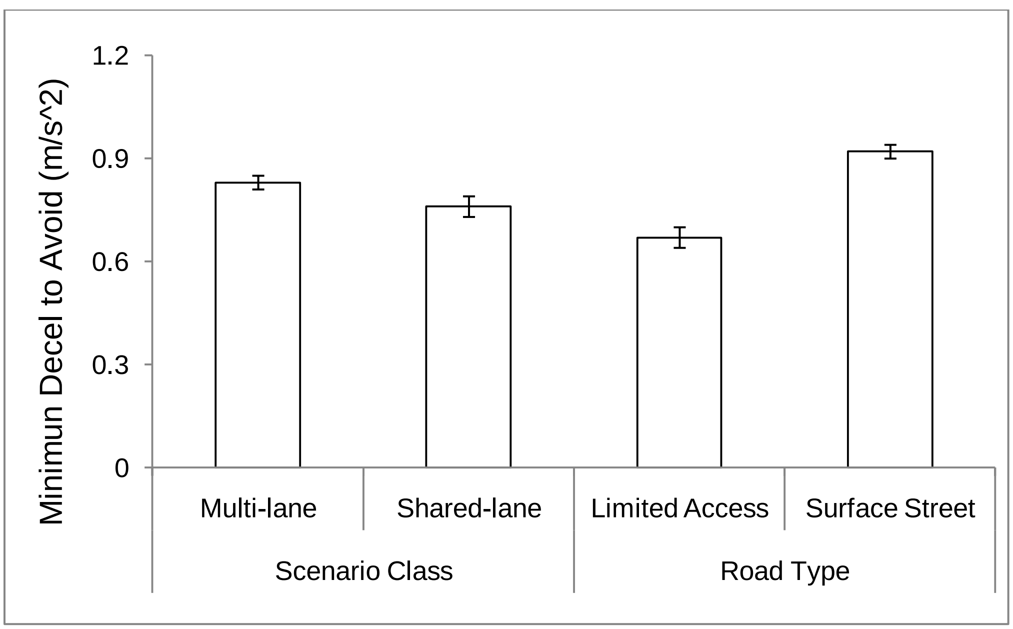

Figure 115: Effects of scenario class and road type on deceleration to avoid collision

Descriptive Statistics: The distribution of the 13,504 conflict events used in this analysis across the independent variable categories are summarized in Table 67. Notice that under the “scenario” variable, the occurrence of multiple-lane scenarios with conflict satisfying the “mild” thresholds described earlier is almost three times more common than shared-lane scenarios. Also notice that the conflicts studied here are much more common on surface roads than on limited access highways, by a ratio of 3.9 to 1.

Table 67: Count of the conflict events for the independent variables

Independent Variable	**Level**	**Count**
Condition	Baseline	2757
	Treatment	10747
Scenario	Shared-lane	9809
	Multi-lane	3695
Axel load	Low	8372
	High	5132
Wipers	On	1261
	Off	12243
Road type	Limited Access	2774
	Surface	10730
Speed	Low	10990
	High	2514
Traffic Density	Low	7864
	High	5640

Figure 116 displays histograms of the peak conflict levels for the 13,504 events, with one trace associated with shared-lane scenarios and the other trace with multiple-lane scenarios. Two things are clear from these graphs. First, as stated earlier, multiple-lane scenarios with this level of conflict are more common than shared-lane scenarios. Second, for the time to collision, the multiple-lane scenarios have greater levels of conflict (lower TTCs) than shared-lane. This is consistent with the observation in the Automotive Collision Avoidance System (ACAS) Field Operational Test – Methodology and Results Report (Ervin et. al 2005) that in multiple-lane scenarios, drivers anticipate that the conflict will be resolved through lateral motions, and therefore are temporarily tolerant of higher conflicts in multiple-lane scenarios.

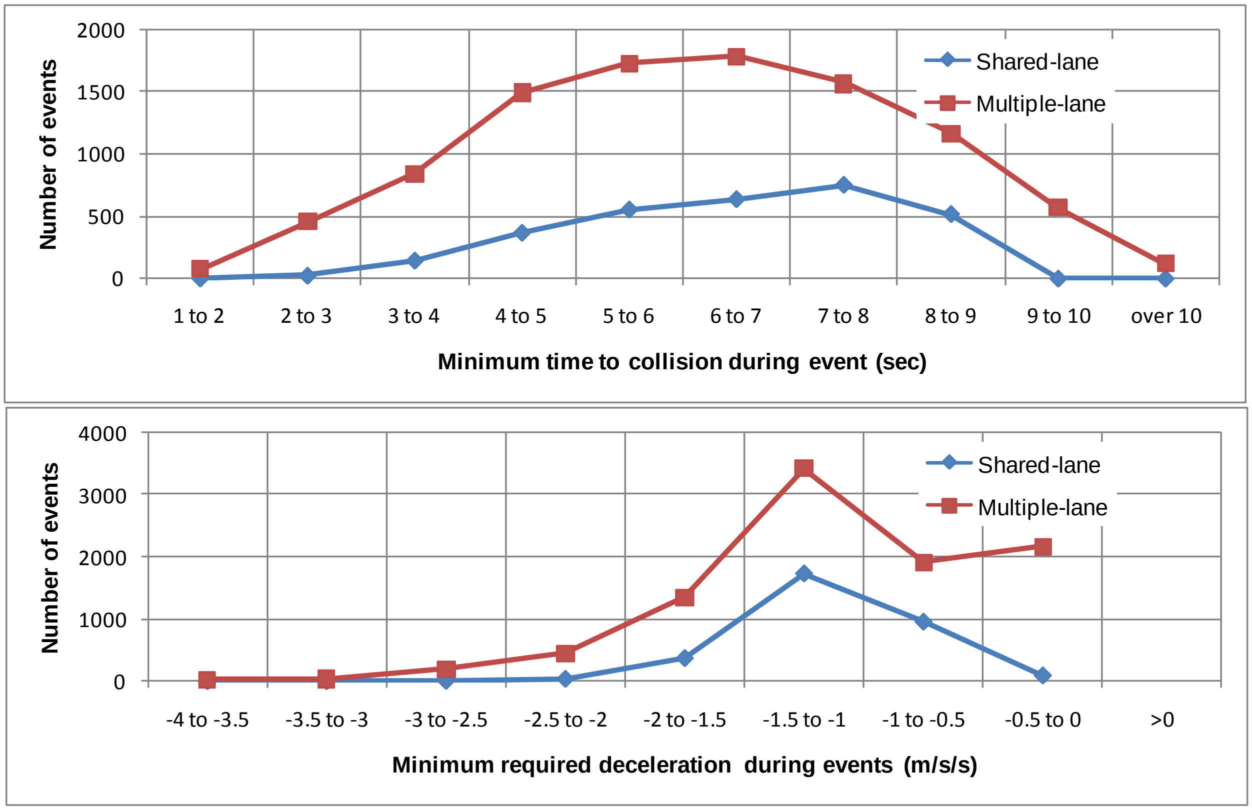

Figure 116: Minimum time to collision and required deceleration during conflict events

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?

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

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

Method: The consideration here of actual braking levels recognizes that hard braking (whether required or not) may contribute to crash risk for heavy trucks because of their unique dynamics. Only those events in which a POV contributed to the driver's use of braking were considered.

For instance, the analysis excluded cases in which the SV was stopping without a POV. Table 68 and Table 69 present the analysis constraints and the independent variables used in the statistical models respectively.

