Evaluation of the Mack Intelligent Vehicle Initiative Field Operational Test

Final Report

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

September 2006

FOREWORD

The Federal Motor Carrier Safety Administration (FMCSA) has been engaged in a cooperative agreement to perform field testing of “Generation Zero” active safety systems as part of the Intelligent Vehicle Initiative (IVI) program since 1999. This Field Operational Test (FOT) focused on an evaluation of a Lane Departure Warning System (LDWS) for large trucks. The purpose of the FOT was to evaluate an LDWS in terms of safety performance and driver acceptance.

LDWS are in-vehicle electronic systems that monitor the position of a vehicle within a roadway lane and warn a driver if the vehicle deviates or is about to deviate outside the lane. LDWS perform this function using forward-looking, video-based systems that process the image to detect the lane boundaries and calculate the position of the host vehicle within those boundaries. The LDWS only provide warnings and do not take any action to avoid a lane departure or to control the vehicle. Therefore, drivers remain responsible for the safe operation of their vehicles.

The experimental plan for the FOT involved installing and utilizing the LDWS on vehicles to collect data during a 12-month test period. To evaluate the system, the data collected during periods with the display on were compared to the baseline data collected with the display off. Data were collected using a specialized system, and uploaded automatically from the vehicles to a project website, which enabled the evaluators to monitor and sort incoming data, as well as change selected reporting parameters.

The information in this document can be used by motor carriers in discerning the viability of LDWS and the functionality of these systems and their integration into the vehicle, which can provide a foundation for future product planning. The carrier which participated in this study had an overall positive experience of LDWS, and drivers found the system to be valuable.

NOTICE

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16. Abstract

This report presents the final results of an independent evaluation of the U.S. Department of Transportation (USDOT) Mack Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT). The IVI is a cooperative effort to conduct FOTs of advanced intelligent vehicle safety systems (IVSS) among the motor carrier industry and four agencies of the USDOT: the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), the Federal Transit Administration (FTA), and the Federal Motor Carrier Safety Administration (FMCSA).

This report summarizes the results of an independent evaluation of the Mack FOT, which was performed under a cooperative agreement with Mack Trucks, Inc., in partnership with McKenzie Tank Lines. The FOT focused on the testing of a lane departure warning system (LDWS). The LDWS is a forward-looking, vision-based system that provides the driver an audible warning of a lane departure situation. Algorithms within the LDWS interpret video images of the lane to estimate the vehicle state (lateral position, speed, heading, etc.) and the road alignment (lane width, road curvature, etc.). By providing lane departure warnings, this system can potentially reduce single-vehicle roadway-departure (SVRD) crashes, rollovers, and lane-change/merge crashes by giving the driver an opportunity to change driving behavior before making a large lane excursion.

The primary goals of the independent evaluation included:

1. **Achieve an in-depth understanding of system benefits**
2. **Obtain measures of driver performance and evaluate user acceptance**
3. **Ascertain the performance and capability potential of the LDWS system**
4. **Assess product maturity for deployment**
5. **Address institutional and legal issues that might impact deployment**

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	Yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					AREA		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
		VOLUME					VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	l	l	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
		MASS					MASS		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lbs)	0.907	megagrams	Mg	Mg	megagrams	1.103	short tons (2000 lbs)	T
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8 C + 32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m2	cd/m2	cd/m2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

***SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.**

ACKNOWLEDGEMENTS

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ACRONYMS

ABS	Anti-lock Brake (or Braking) System
ACN	Automatic Crash Notification
ADRT	Additional Driver Reaction Time
ATA	American Trucking Associations
ATRI	American Transportation Research Institute
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
CATI	Computer-Aided Telephone Interview
CG	Center of Gravity
CPHRE	Centers for Public Health Research and Evaluation (Battelle)
CPI	Consumer Price Index
CRR	Crash Reduction Ratio
CVISN	Commercial Vehicle Information Systems and Networks
CWS	Collision Warning System
ER	Exposure Ratio
FARS	Fatality Analysis Reporting System
FET	Federal Excise Tax
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FOT	Field Operational Test
FTA	Federal Transit Administration
GES	General Estimates System
GPS	Global Positioning System
GVW	Gross Vehicle Weight
HAZMAT or HM	Hazardous Materials
IAHW	Infrastructure-Assisted Hazard Warning
ID	Identification
IRB	Institutional Review Board
ISS	Inspection Selection System
IT	Information Technology
ITS	Intelligent Transportation System

IVI	Intelligent Vehicle Initiative
IVSS	Intelligent Vehicle Safety System
LCM	Lane Change/Merge (Crash)
LDWS	Lane Departure Warning System
LEX	Lane Excursion
MVMT	Million Vehicle Miles Traveled
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
O&M	Operations And Maintenance
OEM	Original Equipment Manufacturer
OMB	Office of Management and Budget
OPS	Operational Data Summary
PR	Prevention Ratio
PTOL	Percentage Time Out of Lane
RBC	Richard Bishop Consulting
RMS	Root-Mean-Squared
RMSLP	(Square) Root-Mean-Squared Lane Position
ROR	Run-Off-Road (See SVRD)
SAS	Statistical Analysis System
SEA	Safety Evaluation Area
SPSS	Statistical Package for the Social Sciences
SVRD	Single-Vehicle Road (or Roadway) Departure
TAZ	Trucker Advisory Zone
TSA	Trucker Safety Advisory
USDOT	U.S. Department of Transportation
VDANL	Vehicle Dynamics Analyses—Nonlinear
VES	Vehicle Enhancement System
VIUS	Vehicle Inventory and Use Survey
VMAC	Vehicle Management and Control
VMT	Vehicle Miles Traveled
VORAD	Vehicle On-board Radar

EXECUTIVE SUMMARY

This report presents the final results of an independent evaluation of the U.S. Department of Transportation (USDOT) Mack Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT). The IVI is a cooperative effort to conduct FOTs of advanced intelligent vehicle safety systems (IVSS) among the motor carrier industry and four agencies of the USDOT: the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), the Federal Transit Administration (FTA), and the Federal Motor Carrier Safety Administration (FMCSA).

The Mack FOT was a cooperative agreement with Mack Trucks, Inc., in partnership with McKenzie Tank Lines, which focused on the testing of a lane departure warning system (LDWS).

The LDWS tested in the FOT is a commercially available system known as SafeTRAC, which is designed, built, and sold by AssistWare Technology. It is a forward-looking, vision-based system that provides the driver with an audible warning of a lane departure situation. Algorithms within the LDWS interpret video images of the lane to estimate the vehicle state (lateral position, speed, heading, etc.) and the road alignment (lane width, road curvature, etc.). By providing lane departure warnings, this system can potentially reduce single-vehicle roadway-departure (SVRD) crashes, rollovers, and lane-change/merge crashes by giving the driver an opportunity to change driving behavior before making a large lane excursion.

Goals

The major focus of the Mack FOT independent evaluation was to determine the safety benefits of the LDWS. In addition, user acceptance, human factors, system performance, product maturity, institutional issues, and legal issues were addressed relating to the technology. The primary safety benefit expected from the deployment of the LDWS is a reduction of large truck crashes and the resulting injuries and fatalities. Other potential benefits include improvements in mobility, efficiency, and environmental quality.

Evaluation Plan

To address the evaluation goals of the Mack FOT, an Evaluation Plan was developed that defined an analysis of the LDWS. This approach included an experimental design of the FOT to isolate and estimate the safety benefits of the LDWS. The primary feature of the experimental design was to compare driving behavior in the following three phases:

- Phase I – Baseline Period: Data collected during this period would characterize the driving behavior of drivers without receiving LDWS feedback.
- Phase II – Active Period: Data collected during this period would characterize the driving behavior of drivers receiving LDWS feedback.
- Phase III – Post-Active Period: Data collected during this period would characterize the driving behavior of drivers who had been driving with LDWS feedback, after the LDWS feedback had been deactivated.

During each phase of the Mack FOT, on-board driving data were collected over a 12-month period (March 2004 to March 2005) for normal, in-service operation of 22 trucks and 31 drivers based in ten terminals throughout the southeastern United States. The trucks involved in the FOT averaged 65,603 miles traveled over an average of 266 days. Experimental design changes occurred in the FOT, however, and the results reflect data that could only be used from six of the 31 drivers in the safety analyses.

Data Sources

Five main sources of data and information were used to conduct the evaluation. The centerpiece of the FOT was vehicle data collected from a suite of sensors and data acquisition devices where on-board data were studied to determine how often and under what conditions possible pre-crash conflicts occur. Another major data source included historical crash and incident data from the host fleet operator and public databases – the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES).

In addition, opinions were solicited from personnel in the FOT, including drivers, mechanics, and corporate staff, to determine whether the LDWS warnings were clear and to gauge the level of user acceptance, product maturity, and institutional and legal issues. Also, the operator's maintenance and operation records that were relevant to the FOT were examined to help estimate the costs or savings associated with using the LDWS. Finally, supplemental tests were conducted that included a series of baseline and system-verification tests to establish trigger criteria for data collection and evaluate the on-board data collection systems.

Findings

Safety Benefits. The primary goal of the safety benefits analysis was to estimate the number of crashes that could be prevented by the deployment of the LDWS in various truck operational scenarios. The steps performed in the analysis were: (1) the examination of historical crash data to determine the frequency of relevant crashes (rollover and roadway departure crashes) and the nature of pre-crash situations (driving conflicts) that led to these crashes, (2) the comparison of the frequency of conflicts with and without drivers receiving LDWS feedback during the FOT, and (3) the comparison of conflict severities or, equivalently, the conditional probabilities of a crash given that a truck is in a conflict. Additional analyses were performed to identify driving conditions or other factors that affect the efficacy of the LDWS in reducing numbers of crashes or the effects of the LDWS feedback on various surrogate measures of safe driving.

To determine how the LDWS could improve safety and reduce vehicle crashes, two important measures were considered:

- Exposure of a vehicle to potential crash situations (driving conflicts)
- Prevention of crashes when a vehicle is in a driving conflict

In addition to crash reduction estimates, other potential benefits of the LDWS were analyzed for drivers, fleets, and society.

During the FOT, the 22 vehicles equipped with the LDWS were not involved in any crashes. The analysis of data collected in this FOT demonstrated that the use of the LDWS could reduce driving conflicts associated with SVRD and rollover crashes. Figure 1 illustrates that these types of conflicts could decrease from a rate of 20.9 to 14.3 conflicts per 10,000 vehicle miles traveled (VMT) using the LDWS, which is a 31 percent decrease in conflicts while driving on straight roads. For conflicts while driving on curved roadways, conflict rates could decrease from 5.0 to 3.3 conflicts per 10,000 VMT using the LDWS, which is a 34 percent decrease in conflicts. The decrease in conflict rates occurring on straight roads was statistically significant at the 95 percent confidence level, while the decrease of conflict rates occurring on curves was not statistically significant.

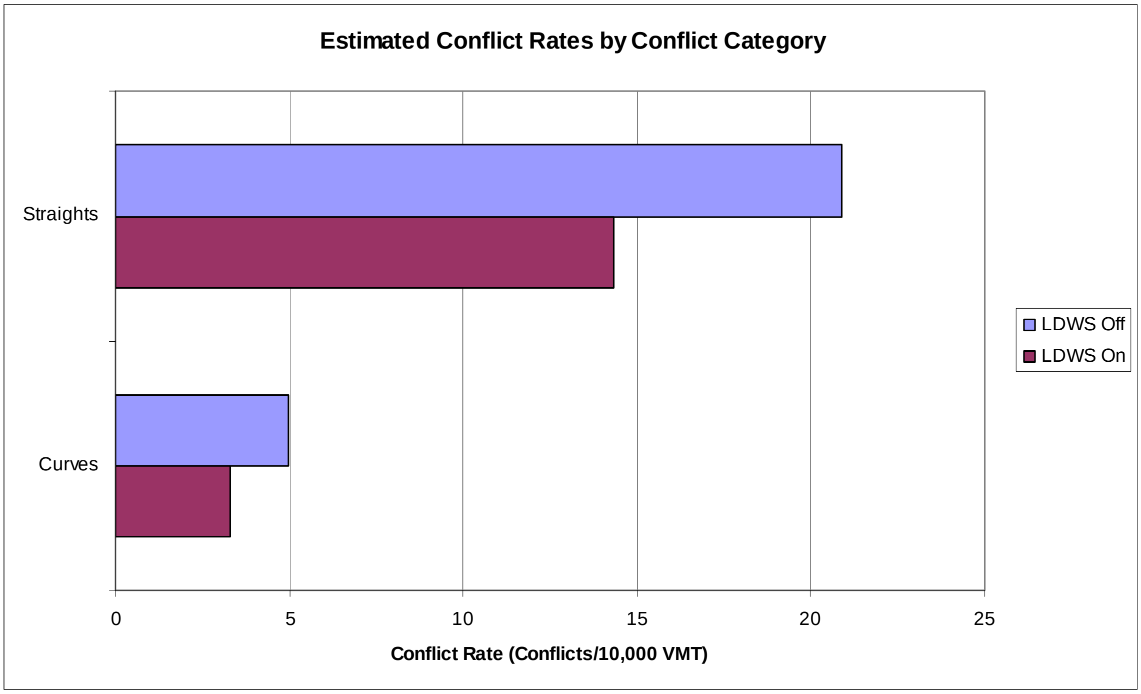

Figure 1. Conflict Rates for Curves and Straight Roads

Driver Acceptance. The assessment of driver acceptance and human factors was based on an initial driver survey conducted at the beginning of the evaluation period before drivers had experience using the LDWS, and a second survey was conducted after the drivers had experience using this system. Survey questions were designed to evaluate: (1) driver's training and learning, (2) driver's understanding of the system capabilities, (3) system usability under real-world driving conditions, (4) potential distraction effects of system operation, (5) driver stress associated with system use, (6) changes in perceived driver workload, (7) usefulness and acceptance, and (8) potential effects on driving behavior and hazardous driving habits.

Since a small number of drivers responded to the surveys, the results were mixed and unlikely to be representative of all truck drivers' opinions about the LDWS. However, the surveys provided a range of reactions to driving with the LDWS in the FOT. The majority of the drivers felt that using the LDWS improved their lane-keeping ability and reduced their workload, but it did not change other aspects of their safety-related driving. Positive comments indicated that the LDWS helped drivers to drive in a straighter path, maintain alertness (especially in late-night driving), and improve concentration on the driving task. Negative comments indicated that the location of the LDWS on the dash obscured the view; the alert tones were annoying, startling, and sometimes difficult to distinguish from tones generated by other systems in the truck; and the LDWS contributed to general "information overload."

Performance and Capability Potential. The performance and capability potential of the LDWS were assessed with respect to functionality, capability, and reliability/maintenance of the system.

During the Mack FOT, the LDWS was assessed to determine the consistency and repeatability of drift alerts. For the FOT, all LDWS were programmed to issue a drift alert when a front tire was just over the lane boundary. The frequency of drift alerts was directly proportional to the frequency of lane excursions; therefore, the FOT data indicated that the LDWS drift alert was strongly related to lane excursions, and the issuance of drift alerts was repeatable and consistent.

Drivers using the LDWS were found to have a lower rate of drift alerts and a lower probability of being out of their lane. The frequency of drift alerts was also lower at night, when driving at highway speeds on predominantly straight roads, or when the driver had been on the road for up to 6 hours in the previous 8 hours.

The operating limits of the LDWS are contained in a set of internal codes for the system. If certain criteria (listed in Appendix C) are not met, the warnings are automatically disabled by the system. During the sampled driving periods, warnings were enabled about 86 percent of the time, with a range of about 78 to 91 percent. Further, warnings were disabled in situations where they could be expected about 6 percent of the time. The availability of the LDWS was indicated by the amount of time that alerts were enabled by the LDWS itself as a percentage of total time moving at speeds greater than 35 mph. The availability for seven trucks in the FOT ranged from approximately 82 to 97 percent.

During the FOT, some of the LDWS units malfunctioned. However, these SafeTRAC LDWS units were considered "prototypes" by the supplier; therefore, these malfunctions could not be determined to be representative of the SafeTRAC LDWS currently on the market and in use by various truck fleets (either as original equipment or through after-market installation). Wider deployment of a more mature and improved SafeTRAC LDWS has occurred following the Mack FOT because the prototype LDWS required improvements to withstand the environment of trucks that may typically log over 1,000,000 lifetime miles.

Benefit-Cost Analysis. The societal benefit-cost analysis (BCA) compared the total cost of deploying and operating the LDWS on various populations of trucks to the total economic benefit. The results from the FOT were used to estimate the reduction in the total number of crashes and crash-related injuries and deaths that would occur if all vehicles in representative operational configurations or scenarios were equipped with the LDWS.

Four installation scenarios were considered: (1) all large trucks (> 10,000 lbs. gross vehicle weight, or GVW), (2) all class 7 and 8 tractors pulling at least one trailer, (3) tractors pulling tanker trailers, and (4) tractors pulling tankers containing hazardous materials (HAZMAT). The BCA included the LDWS deployment in various operational configurations of different truck populations, over a 20-year life cycle. A total of 16 scenarios were modeled in the Mack IVI FOT benefit-cost analysis, as follows:

(4 operational configurations) ×
(2 equipment cost assumptions) ×
(2 crash reduction efficacy assumptions) = 16 BCA scenarios

Installed equipment costs were $750 per tractor and $1,500 per tractor. The manufacturer of the LDWS estimated that commercial off-the-shelf units are expected to have a service life of 5 to 7 years. For the BCA, the more conservative value of 5 years was used for replacement life, assuming purchases of the LDWS for every truck in each fleet in years 2005, 2010, 2015, and 2020. The four truck populations and the two crash-reduction efficacy assumptions (labeled "best estimate" and "conservative") were derived from the statistical modeling of safety benefits. The "best estimate" of the crash reduction efficacy was calculated using estimated exposure and prevention ratios. Since the estimate of prevention ratio was determined not to be statistically significant, a "conservative estimate" was also calculated using the estimated exposure ratio, which was statistically different from 1, and the default value of 1 for the estimated prevention ratio.

Table 1 shows the societal benefit-cost ratios (BCRs), derived from calculations of present (year 2005) dollars at a 4 percent discount rate over a 20-year deployment window, for each of the 16 scenarios modeled. Values greater than 1 indicate a positive economic return on the investment required to deploy the IVSS. BCR values less than 1 indicate that the deployment does not appear to be economically justified based on the assumptions used in this analysis.

Ten of the 16 scenarios show BCRs greater than 1, while the remaining six scenarios were not determined to be economically justified in this analysis. None of the "all large trucks" scenarios was economically justified due to the much larger population of all large trucks, which greatly increases the deployment cost without a proportional increase in costs avoided through fewer crashes. The scenarios involving tractor-trailers pulling tankers were determined to be the most economically favorable over the 20-year life cycle, with BCRs ranging from 1.95 to 5.11.

The HAZMAT tanker scenarios were also determined to be economically justified, with BCRs ranging from 1.19 to 3.20. The cost of each HAZMAT crash is higher, relative to other scenarios, but HAZMAT carriers tend to have lower crash rates. The tractor-trailer scenarios with lower equipment costs are marginally economically justified (BCRs = 1.10 and 1.54), while the high equipment-cost assumptions pull the two remaining tractor-trailer BCRs below 1.

The benefit-cost ratios for the two larger scenarios of all trucks and tractor-trailers were higher for the conservative scenarios than for the best-estimate scenarios. These results are contrary to the results for the two smaller populations of tractor-tankers and HAZMAT tankers, where the best-estimate scenarios yield higher BCRs. This contradiction resulted from the larger populations and smaller populations having different conflict rates and the differences in the crash-reduction ratios for rollover crashes for the conservative and best-estimate calculations.

Table 1. Benefit-Cost Ratios for 16 Scenarios

Population	Cost Assumption	Efficacy	BCR[1]
All Trucks	Low	Best Estimate	0.32[2]
All Trucks	Low	Conservative	0.46
All Trucks	High	Best Estimate	0.16
All Trucks	High	Conservative	0.23
Tractor-Trailers	Low	Best Estimate	**1.10**[3]
Tractor-Trailers	Low	Conservative	**1.54**
Tractor-Trailers	High	Best Estimate	0.55
Tractor-Trailers	High	Conservative	0.78
Tanker Trailers	Low	Best Estimate	**5.11**
Tanker Trailers	Low	Conservative	**3.85**
Tanker Trailers	High	Best Estimate	**2.58**
Tanker Trailers	High	Conservative	**1.95**
HAZMAT Tankers	Low	Best Estimate	**3.20**
HAZMAT Tankers	Low	Conservative	**2.35**
HAZMAT Tankers	High	Best Estimate	**1.62**
HAZMAT Tankers	High	Conservative	**1.19**

[1] BCR = Benefit-Cost Ratio (20-Year Deployment; 4 Percent Discount Rate)

[2] Interpreted as a 32-cent return for each $1 invested (a negative benefit)

[3] Interpreted as a $1.10 return for each $1 invested (a positive benefit)

Figure 2 illustrates the same 16 scenarios, showing which configurations of fleet, equipment cost, and crash-reduction efficacy yield a positive societal return on the investment required to deploy LDWS on all trucks in each fleet. As illustrated in the figure, the best BCR is obtained by deploying LDWS on both tractors with tanker-trailers and tractors with HAZMAT tanker-trailers.

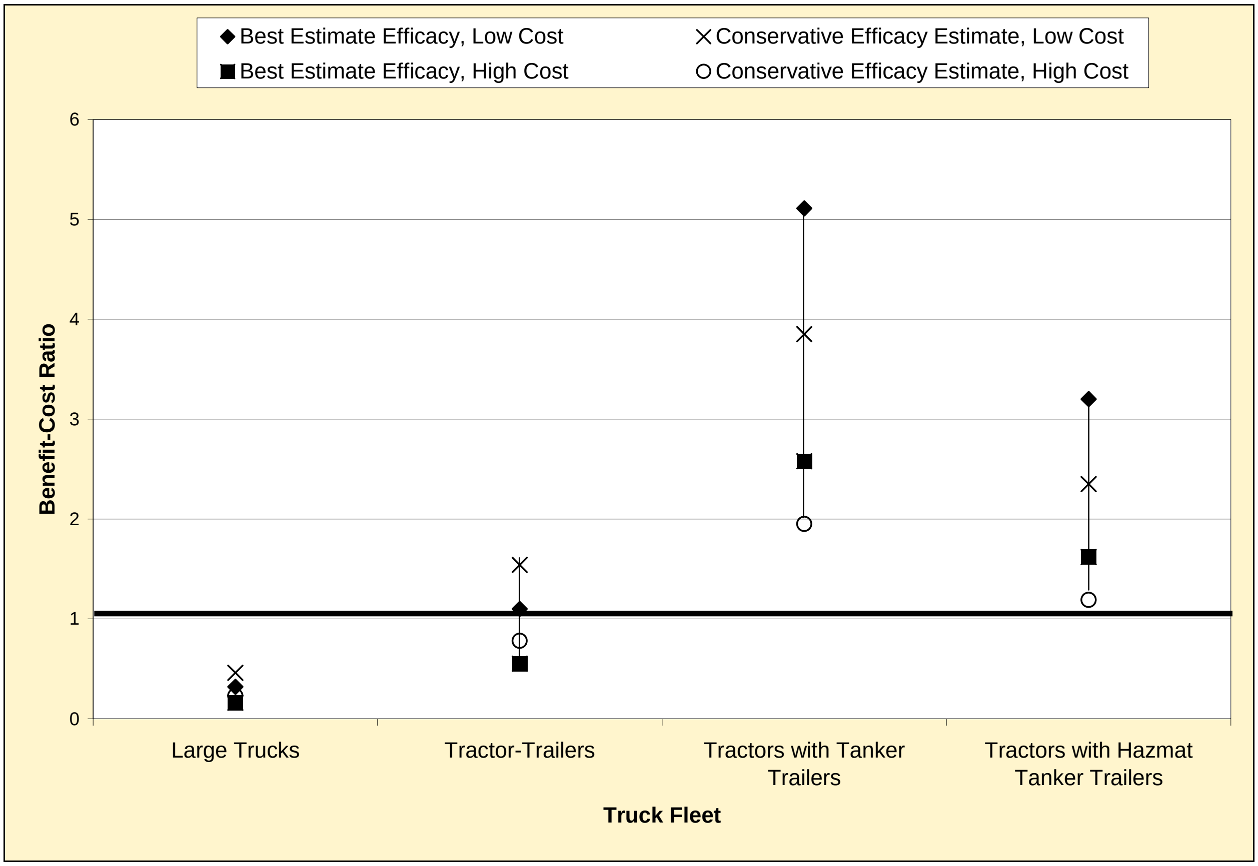

Figure 2. LDWS Benefit-Cost Analysis Results

Implications of Findings

The findings of the independent evaluation indicated that the use of the LDWS could reduce crashes, injuries, and fatalities in crashes involving large trucks. These findings were the result of improved driver lane-keeping behavior and the reduction in the frequency where the driver is exposed to driving conflicts. During the FOT, the LDWS was most effective in reducing lane departures at night and on straight roads, which are conditions where drivers may be less attentive to the driving task.

Because the LDWS used in the FOT were prototypes, conclusions about reliability and performance of the current commercial version could not be drawn. However, the FOT data indicated that the LDWS issued lane departure alerts consistently under the conditions for which it was designed.

From an economic benefit-cost perspective, the system was primarily economically justified for tractors pulling tanker-trailers and for tractors pulling HAZMAT tanker-trailers under conditions similar to the FOT.

1.0 INTRODUCTION

This report presents the final results of an independent evaluation of the U.S. Department of Transportation (USDOT) Mack Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT). The IVI is a cooperative effort to conduct FOTs of intelligent vehicle safety systems (IVSS) among the motor carrier industry and four agencies of the USDOT: the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), the Federal Transit Administration (FTA), and the Federal Motor Carrier Safety Administration (FMCSA).

The intent of the overall IVI program is to improve the safety and efficiency of motor vehicle operations by reducing both the number and the consequences of motor vehicle crashes on U.S. highways. Crash reductions may be achieved by accelerating the development, testing, deployment, and use of new IVSS. IVSS are information technology (IT)-enabled systems and smart technologies designed to reduce crashes and prevent injuries by assisting drivers, increasing vehicle performance, and enhancing vehicle crashworthiness capabilities. These safety improvements may also yield secondary benefits, such as increased transportation mobility, productivity, and other operational improvements.

In 1999, USDOT entered into cooperative agreements with three partnerships to conduct FOTs of advanced IVSS in commercial vehicles:

- Mack Trucks, Inc., in partnership with McKenzie Tank Lines, Inc., focused on testing a lane departure warning system (LDWS) designed to assist drivers in maintaining their lane of travel, and intended to reduce the number and severity of single-vehicle road departure, rollover, and lane-change/merge crashes.
- Volvo Trucks North America, Inc., in partnership with US Xpress Enterprises, Inc., tested a forward collision warning system, an adaptive cruise control, and an advanced electronically controlled braking system for commercial vehicles, intended to reduce the number and severity of rear-end collisions caused by commercial vehicles striking other vehicles from behind.
- Freightliner Corporation, in partnership with Praxair, Inc., tested a roll stability advisor and control system to assist commercial vehicle drivers in avoiding rollover and single-vehicle road-departure crashes.

Each partnership performed a separate FOT to demonstrate and evaluate advanced technologies. A Battelle-led team worked with each partnership to perform an independent evaluation of the technologies being tested. This report summarizes the independent evaluation of the Mack IVI FOT. The results from this evaluation will aid truck manufacturers, component suppliers, fleet operators, government agencies, and others in setting priorities and making decisions regarding the development, support, and deployment of advanced safety technologies in commercial vehicles.

1.1 The Mack Partnership IVI Field Operational Test

The Mack FOT was conducted by Mack Trucks (program manager), McKenzie Tank Lines (fleet operator), Vehicle Enhancement Systems Inc. (system integrator), Aonics (data collection and management), and Richard Bishop Consulting.

The Mack FOT focused on the testing and evaluation of an LDWS in a fleet of 22 tanker trucks over a one-year period (March 2004 to March 2005) of typical revenue service. In addition, the basic functionality of an automatic crash notification system (ACN) and trucker safety advisory system (TSA) was tested. Although the original plan was to evaluate these two systems, logistical problems with the installation of systems and deployment of trucks in the test fleet resulted in the modification to the FOT.

1.1.1 Lane Departure Warning System

As shown in Figure 3, the LDWS tested in the Mack FOT was a commercially available system known as SafeTRAC, which is designed, built, and sold by AssistWare Technology (Gibsonia, PA).

Figure 3. McKenzie Tank Lines Truck Cab

The LDWS tested in the FOT was a forward-looking, vision-based system, consisting of a main unit and small video camera mounted on the vehicle's windshield recording data of the upcoming roadway. The video data are acquired by a main unit, which is about the size of a radar detector, as shown in Figure 4. Algorithms within the LDWS interpret video images of the lane to estimate the vehicle state (lateral position, speed, heading, etc.) and the road alignment (lane width, road curvature, etc.). The LDWS warns the driver of a lane departure when the vehicle is traveling above a certain speed threshold and the vehicle's turn signal is not in use. In addition, the LDWS notifies the driver when lane markings are inadequate for detection, or if the system malfunctions.

LDWS do not take any automatic action to avoid a lane departure or to control the vehicle; therefore, drivers remain responsible for the safe operation of their vehicles. By providing lane departure warnings, this system can potentially reduce single-vehicle roadway-departure (SVRD) crashes, rollovers, and lane-change/merge crashes by giving the driver an opportunity to change driving behavior before making a large lane excursion.

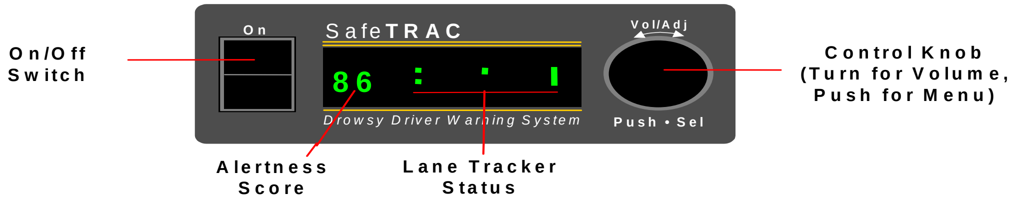

Figure 4. LDWS SafeTRAC Driver Display

The LDWS uses algorithms to interpret video images at a rate of 5 frames per second to estimate the road curvature, lane boundary types, lane width, vehicle position in the lane, lateral velocity, and the remaining time until the vehicle crosses a lane boundary, which is also known as "time to lane crossing" (TLC).

The LDWS SafeTRAC features evaluated in the Mack FOT included:

- A graphical display depicting the vehicle's current position in the lane along with the lane boundary locations and types (dashed, solid, etc.)
- A drift alert, which is an audible tone indicating that the truck is about to travel or has traveled out of its lane (including the case where the driver initiates a lane change without using the turn signal)
- Text messages providing brief (one- or two-word) advisories in the following situations:
    - A turn signal may have been left on unintentionally.
    - The windshield needs to be cleaned (the camera's view is obstructed).
    - The driver has been driving for an extended period of time and may need to take a break.
    - The LDWS alerts have been suppressed to prevent potential false alarms.
    - The LDWS is in self-calibration mode.
    - The driver needs to enter information when initializing the system.

Although the commercially available SafeTRAC LDWS provides a feature called an Alertness Score, this feature was not evaluated in the Mack FOT.

Since it is a vision-based system, the performance of the LDWS may be limited when visibility is poor. The LDWS does not operate at delivery points and roads where the truck travels at speeds below the minimum LDWS tracking speed. As a result, the LDWS notifies drivers when the system is operational, but does not provide warnings under these conditions. LDWS may be beneficial in low-visibility conditions (e.g., rain, fog, and falling snow) when lane markings are present. Due to reflections on wet road surfaces, LDWS may occasionally be unable to detect lane markings; however, the lane-tracking indicator shows that the system is not providing warnings under these conditions. When lane markings are not visible on roads covered by mud, ice, or snow, the lane-tracking indicator shows that the system is inactive.

The independent evaluation of the Mack FOT focused on the use of the LDWS to prevent single-vehicle roadway departures (SVRDs), also known as run-off-road (ROR) crashes, and untripped rollovers not caused by an impact with a roadside feature or other obstacle. Use of the LDWS also has the potential to reduce lane-change/merge crashes and head-on crashes. The safety benefits of the LDWS for these crash types were not evaluated, however, because the available FOT data were not sufficient to identify driving conflicts associated with these crash types. Specifically, identifying a lane-change/merge-related conflict requires knowledge of the location and speed of vehicles alongside the truck in an adjacent or merging lane. Identifying a head-on crash-related conflict requires knowledge of the presence of an adjacent lane of opposing traffic and the speed and location of an oncoming vehicle. This information could not be obtained from the available data with adequate confidence and accuracy.

2.0 OVERVIEW OF THE FIELD OPERATIONAL TEST

This section presents a description of the research plan and a discussion of operational characteristics affecting the FOT.

2.1 Research Plan

The original research plan for the Mack IVI FOT included requirements to install the LDWS, TSA, and ACN systems on a test fleet of 36 tanker trucks operated by McKenzie Tank Lines in normal revenue service over a 19-month period. The final research plan was a revision of the original plan, because several technical problems with the data-acquisition and transmission systems delayed the start of the FOT. This in turn created logistical problems with the installation of systems and deployment of trucks in the test fleet. Consequently, the FOT was performed over a 12-month period, with a primary focus on the safety benefits of the LDWS, which was installed on 22 trucks.