Table 68: Analysis Constraints

Constraints
1. Maximum Speed > 11.2 m/s (25 mph) during the braking events
2. Presence of a leading vehicle
3. Peak braking level is between 0.2g

Table 69: Independent Variables

Dependent Variables
1. Frequency of hard braking events
2. Maximum deceleration during hard braking events
Independent Variables
1. Treatment condition (binary: yes, no)
2. Wiper (binary: on, off)
3. Route type (binary: P&D, LH)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road Type (binary: limited access, surface)
7. Traffic (categorical: sparse, moderate, dense)
8. Hours of service (continuous; units hours)
9. Average axle load (binary: heavy, light)

Two measures regarding the hard braking behavior of truck drivers under both treatment (with integrated warning system) and baseline (without integrated warning system) conditions were calculated and examined:

The frequency (per mile) of hard braking events where the peak braking level is greater than 0.2: A Linear Mixed Model was conducted using the statistical software package SAS 9.2 with the PROC MIXED procedure. Pairwise comparisons using Tukey test were conducted post hoc. Only the significant results were reported in the result section.

Maximum deceleration during the hard-braking events (unit m/s^2): A Linear Mixed Model was conducted using the statistical software package SAS 9.2 with the PROC MIXED procedure. Pairwise comparisons using Tukey tests were conducted post hoc. Only the significant results were reported in the result section.

Results: There were total 18375 hard braking events identified based on the constraints defined in the method section. Of all the hard braking events identified, events occurred on unknown road types or ramps were excluded from the analysis. Therefore, data from a total of 14677 events was used in the final analysis. The general distribution of these events under the different independent variable conditions is summarized in Table 70 below.

Table 70: Count of hard braking events for different variables

Independent Variable	Level	Count
Condition	Baseline	3147
	Treatment	11530
Ambient Light	Day	1696
	Night	12981
Wiper state	On	641
	Off	14036
Load	Light	11753
	Heavy	2924
Road type	Surface	14152
	Limited Access	525
Traffic	Sparse	12488
	Moderate	2166
	Heavy	23
Trailer	Single	12138
	Double	2539

Independent Variable	Level	Count
Month	1	1756
	2	1391
	3	1707
	4	1477
	5	1749
	6	1505
	7	1786
	8	1484
	9	1211
	10	611
Hours Service	1	2476
	2	1960
	3	1946
	4	2049
	5	1659
	6	1425
	7	1270
	8	878
	9	511
	10	503

Hard braking frequency: The integrated crash warning system did not have a statistically significant effect on the frequency of hard braking events. The frequency of hard braking events per mile under the treatment condition (mean = 0.914 per 100 miles) is only slightly less than under the baseline condition (mean = 0.915 per 100 miles). As shown in Figure 117, 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 = 0.09 per 100 miles).

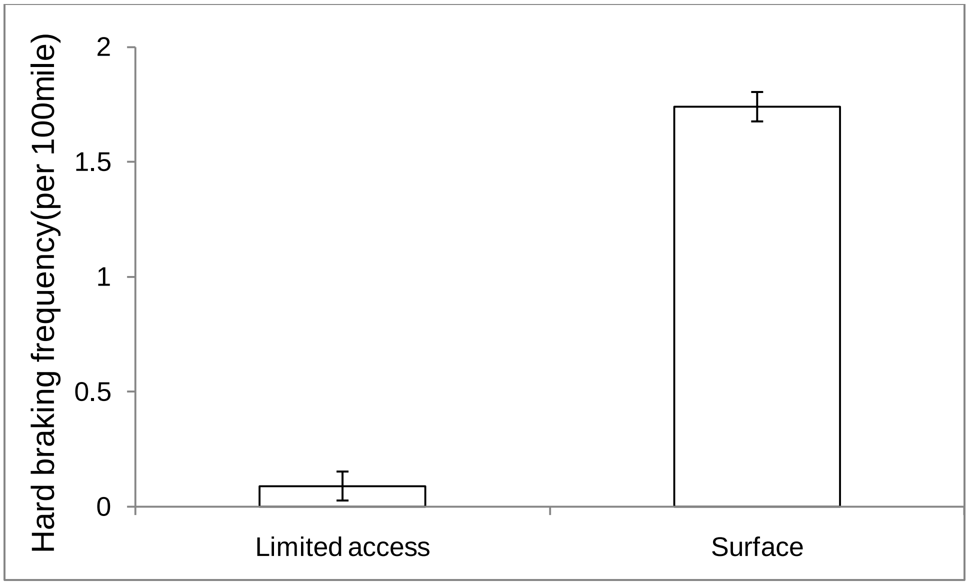

Figure 117: Least squares means of hard braking frequency on different road types

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/s2 to a mean of 2.74 m/s2. The road type did have a statistically significant, but minor effect on the maximum deceleration of hard-braking events ($F(1, 17) = 24.63$, $p < 0.001$). Higher mean maximum decelerations were observed on surface streets (mean = 2.89 m/s2) than on limited-access roadways (mean = 2.44 m/s2), an increase of 18 percent (Δ=0.44m/s^2, 95% CI: 0.25, 0.63, Figure 118).

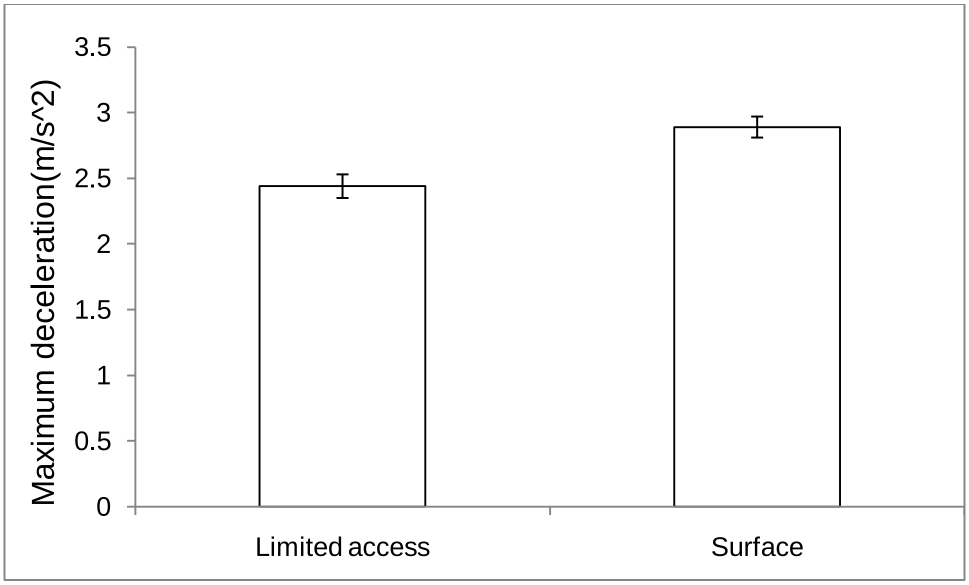

Figure 118: Least squares means of maximum deceleration on different road types

Wiper state effect was also significant in that a higher maximum deceleration value was observed with wiper off ($F(1, 17)=26.19$, $p<0.001$, ($\Delta=0.50$ m/s^2, 95% CI: 0.32, 0.69, Figure 119).