Since the Eaton VORAD (EVT-300) collision warning system (CWS) was standard equipment on the McKenzie Tank Lines tractors used in the FOT, this system was active throughout the FOT. The CWS was not disabled during the FOT, because driving with the CWS was considered to be valid baseline driving for McKenzie Tank Lines drivers, and it would be difficult to separate the effects of removing the CWS and adding the LDWS. All trucks were also equipped with data acquisition and communications equipment.

LDWS Evaluation. Use of the LDWS was expected to affect driving performance in two ways. First, there is the immediate effect of warning the driver of a potential lane excursion, which gives the driver an opportunity to change his or her driving behavior before making a large lane excursion. Second, after gaining experience using the LDWS, the driver's overall driving performance may improve even without the use of the system. Another possibility is that a driver's driving performance may decline when the system is disabled, because the driver may become dependent on the system. Three conditions were compared in the experimental design:

- Phase I – Baseline Period: Data collected during this period would characterize the driving behavior of drivers who were not receiving LDWS feedback.
- Phase II – Active Period: Data collected during this period would characterize the driving behavior of drivers receiving LDWS feedback.
- Phase III – Post-Active Period: Data collected during this period would characterize the driving behavior of drivers after the LDWS feedback had been deactivated.

Three experimental designs were considered for evaluating the LDWS, as illustrated in Figure 5. All three designs focused on evaluating driving behavior with and without LDWS feedback over an 8-month operating period that began after an initial 2-month baseline period. Design 1 illustrates a "before vs. after" design in which all trucks operate with an inactive driver-interface system (i.e., the LDWS driver/vehicle interface is turned off) for a 2-month baseline period, an active driver-interface system ("LDWS interface on") for 5 months, and an inactive driver-interface system again for 1 month. Designs 2 and 3 involve dividing the drivers into two groups. Design 2 includes two groups where one group never uses an active LDWS interface. For Design 3, a modified crossover design, two groups use active LDWS interface feedback, but the times that the system status is changed are staggered. For the FOT, the crossover design was selected, but modified so that both groups had 4 months of active LDWS interface feedback time.

Design 1: Before vs. After

	June	July	Aug	Sep	Oct	Nov	Dec	Jan
All Trucks	OFF	OFF	ON	ON	ON	ON	ON	OFF

- *All trucks have an active interface period at the same time.*
- *Design 1 has the most active LDWS interface time of the designs.*
- *Each driver serves as his/her own control.*
- *LDWS effect confounded with time.*

Design 2: Control vs. Test

	June	July	Aug	Sep	Oct	Nov	Dec	Jan
Group A	OFF	OFF	ON	ON	ON	ON	ON	OFF
Group B	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

- *Control group (Group B) does not have any active LDWS interface time.*
- *Control group helps to account for confounding due to time.*

Design 3: Crossover Design (Selected Experimental Design)

	June	July	Aug	Sep	Oct	Nov	Dec	Jan
Group A	OFF	OFF	ON	ON	ON	ON	OFF	OFF
Group B	OFF	OFF	OFF	OFF	ON	ON	ON	ON

- *All trucks have active LDWS interface time.*
- *Design 3 has before and after data on all trucks.*
- *Deign 3 has a shorter active LDWS interface time per driver than other designs.*
- *Trucks with an inactive LDWS interface help control for confounding due to time.*

Legend:

shaded	Inactive LDWS Interface (System Interface Off)
not shaded	Active LDWS Interface (System Interface On)

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Figure 5. Experimental Designs

A modified experimental Design 3 was implemented and adjusted during the FOT to account for equipment installation schedules, events of nature, such as hurricanes, and equipment failures. Data collection commenced from March 1, 2004 through March 1, 2005. Table 2 summarizes the groups of trucks, the amount of vehicle miles traveled (VMT) collected during the FOT, and the LDWS interface activation status. Trucks that had recorded baseline driving data as of July 2004 were assigned to either Group A or Group B. Trucks that became active in the FOT at a later date after approximately 1 month of baseline driving were assigned to Group O. Due to problems with the development, installation, and verification of the on-board systems, only 22 of the planned 36 trucks participated the FOT. The chosen design included the staggered LDWS interface activation dates for different trucks; because drivers sometimes changed trucks, the VMT by driver and activation sometimes differed, as described in Section 4.2.2.

Table 2. VMT Collected During FOT by Truck

Truck ID	Design Group	System Status	Mar-04	Apr-04	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05
6101	A	Inactive	0	0	5,860*	7,032	9,842	3,276	**P****	0	0	0	0	0
6101	A	Active	0	0	0	0	0	0	6,423	11,804	8,438	7,422	204	3,229
6102	A	Inactive	0	10,094	14,036	2,523	0	**P**	0	0	0	0	0	0
6102	A	Active	0	0	0	0	0	8,198	8,005	11,992	5,610	10,129	643	0
6106	A	Inactive	0	0	3,962	9,890	4,464	**P**	0	0	0	0	0	0
6106	A	Active	0	0	0	0	0	8,268	9,958	7,336	1,877	0	0	0
6108	A	Inactive	0	0	0	701	6,426	2386	0	0	0	0	40	0
6134	A	Inactive	0	0	4,448	7,910	0	**P**	0	0	0	0	**P**	6,392
6134	A	Active	0	0	0	0	0	5,821	4,831	0	6,726	3,974	8,741	
6204	A	Inactive	905	11,104	0	0	0	0	0	0	0	0	**P**	3,467
6204	A	Active	0	0	0	0	0	0	0	0	7,231	4,363	5,271	0
6206	A	Inactive	7,054	2,559	0	0	0	0	0	0	0	0	**P**	363
6206	A	Active	0	0	0	0	0	375	2,089	2,845	6,233	838	3,400	0
6103	B	Inactive	0	11,200	5,833	0	0	0	0	0	0	0	0	0
6104	B	Inactive	13,239	8,034	6,589	1,081	0	0	4	2,151	10,093	10,093	11,381	3,242
6116	B	Inactive	0	315	4,293	11,600	8,963	7,279	7,819	9,018	P	0	0	0
6116	B	Active	0	0	0	0	0	0	0	0	5,312	6,949	11,201	9,962
6120	B	Inactive	0	0	7,834	9,382	10,844	8,356	1,525	7,704	**P**	0	**P**	7,469
6120	B	Active	0	0	0	0	0	0	0	0	6,494	7,571	8,542	0
6122	B	Inactive	1,847	9,967	6,271	407	3,420	9,758	8,434	4,499	6,683	5,868	2,038	1,829
6201	B	Inactive	4,157	1,323	0	0	3,320	5,392	0	4,260	139	6,438	**P**	0
6201	B	Active	0	0	0	0	0	0	0	0	0	0	9,132	8,790
6107	C	Inactive	0	0	0	0	1,969	6,994	9,378	10,159	7,413	8,182	6,296	6,370
6111	C	Inactive	0	0	0	0	0	0	2,000	0	0	0	0	0
6112	C	Inactive	0	0	0	0	2,982	8,211	0	0	1,165	4,575	**P**	0
6112	C	Active	0	0	0	0	0	0	0	0	0	0	9,469	8,557
6113	C	Inactive	0	0	0	0	0	0	0	1,519	0	0	0	0
6115	C	Inactive	0	0	0	0	0	0	0	537	0	908	**P**	0
6115	C	Active	0	0	0	0	0	0	0	0	0	0	7,763	0
6119	C	Inactive	0	0	0	0	0	0	0	7,131	8,995	6,979	4,300	6,394
6121	C	Inactive	0	0	0	0	36	4,432	7,259	6,263	0	0	0	0
6121	C	Active	0	0	0	0	0	0	0	0	0	0	0	2
6124	C	Inactive	0	0	0	0	0	0	0	4,446	4,283	0	0	0
6131	C	Inactive	0	0	0	0	1,959	3,955	5,957	8,297	1,412	0	0	0

* Shading indicates LDWS inactive interface.

* **P** indicates that an unspecified portion of the data points in the corresponding Active cell were collected when the system was Inactive.

Table 3 shows VMT and the amount of data collected from 22 trucks during the 12-month data collection period. The trucks averaged 65,603 miles traveled over an average of 266 participation days.

The overall average data completeness, as measured by the percent of VMT included in the operational data summary (OPS) files, was 57 percent, yet it was not uniform among the participating trucks. These low percentages of VMT were attributed primarily to malfunctions of the LDWS and the on-board data collection and transmittal systems. Data completion rates for half of the trucks were 71 percent or more. One anomaly in the data for truck 6119 showed that 105 percent of the total VMT was accounted for in the OPS files. An explanation for this anomaly is the OPS files for this truck were received both before the first odometer reading and after the last odometer reading. Sections 4 and 5 contain additional information about the amount of data that were used to perform the safety benefit analysis.

Table 3. Driving Data Collected During the FOT[*]

Truck	Design Group	FOT Start Date	Date of Last File	Days in the FOT	Total VMT1	Miles Accounted for in OPS Files	% of VMT Included in OPS Files
6101	A	5/13/2004	3/1/2005	293	65,092	63,530	98%
6102	A	4/2/2004	1/2/2005	334	104,280	71,160	68%
6106	A	5/7/2004	2/28/2005	299	64,328	45,755	71%
6108	A	6/23/2004	1/14/2005	252	13,092	9,553	73%
6134	A	5/15/2004	3/1/2005	291	59,803	48,843	82%
6204	A	3/29/2004	2/28/2005	338	107,031	32,341	30%
6206	A	3/1/2004	3/1/2005	366	151,365	25,756	17%
6103	B	4/2/2004	2/25/2005	334	110,092	17,033	15%
6104	B	3/1/2004	2/28/2005	366	110,088	65,907	60%
6116	B	4/29/2004	3/1/2005	307	95,059	82,711	87%
6120	B	5/5/2004	3/1/2005	301	84,560	75,721	90%
6122	B	3/26/2004	2/25/2005	341	86,146	61,021	71%
6201	B	3/1/2004	2/27/2005	366	52,632	42,951	82%
6107	O	7/14/2004	3/1/2005	231	61,924	56,761	92%
6111	O	9/10/2004	9/16/2004	173	2,060	2,000	97%
6112	O	7/27/2004	3/1/2005	218	36,041	34,959	97%
6113	O	10/1/2004	2/28/2005	152	46,484	1,519	3%
6115	O	10/4/2004	2/27/2005	149	21,481	9,208	43%
6119	O	10/9/2004	3/1/2005	144	32,275	33,799	105%
6121	O	7/27/2004	2/28/2005	218	52,499	17,992	34%
6124	O	10/1/2004	2/18/2005	152	29,476	8,729	30%
6131	O	7/28/2004	2/24/2005	217	57,467	21,598	38%
Total (22 Trucks)				**5,842**	**1,443,275**	**828,847**	**57%**
Average				**266**	**65,603**	**37,675**	**57%**

[*] Estimates of total VMT are subject to uncertainties in the dates on which odometer readings were recorded.
Note: The table entries are rounded values of the actual estimates.

2.2 Operational Characteristics Affecting FOT Evaluation

The FOT participating carrier, McKenzie Tank Lines, Inc., headquartered in Tallahassee, Florida, operates a fleet of 585 tractors and approximately 1,000 trailers out of 30 locations, and serves customers across the United States and Canada. Almost all of the trailers are stainless steel, aluminum, high pressure, dry bulk, or specialized tankers. Approximately 65 percent of the deliveries involve HAZMAT. The average power unit travels approximately 75,000 miles per year. In this FOT, the average truck mileage was about 90,236 miles per year.

During the FOT, the experimental plan execution was strongly influenced by the condition that McKenzie Tank Lines' normal operating procedures (driver selection, truck assignments, route selections, etc.) were a priority during the FOT data-collection period. The effects of this prioritization of normal operating conditions during the FOT were:

- The VMT associated with each driver/truck combination could not be entirely controlled by the experimental design. As a result, only a small percentage of collected data could be used to assess safety benefits.
- Malfunctions of the systems used in the test did not affect the ability of the trucks to make deliveries, so access to the trucks to remedy any malfunctions during the FOT data-collection period was limited to normal operational situations when the trucks returned to terminals. These situations included scheduled maintenance, changes in driver assignments, and the need for repairs.
- The administration of driver surveys was restricted to times when the drivers were at their terminals.
- Drivers' familiarity with routes could not be controlled.
- Driver training on the operation of the LDWS and other on-board systems installed for the FOT was limited to informational brochures and LDWS manuals distributed by McKenzie Tank Lines fleet management to the terminals where the drivers were assigned. Consequently, the amount of training provided to each driver was not controlled well.
- The estimated safety benefits and effects of the LDWS on driving behavior were in the context of adding the LDWS on trucks already equipped with another type of IVSS, which introduced bias impacting the accuracy of extrapolating the FOT results to other drivers who do not have experience using any type of IVSS. McKenzie Tank Lines' trucks are normally equipped with a CWS, which was active at all times during the FOT; therefore, all drivers in the FOT had previous driving experience with the CWS.

2.3 Limitations of the FOT Evaluation

There were several other limitations that affected the FOT evaluation. The prediction of safety benefits required the ability to identify driving conflicts from the on-board measurements. Because the amount of instrumentation that could be installed on the trucks was limited by both cost and data-transmission constraints, there were no direct measurements of some potentially valuable data, such as steering wheel rotation, driver eye movements, trailer dynamics, and video recording of driver activity and workload (e.g., checking the side-view mirror, using the two-way radio, adjusting the cab temperature, eating a sandwich, etc.). Consequently, some of these variables were estimated using the on-board measurements in a truck simulation model. Other variables, such as driver activity and workload, could not be fully characterized. The LDWS could also potentially prevent other types of conflicts and crashes in addition to the SVRD and untripped rollover crashes analyzed in this evaluation. It is possible that the “other” conflict types, as well as those that lead to other crash types (e.g., lane-change/merge crashes), might also be mitigated by an LDWS; however, it was not possible to consider those conflicts in this study without the additional data-collection tools.

Factors such as low sampling rates and sensor performance also increased the difficulty in identifying driving conflicts, due to the choice to transmit data over the air, rather than record on-board and download records conventionally. Because of limitations placed on the volume of data that could be transmitted and the associated data-transmission costs, measurements were sampled at a maximum rate of 1 Hz for all variables except tractor lateral position and lateral velocity, which were sampled at 5 Hz. Analyses of the measurement time histories indicated that the 1 Hz sample rate was marginally low for measurements of tractor-cab tilt angle, lateral acceleration, and yaw rate. The tractor dynamic behavior in lane departures included significant motions at frequencies greater than 1 Hz; consequently, sampling at 1 Hz effectively filtered out the higher frequency response, and the maximum values of variables sampled were not always captured.

Due to these data volume issues, measurements were restricted to those designed into the on-board systems (e.g., the LDWS, the VES box, and the EVT-300 CWS). The VES box provided the only measurements of lateral acceleration and tilt angle. The tilt sensor and accelerometer used in the VES box design had performance limitations that affected the accuracy with which the vehicle dynamics could be interpreted.

The tilt sensor had a relatively slow response time (approximately 1s to respond to a step change in angle from 10 percent to 90 percent of full scale at 25°C). Therefore, it was incapable of measuring rapid changes in tractor roll that may occur during a lane departure. The lateral accelerometer was also sensitive to tilt angle; thus, the output signal was sensitive to both the truck cab’s lateral acceleration and tilt angle, making it difficult to determine the true acceleration response.

A critical and unavoidable limitation of the measurement system was that the LDWS was used to provide measurements for evaluating itself. The self-evaluation process was problematic, particularly when assessing system performance. The LDWS was the sole source of data on truck position in the lane; therefore, it was impossible to identify and characterize lane departures that occurred if the LDWS either malfunctioned or functioned correctly but, by design, suppressed the lane-position-calculation algorithm. When the system was known to be malfunctioning, the VMT associated with the malfunctioning truck were not used in the safety benefits. Alert suppressions were expected to occur at the same rate for all trucks; therefore, they were determined not to affect the estimated percent reduction in crashes. The only way to overcome this situation would have been to use complete, independent measurement systems on the trucks.

Another limitation of the FOT involved using a prototype version of the LDWS version in the FOT; therefore, conclusions regarding the reliability of the current commercial version of the LDWS could not be drawn. Finally, a low percentage of driver surveys were completed and returned for the evaluation of driver acceptance. As a result, conclusions could not be drawn about overall driver acceptance of the LDWS.

3.0 EVALUATION GOALS

This section describes the goals and objectives that guided the evaluation of the Mack FOT and the generation of specific hypotheses for evaluation and testing.

Four terms are used to describe elements of the evaluation: goals, objectives, hypotheses, and measures. ***Goals*** define the broad areas of benefits evaluated in the IVI program, such as "assess safety benefits." These goals were developed based upon the priorities of the USDOT and the Mack Partnership defined in a January 2000 workshop. The goals were then applied to define evaluation ***objectives***, which specify information about driver or system performance that should be obtained to satisfy the goal, such as "determine if drivers drive more safely with IVSS." These objectives were subsequently translated into specific ***hypotheses***, or declarative statements, which could be tested in the FOT. Lastly, specific ***measures*** were identified that are specific data or variables that can be analyzed to prove or disprove the hypotheses.

In 1999, the USDOT suggested five goal areas along with some generic objectives for each goal. These objectives were to be tailored to meet the needs of each IVI FOT.

These goals were first discussed with the Mack FOT partners and the USDOT during an evaluation workshop on January 14, 2000. The purpose of the workshop was to develop an initial framework of goals and methods for conducting the evaluation and to reach preliminary agreements on the priorities for the evaluation goals. Nine evaluation goal areas were discussed during the workshop, and priorities were established by polling the participants. Within each goal area, a number of specific objectives and hypotheses were proposed. Following the workshop, further discussions with the Mack Partnership and the USDOT helped to clarify and refine the evaluation objectives. Each of the goal areas is described below, along with objectives and supporting hypotheses that guided the evaluation of the LDWS. The goals, objectives, hypotheses, and measures stated below were modified from the original version to reflect the changed focus of the FOT on the evaluation of the LDWS versus other IVSS.

Goal 1A. Achieve an In-Depth Understanding of Safety Benefits
The primary safety benefit expected from the deployment of the LDWS is a reduction in the number and severity of large truck crashes and the resulting injuries and fatalities. This benefit can also result in a direct safety benefit to the driver or persons involved in or in the vicinity of the crash.

Objective 1A.1 Determine if driving conflict and crash probabilities will be reduced for drivers using the LDWS.

Improvements in driving behavior (driving more safely) and advance warnings of potential dangers are expected to result in fewer crashes. This objective focuses on the relationship between driving behavior and crashes under the conditions that are encountered during the FOT. The key measures are the relative frequencies where LDWS-equipped versus non-equipped trucks encounter "driving conflicts" and the associated probabilities of being involved in a crash for each type of driving conflict. Specific hypotheses to be tested include:

1A.1-1 Drivers using LDWS will have fewer SVRD and rollover driving conflicts than baseline drivers.

1A.1-2 Drivers using LDWS will have reduced probability of SVRD and rollover crashes under conditions encountered in the FOT than baseline drivers.

Objective 1A.2 Determine if drivers drive more safely using the LDWS.

The LDWS is designed to warn drivers who are inattentive and begin to deviate from the lane or roadway. It has the potential to improve overall driving behavior. The key measures related to this objective are the frequencies with which drivers encounter dangerous situations and various measures associated with safe driving (e.g., vehicle speed, reaction time, use of turn signals). Specific hypotheses to be tested include:

1A.2-1 Drivers using LDWS will have fewer unplanned lane and road departures than drivers without the systems.

1A.2-2 Drivers using LDWS will use turn signals more often, drive at slower speeds, and react more quickly to dangers than drivers without the systems.

1A.2-3 The effect of LDWS on driver behavior (as defined in 1A.1-1 and 1A.1-2) will be greater after several hours on the road.

1A.2-4 After using the LDWS, drivers will either (a) become dependent on the systems, thus degrading safe driving behavior in non-equipped vehicles, or (b) become more alert to dangers even when not using the systems.

Objective 1A.3 Determine if the number of crashes, injuries, and fatalities could be reduced if all fleets operating in the United States were equipped with LDWS.

This objective focuses on extrapolating the results observed in the FOT to predict crash, injury, and fatality reductions for the entire nation. This requires an assessment of the potential impacts of driver experience and fleet characteristics on the effectiveness of IVSS. Key measures include a variety of national crash statistics and the effects of driver characteristics on IVSS effectiveness. Specific hypotheses to be tested include:

1A.3-1 Characteristics (e.g., age, experience, driving record) of McKenzie Tank Lines drivers are typical of drivers across the country.

1A.3-2 Characteristics (e.g., policies, truck/cargo type, routes) of the McKenzie Tank Lines fleet are typical for fleets across the country.

1A.3-3 The frequencies with which McKenzie Tank Lines vehicles encounter driving conflicts are typical for fleets across the country.

1A.3-4 The effectiveness of the LDWS in helping the drivers from the McKenzie Tank Lines fleet to avoid driving conflicts and reduce the probability of crashes can be expected to be the same for drivers across the country.

Objective 1A.4 Determine if drivers using the LDWS will have less severe crashes than drivers without the system.

In cases where the warnings from the LDWS do not result in crash avoidance, the warnings might allow the driver to take actions (e.g., reduce speed, avoid objects) that will lessen the severity of the crash. Key measures will focus on driver reaction times and changes in vehicle dynamics following driver reactions. The specific hypothesis to be tested is:

1A.4-1 Drivers receiving a warning prior to or during a driving conflict will take corrective action to reduce the severity of potential crashes.

For example, if a truck drifts off the road onto a narrow shoulder due to a drowsy driver, an LDWS warning might not provide enough time for the driver to become attentive and steer the vehicle back onto the road, but it might provide enough time for the driver to at least begin a corrective maneuver and reduce the severity of impact with the guardrail.

Goal 1B. Achieve an In-Depth Understanding of Mobility Benefits

Transportation mobility refers to the ease of movement, or perceived ease of movement as viewed by traveling public. Benefits are usually measured in terms of travel-time savings, reduced congestion, and improvements in "customer" satisfaction. Reducing the number of crashes involving large trucks, an expected outcome of deploying IVSS, will produce a mobility benefit. The number of crashes avoided with full deployment of IVSS will be used along with information from the literature to estimate the value of the mobility benefits.

Objective 1B.1 Determine the value of the mobility benefits resulting from reduced truck-related crashes for inclusion in an overall benefit-cost analysis of IVSS.

Key measures include literature-derived estimates of the impact of large-truck crashes on congestion, travel time, and traveler satisfaction. The only relevant measure obtained from the FOT used in this analysis is the number of crashes avoided due to the deployment of IVSS. The specific hypothesis to be tested is:

1B.1-1 Deployment of IVSS will result in significant mobility benefits due to reductions in crashes involving large trucks.

The value of mobility benefits is included in a benefit-cost analysis. (See goal area 1D.)

Goal 1C. Achieve an In-Depth Understanding of Efficiency Benefits

Efficiency generally refers to the amount of output (e.g., cargo-ton miles) for a given input (driver/vehicle days). IVSS affect the efficiency of commercial fleet operations through the reduction of the number of crashes or through operational impacts that can be measured in terms of productivity gains or losses (cost savings or increases). Thus, this goal area is combined with goal area 1D – Productivity.

Goal 1D. Achieve an In-Depth Understanding of Productivity Benefits

Deployment of IVSS can result in productivity increases through cost savings from reduced numbers of crashes and lower insurance rates. Other indirect productivity benefits will be documented and valued. There are cost increases associated with the purchase and maintenance of the systems, training costs for drivers and mechanics, and possibly operating costs.

Objective 1D.1 Determine the total costs of deploying and maintaining IVSS technologies for fleet operations.

Key measures include purchase costs, annual maintenance costs, operating costs (e.g., wireless communication charges, geocell database updates), and training costs. The specific hypothesis to be tested is:

1D.1-1 Deployment of IVSS will increase the costs of operating commercial trucking fleets.

Objective 1D.2 Identify and document cost savings that might be realized when deploying IVSS technologies in fleet operations.

Key measures include savings due to fewer crashes, lower insurance costs, and lower driver turnover due to driver satisfaction. The specific hypotheses to be tested are:

1D.2-1 Commercial truck fleets will save money (directly or indirectly through lower insurance premiums) due to crash reductions attributable to the deployment of IVSS.

1D.2-2 Commercial truck fleets will save money due to reduced driver-turnover rates attributable to increased job satisfaction by drivers using IVSS.

Objective 1D.3 Conduct a comprehensive benefit-cost analysis to determine if the total benefits (from all sources) to society exceed the costs to develop and deploy.

A general framework for conducting a benefit-cost analysis of IVSS includes the separate Volvo and Freightliner IVI programs. The specific hypothesis to be tested is:

1D.3-1 The total cost to society of developing, deploying, and maintaining IVSS will be less than the combined value of all of the benefits.

Goal 1E. Achieve an In-Depth Understanding of Environmental Quality Benefits

In addition to preventing injuries and fatalities, a reduction in the number of crashes resulting from the deployment of the LDWS also benefits the environment in terms of fewer HAZMAT spills and reduced air pollution from traffic congestion caused by crashes.

Objective 1E.1 Determine the value of any environmental benefits that result from fewer truck-related crashes (especially HAZMAT-carrying trucks) for inclusion in a benefit-cost analysis.

Environmental benefits or impacts may come from reductions in crash-related congestion or HAZMAT spills. Key measures include literature-derived estimates of the impact of large-truck crashes on the environment and the value of those impacts. The only relevant measures from the FOT include the number of crashes avoided due to the deployment of IVSS. The specific hypothesis to be tested is:

1E.1-1 Deployment of IVSS will result in a significant benefit to the environment due to reductions in crashes involving large trucks.

The value of environmental impacts is also considered in the benefit-cost analysis. (See goal area 1D.)

Goal 2. Assess User Acceptance and Human Factors

This goal area focuses on how IVSS technologies affect the driving environment and the acceptability of the systems by the drivers and fleet operators. While Goal 1A (Safety Benefits) deals with the objective assessment of the impacts of IVSS on safe driving behavior, this goal focuses on understanding if and how human factors may play a role in the eventual acceptance and deployment of the systems.

Objective 2.1 Determine the usability of the IVSS technologies under normal driving conditions.

This objective focuses on how IVSS are used and understood by the drivers, as derived from driver questionnaires and interviews. In particular, this objective evaluates the drivers' understanding of signals and information; perceptions of consistency and robustness of signals; how the information is integrated and presented to the driver; and the ease of learning, use, and control. Specific hypotheses to be tested are:

2.1-1 Drivers have reasons for using the IVSS under specific, if not all, driving conditions (to be determined).

2.1-2 Drivers find the IVSS and components easy to learn.

2.1-3 Drivers believe that they are adequately trained to use these systems.

2.1-4 Drivers find the IVSS and components easy to use and control.

2.1-5 Drivers understand the IVSS capabilities.

2.1-6 Drivers understand the signals and controls.

2.1-7 Drivers perceive that the IVSS signals are recognizable and easy to see or hear.

2.1-8 Drivers trust the IVSS and perceive that they are useful.

2.1-9 Drivers understand how to use information from the IVSS.

2.1-10 Drivers believe that the IVSS messages are unambiguous and clearly understood.

Objective 2.2 Determine how IVSS technologies affect the perceived stress or workload of drivers.

This objective focuses on how the IVSS affect the driving environment as derived from driver questionnaires and interviews. Of particular interest are the effects of false alarms and the impacts on driver-workload related to system performance established under Goal 3. Specific hypotheses to be tested are:

2.2-1 Drivers perceive that the IVSS are effective under specific (if not all) driving conditions (to be determined).

2.2-2 Drivers perceive that IVSS reduce their driving workload.

2.2-3 Drivers perceive that IVSS reduce their levels of stress or fatigue.

2.2-4 Drivers perceive that IVSS do not distract them or interfere with their other tasks.

2.2-5 Drivers perceive that IVSS false positive alarms are a nuisance.

2.2-6 Drivers perceive that IVSS false negative alarms degrade their confidence in the systems.

2.2-7 IVSS increase the job satisfaction of drivers.

Objective 2.3 Determine the perceived impacts on driver risk and vigilance.

While Objective 1A.1 addresses whether or not drivers modify their driving behavior (and the degree to which modified behavior is safe), this objective is concerned with learning why drivers modify their driving behavior. Key measures, derived from interviews and questionnaires, include drivers' explanations of driving behavior modifications. Specific hypotheses to be tested include:

2.3-1 Drivers with the systems are aware that they take fewer risks than drivers without the systems because they have a greater awareness of potential safety hazards.

2.3-2 Drivers with the LDWS are aware that they are more vigilant in their lane-keeping behavior than those without the system because of the feedback provided by the system.

2.3-3 Drivers with the systems become more dependent on the systems over time, which degrades their safety-related driving performance when driving vehicles without the systems.

2.3-4 Drivers are aware that they modify their driving behavior (speed, braking, lane keeping, turn signal usage) for particular reasons (to be determined) in response to the IVSS.

Objective 2.4 Determine perceptions of product quality, maturity, etc.

Information derived from interviews and surveys with various user groups on the perceived quality, value, and maturity of the IVSS from the perspective of the users (drivers, mechanics, and other fleet personnel) relate to the willingness to deploy IVSS. Specific hypotheses to be addressed include:

2.4-1 Drivers and mechanics have recommendations for changes that might improve the performance or functionality of the IVSS.

2.4-2 Drivers and mechanics have recommendations for changes that might make it easier to use or learn how to use the IVSS.

2.4-3 Fleet operators understand the potential benefits of IVSS and, depending on costs, are willing to deploy these technologies in their fleets.

Goal 3. Assess IVSS Performance and Capability Potential

This goal area deals with the ability of the IVSS to perform their functions according to design specifications, and meet minimum reliability and maintainability criteria. Performance, reliability, and maintainability are necessary conditions for achieving the expected benefits.

Objective 3.1 Characterize the performance and functionality of each IVI system.

The performance and functionality of each system are characterized by analyzing the FOT test data with regard to repeatability, accuracy, system availability (down-time), LDWS-calculated confidence levels in lane-position estimates, and the effectiveness with which the information is communicated to and interpreted by the driver. Specific hypotheses to be tested include:

3.1-1 The performance characteristics of the systems are sufficient to provide accurate messages to the driver regarding driving conditions and potential hazards.

3.1-2 The systems are functional for a sufficiently large portion of driving time to be effective.

3.1-3 The systems perform well under a variety of conditions and are not affected by weather, age of the equipment, or other factors.

Objective 3.2 Assess the capability of system components.

The capabilities of the components comprising the IVSS are assessed by reviewing the design, test and analysis activities performed by the Mack Partnership and the LDWS developer (AssistWare Technologies, Inc.). The results of this assessment define the limitations of the system components (e.g., measurement range, accuracy, repeatability). The specific hypothesis to be tested is:

3.2-1 The capabilities of the components are adequate to meet the performance requirements of the IVSS.

Objective 3.3 Determine the reliability and maintainability of the IVSS during the FOT.

The reliability and maintainability of the IVSS are determined by the analysis of the FOT data and by reviewing the maintenance, repair, and calibration records for each truck in the test fleet over the FOT data-collection period. The following hypotheses are associated with this objective:

3.3-1 The IVSS have sufficiently high reliability to meet the performance requirements.

3.3-2 The calibration and maintenance requirements for the IVSS are acceptable and manageable by the fleet operator.

Goal 4. Assess Product Maturity for Deployment

Although tangible benefits (Goals 1A to 1E) and user satisfaction (Goal 2) are necessary to achieve widespread deployment of intelligent vehicle systems, there are other factors that determine success. In particular, it is important to consider the logistics and feasibility of large-scale production, production and installation costs, related infrastructure investments (if any), and the need to achieve consistency with ITS standards and architecture (as applicable).

Objective 4.1 Estimate production system purchase price, installation (after market) cost, and maintenance costs.

The purchase, installation, and maintenance costs related to the LDWS as tested in this FOT are important. However, it is equally important to project these costs into the future when the systems are mass-produced and more fully deployed. Key measures include actual costs as reported by the FOT partners and vendors and estimated costs projected by experts in the areas of new technology deployment. The specific hypothesis to be tested is:

4.1-1 The costs of purchasing, installing, and maintaining IVSS technologies are reasonable for commercial motor carriers.

Objective 4.2 Assess infrastructure investment needs.

Infrastructure investments related to the LDWS may be identified and estimated. The specific hypothesis to be tested is:

4.2-1 Infrastructure investments are needed to operate and maintain the LDWS.

Objective 4.3 Check the availability of state-of-the-art, low-cost manufacturing capabilities.

Special manufacturing capabilities might be needed to mass-produce IVSS at competitive costs. Assessments of the manufacturing capabilities by the FOT participants, as well as those from independent experts in technology development, are needed. The specific hypothesis to be tested is:

4.3-1 Low-cost, state-of-the-art capabilities will be available to mass-produce the IVSS.

Objective 4.4 Assess the need for modifications to ITS standards to facilitate deployment.

The performance of the LDWS could be affected by surrounding infrastructure. For example, the road layout and markings could affect the LDWS performance. Therefore, the dependence of IVSS on existing infrastructure or the influence of infrastructure deployment on the IVSS under test must be determined. Any infrastructure identified as influencing system performance should be analyzed to determine if standards and architecture properly control infrastructure configuration. Specific hypotheses to be tested include:

4.4-1 Existing infrastructure does not influence the performance of the IVSS.

4.4-2 Appropriate ITS standards will address the interdependence of IVSS and infrastructure.

Objective 4.5 Determine whether the system is suitable for widespread deployment.

The IVSS are used on a single type of vehicle during the FOT. Achieving nationwide benefits will require that the system be deployed in a variety of vehicle types, cargoes, and businesses. Most of the evaluation analysis concerns the system used during the FOT, but this objective determines whether the system is mature enough to be deployed in other operations. The specific hypotheses to be tested are:

4.5-1 The IVSS can be used with different types of tractors with little or no adaptation.