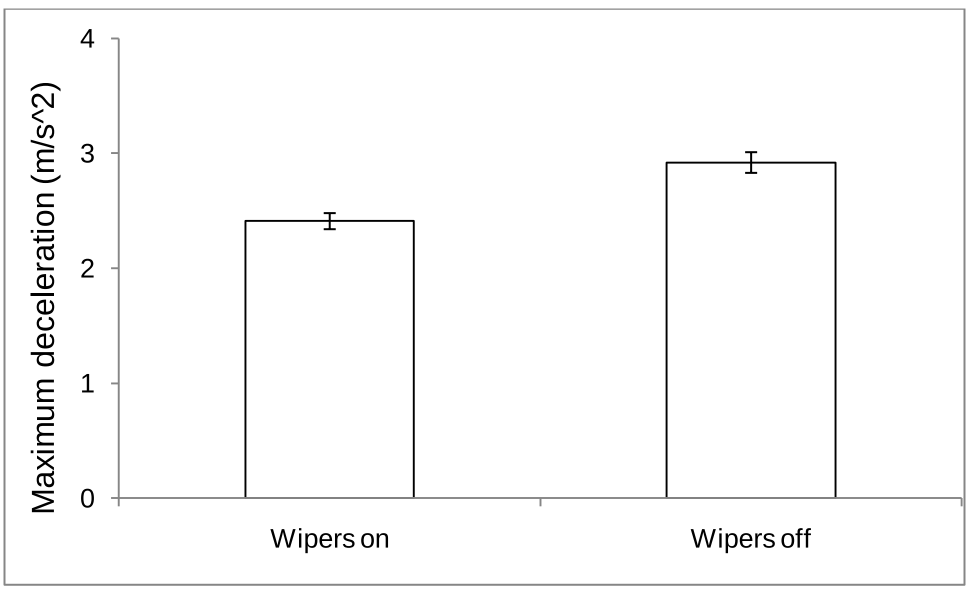

Figure 119: Least squares means of maximum deceleration with different wiper states

Interpretation: The results showed no 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, 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 under 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?

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

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

Method: For this analysis, data from two types of closing conflict events were examined: "slowing objects" warning and "closing, half-second" warning. "Stopped object" warning events were excluded from this part of analysis because over 95 percent of these warnings were invalid. Three dependent measures regarding drivers' responses to those warnings events were calculated and evaluated:

- **Driver reaction time** (in seconds), was calculated as the duration of time between the warning onset and the time at which driver responded by releasing the accelerator pedal. This measure was used to evaluate whether the integrated system had an impact on how quickly drivers respond to a closing conflict event. A Linear Mixed Model was conducted using the statistical software package SAS 9.2 with the PROC MIXED procedure. Only the significant results were reported in the result section.
- **Brake response** was recorded as a binary variable (yes or no) regarding whether the truck drivers pressed the brake pedal during each closing conflict event. This measure was used to evaluate whether the integrated system had an impact on the likelihood of braking during a closing conflict event. A Logistic Regression Model was conducted using the statistical software package SAS 9.2 with the PROC Genmod procedure. Only the significant results were reported in the result section.
- **Braking reaction time** (in seconds), was calculated as the duration of time between the warning onset and the time at which driver hit the brake when there was a brake reaction (i.e., brake response is yes). This measure was used to evaluate whether the integrated system would had impact on the braking reaction time during a closing conflict event. Linear Mixed Model was conducted using the statistical software package SAS 9.2 with the PROC MIXED procedure. Only the significant results were reported in the result section.

Table 71 and Table 72 present the analysis constraints and the independent variables used in the statistical models respectively. The constraints shown in Table 71 were used to eliminate those false FCW warnings (e.g., FCW warning triggered when no presence of a leading vehicle) and exclude events in which drivers responded to new conflicts other than the FCW warnings. The 5 seconds limit was chosen based on the video sampling results to maintain that in greater than 95 percent of the events that drivers responded to the current conflict rather than a new conflict (e.g., a different leading vehicle or made a lane change)

Table 71: Analysis Constraints

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

Table 72: Independent Variables

Dependent Variables
1. Driver reaction time
2. Brake response
3. Braking reaction time
Independent Variables
1. Treatment condition (binary: yes, no)
2. Wiper (binary: on, off)
3. Route type (binary: P&D, LH)
4. Trailer (binary: single, double)
5. Ambient light (binary: day, night)
6. Road Type (binary: limited access, surface)
7. Traffic (categorical: sparse, moderate, dense)
8. Hours of service (categorical:1,2,3,4,5,6,7,8,9,10)
9. Average axle load (binary: heavy, light)

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. There were a total of 982 closing conflict events identified based on the constraints defined in the method section and these were used in the final examination. The general distribution of these events under different independent variable conditions is summarized in Table 73.

Table 73: Count of FCW warning events for different variables

Independent Variable	Level	Count	Independent Variable	Level	Count
Condition	Baseline	199	Month	1	115
	Treatment	783		2	84
Ambient Light	Day	874		3	119
	Night	108		4	131
Wiper state	On	48		5	113
	Off	934		6	101
Load	Light	689		7	110
	Heavy	293		8	101
Road type	Surface	811		9	77
	Limited Access	171		10	31
Traffic	Sparse	555	Hours Service	1	224
	Moderate	413		2	103
	Heavy	14		3	93
Trailer	Single	763		4	108
	Double	211		5	76
				6	98
				7	93
				8	90
				9	46
				10	51

Driver reaction time: The impact of the treatment condition was found to be significant ($F(1, 17)=4.61$, $p<0.05$). As shown in Figure 120, driver reaction time between the warning and the time at which driver released the accelerator pedal under treatment condition (least squares mean = 1.35s) is significantly shorter than the time under baseline condition (least squares mean = 1.56s, differences between least square means: $\Delta=0.22$ s, 95% CI: 0.004,0.43). Drivers were also found to have different reaction times under different traffic density conditions ($F(2,25)=3.57$, $p<0.05$). The further pairwise comparison showed that reaction time when the traffic density is dense (least squares mean = 0.95s) was significantly shorter than the situation when the traffic density is sparse (least squares mean= 1.69s, Figure 121) and the situation when the traffic density is moderate (least squares mean = 1.73s). Reaction time when driving on limited access roads (least squares mean = 1.61s) was found significantly longer than on surface streets ($F(1, 16)=7.32$, $p<0.02$, least squares mean = 1.30s) Figure 122)

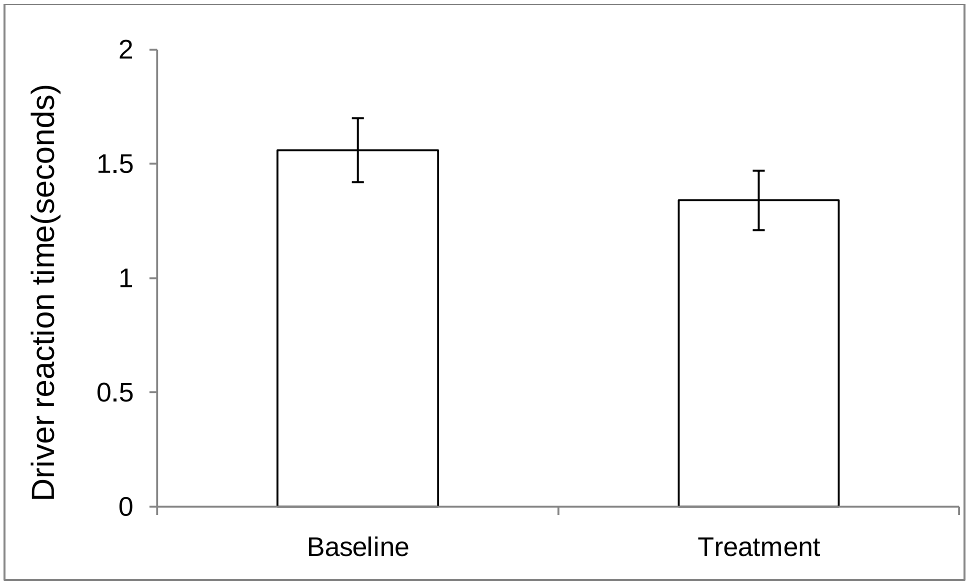

Figure 120: Least squares means of driver reaction time under two treatment conditions

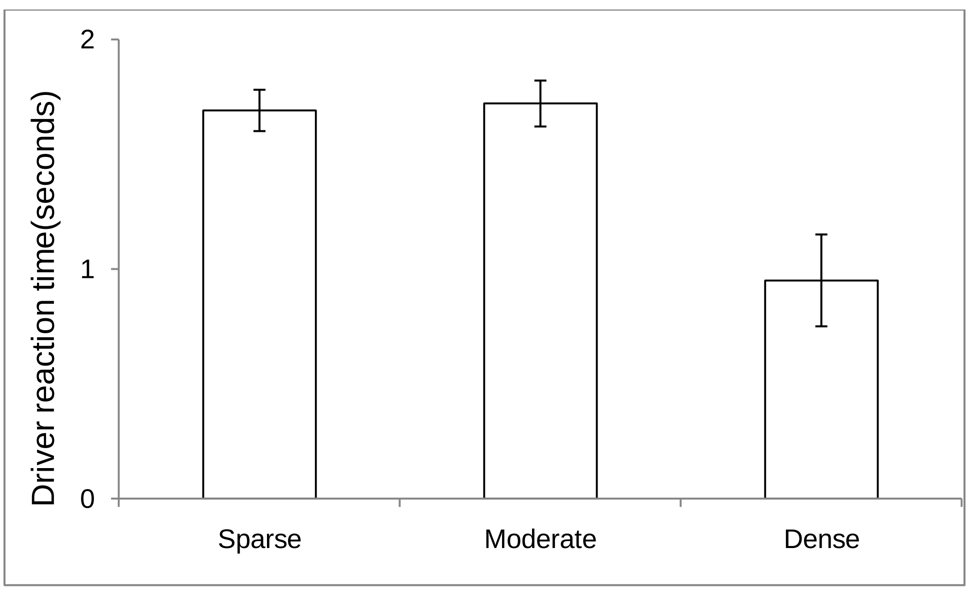

Figure 121: Least squares means of driver reaction time under different traffic density conditions

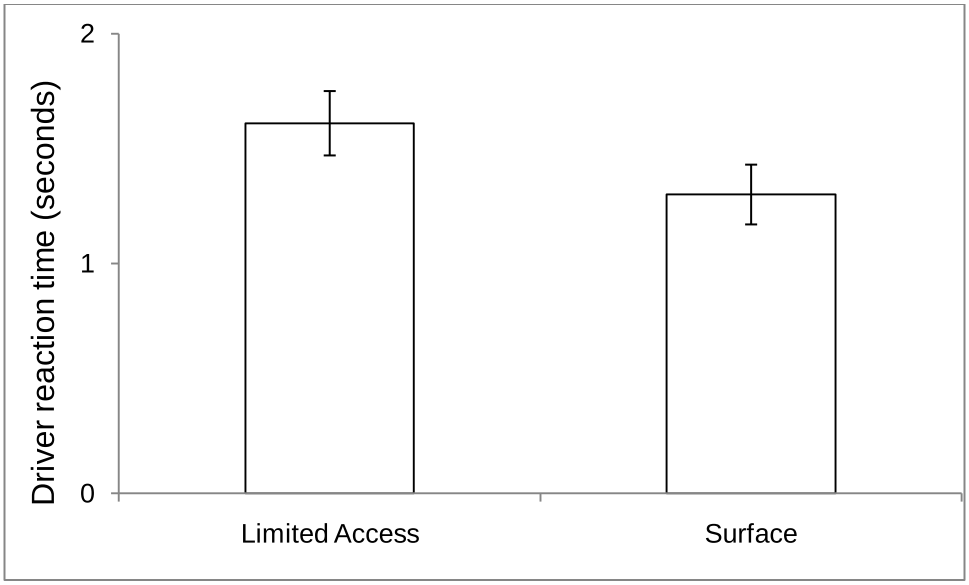

Figure 122: Least squares means of driver reaction time under different traffic density conditions

Brake response: The likelihood of applying brake under treatment condition (mean = 76.1%) was higher than under the baseline condition (mean = 70.8%), but not at a statistically significant level. The likelihood of applying brake during closing conflict events on surface roads was significantly higher (mean = 80.39%) than on the limited access highways (mean = 49.71%, $\chi^2(1) = 6.91$, p=0.009). The impact of wiper state was also found significant ($\chi^2(1) = 4.95$, p=0.03 with a higher value found with the wipers off (mean = 76.23%) than when the wipers were on (mean = 52.08%).

Brake reaction time: Treatment condition was found to significantly affect brake reaction time ($F(1, 17)=5.21$, $p<0.05$). As shown in Figure 123, brake reaction time between the warning and the time at which driver hit the brake pedal under treatment condition is significantly shorter (least squares mean = 1.89s) than the one under baseline condition (least squares mean = 2.18s). No other significant differences were observed.

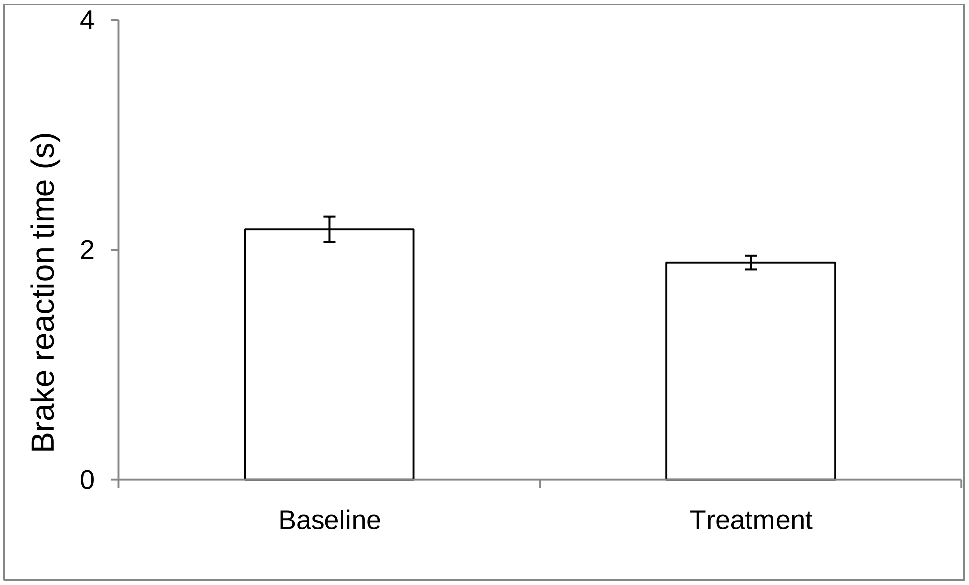

Figure 123: Least squares means of brake reaction time under two treatment conditions

Interpretation: The results showed that truck drivers responded differently to those forward closing conflicts under the two treatment conditions. More specifically that truck drivers responded much quicker to those closing conflict events with a significantly shorter driver reaction time and braking reaction time with the presence of integrated system than without the integrated system. In the safety point of view, the integrated system increases truck drivers' awareness of lead vehicles and closing rates and leads to them reacting much quicker.