4.5-2 The IVSS can be used with different types of trailers with little or no adaptation.

4.5-3 The IVSS can be applied in different kinds of trucking operations with little or no adaptation.

Goal 5. Address Institutional and Legal Issues that Might Impact Deployment

Even though IVSS could effectively meet the performance and benefit goals established, institutional and legal issues could influence the adoption of the technology. Improper performance of any IVI system could result in legal actions by drivers of the trucks with the IVSS or other vehicles. Likewise, institutional issues, such as regions refusing to deploy needed infrastructure, could impair deployment.

Objective 5.1 Identify and determine the potential impact of institutional and legal issues.

Institutional and/or legal issues could influence IVI system development, deployment, and use. For example, failure of the LDWS to notify the driver in a critical situation prior to a crash could result in legal actions. Also, if specific configurations of infrastructure are needed to allow proper IVSS operation, institutional issues could emerge. Transportation authorities within certain regions may not have the resources to deploy needed infrastructure, resulting in inconsistent IVSS performance. Specific hypotheses to be tested include:

5.1-1 Legal and institutional issues can result from the deployment of the LDWS.

5.1-2 Mitigating actions can be taken to help reduce the impact of legal and institutional issues.

4.0 EVALUATION METHODS

Section 3 describes five broad goal areas with specific objectives for the evaluation that were established by the USDOT (1999). In 2004, an Evaluation Plan was developed to present the data sources and the methods to analyze the data collected in the FOT. Some of these methods were modified after the Evaluation Plan was completed, due to changes in the data collected during the FOT. This section highlights the methods that were used to achieve the evaluation goals and objectives.

4.1 Overview of Evaluation Approach

For the evaluation of LDWS, hypotheses from the evaluation goals were linked to one or more measures that helped to define the types of data to be collected. Data came from many sources, including historical databases and the FOT, as discussed in Section 4.2. Furthermore, methods of analyzing the data and applying the data to the evaluation were developed, as summarized in Section 4.3.

Five main sources of data and information were used to conduct the evaluation:

Historical and FOT Crash/Incident Data. Historical and FOT crash/incident data included data from available databases on truck crashes and relevant incidents. The most appropriate sources for this analysis were determined to be the public databases maintained by the USDOT: the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES). The other database that was available for use was the Motor Carrier Management Information System (MCMIS), but it was found to be incomplete and lacked the detailed coding of crashes that was needed for the safety benefits analysis. Historical crash and incident data from the host fleet operator were also used in the evaluation. The analysis was based on crash statistics from 1999 to 2003, the latest five-year period for which complete data were available. These historical crash data were used in the estimation of safety benefits by representing the baseline crash incidence and distribution “without” use of an LDWS.

On-board Driving Data. On-board driving data included all data collected on vehicles during the FOT. On-board data were studied extensively to determine how often and under what circumstances possible pre-crash conflicts (potential crash situations) occur. Critical conflicts in the on-board data were identified in the GES as being relevant to rollovers and SVRDs.

Surveys and Interviews. Opinions were solicited from personnel (including drivers, mechanics, and corporate staff) to determine whether the messages were clear and to gauge the level of user acceptance, product maturity, and institutional and legal issues. Some participating drivers completed a detailed questionnaire at the conclusion of the study.

Fleet Operations Records. The fleet operator’s maintenance and operation records relevant to the FOT were examined to help estimate the costs or savings associated with the IVSS.

Supplemental Tests and Data. Supplemental tests included a controlled experiment to check the functionality of the ACN, benchtop system tests, and a series of baseline and system-verification tests to set data-collection trigger criteria and evaluate the on-board data collection systems. The ACN would provide crash data if a crash occurred during the FOT.

Table 4 shows how these data were used as principal (P) or supplemental (S) data sources for addressing each of the evaluation goals and objectives. The first column lists goals and objectives discussed in Section 3.2. The next five columns identify the data sources used in the analysis of each objective. For example, the on-board driving data were the principal data source for determining if drivers drive more safely with IVSS. Supplemental data sources included any crashes or incidents that occurred, driver interviews, and fleet operations records, such as violations. A brief summary of how these data were used is presented in the comment column.

Table 4. Principal (P) and Supplemental (S) Data Sources

Evaluation Data Sources *GOAL AREA/* **Objectives**	**Historical and FOT Crash/ Incident Data**	**On-board Driving Data**	**Surveys and Interviews**	**Fleet Operations Records**	**Supple-mental Tests and Data**	**Comments**
ASSESS SAFETY BENEFITS						Historical data from GES were used to identify relevant crash types, conflicts, and driving behaviors. Crash avoidance models were based on driving data. Driver interviews and questionnaires added driver perspectives concerning stress, nuisances, etc. Driver records and fleet safety records were used to interpret the extrapolation of results.
1A.1 Estimate conflict and crash reductions	P	P				
1A.2 Determine if drivers drive more safely	S	P	S	S		
1A.3 Estimate crash reductions at full deployment	P	P	S	S		
1A.4 Determine if IVSS reduces crash severity	S	P	S		S	
ASSESS MOBILITY BENEFITS						Literature findings and historical crashes were used to estimate the effect of crash reductions (from 1A.3) on mobility.
1B.1 Assess effect of reduced crashes on mobility	P				P	
ASSESS EFFICIENCY AND PRODUCTIVITY BENEFITS						Interviews, site visits, and fleet records were the primary sources of cost data. The benefit-cost analysis combined literature results with FOT findings on specific costs and benefits to estimate total costs and benefits to society.
1D.1 Determine cost to deploy and maintain IVSS			S	P		
1D.2 Estimate cost savings with IVSS			S	P		
1D.3 Conduct comprehensive benefit-cost analysis	S	S	P	P	P	
ASSESS ENVIRONMENTAL BENEFITS						Literature findings and historical crashes were used to estimate the effect of crash reductions (from 1A.3) on the environment (from reduced congestion and HAZMAT spills).
1E.1 Assess effect of reduced crashes on environment	P				P	
ASSESS USER ACCEPTANCE & HUMAN FACTORS						Interviews and surveys addressed driver perceptions of all aspects of IVSS.
2.1 Determine value of IVSS training and ease of learning		S	P			
2.2 Determine ease of understanding and controlling IVSS		S	P			
2.3 Determine usability of IVSS under normal conditions		S	P			
2.4 Determine perceptions regarding false alarms/distraction		S	P			
2.5 Determine if drivers perceive effects on stress/workload		S	P			
2.6 Determine how IVSS affects driver acceptance		S	P			
2.7 Determine perceived impacts on driver risks and vigilance		S	P			
2.8 Determine perceptions of product quality, maturity, etc.		S	P			
ASSESS IVSS PERFORMANCE AND CAPABILITY POTENTIAL						Component performance, functionality, reliability, and maintainability were addressed using the driving and maintenance data as well as interviews with drivers. Capability was addressed through pre-deployment engineering tests and measurements.
3.1 Characterize performance/functionality of components		P	P	S	P	
3.2 Assess capability of components					P	
3.3 Determine reliability and maintainability of components		P	P	P		
ASSESS PRODUCT MATURITY FOR DEPLOYMENT						In addition to the planned interviews of drivers and fleet managers, special "key informant interviews" were conducted with experts on technology deployment, manufacturing, etc.
4.1 Estimate purchase, installation, and maintenance costs			P	S		
4.2 Assess infrastructure investment needs			P			
4.3 Determine availability of manufacturing capabilities			P		P	
4.4 Assess need for modifications to ITS standards		P	P			
4.5 Determine if IVSS is suitable for widespread deployment			P		P	
ADDRESS INSTITUTIONAL AND LEGAL ISSUES						In addition to the planned interviews of drivers and fleet managers, special "key informant interviews" were conducted with experts in insurance and product liability.
5.1 Identify and determine impact of institutional and legal issues	P		P	S		

4.2 Evaluation Data Sources

This section describes the five types of data that were collected and analyzed during the FOT. For each type of data, a description is provided about the data collection process and how the data were used to test specific hypotheses and address evaluation objectives. Figure 6 presents an overview of four of the five primary sources of data and the configuration of the data management system used for the Mack FOT independent evaluation. The supplemental tests and data were managed separately from the data illustrated in the figure.

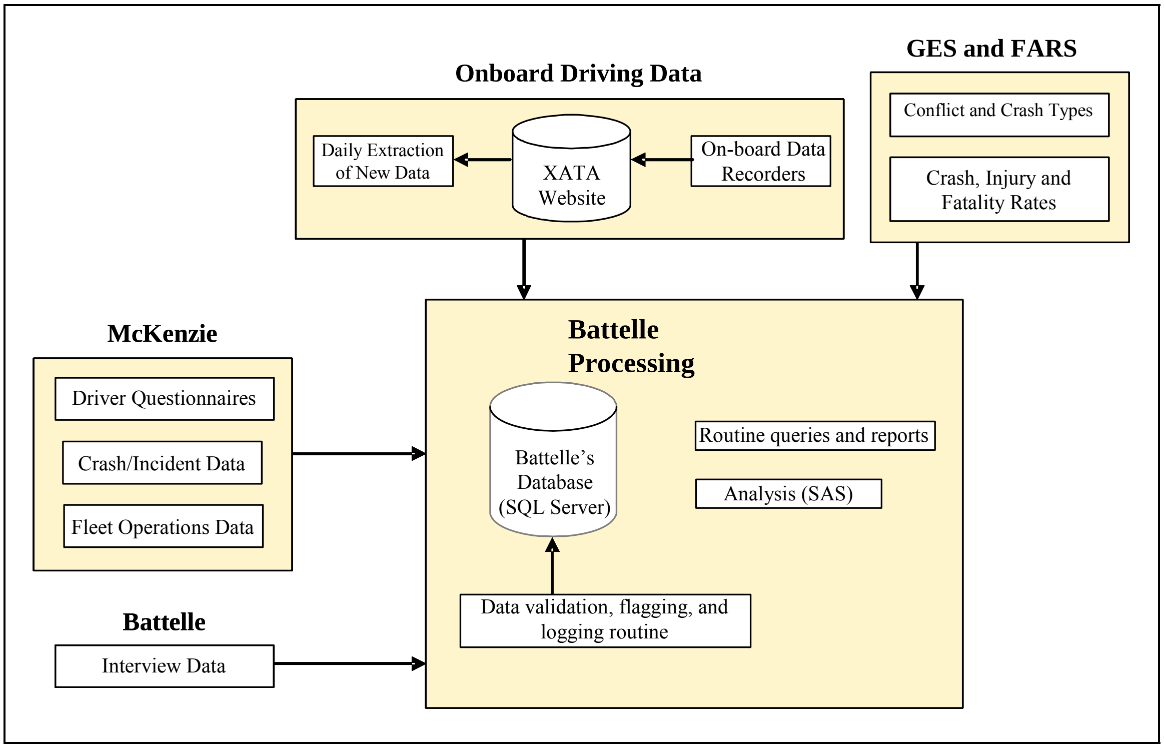

Figure 6. Data Acquisition and Storage Structure

4.2.1 Historical Crash Data

Historical population crash data used in the evaluation of the Mack FOT came from the National Automotive Sampling System (NASS) GES, and the corresponding fatality rates were derived from the FARS. The GES obtains its data from a nationally representative probability sample of police-reported crashes. Police accident reports include crashes resulting in fatalities, injuries, or major property damage, but may exclude some crashes in which no significant personal injury and only minor property damage occurred. The Safety Benefits Estimation Methodology (Battelle, 2000) documents the GES data, and a technical paper published prior to the start of the FOT (Neighbor, 2001) contains a more detailed description of the GES data, including sampling design, relevant variable information, and database acquisition. Annual rates of crashes, injuries, and fatalities were based on averages for the years 1999 – 2003. McKenzie Tank Lines also provided information on its own rollover and roadway departure crashes. If any relevant crashes or incidents occurred during the FOT, they would have been investigated, but no crashes occurred.

The number of SVRD and rollover crashes that occurred each year delineated the scope of the crash problem and defined the opportunities for crash reduction using the LDWS. The data identified which driving conflicts lead to SVRD and rollover crashes and provided estimates for the probability that a particular driving conflict precedes a crash, given that a crash occurred involving a large truck without an active LDWS. These data also provided a baseline to compare improvements or degradations in safety when an LDWS was introduced. The fleet crash statistics and safety data were also used to assess the applicability of safety benefits estimates of the FOT to different scenarios.

Table 5 and Table 6 list the conflict types that are common to both SVRD and rollover crashes. Unlike the conflicts that are caused by vehicle failures, the first four conflict types were expected to be mitigated by the use of the LDWS. It is possible that the "other" conflict types, as well as those that lead to other crash types (e.g., lane-change/merge crashes), might also be mitigated by an LDWS; however, it was not possible to consider those conflicts in this study without additional data-collection tools, such as cameras and side object-detection devices. Most of the "other" conflicts involve another vehicle encroaching in the lane of the host vehicle or a lack of detailed information on the circumstances surrounding the crash. Table 5 and Table 6 also present the numbers of trucks in crashes and the relative frequencies where the relevant safety-critical situations precede SVRD and rollover crashes, respectively. Conflict rates were determined for the four scenarios in the safety benefit analysis (all large trucks, tractors with trailers, tractors with tanker-trailers, and tractors with tanker-trailers carrying HAZMAT) using data from the years 1999 through 2003.

Table 5. Annual Numbers and Relative Frequencies of Trucks in SVRD Crashes*

SVRD Conflict Number	Description	Annual No. Trucks in Crashes Heavy Trucks	Annual No. Trucks in Crashes Truck-Tractor with Trailer	Annual No. Trucks in Crashes Truck-Tractor with Tanker-Trailer	Annual No. Trucks in Crashes Truck-Tractor with HAZMAT Tanker-Trailer	Relative Frequencies Heavy Trucks	Relative Frequencies Truck-Tractor with Trailer	Relative Frequencies Truck-Tractor with Tanker-Trailer	Relative Frequencies Truck-Tractor with HAZMAT Tanker-Trailer
1.1**	Truck is traveling at constant speed and travels over the edge of the road	6,061	2,774	139	35	19%	17%	13%	11%
1.2**	Truck is turning or negotiating a curve and travels over the edge of the road	8,872	6,218	274	82	28%	37%	26%	27%
1.3**	Truck is traveling at constant, excessive speed and loses control	1,025	492	91	14	3%	3%	9%	5%
1.4**	Truck is turning or negotiating a curve at excessive speed and loses control	2,154	1,274	186	80	7%	8%	17%	26%
1.5	Truck loses control due to vehicle-related failure	2,916	1,664	135	55	9%	10%	13%	18%
1.6	Other unidentified or unrelated conflicts	10,309	4,215	242	44	33%	25%	23%	14%
	Total	31,338	16,638	1,067	311	100%	100%	100%	100%

*NASS-GES 1999 – 2003
**Conflicts mitigated by LDWS
Note: The table entries are rounded values of the actual estimates.

Table 6. Annual Numbers and Relative Frequencies of Trucks in Rollover Crashes

Rollover Conflict Number	Description	Annual No. Trucks in Crashes Heavy Trucks	Annual No. Trucks in Crashes Truck-Tractor with Trailer	Annual No. Trucks in Crashes Truck-Tractor with Tanker-Trailer	Annual No. Trucks in Crashes Truck-Tractor with HAZMAT Tanker-Trailer	Relative Frequencies Heavy Trucks	Relative Frequencies Truck-Tractor with Trailer	Relative Frequencies Truck-Tractor with Tanker-Trailer	Relative Frequencies Truck-Tractor with HAZMAT Tanker-Trailer
4.1**	Truck is traveling at constant speed and travels over the edge of the road	109	68	0	0	5%	4%	0%	0%
4.2**	Truck is turning or negotiating a curve and travels over the edge of the road	50	50	0	0	2%	3%	0%	0%
4.3**	Truck is traveling at constant, excessive speed and loses control	12	12	0	0	1%	1%	0%	0%
4.4**	Truck is turning or negotiating a curve at excessive speed and loses control	879	686	43	7	43%	44%	90%	75%
4.5	Truck loses control due to vehicle-related failure	453	320	0	0	22%	21%	0%	0%
4.6	Other unidentified or unrelated conflicts	565	427	5	2	27%	27%	10%	25%
Total		2,068	1,562	48	9	100%	100%	100%	100%

*NASS-GES 1999 – 2003
**Conflicts mitigated by LDWS
Note: The table entries are rounded values of the actual estimates.

The following five-step process was used to identify driving conflicts in the 1999 – 2003 GES data:

1. Identify the subset of data that were relevant for the target fleet (e.g., all heavy trucks, tractor-trailers).
2. Select data according to crash type (i.e., rollovers and SVRDs).
3. Identify the predominant critical events that led to the truck's involvement in the crash.
4. Identify the movements prior to those critical events.
5. Use the combination of the critical events and the movements before the crash to define the driving conflicts.

The GES also provided estimates of the average annual numbers of injuries and fatalities for every combination of crash type and conflict category; however, the estimated numbers of fatalities in each conflict category was adjusted in this study so that the total number of fatalities for each crash type matched the number of fatalities reported in FARS. This approach was taken because FARS contains data on all fatal crashes, while GES has estimates based on data from only a probability sample of police reports. The historical numbers of injuries and fatalities for each combination of crash type, conflict type, and truck fleet are provided in Section 5.1.3. Appendix A describes the specific coding scheme used in GES and FARS to define conflict and crash types, as well as vehicle types.

In addition to the historical crash statistics on the national fleets, McKenzie Tank Lines provided descriptions of more than 1,000 crashes and property damage incidents involving McKenzie Tank Lines trucks between 2002 and 2005. These reports were reviewed to estimate historical rollover and SVRD crash rates for the entire McKenzie Tank Lines fleet.

4.2.2 On-board Driving Data

The on-board measurement system was a critical source of data for evaluation of the LDWS. The system was the only means available for providing the following information:

- Vehicle state
- Driving behavior
- Roadway alignment and lane markings
- Presence of precipitation
- LDWS operational status
- LDWS alerts
- Surrounding traffic
- Location

A schematic describing the overall scheme is shown in Figure 7.

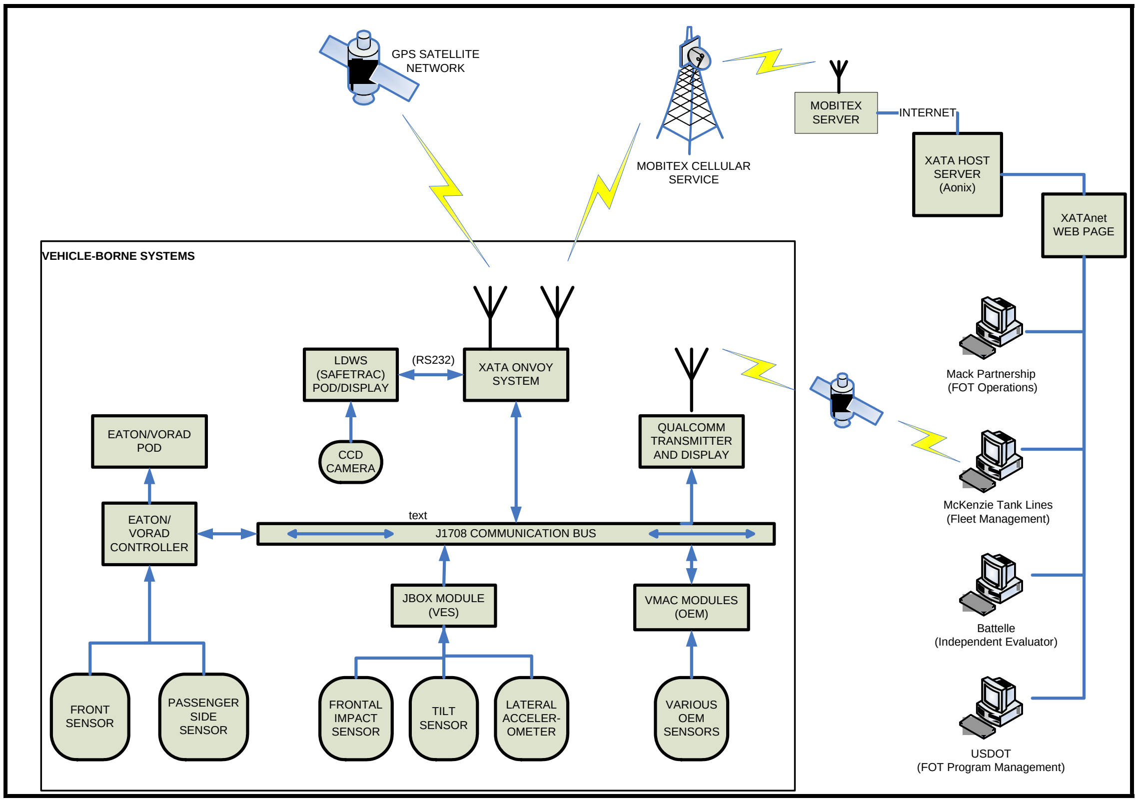

Figure 7. Data Measurement, Acquisition, Transmission, and Storage Systems

An overview of the data collection and transmission process is provided below:

1. Data were acquired on board the vehicle from five sources: the LDWS, the Eaton VORAD CWS, the JBOX Module, the Vehicle Management and Control (VMAC) Modules, and GPS.
2. Data were sent from the five sources over the SAE J1708 data bus and a RS232 connection to the XATA Onvoy system.
3. The Onvoy system filtered and collected data at rates of 1 Hz and 5 Hz and transmitted the data via cellular service to a Mobitex server.
4. The XATA host server received the data via the Internet. Data reports were generated and made available on the XATANET web page, and data packages were sent daily for the independent evaluation activities.
5. Messages were exchanged as needed between fleet management and the trucks via the “QUALCOMM transmitter and display,” consisting of a mobile satellite-based communications system and a dash-mounted monitor for displaying normal operational data and messages from fleet management.

Note that XATA and Qualcomm were communications and logistics management service providers used by McKenzie Tank Lines. A more detailed description of the data measurement, acquisition, transmission, and storage systems is provided below.

Data Sources and Types

Data were acquired from the following sources:

- Eaton VORAD EVT-300 CWS – This original equipment manufacturer (OEM) rear-end CWS was installed on all trucks in the FOT test fleet. Using radar, it collected information on the position and velocity of the truck relative to nearby vehicles. It also provided data on tractor yaw rate from a rate gyro, collected driver ID, and provided an indication that a vehicle was present on the passenger side of the truck.
- VMAC III Modules – These modules were the standard Mack Truck electronic powertrain control modules that broadcasted operational data packets via the SAE J1708 data bus containing information on vehicle and engine speed, ambient temperature, throttle position, cruise control status, brake status, truck VIN, fuel consumption rate, and truck time in motion.
- VES JBox Module – This module was installed on FOT trucks, and broadcasted, via the J1708 data bus, data on tractor roll angle (measured with a Kavlico Model TS904 Tilt Sensor), lateral acceleration (measured with a Kistler Model 8303A2 K-Beam Accelerometer), windshield wiper status, and turn signal status.
- SafeTRAC LDWS – This system was the primary focus of the evaluation and, through sophisticated algorithms that interpret video images, provided critical information on truck lane-keeping behavior, along with estimates of lane width, lane boundary type, and road curvature. The LDWS also provided data on the status of warnings enabled or disabled, and event codes that described its interpretation of an event (e.g., drifts and lane changes to the right and left).
- Onvoy Module – This module provided GPS coordinates provided by its built-in GPS receiver, as well as date and time information.

Data Collection and Reporting

A list of all on-board measurements and how they were used in these analyses is provided in Table 7. The first column lists the module on the truck that supplies the data. The second and third columns list the variable recorded and the source of the data, respectively. The remaining columns indicate (with an “X”) how the variables are used in the analyses, the safety benefits objective it helps to address, and other notes regarding the variable. Data were collected in a 7-minute circular buffer and, when data trigger criteria were met, stored in records saved in persistent storage for future analysis. Additional details of LDWS data records are presented in Appendix C.

Table 7. Summary of On-board Measurements

MODULE	VARIABLE(S)	SOURCE(S)	PAV/IEA* Data Screening and Quality Checks	PAV/IEA Trigger Data Collection (Report Type)	PAV/IEA Characterize Driving Conflicts	PAV/IEA Calculate Exposure Ratio	PAV/IEA Calculate Prevention Ratio	PAV/IEA Assess Safety Benefits (Goal 1A Objectives)	PAV/IEA Assess IVSS Performance and Capability Potential (Goal 3)	PAV/IEA Other
LDWS (SafeTRAC)	Lateral Offset	Video Image	X	X (LEX)	X	X	X	1A.1, 1A.2, 1A.4	X	
LDWS (SafeTRAC)	Lateral Velocity	Video Image						1A.4		
LDWS (SafeTRAC)	Left and Right Boundary Types	Video Image	X	X (LEX)	X			1A.1,1A.2,1A.4	X	
LDWS (SafeTRAC)	Road Curvature	Video Image	X		X	X		1A.1,1A.2,1A.3,1A.4		
LDWS (SafeTRAC)	Lane Width	Video Image	X		X				X	
LDWS (SafeTRAC)	Event Code	Video Image	X	X (LEX)	X	X		1A.1,1A.2	X	
LDWS (SafeTRAC)	Confidence in Lateral Offset Calculation	Video Image	X	X (LEX)					X	
VES JBox	Lateral Acceleration	Accelerometer	X							
VES JBox	Roll Angle	Tilt Sensor	X		X					
VES JBox	Longitudinal Acceleration	Accelerometer								Sensor not activated during FOT
VES JBox	Turn Signal Status			X (LEX)	X			1A.1,1A.2	X	
	Wiper Status				X			1A.1,1A.2		
Eaton VORAD EVT-300	Presence of Vehicle on Right	Side-Look Radar			X					
Eaton VORAD EVT-300	Critical Target Range	Forward-Looking Radar			X					
Eaton VORAD EVT-300	Critical Target Range Rate	Forward-Looking Radar			X					
Eaton VORAD EVT-300	Critical Target Azimuth	Forward-Looking Radar			X					
Eaton VORAD EVT-300	Tractor Yaw Rate	Rate Gyro			X					
Eaton VORAD EVT-300	Driver ID							1A.1, 1A..2		
Eaton VORAD EVT-300	No. Vehicles in Forward Area)	Forward-Looking Radar			X					
VMAC III	Vehicle Speed	OEM VMAC Module	X	X (LEX, ACN)	X	X	X		X	
VMAC III	Cruise Control Status				X			1A.1,1A.2	X	
VMAC III	Brake Status				X			1A.1,1A.2	X	
VMAC III	Total Moving Time				X	X			X	
VMAC III	Moving Time Over 35 mph					X			X	
ONVOY	Location (GPS coordinates)	GPS Receiver			X	X				Calculate Road Curvature
ONVOY	Date							1A.1, 1A.2		Database management
ONVOY	Time of Day			X (OPS)	X			1A.1, 1A.2		Database management
ONVOY	Message ID			X (TSA)					X	
ONVOY	Data Summaries at 15-min Intervals	LDWS Variables, Moving Time, Moving Time Over 35 mph	X					1A.1,1A.2,1A.3	X	

* Primary Application Of Variable In Independent Evaluator Analyses

To support the independent evaluation of the LDWS, on-board data were reported in several types of records: Lane Excursion (LEX) files, 15-minute OPS files, and (if applicable) ACN Crash Event Reports.

LEX Files. A LEX file described a candidate driving-conflict scenario, and was used in analyses to determine the probability of a crash given that scenario. The general strategy for generating a LEX file was to capture events where the truck had gone more than 18 inches out of its lane with the turn signals off. Turn signal status was used, because it was assumed that, if the driver left the lane when the turn signal was on, then the lane departure was intentional. Therefore, the vehicle was not in a driving conflict related to SVRD or rollover crashes. A lane excursion is illustrated in Figure 8, which depicts an overhead view of the path of the tractor's front axle on a pavement.

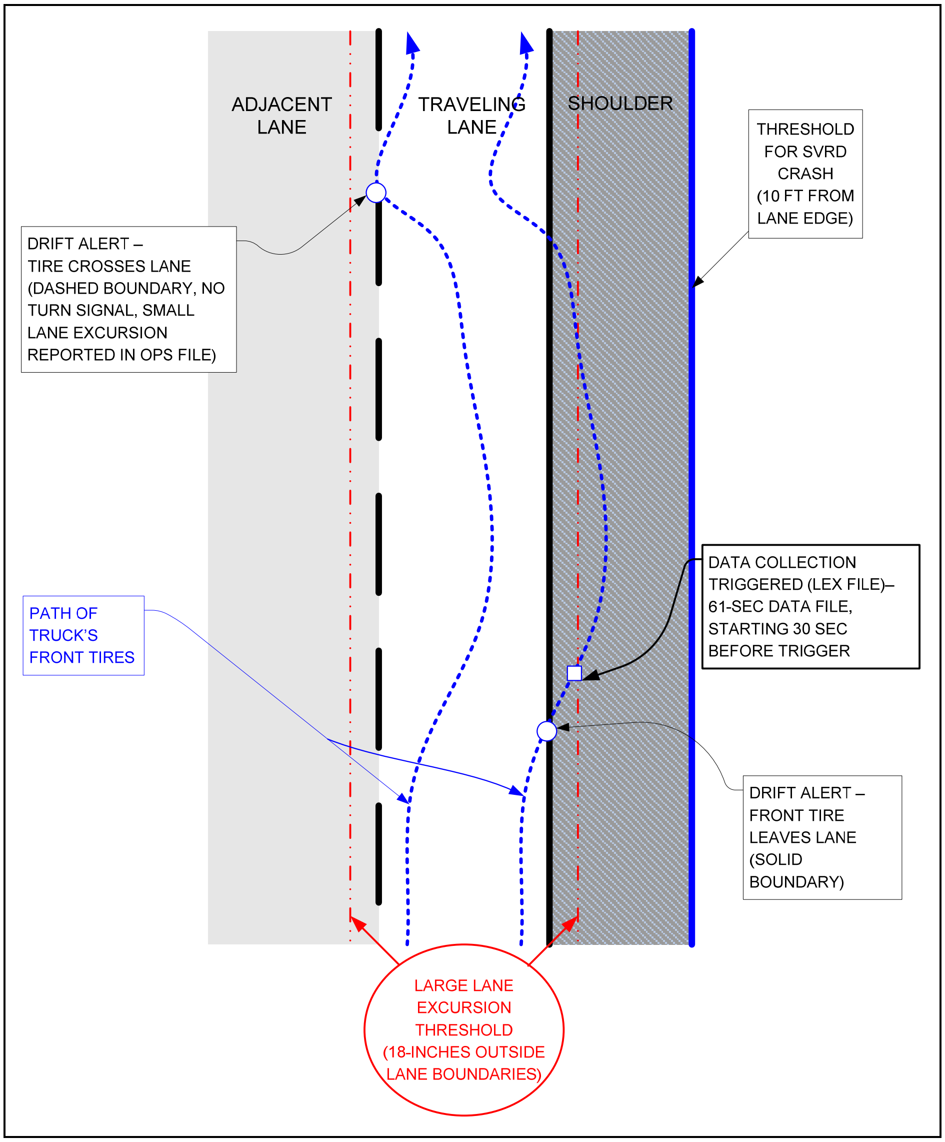

Figure 8. Illustration of a Lane Departure Scenario

Each LEX file was 61 seconds long, beginning 30 seconds prior to, and ending 30 seconds after, the approximate data-trigger event. Two variables, namely the lateral position and lateral velocity of the truck, were recorded at five samples per second. All other information in the LEX files was reported at 1 sample per second. Time-history plots, bar charts with time-varying information, and descriptions of all information contained in a LEX file are provided in Appendix B.

The following criteria were used to trigger data collection and generate a LEX file:

1. The lane boundary, as determined by the LDWS, was either a painted line (dashed or solid) or a virtual line, in the direction of the truck's lane departure. The LDWS interpreted video images to determine the lane boundary type. A lane boundary was determined to be virtual if there were no identifiable painted lines, but the lane edge was indicated by changes in the road surface and/or the existence of painted lines "upstream" of the virtual boundary.
2. The LDWS issued a drift alert when it determined that the truck was heading out of its lane with the turn signals off.
3. A tire on the tractor's front axle traveled at least 18 inches (nearly 2 tire widths) outside of the lane. A peak lane excursion of at least 18 inches was selected to control the volume of data that was collected. Lane departures with peak excursions of less than 18 inches were less likely to be driving conflicts; therefore, they were filtered out of the data collection.
4. The tire returned to the original lane within 13 seconds after the drift alert. If the truck stayed outside the lane for more than this amount of time, it was considered likely that this was a deliberate maneuver to drive the truck onto the shoulder, and not a LEX event. In the event of this type of lane departure, a truck driver may drive for some distance on the shoulder, ensuring that the truck is stabilized and traffic is sufficiently clear to return the truck to the lane. This situation was discussed with McKenzie Tank Lines, which advised that 13 seconds was sufficient in most situations to complete this maneuver.
5. A lane change had not occurred within 8 seconds prior to the tire traveling 18 inches outside the lane. This criterion was used to eliminate maneuvers that are part of a lane change (e.g., the truck may overshoot the lane that it is changing to).

OPS Files. The OPS file provided a summary of the lane-keeping behavior of the driver during the day, which included counts of lane excursions, alerts as functions of the magnitude of the excursion (small = less than 10 inches, medium = 10-18 inches, large = greater than 18 inches), turn signal usage, boundary type, and roadway curvature.

A description of the contents of an OPS file is provided in Appendix B.

Data collection began for an OPS file when the truck started to move. Data collection continued until 15 minutes had elapsed. An OPS file was generated and data collection for the next OPS file began. Exceptions to this process were:

1. If the truck was stationary for 10 consecutive minutes no OPS file was reported for that time.
2. If the truck was stationary at the end of the 15-minute time block the next 15-minute block of data collection did not begin until the truck was in motion again.

ACN Crash Event Report. In the event of a crash, an ACN Crash Event Report would be issued. The ACN Crash Event Report was triggered if either of the following conditions were met:

1. The tractor roll angle exceeded 30 degrees.
2. The truck's deceleration (as indicated by the speed profile) was greater than 14 mph/s for at least 2 seconds, after which the truck came to rest and stayed at rest for at least 3 seconds.

The Mack Partnership could not implement an effective frontal-impact-sensing scheme in time for the FOT; therefore, a longitudinal acceleration measure was not available during the FOT. A crash report would have provided the vehicle and driver IDs; the date and time that data collection was triggered, the location of the truck in terms of city, state, and GPS coordinates; the sensor that met the trigger criteria; and the truck's pre-crash road speed.

Data Processing

The Onvoy module acquired all information from the data sources through the J1708 bus and an RS232 connection to the LDWS. Lateral position and lateral velocity were acquired at a rate of 5 samples per second, while other variables were acquired at 1 sample per second.

The Onvoy module also operated on the LDWS data to generate counts of lane changes with and without the turn signal on; seconds spent on straight and curved roads; lane excursions parsed by excursion magnitude, direction, and lane boundary type; and drift alerts by lane boundary type and direction. It also calculated the "area" (time × distance) spent out of lane, the total time that the LDWS alerts were enabled, and the mean-squared lateral position of the truck in the lane.

As part of the ACN, the Onvoy module applied criteria to data on speed and tilt angle to determine if a crash occurred.

Data Transmission and Archive

Data records were transmitted to the host server via wireless communication when wireless communication coverage was available. If a crash event was detected, the transmittal of a crash notification record was given priority over other records. For the FOT, Cingular cellular service was used along with a Mobitex digital networking system. The host server archived all records and posted them on the XATANET website. Users with access (username and password) could select records and request that they be emailed to them. The host server was maintained by Aonix. The independent evaluator also maintained a separate FOT database archive.

Data Quality

All data records were screened for accuracy and validity with the following data-quality checks:

1. *Observed vs. Measured Behavior*: Controlled tests were run on roads near McKenzie Tank Lines' Tallahassee maintenance facility – a driver was instructed to perform various maneuvers, including lane departures, lane changes, and turns. The data records generated during these runs were compared to observations by a test engineer riding as a passenger in the tractor cab and videotapes of the truck taken from a lead vehicle. Of primary interest was that the measured truck lateral position was similar in direction and magnitude to what was estimated from passenger observations and video records.
2. *Driver/Truck Assignments*: Driver and truck IDs contained in the data reports were checked against McKenzie Tank Lines records of driver and truck assignments. Discrepancies were resolved by using the driver identified in McKenzie Tank Lines' records if the drivers failed to enter the proper IDs for the data reports.
3. *Out-of-Range Measurements*: The performance characteristics of the sensors, signal conditioning, and data-recording equipment were evaluated to determine the measurement range for each variable. Reported values outside of the associated range were defined as invalid. The criteria that were used to flag specific variables as potentially invalid are described in Table 8. For example, if the average speed in an OPS file was greater than 85 mph the file was removed. If this occurred for a large percentage of OPS files during a week all data from that week and truck were removed.
4. *Unrealistic Signal Waveforms*: Rules were developed and implemented for invalid signal characteristics. Acceleration, roll angle, or yaw rate data that indicated values higher than physically achievable (e.g., lateral accelerations of greater than 2 g or roll angles greater than 20 degrees without an associated rollover event) or that had unrealistic time-varying behavior (e.g., a yaw rate signal that has a constant value for several seconds), are examples of these rules. Rules were developed to identify unrealistic, sudden jumps in measured values and noisy signals.

Table 8. Criteria to Flag Measurement Variables as Potentially Invalid

Variable Name	Description	Units	Expected Range	Variable Type
Heading	Heading of Tractor	degrees	0 to 360	Real
Speed	Vehicle Speed	mph	0 to 85	Real
Cruise	Cruise Control Status (On or Off)	—	0 or 1	Integer
Brake	Brake Application Status (Applied or Not Applied)	—	0 or 1	Integer
Alarm System Status	LDWS Status Codes	—	1 to 15	Integer
Yaw	Tractor Yaw Rate	deg/s	Should not have a constant value for more than 5 seconds	Real
LatAcc	Tractor Cab Lateral Acceleration	g	-2 to 2	Real
Tilt	Tractor Cab Tilt (Roll) Angle	deg	-20 to 20	Real
Signal	Turn Signal Status	—	0, 1, 10, 11	Integer
Event	LDWS Event Code	—	0 to 23	Integer
Confid	LDWS-Reported Confidence in Lane Position Measurement	%	0 to 100	Real
Boundary	LDWS Reported Lane Boundary Type	—	0, 1, 2, 3, 10, 11, 12, 13, 20, 21, 22, 23, 30, 31, 32, 33	Integer

Data Screening

In addition to the quality checks performed on the data, additional data processing and screening steps were performed prior to analyzing safety benefits. OPS and LEX files were excluded for the following reasons:

- The dates/times of the reports were recorded outside the FOT period.
- Driver/truck IDs in the reports could not be verified against McKenzie Tank Lines fleet operations records.
- The reports were associated with systems check-out tests.
- The reports for a given driver represented less than 1,000 VMT of driving in each of the baseline and active LDWS interface feedback periods.
- There was no OPS file associated with a particular LEX file.

LEX files were also excluded if the event that triggered the file was a lane change or intentional curve cutting. An event was considered a lane change if the LDWS event code indicated a lane change or the lateral position signal included a sudden large shift in value corresponding to a shift in the location of a virtual or dashed boundary from left to right or from right to left. An event was considered curve cutting if the direction of lane departure was in the direction of the curve. This criterion ensured that all curve-cutting events were identified and excluded, but also excluded any unintentional lane departures to the inside of the curve.

Table 9 and Table 10 summarize the data processing steps for the OPS and LEX files, respectively. The intermediate totals represent the amount of data collected during the FOT period for which valid truck and driver IDs were assigned. Note that the majority of the FOT data excluded from the safety benefits analysis was due to insufficient VMT during both the baseline and LDWS active interface period. A large proportion of these data contained valid records that may be useful for other purposes, yet they were not be used in the safety benefits analysis due to the need for comparisons of baseline conditions with active LDWS interface feedback conditions.

A breakdown of the numbers of LEX files and VMT by driver and LDWS activation status is presented in Table 11. Although it appears in Table 11 that nine drivers met the 1,000-mile criteria in both periods, only six drivers actually met the criteria following the data quality checks. Table 12 presents the same data as Table 11, but only for the drivers with at least 1,000 VMT with and without LDWS feedback. It also indicates the reasons that the other three drivers were not included in the analyses.

Table 9. Data Processing Steps for OPS Files and VMT

Data	Description	Number of OPS Files	VMT	Comments
Total Data	**Generated**	**95,475**	**1,236,471**	**Each report covers a 15-minute period when the truck is moving at least part of the time.**
Data Excluded from Analyses	Driving data collected outside of FOT period	29,327	372,430	Reports were generated during systems installation and checkout activities prior to the start of the FOT period, and after the end of the FOT period.
Data Excluded from Analyses	No matching driver ID	2,915	35,194	
Total Data	**in FOT period with valid truck and driver IDs**	**63,233**	**828,847**	**Available data before quality and completeness checks.**
Data Excluded from Analyses	Insufficient VMT (< 1,000 VMT in Baseline and Active Interface Periods)	39,788	517,185*	Amount of driving data too small for valid comparative and conditional analyses.
Data Excluded from Analyses	No LEX files received	3,036	37,135	OPS Reports covering a period of at least a week when no large lane departures were recorded.
Data Excluded from Analyses	Invalid data	1,118	15,557	Speed, time/distance outside lane, and/or elapsed miles data are missing or physically unrealizable.
Data Excluded from Analyses	Systems check-out tests	1,833	25,220	Controlled tests conducted during FOT period to check performance of on-board systems.
Total Data	**Available for Analyses**	**17,458**	**233,750**	**Used to estimate safety benefits and determine if drivers drive more safely with the LDWS.**

*These 500,000 VMT contains valid data, but could not be used in the safety benefits analysis because the driver did not have experience driving with LDWS active feedback (or did not have experience driving without LDWS feedback).

Table 10. Data Processing Steps for LEX Files

Description		Number of LEX Files	Comments
Total Number of Reports	**Generated**	**11,185**	**Each report is a 61-second record of truck behavior and LDWS performance before/during/after a lane excursion of > 18 inches.**
Data Excluded from Analyses	Driving data collected outside of FOT period	3,430	Reports were generated during systems installation and checkout activities prior to the start of the FOT period, and after the end of the FOT period.
Data Excluded from Analyses	No matching driver ID	185	
Total Number of Reports	**In FOT period with valid truck and driver IDs**	**7,570**	**Available data before quality and completeness checks.**
Data Excluded from Analyses	Insufficient VMT (< 1000 VMT in Baseline and Active Interface Periods)	5,237*	Amount of driving data too small for valid comparative and conditional analyses.
Data Excluded from Analyses	Lane changes	873	Truck moved to and stayed in adjacent lane.
Data Excluded from Analyses	Curve-cutting	99	Lane departure in the same direction as curve.
Data Excluded from Analyses	Missing or bad OPS files	15	LEX reports during period where the OPS reports are missing or invalid.
Data Excluded from Analyses	Invalid data	463	Data out of measurement range, noisy signals, and waveforms indicate physically unrealizable behavior.
Data Excluded from Analyses	Systems check-out tests	248	Controlled tests conducted during the FOT period to check the performance of on-board systems.
Total Number of Reports	**Used in Analyses**	**635**	**Used to evaluate if drivers drive more safely with the LDWS.**

*These 5,237 LEX files contain valid data, but could not be used in the safety benefits analysis because the driver did not have experience driving with LDWS active feedback (or did not have experience driving without LDWS feedback).

Table 11. Data Volume (VMT and LEX files) by LDWS Interface Activation Status and Driver[1]

Driver ID	LDWS Inactive (Baseline) VMT	LDWS Inactive (Baseline) LEX Files	LDWS Active VMT	LDWS Active LEX Files	LDWS Inactive (Post Active) VMT	LDWS Inactive (Post Active) LEX Files	Total VMT	Total LEX Files
143	33,799	280	0	0	0	0	33,799	280
144	65,907	548	0	0	0	0	65,907	548
146[2]	26,648	243	36,882	352	0	0	63,530	595
150	56,761	72	0	0	0	0	56,761	72
156	2,419	27	0	0	0	0	2,419	27
159	37,671	478	0	0	0	0	37,671	478
161	1,519	9	0	0	0	0	1,519	9
164	61,021	404	0	0	0	0	61,021	404
181	23,203	160	0	0	0	0	23,203	160
192	25,336	155	20,443	102	0	0	45,779	257
194	48,166	292	15,622	22	11,933	0	75,721	314
197[3]	9,613	172	14,077	403	2,066	50	25,756	625
198	17,033	214	0	0	0	0	17,033	214
199	29,336	341	13,520	75	0	0	42,856	416
204	5,058	24	4,150	7	0	0	9,208	31
205	13,732	58	22,021	37	13,090	0	48,843	95
206[4]	23,293	820	14,178	104	0	0	37,471	924
210	7,134	79	0	0	0	0	7,134	79
211	17,990	22	2	1	0	0	17,992	23
213	2,000	13	0	0	0	0	2,000	13
214	8,556	548	173	5	0	0	8,729	553
215	0	0	14,383	245	0	0	14,383	245
218	0	0	12,092	285	8,240	0	20,332	285
500	21,598	103	0	0	0	0	21,598	103
502	1,365	8	0	0	0	0	1,365	8
505	5,480	142	0	0	0	0	5,480	142
506	12,009	315	0	0	0	0	12,009	315
508	0	0	15,984	64	9,659	69	25,643	133
509[5]	1,551	11	28,213	145	0	0	29,764	156
510	0	0	1,424	0	0	0	1,424	0
511	0	0	12,497	66	0	0	12,497	66
Total	**558,198**	**5,538**	**225,661**	**1,913**	**44,988**	**119**	**828,847**	**7,570**

[1] All data collected within test period (March 1, 2004 to March 1, 2005) and with matching driver and truck IDs.

[2] Shading indicates drivers used in safety benefits analysis.

[3] Truck records could not be separated from system check-out tests.

[4] Invalid data resulted in driver having fewer than 1,000 VMT with active LDWS interface feedback available for analysis.

[5] Truck out of service.

Table 12. Data Volume (VMT and LEX files) by LDWS Interface Activation Status and Drivers with 1000 VMT of Driving

Driver ID	System Status	Mar-04	Apr-04	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04	Jan-05	Feb-05
146	Off	0	0	5,860	7,032	9,842	3,276	638	0	0	0	0	0
146	On	0	0	0	0	0	0	5,785	11,804	8,438	7,422	204	3,229
192	Off	0	0	3,962	9,890	4,464	7,020	0	0	0	0	0	0
192	On	0	0	0	0	0	3,149	9,958	7,336	0	0	0	0
194	Off	0	0	7,834	9,382	10,844	8,356	1,525	7,704	2,521	0	4,464	7,469
194	On	0	0	0	0	0	0	0	0	3,973	7,571	4,078	0
197[1]	Off	7,054	2,559	0	0	0	0	0	0	0	0	1,703	363
197[1]	On	0	0	0	0	0	375	2,089	2,845	6,233	838	1,697	0
199	Off	0	10,094	14,036	2,523	0	2,683	0	0	0	0	0	0
199	On	0	0	0	0	0	5,515	8,005	0	0	0	0	0
204	Off	0	0	0	0	0	0	0	537	0	908	3,613	0
204	On	0	0	0	0	0	0	0	0	0	0	4,150	0
205	Off	0	0	4,448	7,910	0	1,374	0	0	0	0	6,698	6,392
205	On	0	0	0	0	0	4,447	4,831	0	6,726	3,974	2,043	0
206[2]	Off	0	0	0	0	3,320	5,392	0	4,260	139	6,438	3,744	0
206[2]	On	0	0	0	0	0	0	0	0	0	0	5,388	8,790
509[3]	Off	0	0	0	0	0	0	1,233	318	0	0	0	0
509[3]	On	0	0	0	0	0	0	0	0	101	6,949	11,201	9,962

[1] Truck records could not be separated from system check out tests.
[2] Invalid data resulted in driver having fewer than 1,000 VMT with active LDWS interface feedback available for analysis.
[3] Truck out of service.

4.2.3 Surveys and Interviews

The assessment of driver acceptance and human factors relied upon two independent surveys, one conducted at the beginning of the evaluation period before drivers had experience with the LDWS and a second survey conducted after the drivers had accumulated experience with this system. The primary objective was to assess driver responses to the LDWS. Survey questions were constructed to evaluate training and learning, understanding of the system capabilities, usability under real-world driving conditions, potential distraction effects of system operation, stress associated with system use, changes in perceived workload, usefulness and acceptance, and potential effects on driving behavior and risk taking.

The baseline survey was conducted in October and the first half of November 2004, as shown in Figure 9. The baseline questionnaire was programmed into a Computer-Aided Telephone Interview (CATI) system. Drivers were notified on their satellite-based mobile communications system in their trucks to phone an 800 number on certain days and times during a convenient stop to participate in a telephone interview with a trained interviewer.

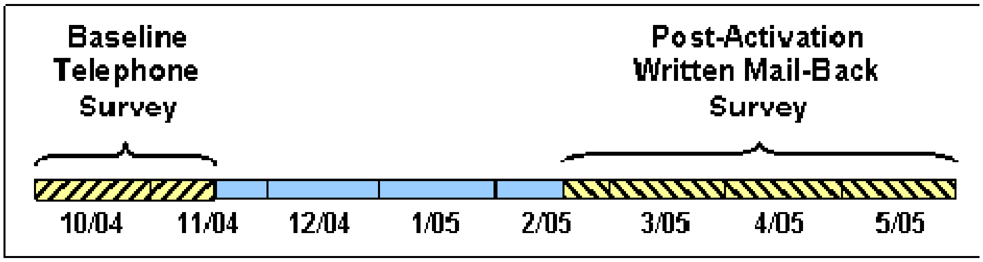

Figure 9. Mack Driver Survey Schedule

The post-activation survey was conducted differently from the baseline survey. After about a 3-month driving period with the LDWS providing active feedback in their trucks, drivers were provided a written questionnaire and a post-paid mail-back envelope. An incentive of $50 was offered to drivers who completed this survey. The incentive was paid by their employer, McKenzie Tank Lines. These printed surveys were mailed to the respective terminal managers to be distributed to each driver. Confidentiality of all responses by the drivers was assured. Prior to implementation, each survey was approved by the human subjects Institutional Review Board (IRB) of the Battelle/Centers for Public Health Research and Evaluation (CPHRE, Durham, NC) to assure fair and equitable treatment of respondents. Individual driver identity was protected throughout the survey process. Survey questions were pre-tested for clarity by both survey staff and McKenzie Tank Lines drivers.

Table 13 provides the number of drivers contacted for each survey and the response rate for each. Only two drivers responded to both of these surveys. Due to the unpredictable individual schedules of the drivers operating out of seven different terminals across four southern states, the evaluators did not individually meet with the drivers to explain the objectives of the evaluation, gain their support, or conduct any in-person interviews or group discussions. For these reasons and due to the very low response to both surveys, the data were inadequate to support a meaningful analysis. Data from the second survey were entered into an Access database and verified, and erroneous values were removed from further analyses. Selected results from the baseline survey were used where possible to supplement the post-activation survey findings.

Table 13. Summary of Survey Response Rates

	Baseline	Post-Activation[1]
# of drivers notified	7	21
# of respondents	0 4[2]	14
Response rate	*42.9%*	*66.7%*

[1] Three of the drivers left the company during the evaluation period; one of them agreed to complete a survey.

[2] One driver called in for an interview who was not on the survey list of drivers. The response rate for the baseline reflects only the targeted respondents (3 out of 7).

4.2.4 Fleet Operations Records

The following types of data were provided by McKenzie Tank Lines for use in the FOT evaluation:

Driver Profile. McKenzie Tank Lines provided information on the drivers' ages, years of truck driving experience, number of citations, and number of accidents for the drivers who were operating the trucks with the LDWS. During the design stage, this information was used to assign trucks to the "active LDWS interface" and "inactive LDWS interface" groups according to the experimental design. The data were also used in a conditional analysis of the effects of driver age, years of experience, and safety record on the efficacy of the LDWS.

Driver Assignments. McKenzie Tank Lines provided a data file that linked the driver, truck, and the driving date on each day that a truck was operating. This file was the primary means of linking driving behavior with individual drivers.

Maintenance Information. Both McKenzie Tank Lines and the supplier of the LDWS provided a general overview of the frequency and types of related equipment failures and brief summaries of the maintenance and repair activities performed on the LDWS during the FOT. This information provided an indication of the reliability and maintenance requirements for the LDWS for the assessment of system performance.

Fleet Accident Statistics. Detailed crash data for the entire McKenzie Tank Lines fleet were provided for the period 1999 to 2004. These data established a baseline for fleet driving safety, which were compared to national statistics and safety-related driving as indicated in the FOT data.

Fleet Mileage. McKenzie Tank Lines provided data on the fleet VMT from 1999 to 2004. These data were used to establish a reference for the FOT-based conflict Exposure Ratios.

Table 14 presents some truck population statistics that were used in various analyses in this report, including information on the McKenzie Tank Lines fleet for reference. These statistics were used in the calibration of the safety benefits model (Section 4.3.1), extrapolation of safety benefits to other fleets (Section 5.1.3), and the benefit-cost analysis (Section 5.9).

Table 14. U.S. Truck Populations and Average Annual VMT

Truck Population	Number of Trucks in 2003	Average Annual VMT per Truck	Total Annual VMT (millions)
Large Trucks[1]	7,912,018[5]	27,286[9]	215,885[5]
Tractor-Trailers[2]	1,757,288[6]	64,964[9]	114,160[6]
Tractor with Tanker[3]	112,145[7]	68,145[10]	7,642[9]
Tractor with HAZMAT Tanker[4]	78,502[8]	68,145[10]	5,350[9]
McKenzie Tank Lines[11]	585	75,000	n/a

[1] Over 10,000 lbs GVW
[2] Class 7 or 8 tractor with at least one trailer
[3] Class 7 or 8 tractor with a tanker-trailer
[4] Class 7 or 8 tractor with a tanker-trailer with HAZMAT
[5] Highway Statistics 2003, Table VM-1, columns 7 plus 8
[6] Highway Statistics 2003, Table VM-9
[7] Vehicle Inventory and Use Survey (VIUS) 2002, Table 2a, inflated by 3 percent
[8] 70 percent of the number of tractors with tankers (based on information from The National Tank Truck Carriers, Inc. website)
[9] Calculated from the total or average VMT and the total number of trucks
[10] Calculated using average VMT in VIUS 2002, Table 2a (truck-tractors with 1-3 trailers)

4.2.5 Supplemental Tests and Data

The following supplemental tests were also included in the Mack FOT:

Benchtop Systems Tests. Benchtop testing of the ACN components was performed at VES, a member of the Mack team. The purpose of the tests was to verify the performance of the VES box, which contained the ACN and provided essential measurement data, including tilt angle and lateral acceleration. The LDWS was subjected to testing by Carnegie Mellon University's Robotics Institute and AssistWare Technology as part of its original development preceding the FOT.

Baseline and Systems Verification Tests. Prior to the FOT data collection period, McKenzie Tank Lines and the independent evaluator conducted a series of baseline tests. The objectives of the tests were to set the data-collection trigger criteria, evaluate on-board measurements in specific controlled maneuvers, and troubleshoot potential problems with the on-board measurement system. In these tests, complete data packages were collected for a test truck during controlled tests over a variety of roads near Tallahassee, FL. The truck was operated in simulated in-service driving conditions, and also was driven in specific maneuvers involving lane departures and lane changes. Video footage of the maneuvers, taken from a lead vehicle looking back at the front of the truck, was used to compare on-board measurements to observed behavior.

4.3 Analysis Methods

To achieve certain evaluation goals and objectives, the results from various evaluation "tests" were combined into a comprehensive analysis. Section 4.2 provided an overview of the types of data that were collected and Table 4 identified the principal and supplemental data sources that were employed for each evaluation objective. In this section, the analysis methods are described.

4.3.1 Goal 1A. Assess Safety Benefits

The primary focus of the safety benefits evaluation of the LDWS was to estimate the numbers of crashes, injuries, and fatalities that can be avoided through widespread deployment. Four safety-related objectives were defined to guide this analysis:

1A.1 Determine if driving conflict and crash probabilities will be reduced for drivers using the LDWS.

1A.2 Determine if drivers drive more safely using the LDWS.

1A.3 Determine reductions in crashes, injuries, and fatalities if all fleets operating in the United States were equipped with LDWS.

1A.4 Determine if drivers using the LDWS have less severe crashes than drivers without the system.

As described in Section 4.2.1, the driving conflicts relevant to evaluating the LDWS involve loss of control, usually due to high speed, or an unintentional roadway departure. The four relevant conflict types were defined in terms of vehicle speed and whether the vehicle was turning or in a curve, or going straight.

For this evaluation, the driving conflicts served as surrogate safety measures and as intermediaries for estimating the number and severity of crashes and the number of injuries and fatalities that could be prevented by drivers using the LDWS. Figure 10 presents an overview of the analytical approach that was used to address the safety objectives. The two primary sources of data were the historical crash statistics from GES and FARS and the on-board driving data consisting of LEX files, OPS files, and the ACN data files. The historical data were initially used to identify the conflicts that precede rollover and SVRD crashes. Later, they were used to extrapolate the crash reduction findings to various operational scenarios.

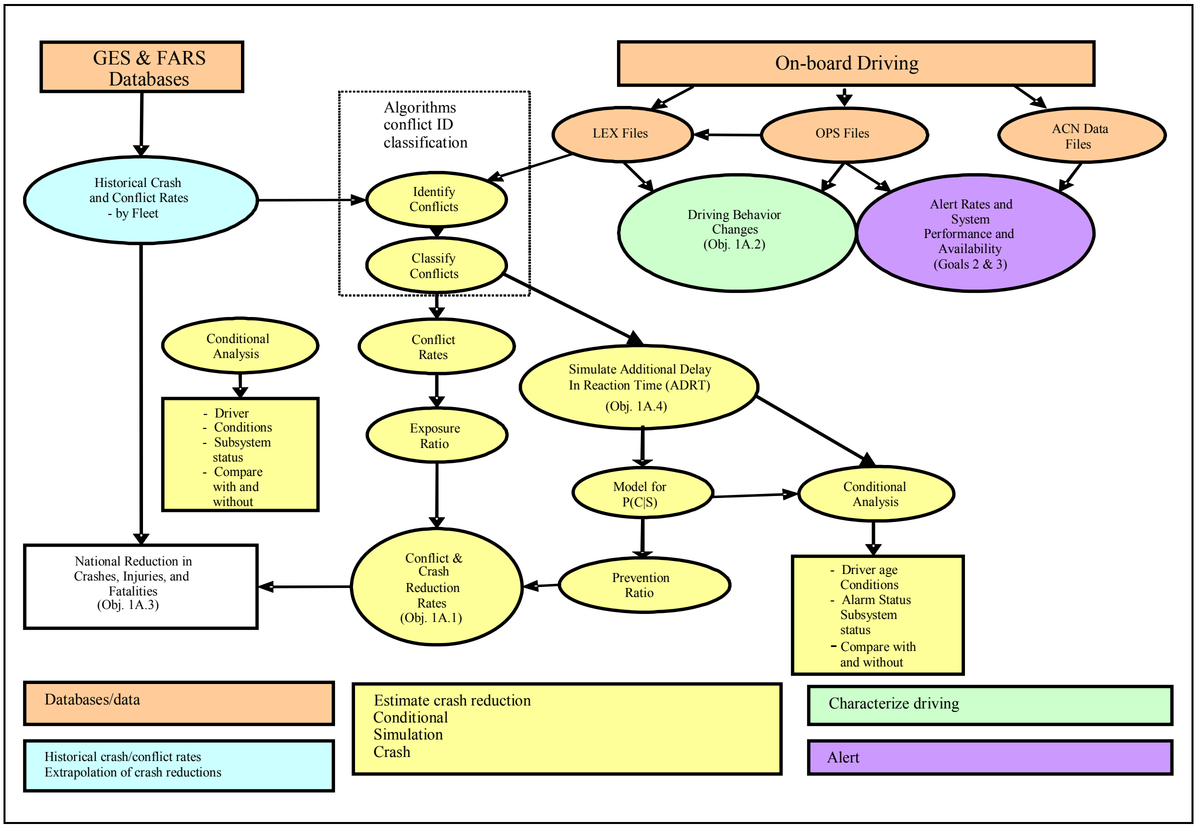

Figure 10. Overall Safety Analysis Methodology

After identifying which LEX files were conflicts, classifying each conflict into the four conflict types (Table 5), and determining the associated VMT using the OPS data, conflict rates were calculated for each combination of driver and activation period. The ratio of conflict rates with and without an activated LDWS is called the **Exposure Ratio (ER).** Another important parameter used to estimate crash reductions, used in Objectives 1A.1 and 1A.3, is the **Prevention Ratio (PR)**. The PR is a ratio of the conditional probabilities of a crash given a conflict with and without the LDWS. These probabilities were estimated using a truck analytical model in computer simulation studies based on the data from each LEX file identified as a conflict. These tools were used to determine the additional delay in reaction time (ADRT) that would result in a crash. The times were then used to estimate the probability of a crash for each conflict type. A detailed description of the model and simulation studies is provided later in the section “Determination of Conflict Severity.” These times were also used to evaluate impacts on crash severity (Objective 1A.4) using information on driver reaction times and vehicle speeds. The ER and PR were combined to estimate the crash reduction rates. In addition, conditional analyses were performed to determine if there were other variables (e.g., time of day) that had an affect on the ER or PR.

Extrapolation of the safety benefits to various operational scenarios (Objective 1A.3) was achieved by combining the FOT-derived crash reduction rates with historical conflict and crash statistics. Changes in driving behavior (Objective 1A.2) were evaluated using a combination of LEX and OPS file data. In addition to using the data sources identified in Figure 10, the safety benefits analysis incorporated data from driver surveys, system performance tests, and maintenance or other operational data. The remainder of this section provides additional details on how each of the safety objectives was met.

Objective 1A.1. Determine if Drivers Using LDWS Have Reduced Driving Conflict Rates and Crash Probabilities

Estimating the reductions in the probability of rollover and SVRD crash under conditions in the FOT was the primary emphasis of the assessment of safety benefits. The methodology, as follows, was similar to the approach developed by NHTSA, FHWA, and the Volpe National Transportation Systems Center (Najm 1999, Najm and daSilva 1999a, 1999b, 2000).

The potential reduction, R, in the probability of a rollover or SVRD crash (the benefits equation) is:

$$R = P_{wo}(C) - P_{w}(C)$$

where P_{wo} (C) represents the probability of a crash per FOT VMT without the IVSS deployed, and P_{w} (C) represents the corresponding probability with the IVSS deployed.

The methodology did not necessarily rely on the analysis of crashes, because no crashes were predicted to occur during the Mack FOT and, in fact, none occurred. Instead, the methodology partitions all crashes according to the *driving conflict* preceding each crash, and then looks simultaneously for a reduction in exposure to driving conflicts (ER) and in the chance of a crash after a driving conflict has occurred (PR).

Driving conflicts are particular safety-critical driving scenarios, which precede crashes and are determined by the dynamic conditions of the test vehicle and the roadway. All crashes are preceded by a driving conflict, but all driving conflicts do not necessarily result in a crash, as conflicts are usually resolved before a crash occurs. Thus, driving conflicts, by definition, occur more frequently than crashes, and a significant number occurred in the FOT. The vehicle dynamic situations that precede rollover and SVRD crashes were identified based on an analysis of GES data (Section 4.2.1) for the FOT evaluation, which resulted in the five types of rollover and SVRD driving conflicts.

The expression for the potential reduction, R, in the probability of a rollover or SVRD crash given in Equation 4-1 can be algebraically manipulated with algebra and the rules of conditional probability to be expressed as:

$$R = P_{wo}(C) \times \sum_{i} P_{wo}(S_{i} \mid C) \times \left[1 - \frac{P_{w}(C \mid S_{i}) \times P_{w}(S_{i})}{P_{wo}(C \mid S_{i}) \times P_{wo}(S_{i})}\right]$$

where S_i is a driving conflict of type *i*, and $P_{w}(C \mid S_{i})$ is the conditional probability that a rollover or SVRD crash occurred, given that driving conflict S_i occurred, with active LDWS interface feedback. $P_{w}(S_{i})$ is the probability that driving conflict S_i occurred with active

LDWS interface feedback. Quantities subscripted with "*wo*" have the same interpretation, but for vehicles without LDWS feedback. The probability that driving conflict S_i occurred prior to a crash, given that a rollover or SVRD crash occurred without LDWS feedback, $P_{wo}(S_i \mid C)$, is also required in the Benefits Equation and estimated from the GES data.

The exposure and PRs for each conflict type *i* are calculated as

$$ER_i = \frac{P_w(S_i)}{P_{wo}(S_i)}$$

and

$$PR_i = \frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}.$$

There are two key ratios in the Benefits Equation, namely $\frac{P_w(S_i)}{P_{wo}(S_i)}$ and $\frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}$.

If the ER is less than 1, this indicates that an active LDWS will reduce exposure to potential crash situations. If the PR is less than 1, safety benefits of an active LDWS can be inferred. Equation 4-2 can be rewritten in terms of the exposure and PRs as

$$R = P_{wo}(C) \times \sum_i P_{wo}(S_i \mid C) \times \left[1 - PR_i \times ER_i\right]$$

Figure 11 presents the benefit equation in terms of the number of crashes that would be avoided (B) under a nationwide deployment plan. It also indicates the primary data soures that are used to estimate each part of the equation. In this version of the benefits equation, N$_{wo}$ represents the annual number of relevant crashes (i.e., untripped rollovers or SVRD crashes) without the use of LDWS for the number of trucks under consideration in each operational scenario (e.g., tractor-trailers, tankers).

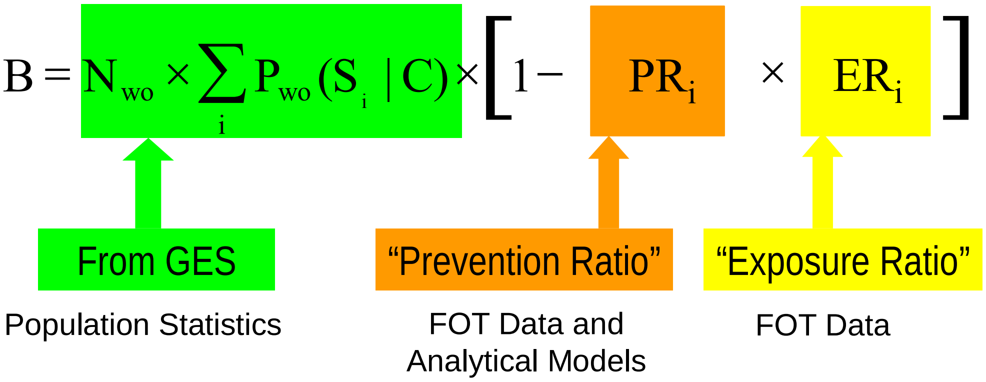

Figure 11. Benefits Equation

The Benefits Equation is a robust approach to benefits estimation, because each of the ratios used in computing benefits is based on a numerator and a denominator obtained by a consistent approach.