3.4.8 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 were accepting of the FCW subsystem as a concept; however many had reservations about the frequency of false alarms. When asked what aspect(s) of the integrated system drivers liked most, only 2 responded with the general FCW subsystem. However, 5 drivers mentioned specifically that they liked the feature of the FCW subsystem that displayed their time-headway once they were within 3 seconds of a lead vehicle. Conversely, 7 drivers specifically mentioned false forward crash warnings as their least favorite aspect of the integrated system.

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 the line-haul drivers, but does poorly among P&D

drivers, especially in terms of driver satisfaction. Figure 124 below presents the Van der Laan ratings broken down by route type for the FCW subsystem.

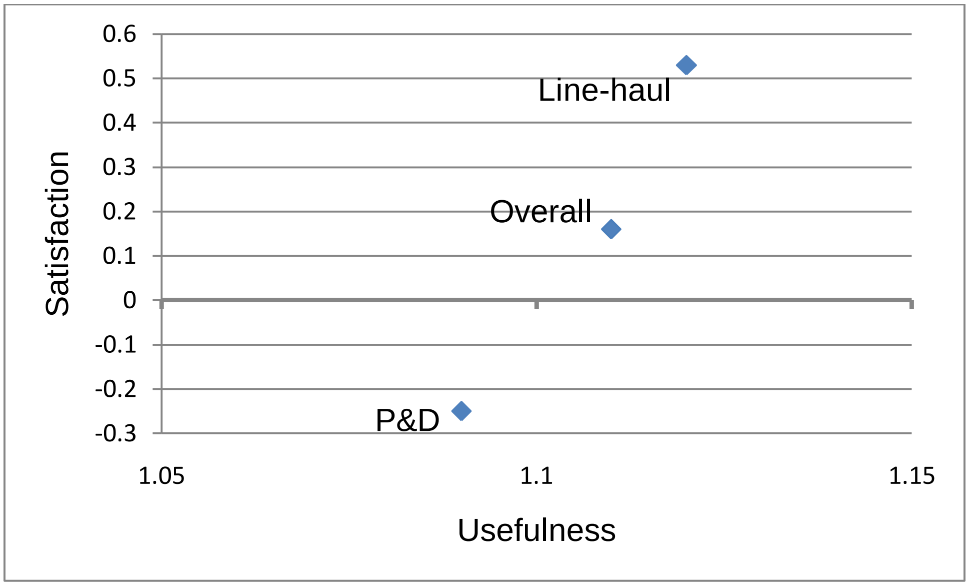

Figure 124: Van der Laan scores for the FCW subsystem broken down by route type

From Figure 124 above, P&D drivers actually 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 any Van der Laan category. This discrepancy between P&D drivers' scores for usefulness and satisfaction seems to indicate drivers liked the idea of the FCW subsystem based on the benefits it provided in terms of awareness of the forward area, but were not satisfied with the actual operation of the system based on the frequency of invalid warnings.

In Q28, when asked whether they received Forward crash warnings when they did not need them, P&D and line-haul drivers basically agreed. P&D drivers were slightly more likely to disagree with this statement than line-haul drivers (indicating line-haul drivers more strongly felt that they received warnings that they did not need). Responses to Q28 are presented below in Figure 125.

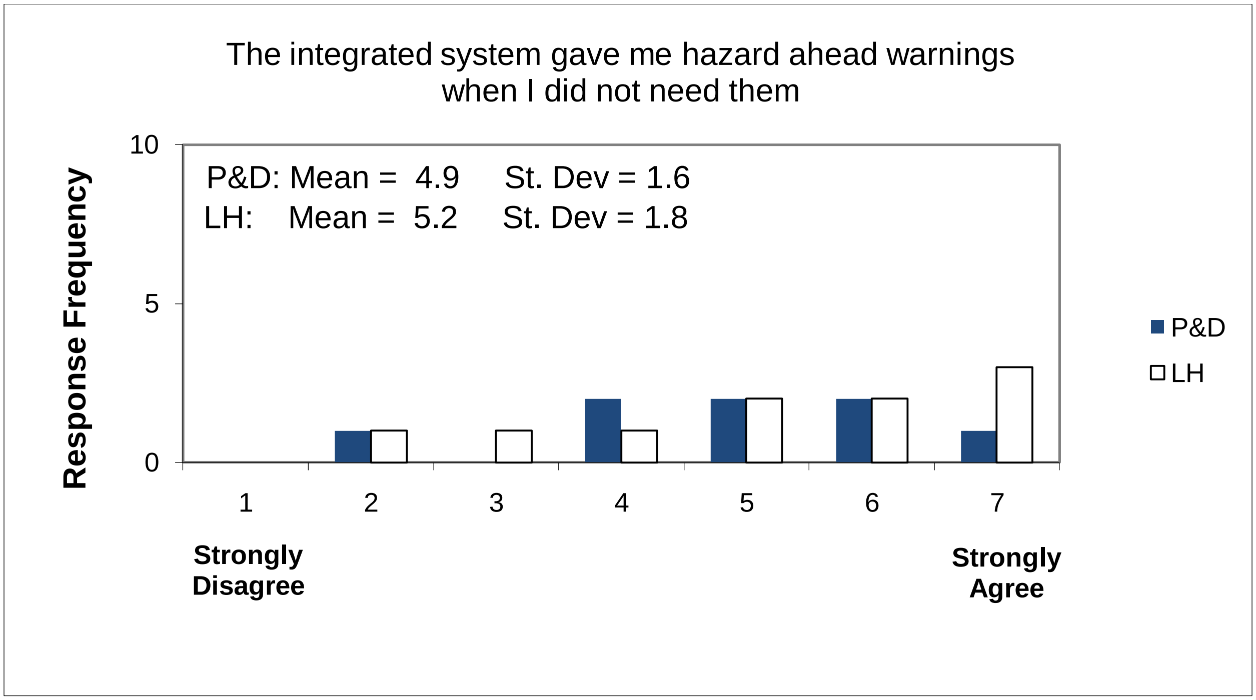

Figure 125: Q28 "The integrated system gave me hazard ahead warnings when I did not need them"

When examining Forward crash warnings, it was found that line-haul drivers experienced far more warnings in general and also more invalid forward crash warnings than their P&D counterparts. Counts of Forward crash warnings and the associated usefulness are presented in Table 74 below. (FCW's with threat level of "8" were considered invalid warnings as over 99% were elicited by an out-of-path road feature.)

Table 74: Counts and associated usefulness of FCW's 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.

3.5 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 easy to understand?

Table 75: Compiled post-drive questionnaire results relating to drivers' opinions on the Driver-vehicle interface.

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q15	I always knew what to do when the integrated system provided a warning. *1=strongly disagree, 7=strongly agree*	5.7	1.2	6.1	0.6	5.3	1.4
Q16	I could easily distinguish among the auditory warnings? *1=strongly disagree, 7=strongly agree*	5.7	1.0	5.8	0.9	5.7	1.1
Q31	The integrated system display was useful. *1=strongly disagree, 7=strongly agree*	5.0	1.2	5.0	1.2	5.0	1.3
Q37	The half circle icons on the center display helped me to understand and use the integrated system. *1=strongly disagree, 7=strongly agree*	4.8	1.2	5.0	0.9	4.7	1.2

Drivers' responses relating to the driver-vehicle interface (DVI) are presented above in Table 75. For the most part, drivers rated the DVI for the integrated system positively. Drivers responded that they clearly understood what the DVI was trying to convey when they received warnings, agreeing strongly with the statements in Q15 and Q16. In general, P&D drivers expressed more confidence in their understanding of the systems' warnings, agreeing more strongly with Q15. Responses to Q15 are displayed below in Figure 126.