The following sections include discussions on the conflicts identified in the FOT data; calculation of conflict rates and the ER; conditional analysis of the ER; determination of conflict severity; estimation of conditional crash probabilities and the PR; conditional analysis of the PR; and estimation of crash-reduction ratios and the percentage reduction in crashes.

Determination and Characterization of Driving Conflicts

In Figure 12, a flow chart depicts the process for determining the driving conflict type and using the simulation model to predict crashes when drivers react more slowly under the conditions observed in the LEX files associated with driving conflicts. The analytical approach involved the combination of measured data, where no crashes had occurred, and analytical predictions, where crash situations are simulated to determine how close a measured lane departure was to becoming a crash. An overview of the process for determining crash probabilities is provided below:

1. *Determine Driving Conflicts in FOT Data*: As described previously, a series of filters was developed and applied to the LEX files to screen the data for events that were not driving conflicts. These events included lane changes and curve-cutting behavior. The data were also screened for quality, and LEX files were rejected if values were not realistic. After the screening process, criteria were applied to categorize each of four driving conflict types.
2. *Calculate ERs based on FOT Data*: The ER is defined as the ratio of conflict rates with LDWS feedback to conflict rates without the LDWS feedback. The calculations used the VMT; this rate was determined from cumulative mileage reported for every 15 minutes of driving in the OPS files. This step was not shown in the flow chart because the calculations were performed on the final group of driving conflicts.
3. *Predict Necessary Conditions for a Crash*: An analytical model of a tractor-tanker was developed and implemented in a time-domain computer simulation. For each LEX event, a simulation study was performed to determine how long the driver could have delayed a recovery maneuver and still have avoided a crash.
4. *Estimate Probability of Crash*: A relationship between additional driver reaction-time (ADRT) and the probability of a rollover or SVRD crash was assumed, where the parameters in the relationship were selected such that the number of predicted rollover and SVRD crashes associated with truck lane departures without LDWS feedback (i.e., during the Baseline Period) was the same as that predicted using the crash rates associated with observed historical data. Then, the probability of a crash given the departure conditions in a LEX file, P(C|S), was calculated based on an assumed distribution of ADRT and times calculated in the simulation studies.

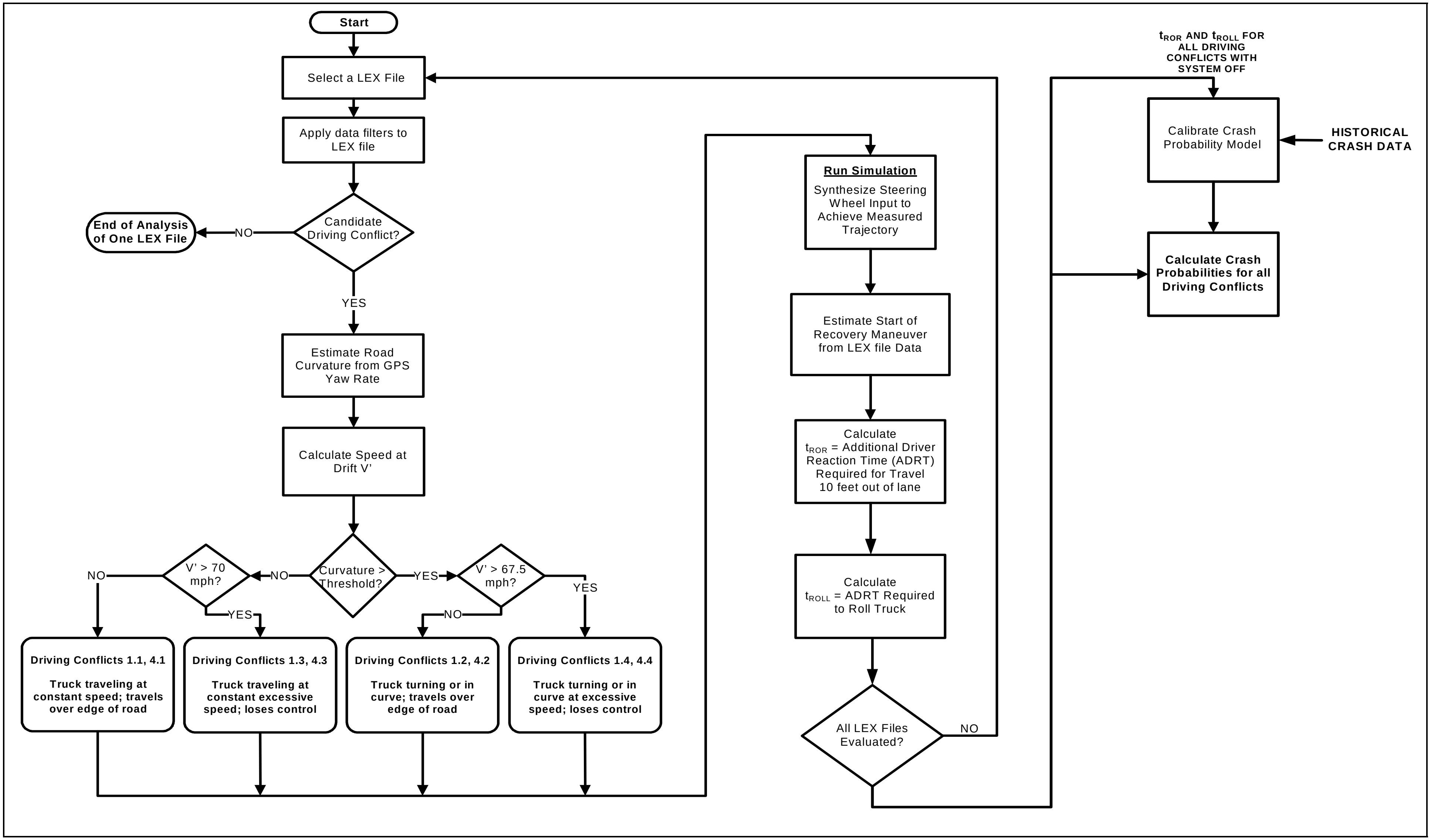

Figure 12. Methodology for Determining Driving Conflict Types and Predicting Crashes

The effectiveness of this approach was impacted by limitations in the measured data, which in turn limited the accuracy of the simulation results. In particular, the following information could not be provided by the measurements:

- *Intention of the driver during a LEX event*: A driver's maneuvers during a LEX event could have been deliberate (e.g., to avoid an obstacle in the road or to maneuver around or through traffic). To screen some of the deliberate maneuvers, all LEX events involving a lane departure in the direction of the curved road were considered to be curve-cutting events not used in the analyses. Further, if the truck did not crash or return to the lane within 13 seconds following its departure, this event was considered a deliberate maneuver to drive the truck onto the shoulder, and it was not used in the analyses.
- *Road and roadside characteristics (shoulder width, curve superelevation, presence/location of light poles, guardrails, etc.)*: The presence and proximity of roadside features to the truck could influence the driver's response to the lane departure. Since data on shoulder width and curve superelevation were not obtained during the Mack FOT, a 10-foot shoulder width, a 12-foot wide lane, and flat curves were assumed. Measured GPS coordinates were used to estimate the roadway curvature.
- *Steering wheel angle*: FOT measurements did not include steering wheel angle; therefore, this information was obtained by running a baseline simulation case for each LEX file.
- *Individual tanker and cargo properties*: During the FOT, information was not collected on the specific inertial and suspension properties; mass; volume and weight of the cargo; and resulting center of gravity location of each tanker that was hauled. Consequently, the simulation studies used the same loaded trailer configuration to analyze all LEX events.

These limitations ultimately affect the accuracy of the analysis results, but the extent was undetermined.

Estimation of Conflict Rates and Exposure Ratios by Conflict Type

Conflict rates were estimated for each conflict type using the number of conflicts found in the FOT data and the estimated VMT from the OPS files. The rates were estimated by driver, system status, and conflict type. Then, the ER was estimated by aggregating these conflict rates across drivers. Two options were explored for this aggregation. First, conflict counts and VMT could be summed across all drivers, and the ER for each conflict type would be the ratio of the conflict rate with the LDWS to the conflict rate without the LDWS. The other method was to include a "random effect for driver" in a Poisson regression model. The inclusion of a "random effect for driver" adjusts the effect of one driver who may experience a much higher rate of conflicts, or a much lower rate of conflicts, compared to another driver and allows each driver to act as his or her own baseline.

Using both methods, standard errors were computed for the ER from the Poisson model. These standard errors were used to determine whether the ER was statistically different from 1. The results obtained by the two methods were not the same, but they were consistent with each other.

Conditional Analysis of Exposure Ratio

To understand how driving behavior and conditions affect the rate of lane excursions and the ERs, a Poisson regression analysis was performed on the data. In this application, the number of excursions was assumed to be proportional to the VMT, and the driver was included in the model as a random effect. This Poisson regression model also included covariates that could help to explain variability in conflict rates. The Poisson distribution is frequently used for count data, such as in this situation. By including a random effect for driver, the set of drivers contained in this study was assumed to be a random selection from a larger population. Therefore, it would not be informative to infer the effect of a specific driver on the number of conflicts. As the actual model fitting for a Poisson regression was performed via a log link, the driver effect reduced to a random intercept term on the log-scale. Details on Poisson regression can be found in McCullagh and Nelder (1989).

The goal of the model-building process was to determine which driver characteristics and driving parameters explained the variability present in the conflict counts and rates. Table 15 lists the variables considered. Backward elimination was used to select the terms included in the final model. This method places all the variables being considered into the model, and the non-significant terms are removed one at a time, starting with the least significant. This process continues until all of the variables left in the model are significant. Since system status was of primary interest, this variable was never removed from the model, regardless of its significance. A term representing the interaction with system status was also included for each of the variables. If any interaction term was significant, its main effect was also left in the model even if it was not significant. The significance level for excluding variables was set at 0.05. For more details on this model-building approach, see Neter et al. 1996. A significant interaction indicates that the estimate of the effect of one variable is dependent on the value of the variable with which it is interacted. In this case, a significant interaction between a variable and system status indicated that the variable has an impact on the ER; the ER is different for different values of the variable. All of the included variables have a multiplicative effect on the rate of driving conflicts, as specified in the model.

Table 15. Variables for the Poisson Regression Model

Variable	Description
System status	Indicator of whether or not the system was providing feedback
Percent road speed > 35 mph	Percentage of time road speed exceeded 35 mph
Percent in curve	Percentage of time that was in a curve
Percent with cruise control	Percentage of time with cruise control active
Average road speed	Average road speed
Hours in motion in last 8 hours	Number of hours the vehicle was in motion in the last 8 hours
Hour of the day	Sine and cosine of hour of day (allows hour of day to have a sinusoidal effect)

Season and day of the year were also considered as predictors, but confounding with the active and inactive LDWS interface, feedback time intervals precluded their use. There were no valid files where the system was activated for April through July, and data from only six drivers were used in the analysis.

Determination of Conflict Severity

A truck simulation model was developed and used to provide predictions complementing the on-board data contained in the LEX files. The on-board data accurately described the path of the truck during a large lane excursion, but the measurements were insufficient to identify the beginning of the driver's recovery maneuver (i.e., when a driver begins to turn the truck back into the original lane). This information was necessary to implement the methodology for determining conflict severity. The simulation model enabled the prediction of the beginning of the driver's recovery maneuver for each LEX file, which in turn allowed the determination of the amount of delay in that recovery maneuver that would result in a crash.

The truck simulation model was developed and implemented in the commercial simulation code VDANL (Vehicle Dynamics Analyses – Nonlinear). The simulation model described the rigid body dynamics of an articulated vehicle. The model comprised masses for the axle assemblies and the "sprung" portions of the tractor and trailer (i.e., the masses supported on the suspension). The masses were connected by nonlinear suspension elements and rigid links, with appropriate representations of the steering and suspension system kinematics. The translational and rotational motions of the masses were described by a set of nonlinear second-order differential equations. Each of the sprung masses had six degrees of freedom (three translations and three rotations). Nonlinear equations portrayed the forces generated at the tire/road interfaces, in the suspension elements, and in the links connecting the truck's masses.

Tractor parameters representing the Mack tractors used in the FOT were provided by Mack Trucks. The tractor model was used with a tanker model developed and validated by Battelle in the Freightliner FOT (2003). A fully loaded tanker, which is the most common loading condition for McKenzie Tank Lines' tanker hauls, was used to analyze each large lane excursion.[1] The results of a simulation case using VDANL were predictions of the time-varying (dynamic) motions and forces associated with the prescribed road conditions and maneuvers, including losses of control, such as spinouts and rollovers.

Because the FOT measurements did not include steering wheel angle, this information was obtained by running a baseline simulation case for each LEX file. In the baseline case, the truck was forced to follow the measured path. The variable, LatOff, represented the lateral position of the tractor center of gravity with respect to the instantaneous lane center. The simulation model synthesized the steering-wheel-angle time history associated with the path described by the LatOff time history. Then, the steering-wheel time history was evaluated to estimate the moment when the driver initiated a recovery maneuver to prevent the truck from running off the road or rolling over. Criteria for estimating the beginning of a recovery maneuver were developed from evaluating baseline simulations of 57 randomly selected LEX files. The following criteria were defined for the beginning of the recovery maneuver:

- Truck is heading out of the lane.
- Steering wheel angle begins to change in an opposite direction to the lane departure direction.

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[1] McKenzie Tank Lines estimates that it hauls full, empty, and partially full tankers in about 57 percent, 40 percent, and 3 percent of its tanker hauls, respectively (2006).

The credibility of these criteria was influenced by the data quality, specifically the LatOff variable, which was sampled at 0.2-second intervals. In some cases, the "noise" in the data caused an estimate that was clearly too late or too early. In these cases, an alternate method was used to estimate the beginning of the recovery maneuver. With the alternate method, a 3rd-degree polynomial was fit to the LatOff signal over a 10- second interval that ended at the point of maximum lateral position. Then the moment that the recovery maneuver began was estimated as the inflection point in the fitted curve. The visualization tool was used to check the credibility of the inflection point-based estimate.

The results of the baseline simulation case were used to determine how much additional delay in the driver's reaction would result in an SVRD or rollover event. The criterion for an SVRD event was that the truck traveled at least 10 feet out of its lane. The criterion for a rollover event was that the required recovery maneuver to avoid going 10 feet out of the lane would cause a rollover, based on threshold criteria developed from a series of simulation runs made with the truck model.

The baseline simulation case provided predictions of the tractor yaw angle with respect to the lane edge and the tractor yaw rate. The lateral positions of the tractor center of gravity (CG) and the front tires were used in calculations.

Assuming that as the delay in the driver's reaction to the lane departure increases, the truck would travel further out of the lane at a constant speed and yaw rate, the lateral position and yaw angle of the truck at the beginning of recovery was calculated as a function of ADRT.

The minimum ADRT when the tractor's front tire traveled at least 10 feet out of the lane was defined as the SVRD (run-off-road) time or t_{ROR}.

The largest radius path of the outer front tire that would bring the truck parallel to and 10 feet out of the lane was calculated as a function of ADRT. The minimum ADRT when the required recovery trajectory would roll the truck (i.e., the recovery trajectory in which the largest achievable radius of curvature is less than or equal to the radius of curvature at the rollover threshold [illustrated in Figure 13]), was defined as the rollover delay time or t_{ROLL}. As the largest achievable radius of curvature decreases as the truck gets closer to the 10-foot limit, and goes to zero at the 10-foot limit, $t_{ROLL} < t_{ROR}$ for all cases.

In executing the simulation studies, the value of ADRT was increased in 0.25-second increments to a maximum value of 20 seconds. In cases where the truck did not roll for ADRT = $t_{ROR}{}^{-0.25}$, it was assumed that the rollover would occur at a value of ADRT that is 0.125 second (half of one time increment) earlier than the SVRD crash. Thus, the rollover delay time was adjusted as follows:

$$t_{ROLL} = t_{ROR}{}^{-0.125}$$

The calculated values of t_{ROR} and t_{ROLL} were used in statistical analyses to estimate the PR.

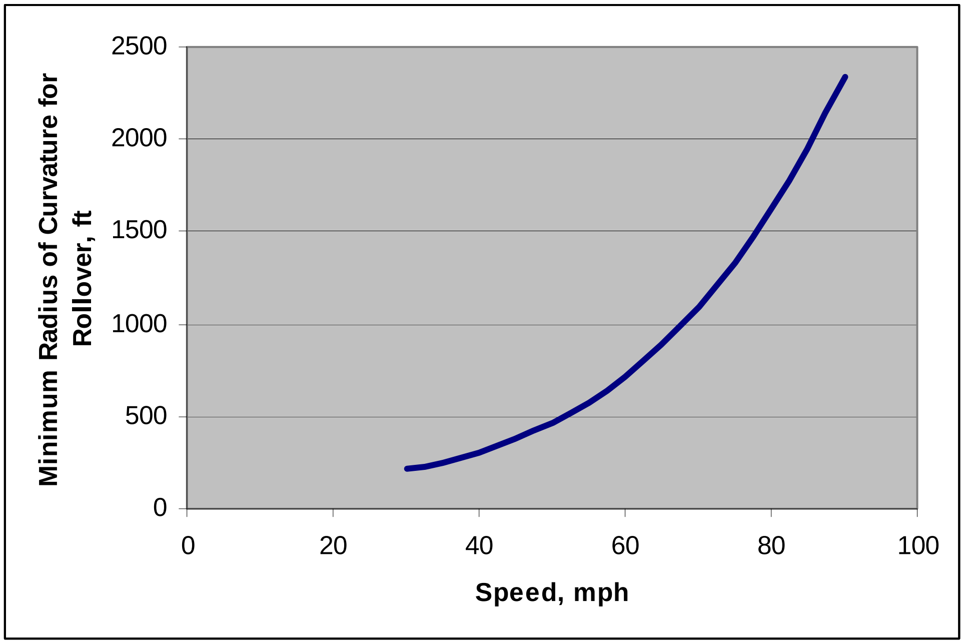

Figure 13. Rollover Threshold for the Truck Simulation Model

Estimation of Conditional Crash Probabilities and Prevention Ratio

The values of t_{ROR} and t_{ROLL} calculated for each of the 635 conflicts were used to estimate the probabilities of an SVRD crash and a rollover crash for each conflict. The approach was based on the assumption that if a driver experienced the same conditions several times, his or her reaction time would be different each time. An additional delay in reaction time could be caused by other factors not measured in the FOT (e.g., poor visibility, various driver distractions), and if the delay was long enough, a crash would have resulted. The distribution of delay in reaction time was assumed to be exponential. The exponential distribution is often used for waiting times (time to event), which was appropriate for modeling ADRT; however, data were unavailable to validate this assumption. Since t_{ROR} is the delay in the reaction time that results in an SVRD crash, any ADRT greater than t_{ROR} will result in an SVRD crash. The parameter t_{ROLL} represented the time when the driver will roll the truck if a more aggressive recovery maneuver is executed and run off the road if a less aggressive recovery maneuver is executed. Values of additional reaction times that are between t_{ROR} and t_{ROLL} could result in either type of crash. The following relationships were assumed:

$$P(ROLL \mid S_i) = P(ROLL \mid t_{ROR}, t_{ROLL}) = (1-\alpha)\left(e^{-t_{ROLL}/\theta} - e^{-t_{ROR}/\theta}\right),$$
$$P(ROR \mid S_i) = P(ROR \mid t_{ROR}, t_{ROLL}) = (1-\alpha)e^{-t_{ROR}/\theta} + \alpha e^{-t_{ROLL}/\theta} .$$

Figure 14 illustrates this relationship between additional delay in reaction times and the probability of each crash type. The parameter α determined what proportion of the time between t_{ROR} and t_{ROLL} was assigned to each type of conditional crash probability (rollover or SVRD).

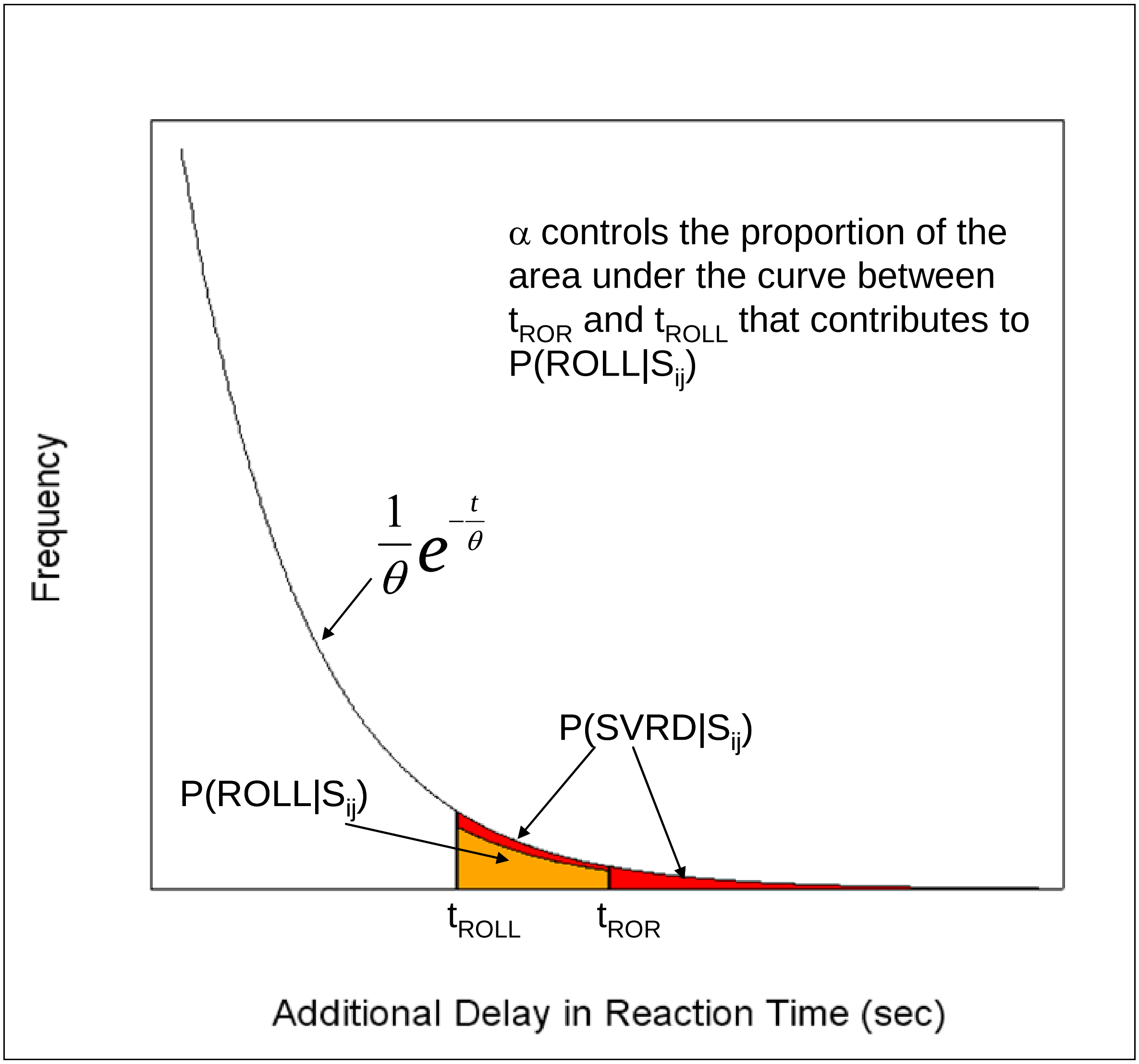

Figure 14. Probabilities of Crashes Relative to Driver Reaction Time Delay

Before this model could be used, the parameters θ and α were estimated, such that the expected number of crashes estimated from historical crash data was equal to the expected number of crashes using the model on the baseline data from the FOT for each conflict category. The equation below was used to adjust the model to the historical data:

$$P_{GES}(C,S_i) = P_{GES}(S_i \mid C) \times P_{GES}(C),$$

where $P_{GES}(S_i|C)$ is the probability of having a conflict of type S_i given that a crash has occurred and $P_{GES}(C)$ is the probability of a crash, both of which are estimated from the historical crash data. Then, using the rules of conditional probabilities:

$$P_{WO}(C \mid \tilde{t}_{ROR}, \tilde{t}_{ROLL}) = \frac{P_{GES}(C, S_i)}{P_{WO}(S_i)}$$

where $\tilde{t}_{ROR}$ is the location parameter associated with the t_{ROR}s for each conflict and $\tilde{t}_{ROLL}$ is the location parameter associated with the t_{ROLL}s for each conflict, $P_{WO}(C| \tilde{t}_{ROR}, \tilde{t}_{ROLL})$ is the probability of a crash given a conflict from the FOT data and $P_{WO}(S_i)$ is the probability of a conflict of type S_i from the FOT data. The simulation models were only run to a maximum ADRT of 20 seconds, and the distributions of these times were censored at 20 seconds (i.e., when t_{ROR} or t_{ROLL} were not found for ADRT ≤ 20 seconds, it was assumed that they are > 20 seconds). The gamma distribution fit the data well for t_{ROR} and t_{ROLL} when the times were not censored. The parameters of the gamma distribution used for the analysis were estimated using maximum likelihood estimates that took into account the censoring in the data. The estimated 50th percentile, or median, was used as the measure of location to adjust the model to historical crash rates. The result was two equations, one for SVRD crashes and the other for rollover crashes, and two unknowns, θ and α, that were solved simultaneously. Adjusting the crash probability model to the historical data was done separately for each conflict category.

Because the national statistics for tanker-trucks reported zero rollover crashes for conflict types 1, 2, and 3 (Table 7), the rates for truck-tractors with trailers were used to solve for θ and α. Table 16 presents the values used from the GES data to calculate the estimated values of θ and α parameters.

Table 16. GES Data Crash Statistics and θ and α Parameters

Conflict Category	Crash Type	GES $P(S_i \mid C)$ (%)	GES P(C) in 10,000 Miles	GES $P(C, S_i)$ 10,000 miles	FOT Baseline VMT	Expected # of Crashes in Baseline VMT According To GES Rates	θ	α
Straight roads	SVRD	19.6%	0.001457	0.000286	148,160	0.004239	0.88	0.96
Straight roads	Roll	5.1%	0.000137	0.000007	148,160	0.000104	0.88	0.96
Curves	SVRD	45.0%	0.001457	0.000656	148,160	0.009723	1.12	0.86
Curves	Roll	47.1%	0.000137	0.000064	148,160	0.000955	1.12	0.86

Then, the parameters were used to calculate the probability of an SVRD crash and the probability of a rollover crash for each conflict.

The PR was estimated using the probabilities of a crash that were calculated for each conflict with and without active LDWS interface feedback. Similar to the ER, the PR can be estimated with or without a random effect for the driver; however, the effect of the driver was much smaller and could not be estimated by the model in some cases. As a result, no random effect for the driver was included in the estimation of the PR.

To compute the PR, the individual crash probabilities were averaged by crash type, conflict type, and system status. Then, for each crash type and conflict rate, the ratio of the average crash probability with active LDWS interface feedback to the average crash probability without LDWS feedback was the estimated PR. The variability of the PR was estimated using a first-order Taylor series approximation.

Conditional Analysis of Prevention Ratio

For the 635 files with conflicts, probabilities for two types of crashes were computed: rollover and SVRD. Linear regressions were used to model the two probabilities; as the probabilities were quite small, a log-normally distributed response was assumed. A random effect for the driver was also included.

Table 17 lists the variables considered for inclusion in the model. Interactions between Driver Status and the remaining variables were also considered for the model. The same backwards elimination process that was used for the conditional analysis of the ER was also used for this model.

Table 17. Variables for Crash Probability Models

Variable	Description
System Status	Indicator of whether the system was active
Boundary	Type of boundary that was crossed (none, dashed, solid, virtual)
Departure Direction	Direction of lane departure (left or right)
Average Speed	Average speed
Hours In Motion	Number of hours in motion out of the last eight
Wiper Status	Indicator of whether wipers were activated
Target Count	Count of the number of targets (categorical as 0, 1, and > 1)
Roadway	Indicates whether the road was straight or curving
Hour of Day	Sine and cosine of hour of day (allows hour of day to have a sinusoidal effect)

Estimation of Crash Reduction Ratio and Percentage Reduction in Crashes

Using the estimates of the ER and the PR, the Crash Reduction Ratio (CRR) was calculated, which is an estimate of the overall efficacy of the IVSS for reducing crashes:

$$\text{CRR} = \text{ER} \times \text{PR}$$

CRRs were computed for each crash type and conflict type. The variability of CRR was estimated by propagating the estimated variability from the ER and PR using a first-order Taylor series approximation.

To obtain an estimate of the percentage of SVRD crashes and rollover crashes that would be prevented by the system, the CRRs for each conflict type were combined using the conflict rates estimated from the GES data as weights (equation 4-3). To estimate the variability in the percentage of crashes that would be prevented, the GES weights were assumed to be constants, and the CRRs for the different conflict types were assumed to be independent.

Objective 1A.2. Determine if Drivers Using LDWS Drive More Safely

Safer driving was evaluated by comparing data from the Baseline Period (without LDWS feedback) and Active Interface Period (with LDWS feedback) by individual driver. Key comparisons are described in Table 18. Statistical models were fit to these data to determine if there were statistically significant differences in these measures between baseline and active periods.

Table 18. Comparisons to Evaluate LDWS Safety Effects

Hypothesis	Basis for Comparison # LEX files per VMT	Basis for Comparison # Drift Alerts per VMT	Basis for Comparison # Lane Excursions per VMT by Magnitude, Boundary Type and Turn Signal Usage	Basis for Comparison RMS Deviation from Lane Center by Road Curvature	Basis for Comparison % of Lane Changes that Are Unsignaled
Fewer unplanned lane and road departures	Baseline versus Active	Baseline versus Active	Baseline versus Active	—	—
Use turn signals more often, react more quickly	Baseline versus Active	Ratio of # LEX Files per VMT to # Drift Alerts per VMT	Baseline versus Active	—	Baseline versus Active
Effect of LDWS increases with hours on the road	Track versus Cumulative VMT in Active Period	Track versus Cumulative VMT in Active Period	Track versus Cumulative VMT in Active Period	Track versus Cumulative VMT in Active Period	Track versus Cumulative VMT in Active Period

Individual statistical models were used to describe the relationship between system status and several safety related responses while adjusting for covariates. Table 19 lists the responses considered, and Table 20 lists the covariates. Variables were selected via backwards selection for each of the models. In addition to main effects, all interactions with System Status were also considered for each model. The models also included a random effect for driver. Each of these models was simplified using the same backwards selection procedure as for the conditional analyses of the ER and PR.

Table 19. Safety Analyses Responses

Variable	Description
Large Lane Excursion	Count of the number of lane excursions > 18 inches (over a solid boundary with turn signal off)
Drift Alert (Solid)	Count of the number of drift alerts over solid boundaries
Un-signaled Lane Changes	Proportion of lane changes that were not signaled
Root Mean Square Lane Position	Root mean square lane position
Time out-of-lane	Proportion of time spent out of the lane

Table 20. Safety Analyses Covariates

Variable	Description
System status	Indicator of whether or not the system was active
Percent road speed > 35 mph	Percentage of time road speed exceeded 35 mph
Percent in curve	Percentage of time that was in a curve
Average road speed	Average road speed
Hours in motion in last 8 hours	Number of hours the vehicle was in motion in the last 8 hours
Hour of the day	Sine and cosine of hour of day (allows hour of day to have a sinusoidal effect)

Objective 1A.3. Determine the Numbers of Crashes, Injuries, and Fatalities that Can Be Avoided if the LDWS is Deployed Nationwide

The previous objective (1A.2) addressed estimating the probability of reducing SVRD and rollover crashes under the conditions encountered during the FOT. Objective 1A.3 involves extrapolating these results to estimate crash, injury, and fatality reductions under nationwide deployment. However, in order to assess the applicability of these extrapolations, it was necessary to compare the conditions encountered during this FOT with typical driving conditions for drivers and vehicles in various target fleets.

For this objective, the McKenzie Tank Lines fleet and its drivers were characterized in terms of the type of fleet operation (regional tanker deliveries), location, truck type, cargo type, and carrier and driver safety records. SafeStat scores and other information from the Safety and Fitness Electronic Record (SAFER) system were used to determine the safety performance of McKenzie Tank Lines and its drivers relative to other carriers.

In addition to extrapolating the findings from this FOT to the entire McKenzie Tank Lines fleet, four potential scenarios were identified: (a) all class 7 and 8 truck-tractors with tanker-trailers carrying HAZMAT, (b) all class 7 and 8 truck-tractors with tanker-trailers, (c) all class 7 and 8 truck-tractors with any type of trailer, and (d) all large commercial (classes 3 through 8) trucks greater than 10,000 lbs gross vehicle weight (GVW).

It was the most reasonable to extrapolate the findings from this FOT to the entire McKenzie Tank Lines fleet, and possibly to the populations of truck-tractors with tanker-trailers –

HAZMAT or non-HAZMAT carriers. Nevertheless, the differences among fleets were addressed when extrapolating the findings from this FOT.

Although it was not possible to fully validate and justify the extrapolation of safety benefits to all fleets, the benefits were calculated to illustrate the *potential* for crash, injury, and fatality reductions. For each scenario under Objective 1A.2, the safety benefits equation (Figure 11) was used to estimate the potential numbers of crashes avoided if all vehicles in the scenarios were equipped with the LDWS. The same formula was used to estimate the numbers of injuries and fatalities. The historical numbers of crashes, injuries, and fatalities were obtained from the GES and FARS databases using the methods discussed in Section 4.2.1 and Appendix A.