Drivers also responded positively when asked specifically about the dash-mounted display. When asked about the half circle icons on the visual display (to indicate whether the lane lines were being tracked) drivers tended to agree that they helped them to understand the system. Also, 4 drivers in the open-ended questions specifically stated that they liked the visual cues on the display presenting their headway-time-margin in relation to a lead vehicle.

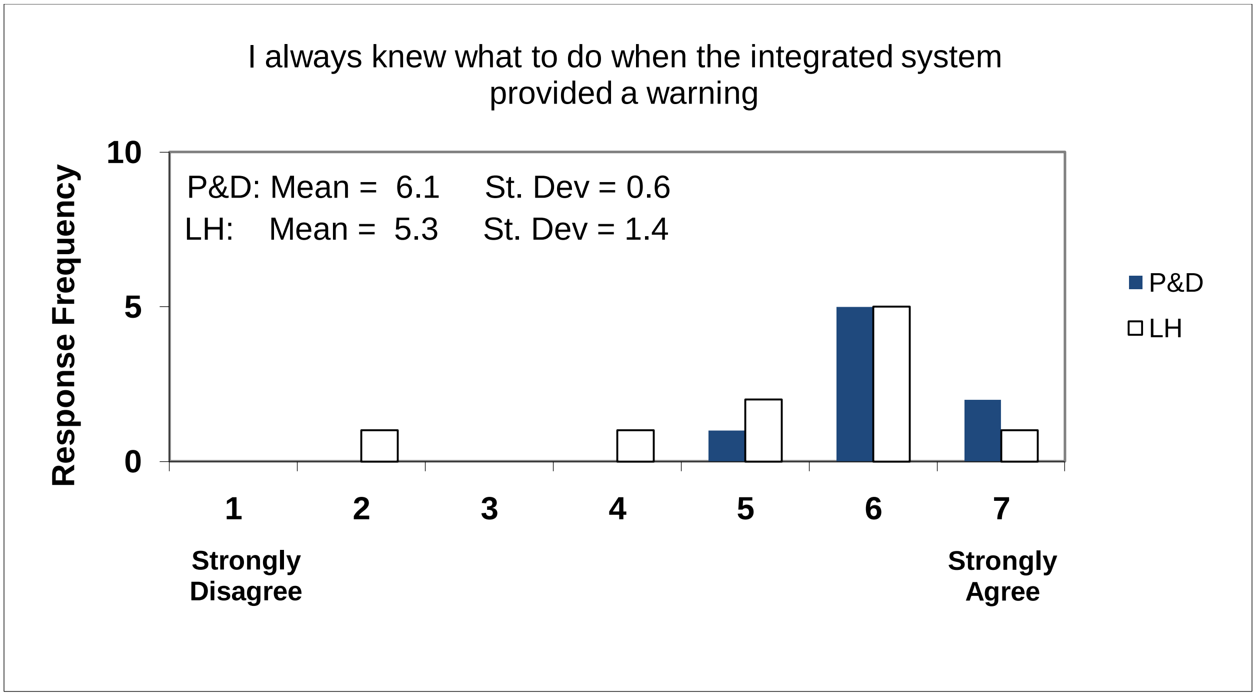

Figure 126: Responses to, "I always knew what to do when the integrated system provided a warning."

Interpretation: This may have been a result of the large number of forward collision warnings and lane change merge warnings line-haul drivers experienced when no target was present to elicit the warning. As mentioned previously in the section on QC9, line-haul drivers only braked in response to 2 percent of forward collision warnings, and only encountered a lateral hazard in 14 percent of lane-change/merge warnings. Both of these fractions were much larger for the P&D drivers, so P&D drivers were likely able to visually identify what in the road environment caused the warnings on a much more regular basis.

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

Table 76: Compiled Post-drive Questionnaire results relating to changes in drivers' behavior

		Overall		**P&D**		**Line-haul**	
Q#	**Question**	**mean**	**stdev**	**mean**	**stdev**	**mean**	**stdev**
Q33	The mute button was useful *1=strongly disagree, 7=strongly agree*	3.9	2.1	4.1	2.4	3.7	2
Q34	The volume adjustment control was useful *1=strongly disagree, 7=strongly agree*	4.1	2.0	4.4	2.1	3.9	2

When asked about the controls for the Driver-vehicle interface, specifically in terms of the auditory warnings, drivers gave a wide range of responses. This was evident in the large standard deviations of responses to both Q33 and Q34 regarding the drivers' use of the mute button and the volume controls respectively. P&D drivers in general found both driver inputs slightly more useful than line-haul drivers. Responses to Both Q33 ("The mute button was useful") and Q34 ("the volume control was useful") are presented below in Figure 127 and Figure 128 respectively.

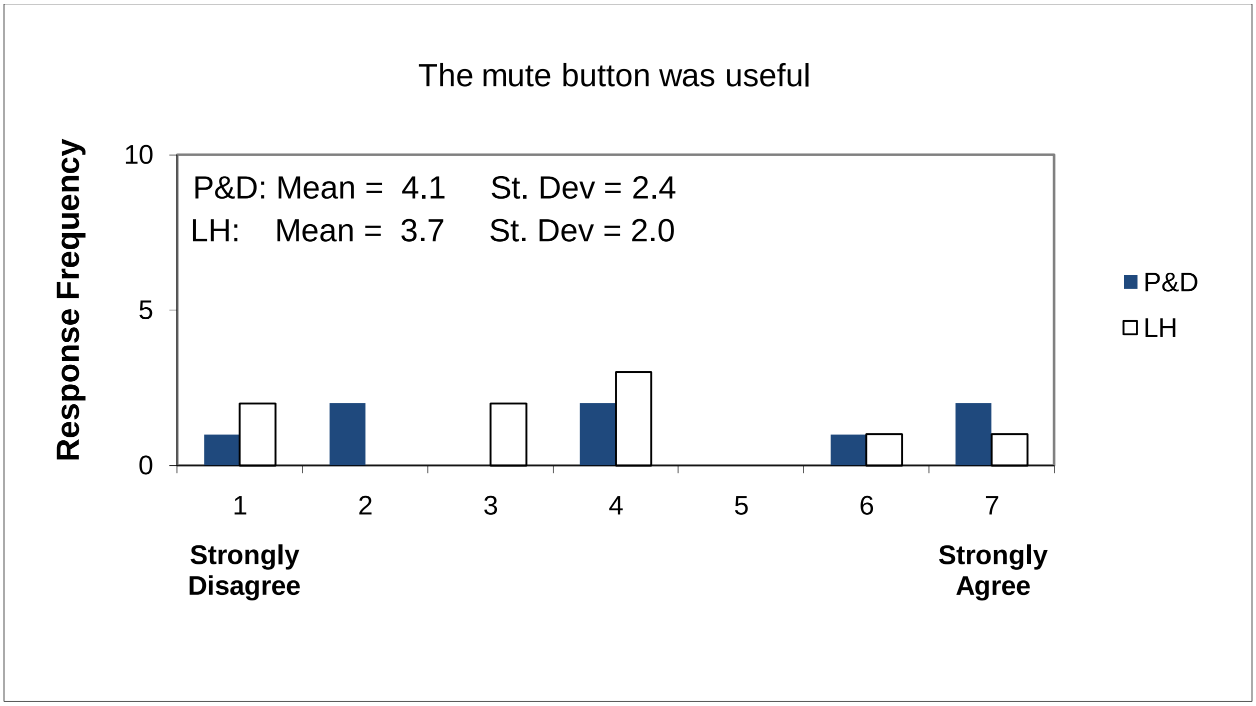

Figure 127: Responses to, "The mute button was useful"

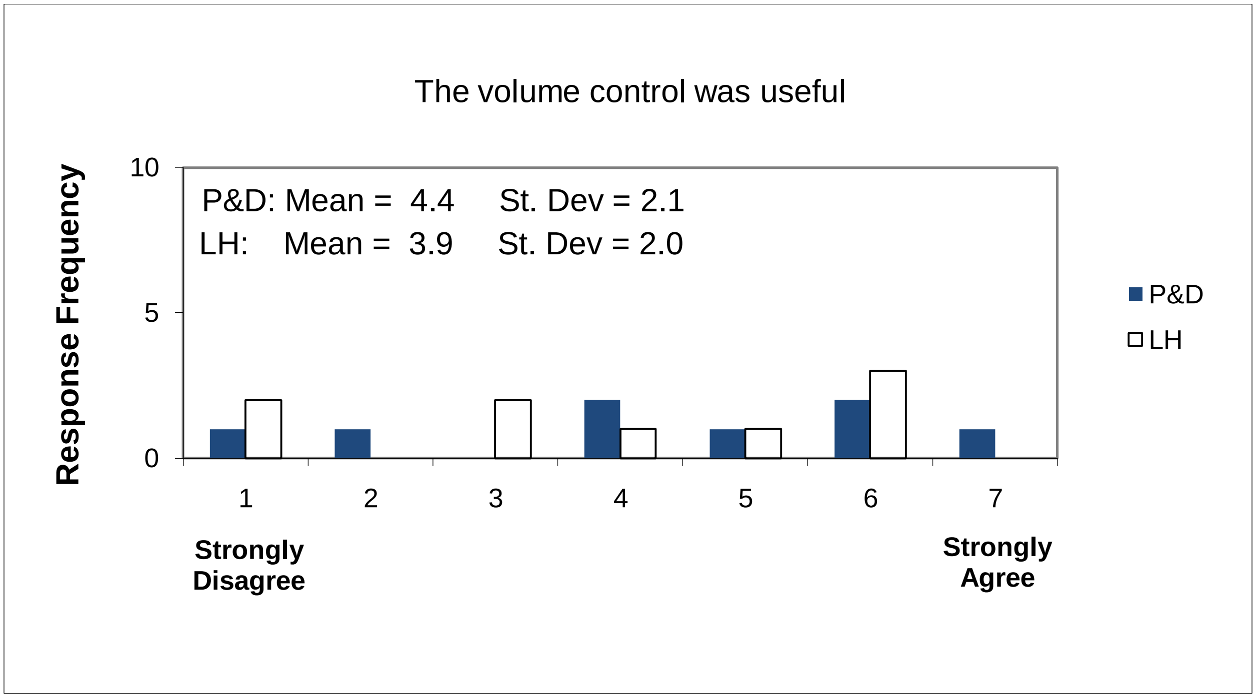

Figure 128: Responses to, "The volume control was useful"

For both the mute and volume controls, 3 drivers (Drivers 6, 7, 25) responded that they never used either of them. Also, Driver 23 said he never used the mute function and Driver 30 said he never used the volume control. Driver 8 said he used the mute function often. Specifically, Drivers 24 and 30 both stated that they used the mute function in construction zones, and both scored the usefulness of the mute function well (Driver 24 - 6 out of 7, Driver 30 - 7 out of 7). Finally, Driver 4 also gave the mute function 7 out of 7 for usefulness, stating that he used it during a period of his exposure when the FCW radar was determined to be out of alignment and likely was giving the driver an increased amount of false forward collision warnings. Table 77 below presents the actual mute button usage by each driver.

Table 77: Actual number of mute button uses by driver

Driver	Number of mutes
2	1
4	1
6	2
7	1
8	235
21	1
24	1
26	1
27	1
28	2
29	1
30	59

Interpretation: Driver route type does not appear to affect the frequency with which the mute button was used. Clearly 2 drivers, (Drivers 8 and 30) used the mute button occasionally while the other drivers simply tried the function once or twice. Of the 4 drivers reporting that they never used the mute, 2 actually did use the mute once. Six drivers never used the mute function. The mean of these six drivers' responses to Q33 was only 2.4 compared to the two drivers with the highest mute usage who both gave Q33 7 out of 7. Unsurprisingly, drivers who liked the mute function the most used it the most frequently.

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

4.1.1 Driver Behavior

- In multiple-threat scenarios, the first warning presented to drivers appeared to be sufficient to direct their attention to perform an appropriate corrective maneuver. This finding, in combination with the rarity of multiple-threat scenarios, 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.

4.1.2 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.

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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 three 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.

Question Number	Research Question	Key Findings
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.
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?	Lateral offset is significantly affected by the integrated crash warning system. 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 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, incursion duration and distance are significantly affected by the hours of service.
QL4	Does turn signal use during lane changes differ between the baseline and treatment conditions?	The results show no 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.

Question Number	Research Question	Key Findings
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 significant effect found was related to the side on which warnings occurred, 77 percent elicited 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 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 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.
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).

Question Number	Research Question	Key Findings
QF1	Does the presence of integrated system affect the following distances maintained by the heavy truck drivers?	The integrated system had a 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 significant effect of the integrated crash warning system on forward conflict levels during approaches to preceding vehicles. However, conflict levels were significantly affected 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?	There was no significant effect of the integrated crash warning system on hard-braking event frequency, but drivers had 56 percent fewer hard braking events per mile in the treatment condition. The integrated crash warning system did not have a significant effect on the maximum deceleration values, but mean maximum decelerations increased 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 significant effect on driver reaction time and brake reaction time. Drivers responded to closing-conflict events with significantly 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 objects, 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 ten-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 global positioning satellite 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 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 capability since braking force is directly related to 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)
Month	-		Months of data collection. Months 1 and 2 are always baseline condition, 3 and above are treatment condition
Road Type	-	Limited Access, Surface, Ramp	Indicates the type of road, derived from HPMS and previous UMTRI FOTs
Route Type	-	P&D, Line-haul	Daytime pick-up and delivery (local roads) and nighttime line-haul delivery between distribution terminals (Each *Driver* is exclusively associated with one of the two route types)
Side	-	Left, Right	Left and right side of the vehicle
Speed	m/s		Estimate of forward speed
Traffic Density	-	Sparse, Moderate, Dense	A count of the number of same-direction vehicles that is smoothed and weighted by the number of thru lanes.
Trailer	-	Single, Doubles	Input from the driver via the DVI and defines the number and length of the trailers attached to the tractor/power unit. Single is single axle 28 and 32 foot trailers and tandem axle 45, 48 and 53 foot trailers. Double is two single axle 28 foot trailers joined by a single axle dolly
Wiper State	-	Wipers on, Wipers off	Wiper switch state from the J1939 CAN bus and relates to the wiper speed and is used as a surrogate for active precipitation