Objective 1A.4. Determine if Drivers Using LDWS Will Have Less Severe Crashes

Since no crashes occurred during the FOT, surrogate measures of crash severity were used to evaluate the influence of the LDWS on the severity of SVRD and rollover crashes. The LDWS was designed to improve safety by preventing situations that may lead to rollover or SVRD crashes. Thus, its effectiveness was related more to reducing the frequency of conflicts than to reducing the consequences of conflicts once they occur. To evaluate crash severity, the following Baseline versus Active Period data were compared:

- Frequency of occurrence of small, medium, and large lane excursions (from the OPS files), where the criteria for small, medium, and large excursions are maximum travel of a front tire out of its lane that was less than 10 inches, between 10 and 18 inches, and more than 18 inches, respectively.
- Frequency of occurrence of LEX events.
- Magnitudes of the excursions and lateral velocities at the time of a drift (from the LEX files).

4.3.2 Goals 1B, 1C, 1D, and 1E. Assess Mobility, Efficiency, Productivity, and Environmental Quality Benefits

These four goals are addressed in the Benefit-Cost Analysis (Section 5.9).

4.3.3 Goal 2. Assess Driver Acceptance and Human Factors

Data for the driver acceptance and human factors evaluation were processed using the Statistical Package for the Social Sciences (SPSS) software package. Frequency distributions were generated for all of the variables in the post-activation survey that allowed for a full descriptive analysis of the survey data. These frequencies are reported in Section 5, using both tables and graphics for every closed-ended variable in the survey. Open-ended questions that required the respondent to write in a response were coded into Microsoft Access database software and printed out for further assessment and reporting.

Due to the small number of cases, as illustrated in Table 12, the usual statistical testing and analysis of the hypotheses from the Evaluation Plan were not feasible. Instead, the analysis was organized around the objectives under Goal Area 2, and hypotheses were examined within the limitations of the small sample size. Percentage distributions were not calculated; the frequencies for each variable are shown in the tables and graphics to present a direct indication of how responses were distributed across the categories of each variable. These results were interpreted qualitatively, since strict hypothesis testing or tests of statistical significance of relationships between variables were not possible with these data.

Since only four driver interviews were successfully conducted in the baseline telephone interviewing, these data were not presented in the analysis. Only selected open-ended responses were referenced in the analysis to aid in the understanding of the post-activation survey results. Since insufficient data existed to perform even a limited time-series (longitudinal) analysis to compare baseline and post-activation responses of individual drivers, the results of the analysis should not be generalized to any larger population of truck drivers.

4.3.4 Goal 3. Assess Performance and Capability Potential

The focus of this part of the evaluation was to assess how well the LDWS performed with respect to functionality, capability, and reliability/maintenance. The following factors were evaluated:

- ♦ Availability or the percentage of time that alerts were enabled
- ♦ Features and their relevance to safety-related driving
- ♦ History of LDWS malfunctions during the FOT
  - Types of malfunctions
  - Corrective actions
- ♦ Limiting conditions for operation (visibility, road features, speeds, etc.)
- ♦ Maintenance requirements (cleaning, camera alignment, calibration, etc.)
- ♦ False alerts and missed events:
  - Lane changes identified as drifts
  - Drifts identified as lane changes
  - Failures to issue drift alert

4.3.5 Goal 4. Assess Product Maturity for Deployment

The objective under this goal area was to make a judgment about the suitability of the LDWS for widespread deployment in the trucking industry. The LDWS installed and tested under this program were prototype systems undergoing development and refinement. To assess the maturity of the LDWS for deployment, interviews were conducted with system developers, Mack representatives who have experience with the system in their trucks, and consultants who were experienced with SafeTRAC and the other major LDWS currently on the market.

Since the LDWS has been modified and improved over the prototype versions used in the FOT, the system currently being sold and used by truck companies is significantly advanced over those earlier prototypes. The LDWS is available for use in private vehicles, and there are similar products on the market and in use at this time.

4.3.6 Goal 5. Assess Institutional and Legal Issues

Institutional and legal issues can influence the success of the IVI program in general and the successful deployment of the LDWS technology in particular. Evaluation of institutional issues required an understanding of the relevant organizations, jurisdictions, and individuals that are key stakeholders in the outcome of this deployment, and the identification of any potential problems due to the deployments that would need to be addressed and managed. Identification of legal issues involved an examination of laws and regulations that apply to the IVI program and the technologies being deployed, program consistency or conflict with these requirements, and an assessment of liability or privacy concerns.

5.0 FINDINGS

In this section, the findings of the independent evaluation of the Mack IVI FOT are presented for each of the evaluation goals:

- Goal 1A. Achieve an In-Depth Understanding of Safety Benefits
- Goal 1B. Achieve an In-Depth Understanding of Mobility Benefits
- Goals 1C and 1D. Achieve an In-Depth Understanding of Efficiency and Productivity Benefits
- Goal 1E. Achieve an In-Depth Understanding of Environmental Quality Benefits
- Goal 2. Assess User Acceptance and Human Factors
- Goal 3. Assess IVSS Performance and Capability Potential
- Goal 4. Assess Product Maturity for Deployment
- Goal 5. Address Institutional and Legal Issues that Might Affect Deployment

Within each goal area, results are organized according to the objectives, hypotheses, and measures listed in Section 3 (Evaluation Goals).

5.1 Goal 1A. Assess Safety Benefits

This section presents findings related to the safety benefits of the LDWS tested in the Mack FOT. The four objectives under this goal are summarized below, along with key highlights of the relevant findings. Following this summary are the detailed results for each objective.

The first objective (Section 5.1.1) was to determine to what extent drivers using the LDWS encounter fewer driving conflicts and crashes than vehicles without the systems. Driving data collected during the FOT were modeled and analyzed to estimate the efficacy of the systems at preventing driving conflicts and crashes. The analysis focused on rollover and SVRD crashes and the four types of the conflicts that typically precede these crash types and might be prevented by the use of the LDWS. These conflicts were classified by vehicle speed and whether the truck was traveling in a curve or going straight.

The second objective (Section 5.1.2) was to determine whether the LDWS helps drivers drive more safely. The frequency of large lane excursions or drift alerts, variations in lane position, and the percentage of lane changes using turn signals were expected to affect the likelihood of SVRDs and rollover crashes. Driving measures related to these parameters were compared between the inactive and active periods of the LDWS interface for each driver.

Section 5.1.3 presents findings for the third objective, extrapolating the efficacy estimates to determine the decrease in the total number of crashes and crash-related injuries and deaths that would occur if all vehicles in representative fleets or operational scenarios were equipped with the LDWS. Four fleets were modeled in the analysis: (1) all large trucks (> 10,000 lbs. GVW),

(2) all class 7 and 8 tractors pulling at least one trailer, (3) tractors pulling tanker-trailers, and (4) tractors pulling tankers containing HAZMAT.

The fourth objective (Section 5.1.4) was to determine if drivers using the LDWS have less severe crashes. The analysis of crash severities used lateral velocity as a surrogate measure. For each LEX file, estimates were made of the lateral velocity at the time when the driver began his or her recovery maneuver and when the truck would have impacted a barrier located 10 feet outside the lane (if the driver remained inattentive).

The following sections discuss the objectives of the safety evaluation in more detail. Three key terms are used in the presentation of results in this section:

- *Counts* are the number of times a specific event or condition occurred. Counts are reported in the OPS files, which provide reports for every 15 minutes of driving.
- *Rates* are the frequencies of occurrence of a specific event or condition, and are reported on a "per 10,000 VMT" basis.
- *Standard Error* is a statistical term that is used in the analyses to calculate 95 percent confidence intervals, which were used to determine whether the effects of active LDWS interface feedback and other variables were significant.

5.1.1 Objective 1A.1. Do Drivers Using LDWS Have Reduced Driving Conflict Rates and Crash Probabilities?

This section addresses the primary safety objective of the study: to estimate the reduction in the rates of driving conflicts and crashes that are attributable to the use of the LDWS in applications similar to those of McKenzie Tank Lines.

To recapitulate the analytical methods described in Section 4.3.1, the analysis of conflict rates and crash probabilities was conducted in three stages.

- First, an estimated "ER" was calculated to determine the efficacy of the system in helping drivers avoid the various driving conflicts that may lead to rollover and SVRD crashes. For each conflict type, the ER compared the estimated probability that a driver will encounter the given conflict when using the LDWS (with LDWS) to the estimated probability that he or she will encounter the same conflict when not using the LDWS (without LDWS*). An ER less than 1 suggested that the LDWS helps the driver avoid conflicts.*

EXPOSURE RATIO

< 1: Fewer driving conflicts with LDWS
= 1: Same amount of driving conflicts with LDWS
> 1: More driving conflicts with LDWS

- Second, a "Prevention Ratio" was calculated to determine if the system is effective at helping drivers avoid a crash after they enter a driving conflict situation. For each conflict, the PR compared the conditional probabilities of an SVRD or rollover crash (with LDWS versus without LDWS), given that the driver is in the specific conflict situation. *A PR less than 1 suggested that the LDWS helps the driver avoid crashes in conflict situations.*

PREVENTION RATIO

For a given driving conflict:

< 1: Smaller probability of a crash with the LDWS
= 1: Same probability of a crash with the LDWS
> 1: Greater probability of a crash with the LDWS

- Third, the final step in the analysis was to combine the ER and PR to estimate a "Crash Reduction Ratio" (CRR), which was used to calculate the percentage reduction in crashes that can be realized using the LDWS.

The first step of the analysis addressed the hypothesis that drivers using LDWS will have fewer conflicts. The second and third steps addressed the hypothesis that drivers using LDWS will have fewer rollover and SVRD crashes. At each stage of the analysis, additional analyses were performed as a function of driving conditions to characterize the conditions where the systems might be more or less effective at producing safety benefits.

The safety benefit of the LDWS may be represented as an exposure benefit or a prevention benefit. The LDWS issues an alert to drivers in situations where they are about to head out of their lane in order to provide enough warning for the driver to safely maneuver the vehicle to avoid going off the road and potentially rolling the vehicle over. Therefore, the LDWS is expected to reduce the frequency of driving conflicts that could lead to SVRD or rollover crashes. Once a driving conflict exists (e.g., the truck is out of its lane and headed off the roadway), it is not expected that the LDWS will prevent crashes. Thus, the primary benefit of the LDWS was expected to be a reduction in the ER. Other potential safety benefits were improved driver attentiveness and better lane-keeping performance.

As discussed in Section 4.2.2, the analysis of safety benefits was restricted to a limited amount of data from only six drivers that were collected during at least 1,000 miles of driving during both the baseline and active periods of LDWS feedback.

Stage 1. Determination of Exposure Ratios

Table 21 presents conflict counts and rates for the four conflict types for each of the six drivers with at least 1,000 VMT in each of the baseline and active periods as well as counts and rates across all drivers. The rates presented are the number of conflicts per 10,000 VMT. Figure 15 also shows the conflict rates for periods with and without active LDWS interface feedback by each conflict for all drivers combined. Figure 16 presents the conflict rates for periods with and without active LDWS interface feedback by each driver for all conflicts combined, with error bars representing approximate 95 percent confidence intervals. This figure shows that for five of the six drivers, conflicts were reduced with active LDWS feedback given to these drivers.

Table 21. Conflict Counts and Rates by Driver and LDWS Interface Status

Driver ID	LDWS Interface Status	VMT	Conflict Type (#) Normal Speed on Straight Road (1) Count	Conflict Type (#) Normal Speed on Straight Road (1) Rate	Conflict Type (#) Normal Speed in Curve (2) Count	Conflict Type (#) Normal Speed in Curve (2) Rate	Conflict Type (#) Excessive Speed on Straight Road (3) Count	Conflict Type (#) Excessive Speed on Straight Road (3) Rate	Conflict Type (#) Excessive Speed in Curve (4) Count	Conflict Type (#) Excessive Speed in Curve (4)) Rate
146	Off	26,648	80	30.0	13	4.9	0	0.0	0	0.0
146	On	36,882	99	26.8	18	4.9	1	0.3	1	0.3
192	Off	25,336	50	19.7	11	4.3	0	0.0	4	1.6
192	On	11,122	26	23.4	5	4.5	1	0.9	0	0.0
194	Off	48,107	75	15.6	19	3.9	0	0.0	0	0.0
194	On	5,294	3	5.7	0	0.0	0	0.0	0	0.0
199	Off	29,304	134	45.7	19	6.5	0	0.0	0	0.0
199	On	13,376	21	15.7	4	3.0	0	0.0	0	0.0
204	Off	5,041	5	9.9	3	6.0	1	2.0	1	2.0
204	On	4,136	1	2.4	1	2.4	0	0.0	0	0.0
205	Off	13,724	21	15.3	4	2.9	0	0.0	0	0.0
205	On	14,972	13	8.7	1	0.7	0	0.0	0	0.0
All Drivers	Off	148,160	365	24.6	69	4.7	1	0.1	5	0.3
All Drivers	On	85,782	163	19.0	29	3.4	2	0.2	1	0.1

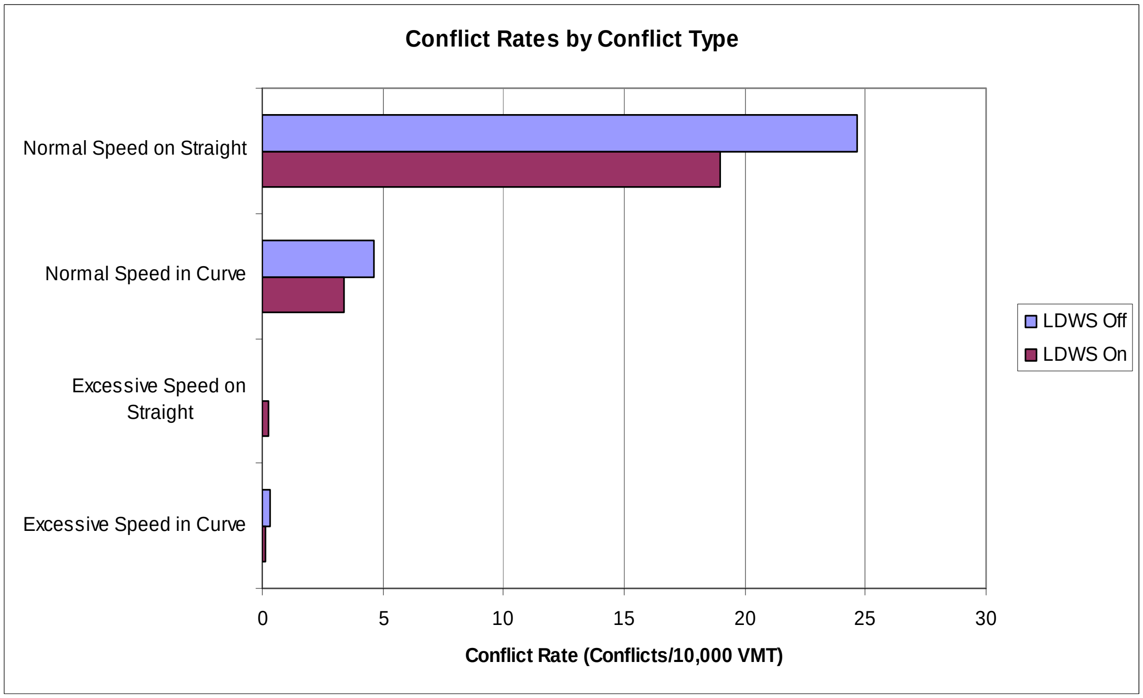

Figure15. Conflict Rates for All Drivers

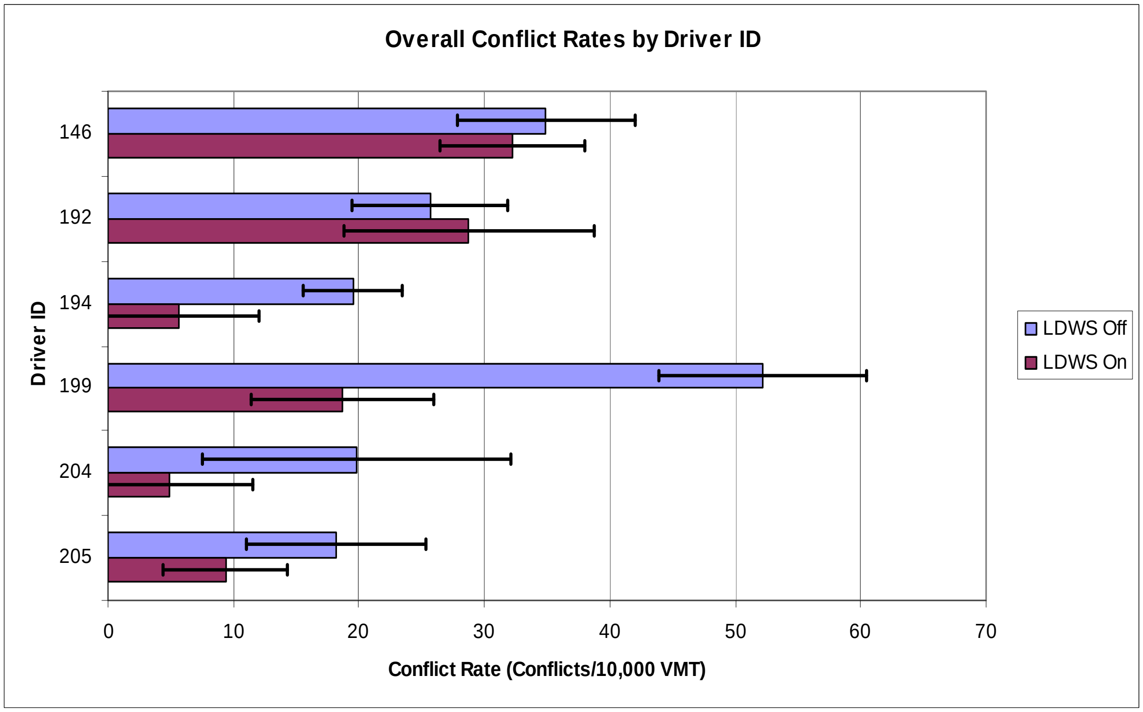

Figure 16. Overall Conflict Rates for Each Driver, with 95 Percent Confidence Intervals

As illustrated in Figure 15, a small number of conflicts were classified as involving excessive speed. Initially, a threshold of 70 mph for conflicts on a straight road and 67.5 mph for conflicts on a curved road seemed appropriate to define excessive speed. However, it was not possible to define excessive speed accurately at each location without knowing the speed limit, traffic and weather conditions, and road characteristics. Therefore, the speed threshold for defining conflicts was eliminated and two conflict categories were created and defined by whether the truck was (1) turning or driving on a curve, or (2) driving on a straight road. The straight-roads conflict category combines the normal-speed-on-straight-road and the excessive speed on straight road conflict types. The curves conflict category combines the normal-speed-in-curve and the excessive-speed-in-curve conflict types. Table 22 contains conflict counts, rates, and standard errors of the rates for these two conflict categories by the driver.

Table 22. Conflict Counts and Rates for Curves and Straight Roads

Driver ID	LDWS Interface Status	VMT	Conflict Category Straight Roads Count	Conflict Category Straight Roads Rate	Conflict Category Straight Roads Standard Error	Conflict Category Curves Count	Conflict Category Curves Rate	Conflict Category Curves Standard Error
146	Off	26,648	80	30.0	3.4	13	4.9	1.4
146	On	36,882	100	27.1	2.7	19	5.2	1.2
192	Off	25,336	50	19.7	2.8	15	5.9	1.5
192	On	11,122	27	24.3	4.7	5	4.5	2.0
194	Off	48,107	75	15.6	1.8	19	3.9	0.9
194	On	5,294	3	5.7	3.3	0	0.0	0.0
199	Off	29,304	134	45.7	4.0	19	6.5	1.5
199	On	13,376	21	15.7	3.4	4	3.0	1.5
204	Off	5,041	6	11.9	4.9	4	7.9	4.0
204	On	4,136	1	2.4	2.4	1	2.4	2.4
205	Off	13,724	21	15.3	3.3	4	2.9	1.5
205	On	14,972	13	8.7	2.4	1	0.7	0.7
All Drivers	Off	148,160	366	24.7	1.3	74	5.0	0.6
All Drivers	On	85,782	165	19.2	1.5	30	3.5	0.6

Comparison of Conflict Rates and Estimation of the Exposure Ratio

Two approaches for estimating the ER were considered. Both approaches included an assumption that conflicts are distributed according to a Poisson distribution, which is commonly used to analyze data on events that occur randomly over time. One approach was to ignore differences among drivers and sum VMT and conflict counts across all drivers, then compute conflict rates and ERs for the different conflict types. When the data are combined this way, the model treats the data as if there was only one driver. The estimated conflict rates and ER from this approach are presented in Table 23.

Table 23. Conflict Rate Estimates and Exposure Ratio Estimates From All Drivers

Conflict Category	Conflict Rates LDWS Interface Off Estimate	Conflict Rates LDWS Interface Off Standard Error	Conflict Rates LDWS Interface On Estimate	Conflict Rates LDWS Interface On Standard Error	Exposure Ratio Estimate	Exposure Ratio 95% Confidence Interval Lower Bound	Exposure Ratio 95% Confidence Interval Upper Bound
Straight roads	24.7	1.3	19.2	1.5	0.8*	0.6	0.9
Curves	5.0	0.6	3.5	0.6	0.7*	0.4	1.0

*Indicates that the ER estimate is significantly different from 1 at the 95 percent confidence level.

Table 24. Conflict Rate Estimates and Exposure Ratio Estimates with Random Effect for Driver

Conflict Category	Conflict Rates LDWS Interface Off Estimate	Conflict Rates LDWS Interface Off Standard Error	Conflict Rates LDWS Interface On Estimate	Conflict Rates LDWS Interface On Standard Error	Exposure Ratio Estimate	Exposure Ratio 95% Confidence Interval Lower Bound	Exposure Ratio 95% Confidence Interval Upper Bound
Straight roads	20.9	4.7	14.3	3.3	0.7*	0.5	0.9
Curves	5.0	0.8	3.3	0.7	0.7	0.4	1.2

*Indicates that the ER estimate is significantly different from 1 at the 95 percent confidence level.

The second approach was to treat the differences among drivers as a random effect and compute conflict rates and ERs using the resulting Poisson regression model. This approach allowed the model to adjust for overall differences in conflict rates for different drivers. The corresponding conflict rates and ERs are presented in Table 24. Figure 17 presents the conflict rates for the two conflict categories with the LDWS interface on and off, with error bars representing approximate 95 percent confidence intervals. Note that the low conflict rate observed in the curves conflict category may be a result of filtering out conflicts that may have been curve cutting. Although the confidence intervals for conflicts with the LDWS interface on and off on straight roads overlapped, the modeled ER was statistically significant. The modeling approach allowed the estimate of the ER to reflect the experimental design with each driver acting as his or her own control. This results in the ER showing a significant benefit by having greater precision than the individual conflict rates.

The comparison of the conflict rates and ER estimates derived from the two approaches showed some consistency in the results. Note that the confidence intervals from the modeling approach contained the estimates from the approach that does not take drivers into account. Yet the data revealed that the drivers have different conflict rates and that the benefits of the system vary among drivers; therefore, it was more appropriate to account for these differences using a random effects model. Furthermore, if the driver effect was not included in the model, the results from drivers with the most miles traveled would overwhelm results for drivers with fewer miles driven.

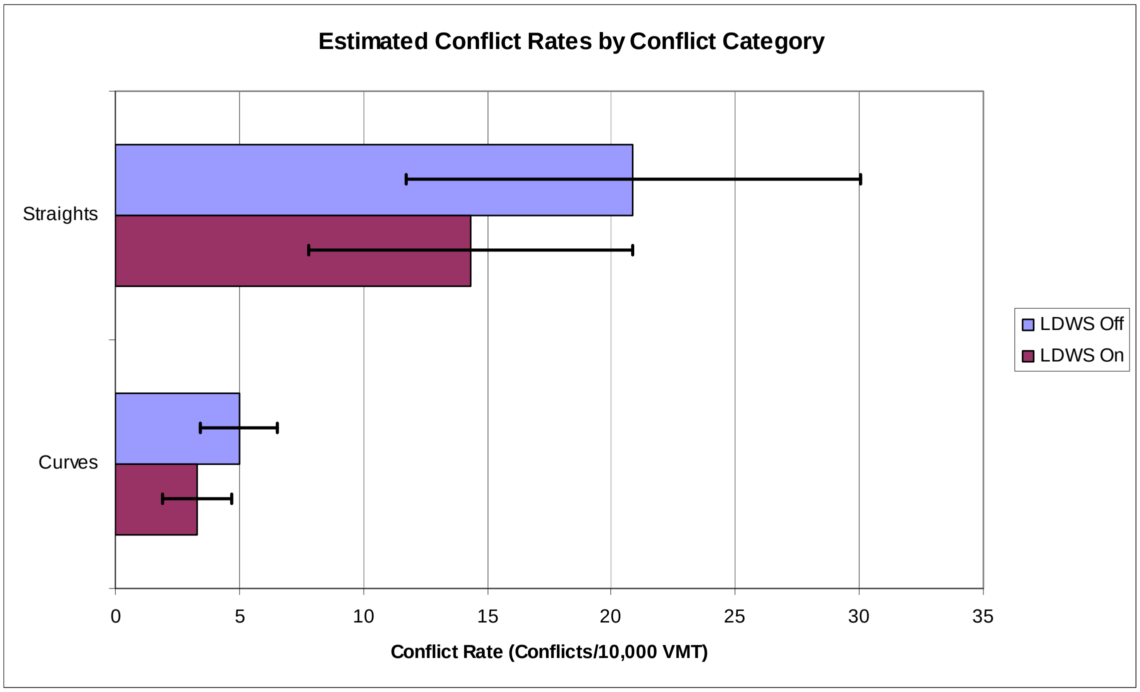

Figure 17. Conflict Rates for Curves and Straight Roads, with 95 Percent Confidence Intervals

As shown in Table 24, the ERs of 0.7 (Straight Roads) and 0.7 (Curves) indicate that the system provides a benefit for the drivers by helping them avoid conflicts. This result was statistically significant for straight roads according to the modeled approach that included a random effect for drivers. However, the result was not statistically significant for curves. A possible explanation for this result is that drivers may be more attentive to their driving task when in a curve, and the LDWS may affect drivers less if they are already attentive. This result may also be due to the limited number of drivers available for this analysis.

These results indicated that the LDWS is effective in reducing the number of situations where an SVRD or rollover crash could result since the LDWS provides advance information that the driver can use to avoid a potential hazard. Using the LDWS, the truck driver is warned about a lane departure when the front tire of the truck is at the lane edge. The amount of time and space that a given driver has to recover from a lane departure will likely vary widely, depending on factors such as truck speed and heading, driver reaction time, shoulder width, and roadside characteristics. Based on the conflict criteria used in the Mack FOT evaluation (e.g., drift alert issued when truck goes at least 18 inches out of the lane), the results indicated that the LDWS is effective for driving conditions typical of the McKenzie Tank Lines fleet.

Conditional Analysis of Exposure Ratio

To determine if the ER was affected by any other factors, a model that contained several covariates was fitted to the data. As described in Table 25, all covariates are variables that were computed from the OPS files. System status was the main variable of interest that indicates whether the driver had an active or inactive LDWS interface. The percentage of time that the truck speed was greater than 35 mph was included in the model, as it represented the percentage of time that the system should be working. The percentage of time that the truck was in a curve was a measure of how often the truck was driven in curves. The percentage of time with cruise control active could be correlated with a driver's attentiveness. The average truck speed could also be correlated with a driver's attentiveness and/or the types of roadway or traffic conditions. Hours in motion during the last eight hours could be related to driver fatigue, and hour of day could be related to fatigue and visibility. Since the main goal of this analysis was to identify the covariates that influence the effectiveness of the LDWS, the interactions between each variable and the system status (active versus inactive LDWS interface) were included in the model.

Table 25. Variables for the Poisson Regression Model

Variable	Description	Min.	Max.	Mean	Significant at the 0.05 Level	Interaction with System Status Significant at 0.05 Level
System Status	Indicator of whether or not the system was active	---	---	---	✓	
Percent truck speed > 35 mph	Percentage of time truck speed exceeded 35 mph	0.9	100	88.7	✓	
Percent in curve	Percentage of time that was in a curve	0	100	9.0		
Percent with cruise control	Percentage of time with cruise control active	0	15.5	7.4		
Average truck speed	Average truck speed	7.1	84.8	58.3	✓	
Hours in motion in last 8 hours	Number of hours the vehicle was in motion in the last 8 hours	0.0	8	3.6	✓	
Hour of the day	Sine and cosine of hour of the day	0:00	23:59	12:30	✓	✓

This analysis was performed on 17,458 OPS files containing 635 conflicts from six drivers who had at least 1,000 VMT of driving in each of the baseline and active periods. Because only six drivers were available for this analysis, the effects of driver age and driver experience were not included in the model. Table 25 contains minimum, maximum, and mean values for each covariate. Appendix E contains histograms showing the observed distribution for each of these variables.

Table 25 also indicates which covariates and interactions with the system status were statistically significant at the 0.05 level. As indicated in the table, the only variables that did not have a significant relationship with the conflict rate were the percentage of time in curves and the percentage of time cruise control was activated. The only variable with a significant interaction with system status was hour of day. Thus, the effect of the system (in terms of percentage reduction in conflicts) was constant for all variables except for hour of day.

As explained in more detail below, Figures 18 through 22 show the effect of each of the significant predictors on the expected number of lane excursions per 10,000 miles driven. In order to generate individual estimates for each predictor, mean values were assigned to the remaining variables in the model. With the exception of the interaction case, there was a constant proportional difference between the System Status On and System Status Off curves as a function of the independent variable (abscissa).

Effects of Hours-of-Service and Time of Day on Conflict Rates and LDWS Efficacy. The effects of time of day and hours-of-service on LDWS effectiveness were evaluated with the model. The objective of the time-of-day analysis was to determine if LDWS provided more benefit to the driver during daytime or night-time driving. The objective of the hours-of-service analysis was to determine if the benefit of the LDWS changed after hours of driving.

Figure 18 shows the relationship between expected conflicts and the number of hours on the road in the last 8 hours. The expected number of conflicts increased with the number of hours in motion. These trends reflected a potential increase in driver fatigue with hours on the road. Increased fatigue may result in decreased attentiveness to the driving task, which could be manifested in greater meandering in and out of the lane and more driving conflicts. The effectiveness of the LDWS in reducing conflicts was indicated by a lower number of conflicts at a given value of hours in motion. The reduction in conflicts as a percent was constant across the range of hours in motion.

Figure 19 describes the effect of the hour of the day on the number of conflicts. Both the sine and cosine of hour of day were included in the model; these allow the hour of the day to have a sinusoidal (same general shape as a sine wave) effect on conflict rate. The plot reflects the contributions of both the sine and cosine along with an interaction term between the system status and cosine of the hour. For both System Status On and System Status Off, the expected number of conflicts peaked in the early morning hours and reached a minimum in the early afternoon. However, the effect was more pronounced for System Status Off. For example, the expected driving conflict rate at Hour 3 (3:00 a.m.) was 53 if the system interface was off and 27 if it was on.

This pattern was more clearly shown in terms of ER, which was plotted as a function of hour of day in Figure 20. The dotted lines represent approximate 95 percent confidence intervals for the estimated ER. For reference, an ER of 1 indicates no benefit of LDWS and less than 1 indicates a benefit. The benefit of the system was not significant near Hour 12 (noon), but the ER decreased to about 0.5 at Hour 24 (midnight). These predictions suggested that the LDWS may be most effective from evening to early morning, when there is generally less traffic, lower visibility, and the driver may be drowsy or less attentive to the driving task.

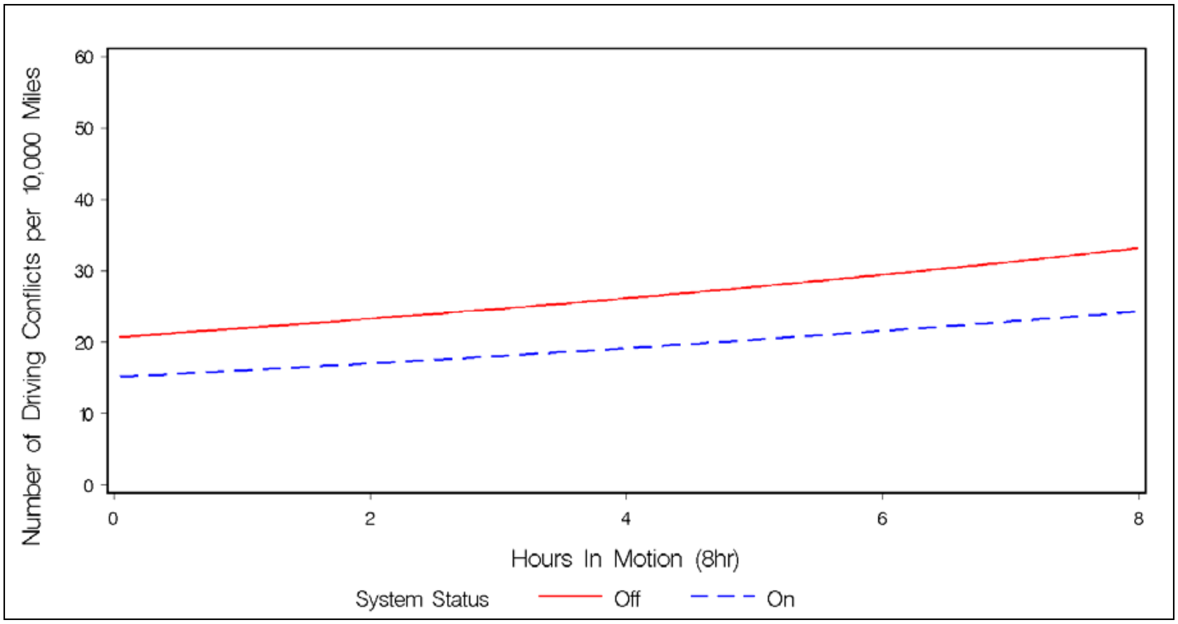

Figure 18. Influence of Hours in Motion over Previous 8 Hours on the Driving Conflict Rate

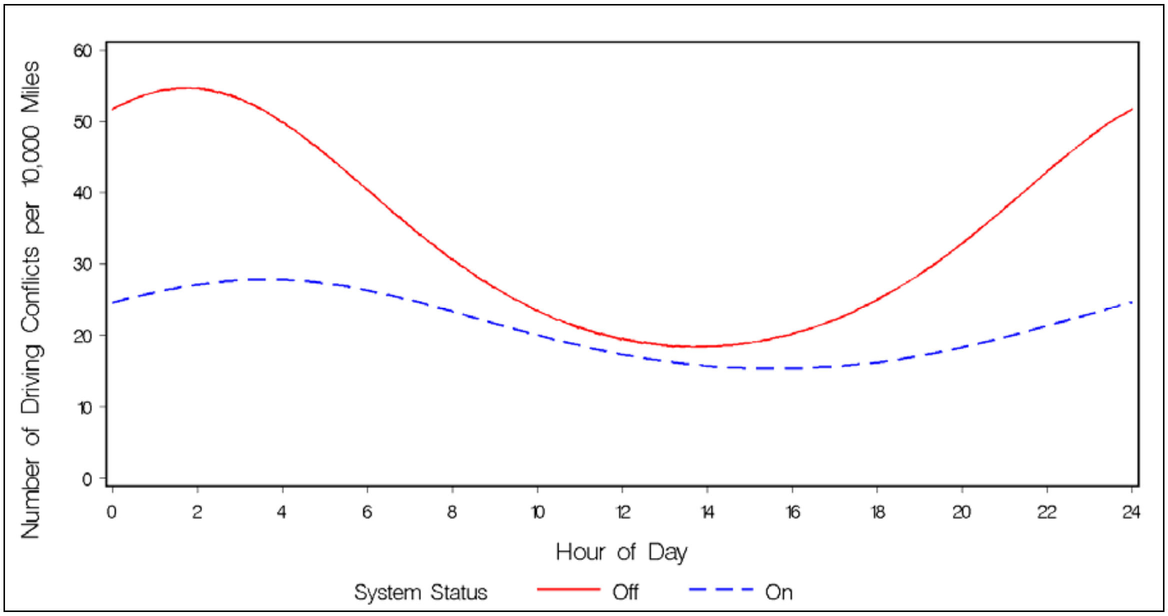

Figure 19. Influence of Hour of Day on the Driving Conflict Rate

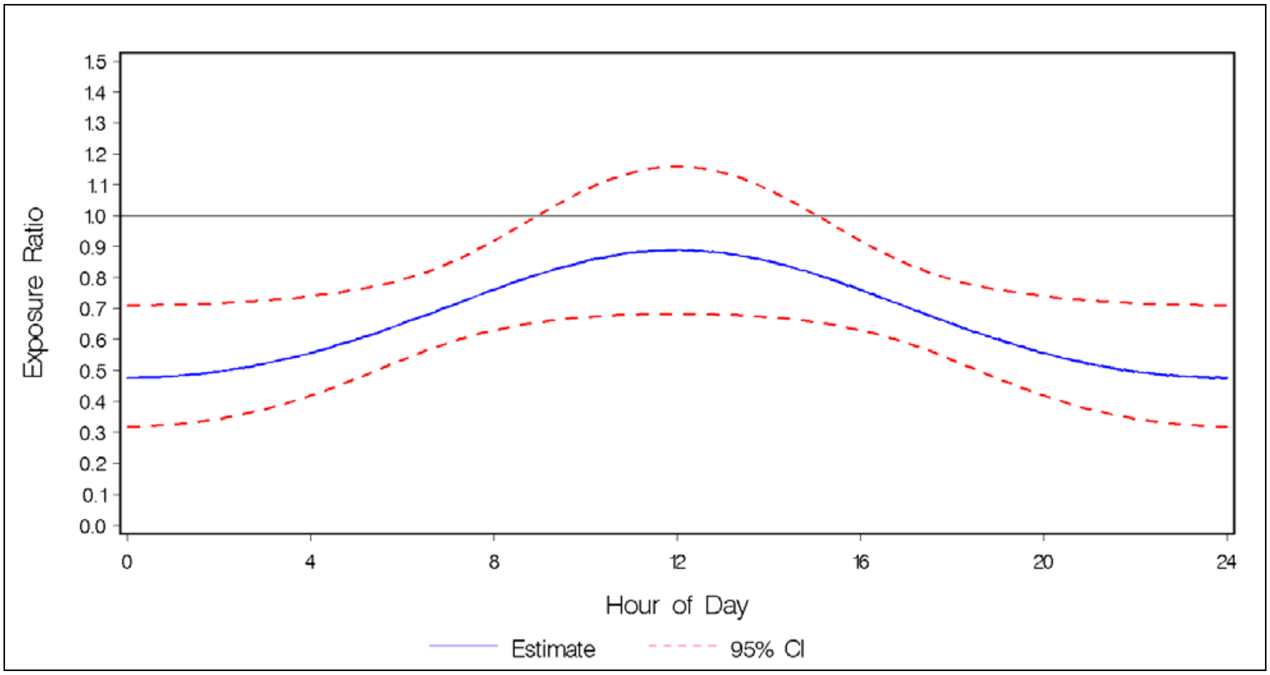

Figure 20. Influence of Hour of Day on the Exposure Ratio

Effects of Speed on Conflict Rates and LDWS Efficacy. The effectiveness of the LDWS as a function of vehicle speed was also evaluated using the model. Specifically, driving conflict rates were compared for System Status On and System Status Off over the speed range that was observed during the FOT. By design, the LDWS provides warnings only when the average speed is greater than a threshold value (set to 35 mph for the FOT). To be effective in preventing crashes on highways, the LDWS must be effective at highway speeds.

Figure 21 shows the relationship between average speed and driving conflict rate. The driving conflict rate decreased with increasing speed, and the rate was less for System Status On over the entire range of speeds shown in the figure. There was a constant percentage reduction in conflicts over the range of average speed.

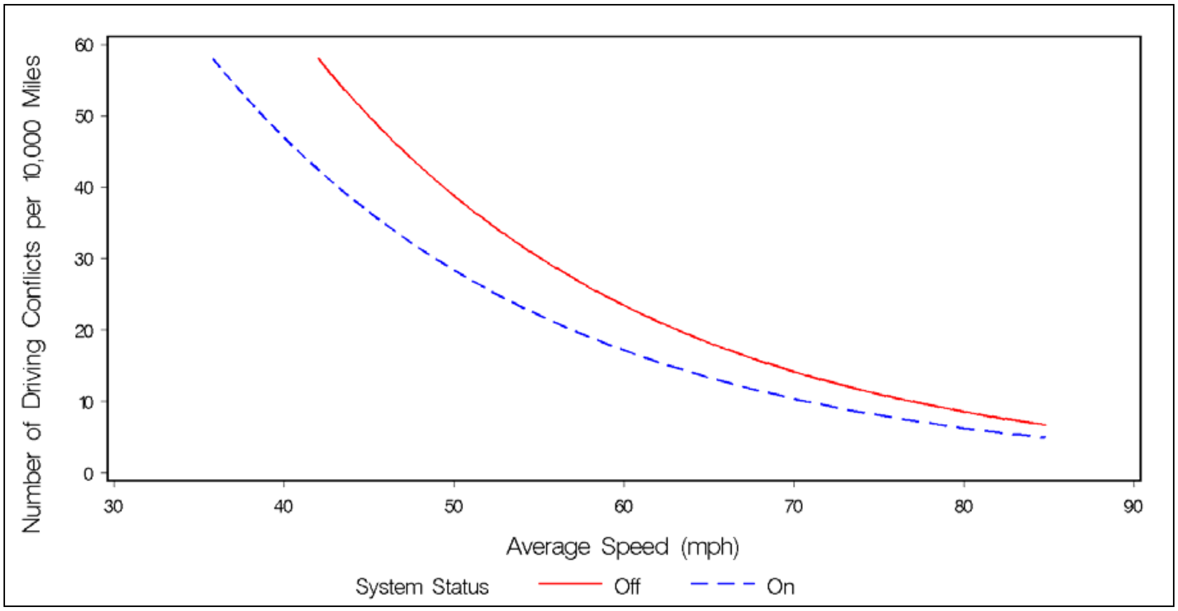

Figure 21. Influence of Average Speed on the Driving Conflict Rate

As shown in Figure 22, the conflict rate increased with increasing percentage of time driving over 35 mph, and the conflict rate was lower for System Status On in all cases. A relatively low percentage of time driving over 35 mph may reflect "stop-and-go" driving, when drivers are likely to be more attentive and the LDWS would have less of an effect. The results indicated that the LDWS was effective in reducing driving conflicts and provided a constant percentage decrease in conflict rate at all speeds for which it is designed.

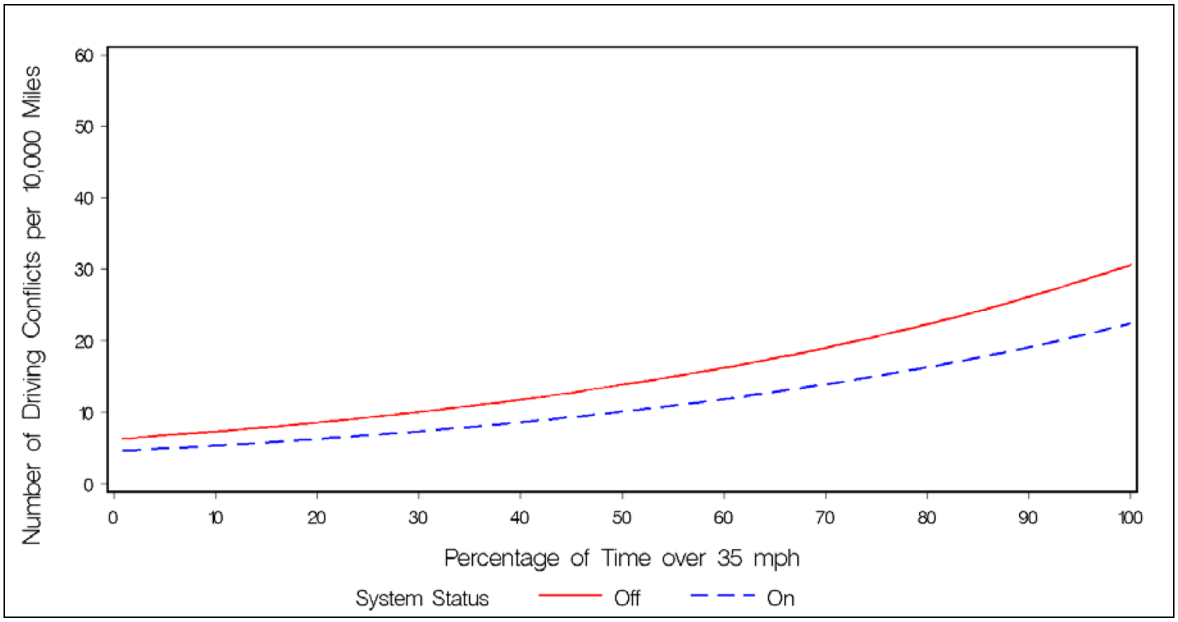

Figure 22. Influence of Percentage of Time Driving over 35 mph on the Driving Conflict Rate

Effects of Driver Age and Experience on Conflict Rates and LDWS Efficacy. As mentioned previously, the data set represented by six drivers was not large enough for a statistical analysis of the effect of driver age and experience on conflict rates and LDWS efficacy. In place of a statistical analysis, a qualitative analysis of the relationship between age and experience and the conflict rates observed for each driver with and without active LDWS interface feedback was performed. Figure 23 illustrates the conflict rates for the periods with and without active LDWS interface feedback observed for each driver plotted against driver experience and driver age. The diameter of each pair of circles is proportional to the conflict rate, so the difference between the two circles is related to the ER for each driver. If the circle for LDWS inactive interface feedback has a larger diameter than the one for LDWS active interface feedback, then the estimated ER for the driver is less than 1, signifying a benefit of the system. The circles are centered at the intersection of the driver's age and experience. The numbers next to the circles are the overall conflict rates with the first number being the overall conflict rate with an inactive LDWS interface, and the second number the conflict rate with the active LDWS interface.

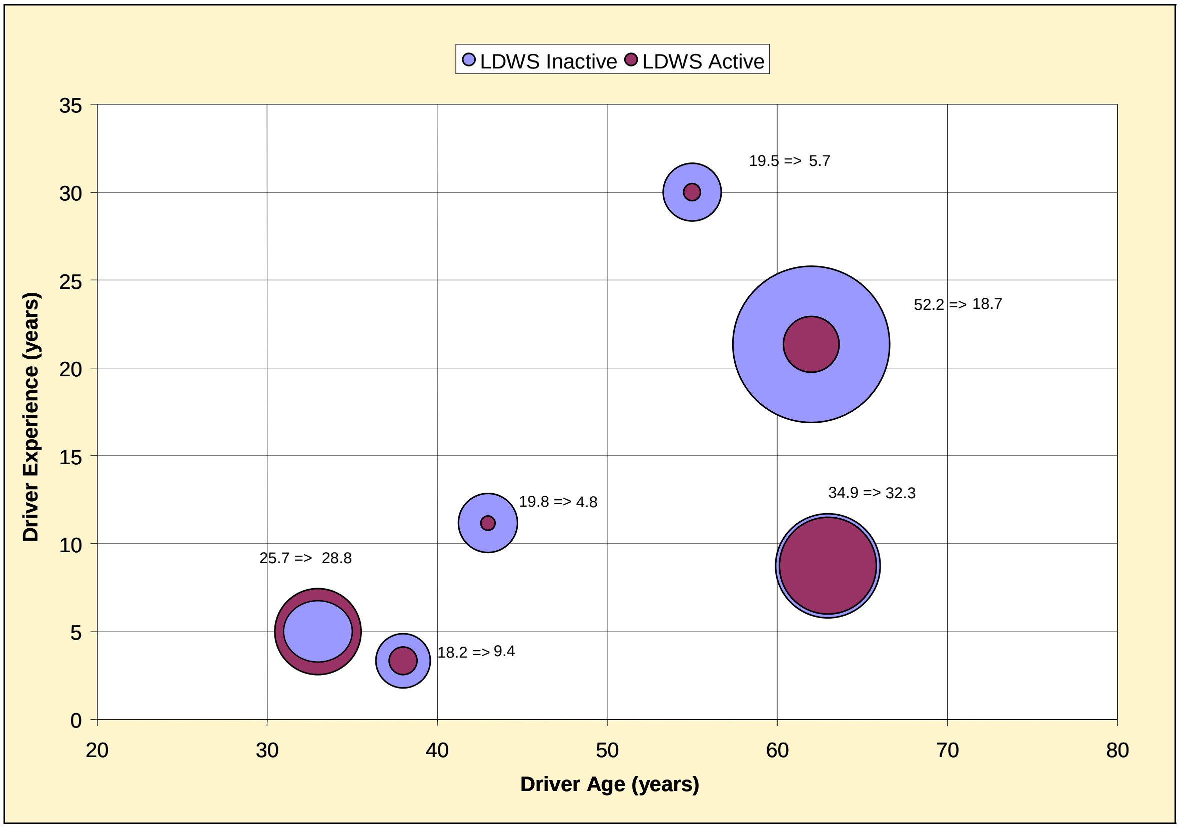

Figure 23. Relationship Among Age, Experience, and Conflict Rates

For all but one driver the system reduced the number of conflicts. The one driver who had more conflicts with active LDWS interface feedback was the youngest driver with nearly the least experience. The other driver with a very small reduction in conflicts with active LDWS interface feedback was the oldest driver, who had a moderate amount of experience. All other drivers had conflict rates reduced by at least 50 percent. Out of all the drivers in the FOT, this set of drivers included the least experienced and the most experienced driver and two in between. The set also included the second-youngest driver and the second-oldest driver.

Although these results were not conclusive, they suggested that the effectiveness of the LDWS at reducing conflict rates was different for individual drivers. These differences may be related to the driver's baseline driving style, which can be affected by many factors including age and experience. The LDWS effectiveness may also be impacted by the ability to adjust settings to each driver. For the Mack FOT, the adjustment features of the LDWS (alert tones, volumes, and truck's proximity to lane edge when alert is issued) were disabled for the FOT for purposes of experimental control.

Stage 2. Determination of Prevention Ratios

Determination of Conflict Severity and Conditional Crash Probabilities

Analytical modeling and computer simulation studies were used to predict the additional delay in driver reaction times required for the observed driving conflicts to result in SVRD and rollover crashes. The simulation code (VDANL) and methods are described in Section 4.3.1.

Figure 24 presents the values of t_{ROR}, grouped by System Status Off ("LDWS Off") and System Status On ("LDWS On") for the 635 conflicts. The simulation model was run for 20 seconds, which can be seen by the large proportion of values in the last bar of these two histograms. The censored or truncated nature of these time values was taken into account by the analytical methods. Because the distributions of t_{ROR} and t_{ROLL} were nearly identical, for clarity and simplicity only the t_{ROR} distributions are shown.

The conflicts for which t_{ROR} >20 sec reflected scenarios where the truck heads off the road at a very small angle of departure. In such cases, it would be expected that unless the driver was unconscious or otherwise physically unable to react, he or she would receive enough visual and audible signals to appropriately maneuver the truck with or without LDWS feedback. For the majority of conflicts with t_{ROR} < 20 sec, t_{ROR} was between 6 and 10 seconds. Thus, for the majority of conflicts measured in the FOT, the analyses predicted that the driver could have avoided an SVRD crash even if he or she initiated a recovery maneuver 6 to 10 seconds later than the time indicated in the observed conflict.

The result that t_{ROR} and t_{ROLL} were nearly identical for the analyzed conflicts indicated that the driver would not have likely rolled the truck in a recovery maneuver until the truck was 1 to 2 inches from going off the road in an SVRD crash. From a vehicle dynamics standpoint, the combined conditions of speed, angle of departure, and position of the truck when the driver started the recovery were not sufficiently severe to cause the driver to roll the truck sooner.

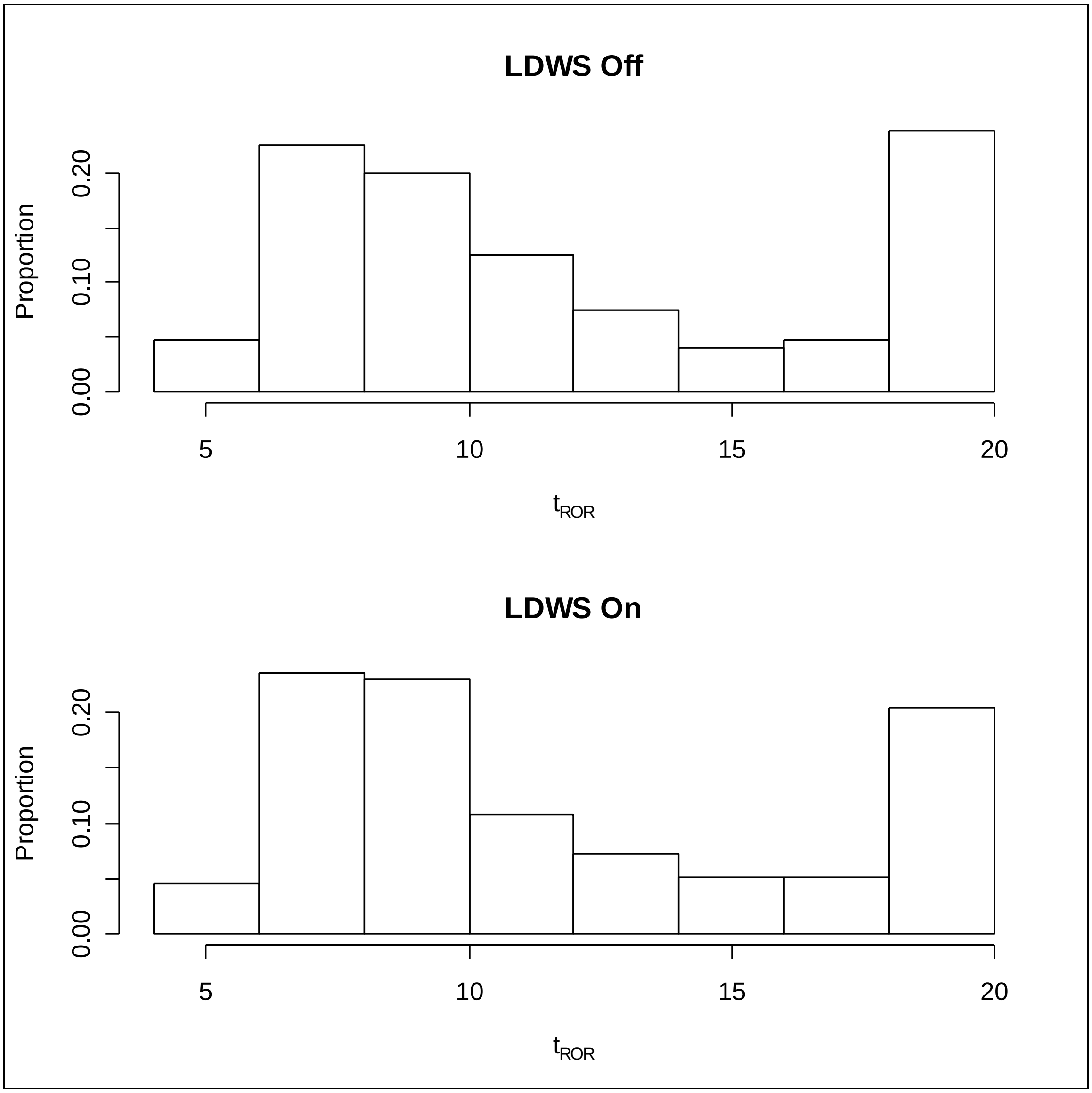

Figure 24. Distributions of t_{ROR} for 635 Conflicts

Figure 25 illustrates this relationship between additional driver reaction times and the probability of each crash type given that a conflict occurred. The estimation of the parameters θ and α is discussed in Section 4.3.1. If the additional reaction time is greater than t_{ROR}, then an SVRD crash would occur. If the time is between t_{ROR} and t_{ROLL}; however, there is the probability of either crash type occurring.

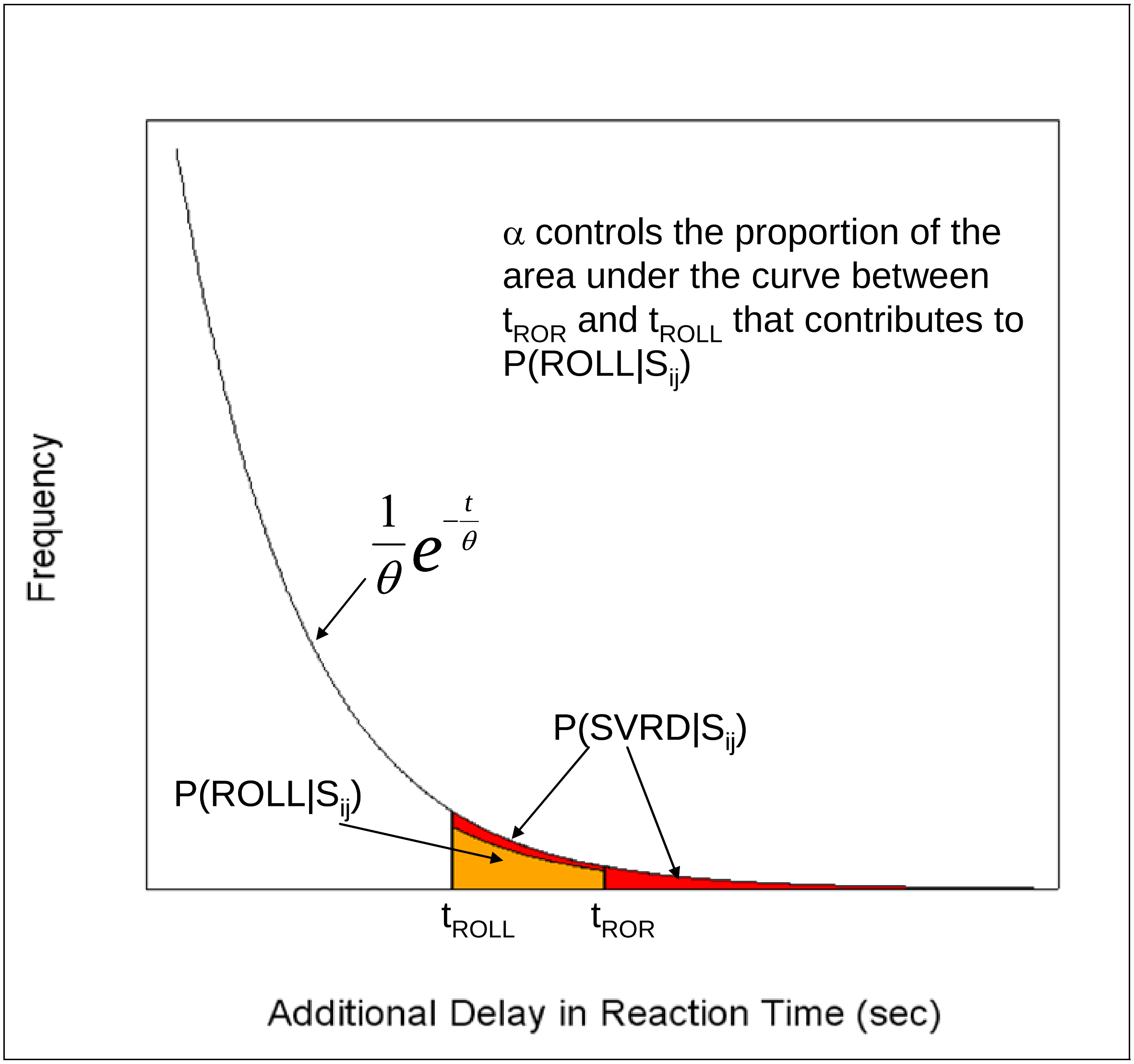

Figure 25. Probabilities of Rollover and SVRD Crashes Relative to Driver Reaction Time Delays

Using this model, the following relationships were used to estimate the probability of a crash given a conflict from t_{ROR} and t_{ROLL} values calculated for each conflict.

$$P(ROLL \mid t_{ROR}, t_{ROLL}) = (1-\alpha)\left(e^{-t_{ROLL}/\theta} - e^{-t_{ROR}/\theta}\right),$$

$$P(ROR \mid t_{ROR}, t_{ROLL}) = (1-\alpha)e^{-t_{ROR}/\theta} + \alpha e^{-t_{ROLL}/\theta}.$$

Table 26 presents the average crash probabilities (given a conflict) and approximate 95 percent confidence intervals calculated in this way for both crash types and each conflict category with and without an active LDWS feedback.

Table 26. Crash Probabilities by Crash Type, Conflict Category, and System Status

Crash Type	Conflict Category	System Status	Count	Geometric Mean	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
SVRD	Straight roads	Off	366	2.1E-04	1.5E-04	2.7E-04
SVRD	Straight roads	On	165	3.7E-04	1.9E-04	5.6E-04
SVRD	Curves	Off	74	8.2E-04	4.4E-04	1.2E-03
SVRD	Curves	On	30	4.8E-04	1.7E-04	7.8E-04
Rollover	Straight Roads	Off	366	1.5E-06	1.0E-06	2.0E-06
Rollover	Straight Roads	On	165	2.4E-06	1.2E-06	3.6E-06
Rollover	Curves	Off	74	1.4E-05	7.6E-06	2.0E-05
Rollover	Curves	On	30	1.0E-05	2.1E-06	1.8E-05

Table 27 presents the PRs for both crash types and the two conflict categories with the data pooled from all drivers. A model containing a random effect for the driver was considered, but this model could not be fitted to the data, because the effect of the driver on the probability of a crash given a conflict was so small.

Table 27. Estimated Prevention Ratios for All Drivers

Crash Type	Conflict Category	Prevention Ratio Estimate	Prevention Ratio 95% Confidence Interval Lower Bound	Prevention Ratio 95% Confidence Interval Upper Bound
SVRD	Straight roads	1.8	0.8	2.8
SVRD	Curves	0.6	0.1	1.0
Rollover	Straight roads	1.6	0.6	2.6
Rollover	Curves	0.7	0.1	1.4

None of the PR estimates were significantly different from 1 for both crash types and both conflict categories. The results included estimates of PR that are greater than 1 for driving on straight roads. However, the 95 percent confidence intervals bracket 1, suggesting that these FOT data do not show statistical evidence of an effect of the LDWS on preventing crashes. These wide confidence intervals may be attributed to random variations in the data. These results are consistent with the fact that the LDWS is a warning device designed to reduce the rate of driving conflicts (i.e., the number of times a situation occurs that may result in an SVRD crash or rollover crash). However, once a driving conflict is created, the LDWS may influence the outcome. Consequently, analyses were performed to evaluate the influence of several variables on PR, as described in the next section.

Conditional Analysis of Prevention Ratio

For the driving conflicts comprising the 635 LEX files, crash probabilities (given a conflict occurred) were calculated for both SVRD and rollover crashes. Although the PRs did not show statistically significant differences between active and inactive LDWS interface feedback, the conditional analysis was performed to determine if there were certain conditions where a benefit in terms of the PR was significant. Linear regressions were used to model the two probabilities; as the probabilities were quite small, a log-normally distributed response was assumed. A random effect for the 0 driver was also included in these models.

Table 28 lists the variables considered for inclusion in the model for the conditional analysis. Windshield wiper status was included in the model as a proxy for weather conditions, and target count (number of objects being tracked by the Eaton VORAD CWS) was included as a proxy for traffic conditions. Appendix E contains histograms of each of these variables, showing the observed distribution of their values. Interactions between Driver Status and the remaining variables were also evaluated. A backward elimination process was used to remove predictors that did not improve the model fit, retaining only those significant at a 0.05 level.

Table 28. Variables for the Crash Probability Models

Variable	Description	Significant at the 0.05 Level	Interaction with System Status Significant at 0.05 Level
System Status	Indicator of whether the system was active	✓	
Boundary	Type of boundary that was crossed (none, dashed, solid, virtual)	✓	
Departure Direction	Direction of lane departure (left or right)	✓	
Average Speed	Average speed	✓	✓
Hours In Motion	Number of hours in motion out of the last eight		
Wiper Status	Indicator of whether wipers were activated	✓	
Target Count	Count of the number of objects being tracked by the collision warning system (categorical as 0, 1, and > 1)	✓	
Roadway	Indicates whether the road was straight or curving	✓	✓
Hour of Day	Sine and Cosine of the hour of the day		

Table 28 also indicates which covariates and interactions with the system status were statistically significant at the 0.05 level. The same variables were found to be significant for models of both the probability of a rollover crash and the probability of an SVRD crash. If the interaction between a variable and system status was not significant, the model estimated the probability of a crash with active LDWS interface feedback to be proportional to the probability of a crash without LDWS feedback, and the PR was constant as a function of that variable.

Effect of Boundary, Departure Direction, Wiper Status, and Target Count on Rollover PR. The categorical variables that were significant in the model are listed in Table 29. This table provides estimates of the probability of a rollover crash for each variable and a 95 percent confidence interval for the probability.

Table 29. Estimated Rollover Crash Probability

Variable	Value	Rollover Estimate	Rollover 95% Confidence Interval Lower Bound	Rollover 95% Confidence Interval Upper Bound
Boundary	None	5.7E-08	1.8E-08	1.9E-07
Boundary	Dashed	3.4E-08	1.5E-08	8.1E-08
Boundary	Solid	1.1E-08	5.1E-09	2.4E-08
Boundary	Virtual	1.8E-08	5.4E-09	6.2E-08
Departure Direction	Left	2.3E-06	1.0E-06	5.0E-06
Departure Direction	Right	2.8E-10	1.1E-10	6.7E-10
Wiper Status	Off	1.1E-08	6.4E-09	2.0E-08
Wiper Status	On	5.6E-08	1.7E-08	1.9E-07
Target Count	0	1.3E-08	6.0E-09	2.8E-08
Target Count	1	2.7E-08	1.2E-08	6.3E-08
Target Count	>2	4.4E-08	1.6E-08	1.2E-07

The type of boundary being crossed in a conflict was marginally significant in predicting the probability of a rollover. However, no differences were found between the particular boundary types after controlling for multiple comparisons. The departure direction variable indicated that the probability of a crash was much greater if the lane departure was to the left as opposed to the right. The activation of the windshield wipers on the truck indicated an increased probability of a rollover. Target count (the number of objects ahead of the truck and detected by the CWS) also showed a significant relationship. Trucks in conflicts where one target was present had a 50 percent higher probability of a rollover than trucks with no target present. Further, trucks in conflicts where more than one target was present had approximately twice the probability of a rollover compared with conflicts where no target was present. These differences are large in percentage terms, but the modeled probabilities were very small; therefore, the change in the probability of a crash was small. A difference between trucks with only one target present versus more than one was found not to be significant after adjusting for multiple comparisons.

According to the analyses, crash probability increased with decreasing available time to recover. These results suggested that the truck's lateral velocity and/or distance out of the lane when recovery begins were higher when other vehicles are present. Yet, the model did not show a significant interaction between any of these variables and system status. Thus, the PR was estimated to be constant for all values of boundary type, departure direction, wiper status, and target count.

Effect of Vehicle Speed and Road Curvature on Rollover PR. Average speed and roadway curvature were found to have significant interactions with driver status, indicating a change in the PR according to the value of these variables. Figure 26 and Figure 27 show the change in the PR as average speed increases for curved and straight roadways, respectively.