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

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

Lane departure			An excursion on either side of the vehicle into an adjacent lane as measured by the lane-tracking component of the LDW subsystem. A lane departure was considered to have occurred when the entire lane boundary was covered by the vehicles tire. Must include both and exit from and a return to the original lane.
Lane incursion			See Lane Departure
Lane Offset Confidence	%		Confidence in the vehicle offset from lane center and lateral speed from the LDW subsystem
Lateral Position			See Lane Offset
Lateral Speed	m/s		Vehicle speed lateral to lane direction from the LDW subsystem
Likert-Type Scale Value	-	1 to 7	A number between 1 and 7 indicating general agreement of a driver with a question included in the post-drive survey. Anchor terms are provided at the two ends of the extreme
MACOM Radars			Radars mounted on the side-mirrors facing backwards down the sides of the trailer
Post-Drive Survey	-		A series of Likert-type scaled and open-ended questions completed by drivers upon completion of their study participation
POV Type	-		A video analysis based classification of the vehicle type (passenger or commercial) for vehicles treated as a Principal Other Vehicle (POV)
Range	m		Distance from the SV to the POV
Range-rate	m/s		Rate at which the SV is closing on the POV
Scenario		Shared-lane, Multi-lane	Number of travel lanes in the same direction as the Subject vehicle's motion

Secondary Task			A task performed by the driver not critical to normal driving.
Steady-state Lane Keeping			A period of time on a single road type with no lane changes or braking where the primary driving task is maintaining lane position
Subsystem			Refers to the Forward crash warning system, the Lane departure warning system or the Lane change/Merge warning system
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
Trailer Reflection			A target detected by the MACOM radars that proves to be simply a reflection from the trailer and not an adjacent vehicle or object
Van der Laan Score	-	-2 to 2	One of two possible scores relating driver perceived usefulness or satisfaction with the system being evaluated in the post-drive survey
Warning Type			One of the three possible warnings from the integrated system on the heavy truck platform (FCW, LDW, LCM)

Appendix C. DAS data collection variables

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

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

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

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

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

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

Appendix D: Heavy Truck Post-Drive Questionnaire

Subject #___________

Date _____________

IVBSS Heavy Truck Field Operational Test - Questionnaire and Evaluation

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

Example:

A.) Strawberry ice cream is better than chocolate.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

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

If a question does not apply:

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

The integrated system consists of three functions. Please refer to the descriptions below as you answer the questionnaire.

Forward Collision Warning (FCW) – The forward collision warning function provided an auditory warning whenever you were approaching the rear of the vehicle in front of you and there was potential for a collision. When you received this type of warning, the display read “Collision Alert”. Additionally, this system provided you with headway information in the display as you approached the rear of a vehicle (e.g., object detected, 3 seconds)

Lane Departure Warning (LDW) – The lane departure warning function provided an auditory warning whenever your turn signal was not on AND you were changing lanes or drifting from your lane. When you received this type of warning, the display read “Lane Drift” and a truck in the display appeared to be crossing a lane line.

Lane Change / Merge Warning (LCM) – The lane change / merge warning function provided an auditory warning whenever there was a vehicle in the truck’s blind spot, your turn signal was on, and the system detected sideways motion indicating your intention to make a lane change. A red LED illuminated in the side display on whichever side your turn signal was on. Additionally, if your turn signal was off, and there was no indication that you were intending to make a lane change, but there was a vehicle in the truck’s blind spot, a yellow LED was illuminated in the side display.

General Impression of the Integrated System

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

____

____

____

____

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

____

____

____

____

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

____

____

____

____

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

1	2	3	4	5	6	7
Not all Helpful						Very Helpful

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

____

____

____

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

8. How long after it became enabled did it take you to become familiar with the operation of the integrated system (a day, a week, etc.)?

____

9. The integrated system made doing my job easier.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

10. Did the integrated system prevent you from getting into a crash or a near crash?
Yes________ No_________

If Yes, please explain ____

____

11. I was not distracted by the warnings.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

1	2	3	4	5	6	7
Very Dissatisfied						Very Satisfied

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

a. If yes, please explain?

____

____

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

a. If yes, please explain.

____

____

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

16. I could easily distinguish among the auditory warnings (i.e., as being a Lane Drift, Forward Collision or Lane Change /Merge warning).

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

17. The auditory warnings' tones got my attention.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

18. The auditory warnings' tones were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

19. The yellow lights mounted near the exterior mirrors got my attention.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

20. The yellow lights mounted near the exterior mirrors were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

21. Did the integrated system perform as you expected it to?

Yes________ No_________

If no, please explain

____

____

22. The number of false warnings affected my ability to correctly understand and become familiar with the system

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

23. The number of false warnings caused me to begin to ignore the integrated system's warnings.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

24. The integrated system gave me warnings when I did not need them.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

25. The false warnings were not annoying.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

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

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

29. **How did the false warnings affect your perception of the integrated system?**

____

____

____

<u>Overall Acceptance of the Integrated System</u>

30. Please indicate your overall acceptance rating of the integrated system *warnings*
For each choice you will find five possible answers. When a term is completely appropriate, please put a check (√) in the square next to that term. When a term is appropriate to a certain extent, please put a check to the left or right of the middle at the side of the term. When you have no specific opinion, please put a check in the middle.

The integrated system **warnings** were:

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

Displays and Controls

31. The integrated system display was useful.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

32. Did you look at the display less as your experience with the integrated system increased?

Yes________ No_________

33. The mute button was useful.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

34. The volume adjustment control was useful.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

35. The two lane change/merge warning displays mounted near the exterior mirrors were useful.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

36. The lane change /merge warnings displays are in a convenient location.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

37. The half circle icons on the center display helped me to understand and to use the integrated system.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

38. In general, I like the idea of having new technology in my truck.

1	2	3	4	5	6	7
Strongly Disagree						Strongly Agree

39. Do you prefer to drive a truck equipped with the integrated system over a conventional truck?

Yes__________ No____________

Why?

____

____

____

40. Would you recommend that the company buy trucks equipped with the integrated system?

Yes_____________ No____________

Why?

____

____

____

Forward Collision Warning (FCW) acceptance

41. Please indicate your overall acceptance rating of the forward collision warnings.

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

Forward collision warnings were:

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

Lane Departure Warning (LDW) acceptance

42. Please indicate your overall acceptance rating of the lane departure warnings.

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

Lane departure warnings were:

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

Lane Change/Merge (LCM) acceptance

43. Please indicate your overall acceptance rating of the lane change/merge warnings.

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

The lane change / merge warnings were:

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

Acceptance of yellow lights mounted near the mirrors

When a vehicle was approaching or was in the research vehicle's blind spots, a yellow light near the exterior mirror was illuminated.

44. Please indicate your overall acceptance rating of the yellow light in the mirrors.

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

The **yellow lights in the mirror** mounted near the exterior mirrors were:

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

Appendix E: Descriptions of Data Analysis Techniques

A. Linear Mixed Models

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

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

B. General Linear Mixed Models

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

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

C. Logistic Regression

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

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

where p is the probability of the event.

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

D. Generalized Logit Models

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

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

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

E. Case Cross-Over and Case-Control

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

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

Table C.1. Case Cross-Over Design Table

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

$$\frac{c}{b}=\frac{p(s\mid w)p(s'\mid w')}{p(s'\mid w)p(s\mid w')}=\frac{p(w\mid s)p(s)p(w'\mid s')p(s')p(w)p(w')}{p(w)p(w')p(w\mid s')p(s')p(w'\mid s)p(s)}$$
$$=\frac{p(w\mid s)p(w'\mid s')}{p(w\mid s')p(w'\mid s)}=\frac{odds(w\mid s)}{odds(w\mid s')} \quad (3)$$

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