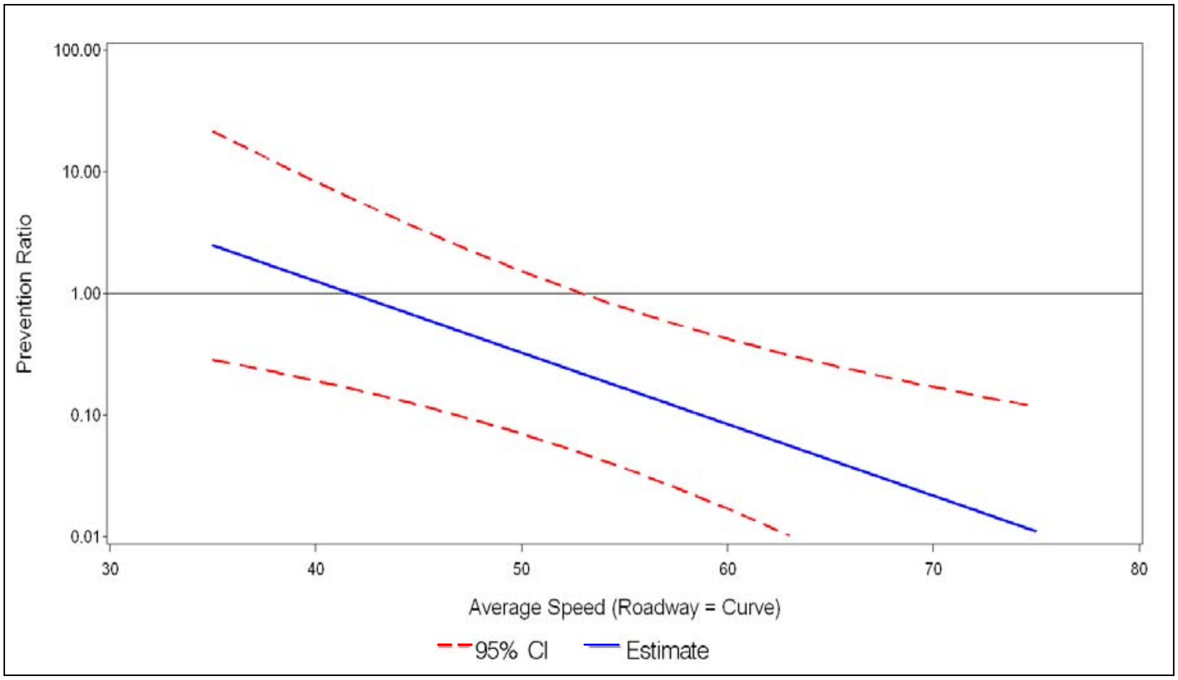

Figure 26. Prevention Ratio for Average Speed on a Curve

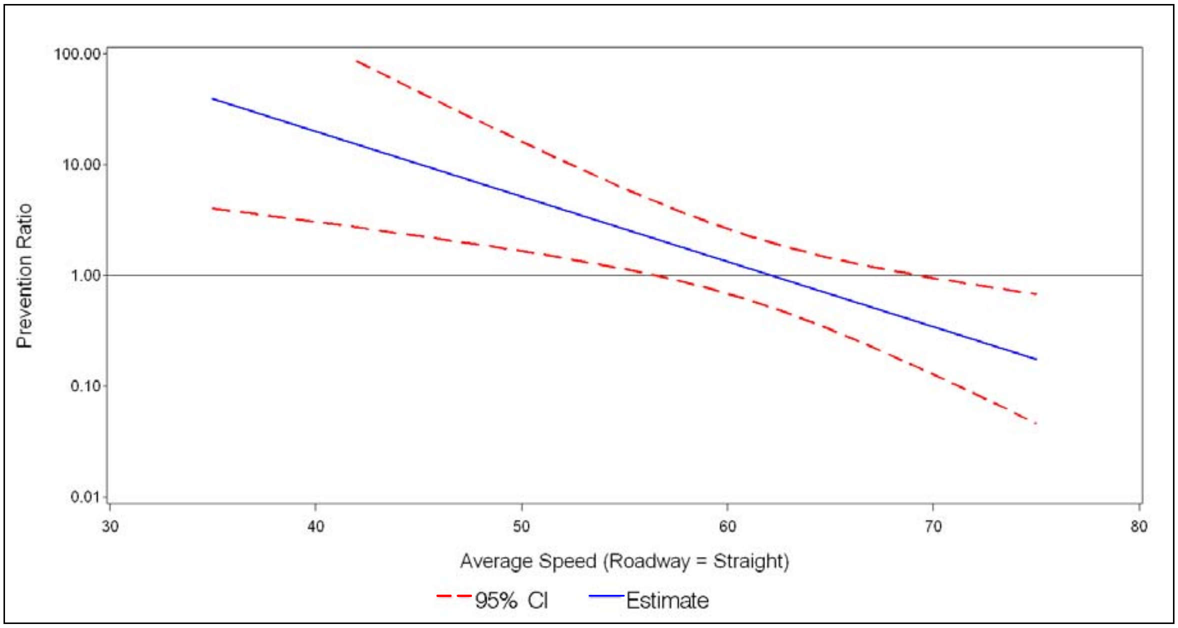

Figure 27. Prevention Ratio for Average Speed on a Straight Road

The results indicated that the LDWS may prevent rollover crashes once a vehicle is in a conflict while negotiating a curve at speeds greater than about 54 mph. For a given angle of departure and driver reaction time at higher speeds, the truck will be farther out of the lane by the time the driver begins to react to the LDWS drift alert. Thus, high speed/high angle of departure driving conflicts may occur at about the same rate with and without an active LDWS warning. This may also be true for conflicts involving going “wide” on sharp curves at high departure angles. Yet, for these conflicts, an active LDWS interface would issue a drift alert, possibly causing the driver to begin a recovery maneuver sooner to prevent a crash.

In contrast, the results indicated that fewer crashes could be prevented given a conflict on a straight road with the LDWS at average speeds of less than about 57 mph. Since the majority of conflicts occurred (over 75 percent) at speeds between 55 mph and 70 mph, the model may not be as accurate in this region.

Effect of Vehicle Speed, Road Curvature, and Other Variables on SVRD PR. The effect of vehicle speed, road curvature, and other variables on SVRD PR variables that were significant in the model are listed in Table 30. Table 30 provides estimates of the probability of a rollover crash for each level of this variable and also provides a 95 percent confidence interval for the probability.

Table 30. Estimated SVRD Crash Probability

Variable	Value	SVRD Estimate	SVRD 95% Confidence Interval Lower Bound	SVRD 95% Confidence Interval Upper Bound
Boundary	None	5.7E-06	1.8E-06	1.8E-05
Boundary	Dashed	3.6E-06	1.5E-06	8.3E-06
Boundary	Solid	1.1E-06	5.2E-07	2.4E-06
Boundary	Virtual	1.8E-06	5.5E-07	6.1E-06
Departure Direction	Left	2.2E-04	9.9E-05	4.8E-04
Departure Direction	Right	3.0E-08	1.2E-08	7.1E-08
Wiper Status	Off	1.1E-06	6.5E-07	2.0E-06
Wiper Status	On	5.7E-06	1.7E-06	1.9E-05
Target Count	0	1.3E-06	6.1E-07	2.8E-06
Target Count	1	2.8E-06	1.2E-06	6.4E-06
Target Count	>2	4.6E-06	1.7E-06	1.2E-05

As in the rollover model, average speed and roadway were found to have significant interactions with driver status, indicating a change in the PR according to the value of these variables. Above, Figure 26 and Figure 27 show the change in the PR as average speed increases for curved and straight roadways, respectively, in this model as well.

The CRR is an estimate of the overall efficacy of the LDWS for reducing crashes and is based on the ER and the PR:

$$\text{CRR} = \text{ER} \times \text{PR}$$

Table 31 presents the CRR and standard errors for each conflict category for SVRD crashes and rollover crashes. The results used the ERs estimated with a random effect for the driver that were presented in Table 24 and the PRs from Table 27.

Table 31. Estimated Crash Reduction Ratios

Crash Type	Conflict Category	Crash Reduction Ratio (CRR) Estimate	Crash Reduction Ratio (CRR) 95% Confidence Interval Lower Bound	Crash Reduction Ratio (CRR) 95% Confidence Interval Upper Bound
SVRD	Straight roads	1.2	0.5	1.9
SVRD	Curves	0.4*	0.0	0.7
Rollover	Straight roads	1.1	0.4	1.8
Rollover	Curves	0.5*	0.0	1.0

*Indicates that the estimate is significantly different from 1 at the 95 percent confidence level.

The CRRs were statistically different from the value of 1 for SVRD and rollover crash types in curves. With CRR estimates of less than 1, the system is expected to offer an overall benefit in terms of preventing SVRD and rollover crashes in curves. For straight roads, the CRR is not statistically different from 1.

Estimated Percentage Reduction in Crashes

Using the CRRs estimated above, the percentage of crashes that could be avoided with the LDWS was calculated for each conflict category and crash type as:

$$\boxed{\text{Percentage Reduction in Crashes} = (1 - \text{CRR}) \times 100 \text{ percent}}$$

In addition, the safety benefits methodology (described in Section 4.3.1) allowed the estimation of an overall reduction in crashes using the weighted sum of these ratios for each conflict category, with the weights being determined from the GES data (Equation 4-2). Table 32 presents the estimated number of SVRD and rollover crashes that could be avoided with the LDWS, using the CRRs presented in Table 31 as a “Best Estimate” and using CRRs that assume that the PR is equal to 1 as a “Conservative Estimate.” When the PR is set to 1, the CRR is equal to the ER. The results are presented for this second method because the estimate of the prevention ratio was determined not to be statistically significant. A “conservative estimate” was calculated using the estimated exposure ratio, which was statistically different from 1, and the default value of 1 for the estimated prevention ratio.

Table 32. Estimated Percent Benefit with Standard Errors—Best Estimate and Conservative Estimate

Crash Type	Best Estimate[1]	Best Estimate 95% Confidence Interval Lower Bound	Best Estimate 95% Confidence Interval Upper Bound	Conservative Estimate[2]	Conservative Estimate 95% Confidence Interval Lower Bound	Conservative Estimate 95% Confidence Interval Upper Bound
SVRD	23.5%[3]	2.4%	44.7%	21.2%*	7.8%	34.6%
Rollover	23.9%[3]	0.8%	47.0%	17.4%*	3.6%	31.2%

[1] Best Estimate based on the estimated Prevention Ratio

[2] Conservative Estimate based on Prevention Ratio =1

[3] Indicates that the estimate is significantly different from zero at the 95 percent confidence level.

The benefit of the system related to the number of SVRD crashes avoided was estimated to be 23.5 percent or 21.2 percent, depending on whether the estimated PR is used or the PR is set equal to 1. Similarly, the percentage of rollover crashes avoided was estimated to be 23.9 percent or 17.4 percent. All of these estimates were statistically greater than 0 as indicated by the approximate 95 percent confidence intervals included in the table.

5.1.2 Objective 1A.2.2. Do Drivers Using LDWS Drive More Safely?

A primary focus of the safety analyses was on identifying conflicts and estimating crash probabilities to determine the number and percentage of crashes that could be avoided if the LDWS were deployed in various operational scenarios. The safety analyses also investigated the influence of the LDWS on other surrogate safety measures. The results of this investigation are reported in this section.

An analysis was conducted to determine if the LDWS affected driving behaviors in other ways in addition to reducing conflict rates and crash probabilities. The variables in this analysis included the number of large lane excursions, number of drift alerts, percentage of lane changes that were not signaled, RMS lane position, and percentage of time out of the lane. Each of these variables was modeled separately, with each model including the effect of system status and the following set of covariates:

- Percentage of time traveling at greater than 35 mph – A low value may be considered to represent stop-and-go traffic, and a high value represents normal highway driving.
- Percentage of time in curves – A low value is considered to represent driving on straight roads.
- Average speed.
- Percentage of time in motion over previous 8 hours – A high value may indicate a higher risk of driver fatigue.
- Time of day – This covariate allows an assessment of night-time versus daytime driving.

Appendix E contains histograms showing the observed distributions of each of these covariates. To adjust for differences among drivers, the driver was included in each model as a random effect. Each model also contained interaction between covariates and system status. Terms that were not significant were removed from the model. For each covariate remaining in the model, a pair of plots showing the effect of the variable on the parameter being modeled was produced.

Large Lane Excursion

The rate of large lane excursions over a solid boundary was used as a surrogate safety measure. Solid lane boundaries are common on most highways and may separate a lane from another lane or a shoulder. The count of large lane excursions over a solid boundary from the OPS files and the elapsed miles for each OPS file were used in this analysis. Figure 28 contains a bar chart with the average number of large lane excursions per 10,000 VMT for each driver with and without LDWS feedback. Although no large excursions are shown for driver 204, this driver did have 7 LEX files generated for excursions that were not over solid boundaries.

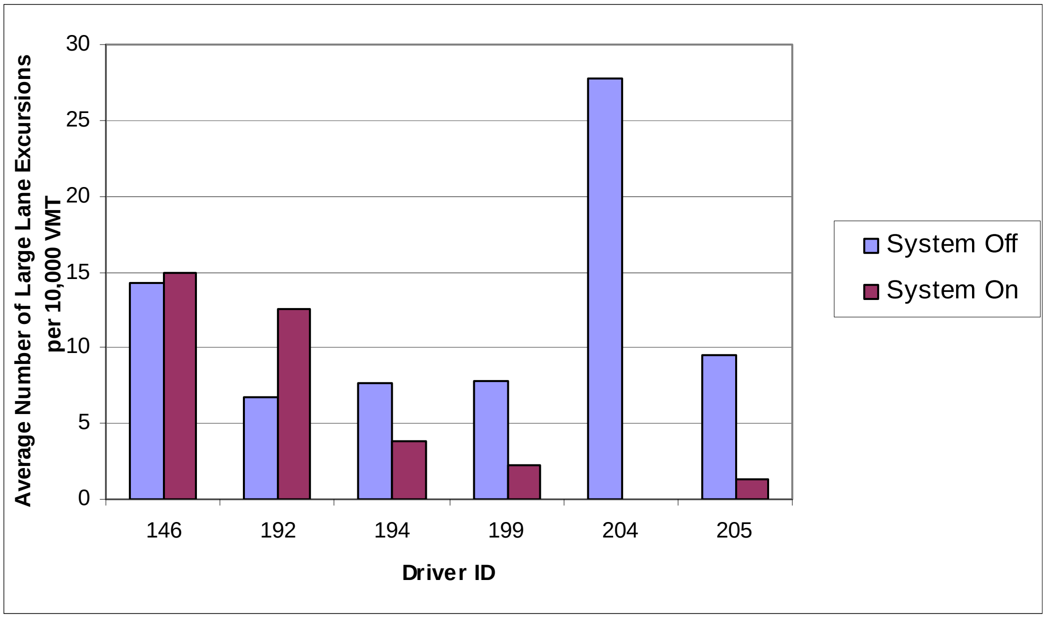

Figure 28. Large Lane Excursions by Driver

Poisson regression was used to model the number of large lane excursions in the files.

The count was assumed to be proportional to the VMT, and the driver effect was considered random, giving the mixed model:

$$E(Y_{ij}) = e^{X_{ij}\beta + \gamma_j} D_{ij}$$

where Y_{ij} is the number of large lane excursions during the 15-minute time period for lane excursion file *i* of driver *j*, X_{ij} is a matrix of continuous and categorical predictor variables (e.g., average road speed, system status), β is a vector of regression coefficients, γ_j is a random effect for driver *j*, and D_{ij} is the VMT. The notation $E(Y_{ij})$ indicates the expected number of large excursions. The significant predictor variables in the LEX model at the 0.05 level were: percent road speed > 35 mph, percent in curve, and average road speed. System status was not significant in this model (p-value = 0.237), indicating that the status of the LDWS did not significantly affect the number of lane excursions (greater than 18 inches) across solid boundaries.

This model's results do not necessarily indicate that the safety-related benefit of the LDWS was not manifested in a reduction in large lane excursions across solid boundaries. This indication may appear to differ from the results presented in Section 5.1.1, which indicated that based on the 635 driving conflicts derived from the LEX files, the LDWS reduces driving conflicts significantly. Yet, this model's results were based on the OPS files, which describe all driving in 15-minute increments. The data screening methods and filters applied to the LEX files were not applied to the OPS files; consequently, all of the large lane excursions described in the OPS files were not necessarily driving conflicts or unintended lane excursions.

Drift Alerts Over Solid Boundaries

Another measure that was analyzed using the OPS files was the rate of drift alerts. Figure 29 shows the average rate of drift alerts per 10,000 miles traveled for each driver by system status. For five of the six drivers, the average number of drift alerts was lower with the system providing feedback.

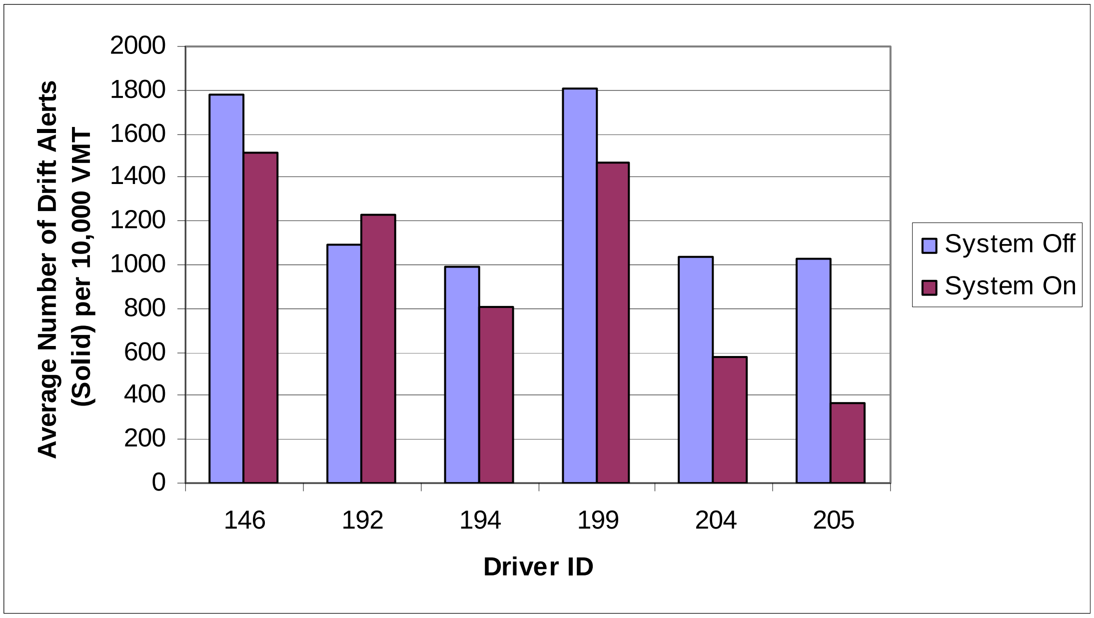

Figure 29. Drift Alerts over Solid Boundaries by Driver

A Poisson regression was used to model the number of drift alerts over solid boundaries. The form of the model was the same as the one used above for large lane excursions. The fit exhibited some evidence of over-dispersion (more variability in the number of drift alerts than expected under the Poisson model), which was adjusted to determine the significance of the predictors. Table 34 lists the variables that were significant at a 0.05 level.

Table 34. Significant Predictors in the Drift Alert over Solid Boundaries Model

Variable	Significant Interaction with System Status
System Status	
Percent road speed > 35 mph	
Percent in curve	✓
Average road speed	
Hours in motion in last 8 hours*	✓
Hour of the day	✓

*Main effect was not significant at the 0.05 level.

System status was a significant predictor in this model (p-value < 0.0001). The estimate of the reduction in the drift alert rate with the system interface active compared to the system interface inactive was 15 percent with a 95 percent confidence interval of (12 percent, 18 percent). The results indicated a significant decrease in drift alerts associated with solid boundaries with the system actively providing feedback under any of the following conditions:

- Less than 20 percent of the roadway contains curves
- Driving between 2 a.m. and 10 a.m.
- Driving less than 75 percent of the time in the previous 8 hours

With active LDWS interface feedback, there were fewer situations where a truck was drifting out of its lane on predominantly straight roads. Driving on curves included intentional out-of-lane driving (curve-cutting), which would not be expected to be affected by the LDWS. In each of these plots, all covariates other than the one being plotted were set equal to their average values.

Unsignaled Lane Changes

The proportion of lane changes where the drivers did not use turn signals was also analyzed to determine if the LDWS had any effect on turn signal usage. Figure 30 shows the proportion of lane changes that were unsignaled by driver and system status.

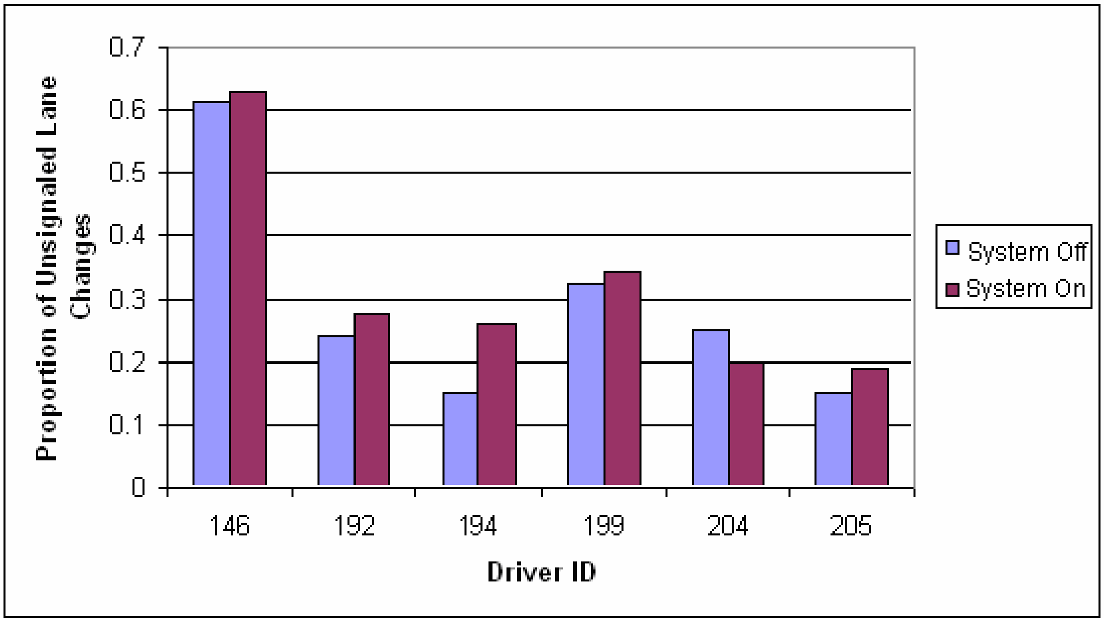

Figure 30. Proportion of Unsignaled Lane Changes by Driver

Logistic regression was used to model the proportion of unsignaled lane changes out of the total number of lane changes. A binomial distribution was assumed, and the following mixed model was used:

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = X_{ij}\beta + \gamma_j$$

where p_{ij} is the expected proportion of unsignaled lane changes during the 15-minute time period for lane excursion file i and driver j, X_{ij} is a matrix of continuous and categorical predictor variables (e.g., average speed, system status), β is a vector of regression coefficients, and γ_j is a random effect for driver j. In addition, each observation was weighted in the model-fitting algorithm according to the number of miles driven. Files that included no lane changes were necessarily excluded from this analysis. This model also showed evidence of over-dispersion, which was adjusted to determine the significance of system status and the covariates in the model. Table 35 lists the significant predictors at the 0.05 level for this model.

System status was a significant predictor in this model (p-value < 0.0001). However, the expected proportion of unsignaled lane changes was approximately 2 percent higher for the active versus inactive LDWS interface with a 95 percent confidence interval of (0.8 percent, 3.9 percent).

Table 35. Significant Predictors in the Unsignaled Lane Change Model

Variable	Significant Interaction with System Status
System Status	
Percent road speed > 35 mph	✓
Average road speed	✓
Hours in motion in last 8 hours*	✓
Hour of the day	✓

*Main effect was not significant at the 0.05 level.

These results indicate somewhat mixed effects of the system status on unsignaled lane changes. With the active system interface feedback, the rate of unsignaled lane changes was significantly lower when driving at speeds of less than 55 mph, or when driving between 8 p.m. and midnight. In contrast, the rate of unsignaled lane changes was significantly higher when driving at speeds above 60 mph, when driving between 4 a.m. and 4 p.m., or when the driver had driven more than 38 percent of the time in the previous 8 hours.

If a driver attempts a lane change without using a turn signal, the LDWS will issue a drift alert. The LDWS drift alerts may make the driver more attentive to the driving task during the daytime because the traffic density tends to be greater, and a driver may be more attentive in denser traffic. In contrast, in the early-to-late evening hours there may be less traffic, and the driver may be annoyed by an alert issued when performing an unsignaled lane change because the driver does not see the need for a turn signal or the alert. Unsignaled lane changes may be intentional to reduce lane-keeping effort in certain situations (e.g., driver uses available space in adjacent lanes to drive when there is no nearby traffic). Therefore, within the limitations of this FOT, safe driving could not be strongly correlated with the rate of unsignaled lane changes, since not using a turn signal may be intentional.

Root Mean Square Lane Position

Using variables in the OPS files, the mean squared lane position was calculated. Figure 31 plots the variable of interest, which is defined as the average square root of the mean squared lane position, otherwise known as RMS lane position (RMSLP), for each driver with and without LDWS feedback.

Linear regression assuming a log-normally distributed response was used to model RMSLP. A random effect for the driver was also included in the model. The resulting model fitted to the data is:

$$E(Y_{ij}) = e^{X_{ij}\beta + \gamma_j}$$

where Y_{ij} is the RMSLP associated with the 15-minute time period for lane excursion file *i* of driver *j*, X_{ij} is a matrix of continuous and categorical predictor variables (e.g., average road speed, system status), β is a vector of regression coefficients, and γ_j is a random effect for driver *j*. The notation $E(Y_{ij})$ indicates the expected RMSLP. In addition, each observation was weighted in the model fitting algorithm according to the number of miles driven. Table 36 lists the predictors that were significant at the 0.05 level.

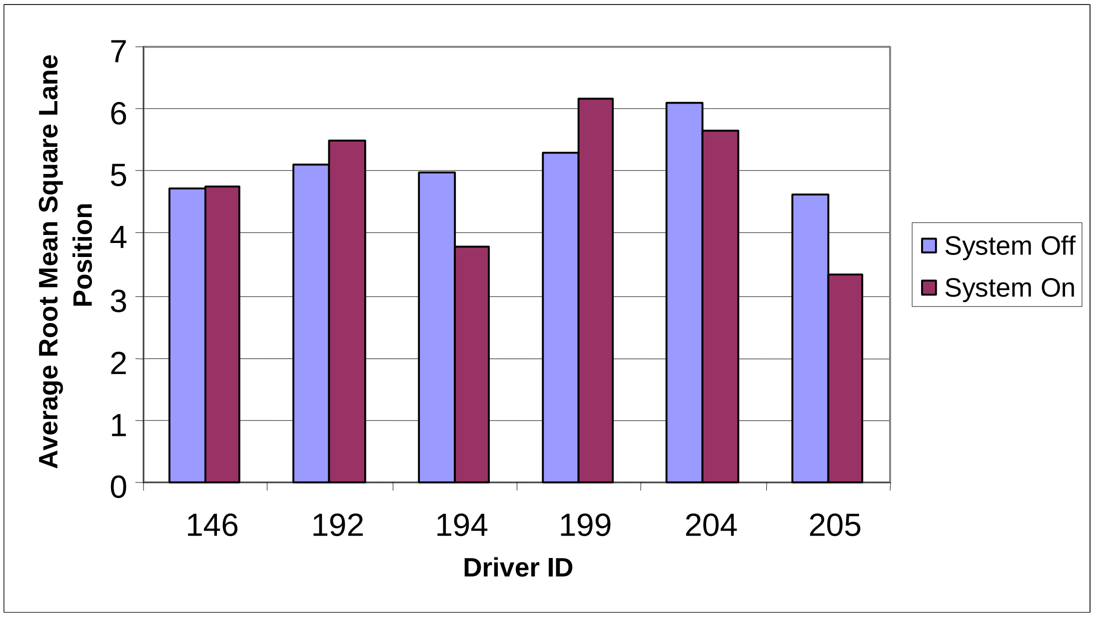

Figure 31. RMSLP by Driver

Table 36. Significant Predictors for the RMSLP Model

Variable	Significant Interaction with System Status
System Status	
Percent road speed > 35 mph	✓
Percent in curve*	✓
Average road speed	✓
Hours in motion in last 8 hours	
Hour of the day	✓

*Main effect was not significant at the 0.05 level.

System status was a significant predictor in this model (p-value < 0.0001). At the mean values of the predictors, the ratio of RMSLP with the active LDWS interface to the inactive LDWS interface was 1.036 with a 95 percent confidence interval of (1.027, 1.046).

The results were mixed for this covariate. With the active LDWS feedback, the RMSLP was significantly lower when driving at speeds below 50 mph or higher than 60 mph. However, the RMSLP was significantly higher when driving between 6 p.m. and 10 a.m.

The RMSLP is a statistical measure of the deviation of the truck from its mean position in the lane. Thus, a higher value indicated more meandering or weaving on the road (i.e., looser control of lane position). The results suggested that there is more apparent meandering from "sunset to sunrise." This driving behavior might be expected due to less traffic on the road, when the driver may intentionally drive faster, relax lane-keeping behavior, and purposely let the truck meander in and out of its lane. Also, this behavior may be an attempt by the driver to reduce workload and stress by relaxing his or her control of lane position.

Percentage of Time Out of the lane

The percentage of time out of the lane was calculated for each OPS file. Figure 32 shows a plot of the average percentage of time spent out of the lane by driver and system status.

This variable did not directly lend itself to analysis because of the high proportion of zeros. Instead of analyzing the percentage of time out of the lane directly, the percentage of time out of the lane (PTOL) was first categorized as either having any time out of the lane or none. This variable was then modeled using logistic regression. With the inclusion of a random effect for driver, the following model results

$$\log\left(\frac{P_{ij}}{1-P_{ij}}\right) = X_{ij}\beta + \gamma_j$$

where P_{ij} is the expected probability of observation *i* for driver *j* being out of the lane, X_{ij} is a

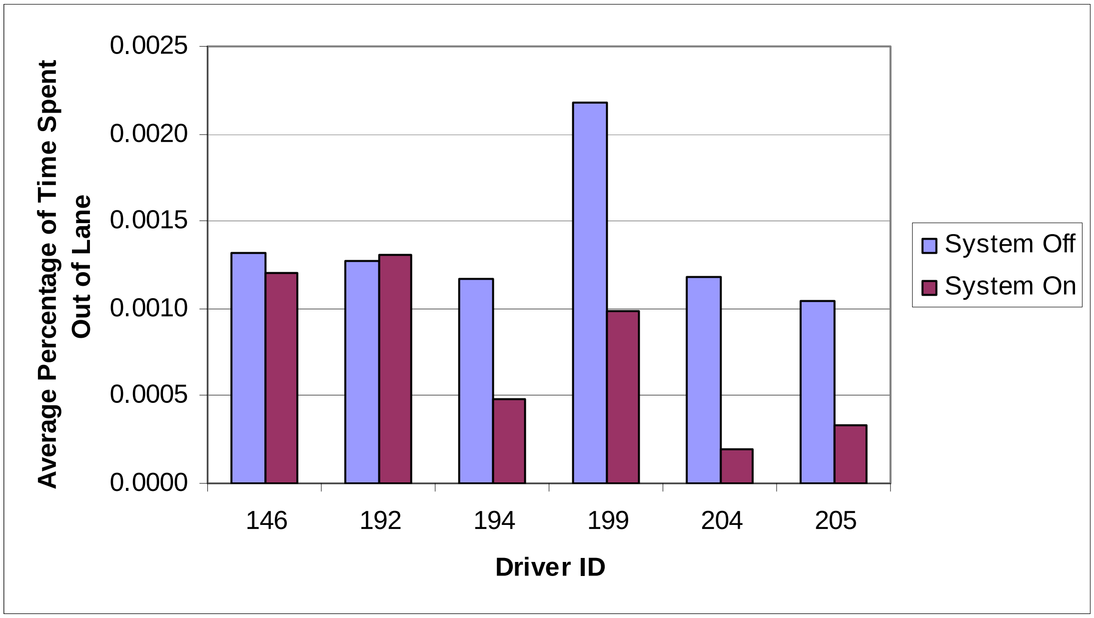

Figure 32. Percentage of Time Out of the lane by Driver

matrix of continuous and categorical predictor variables (e.g., average speed, system status), β is a vector of regression coefficients, and γ_j is a random effect for driver j. Table 37 lists the predictors that were significant at the 0.05 level.

Table 37. Significant Predictors for the Percentage of Time Out of the lane Model

Variable	Significant Interaction with System Status
System Status*	
Percent road speed > 35 mph	✓
Percent in curve	✓
Average road speed	✓
Hours in motion in last 8 hours	✓
Hour of the day	✓

*Main effect was not significant at the 0.05 level.

The main effect of system status was not significant (p-value=0.56), but it was significant in interaction terms. The effect of system status when covariates were set equal to their averages was highly significant (p-value <0.0001).

The results indicated that the PTOL is significantly lower with active LDWS feedback when less than 40 percent of the roadway is curved or when driving above 55 mph. In contrast, the PTOL was significantly higher with the system on when driving below 50 mph. These results suggest that with the LDWS feedback, drivers will not drift out of their lanes as much when roads are mostly straight and at highway speeds. Further, at lower speeds with the LDWS feedback, drivers may tend to go out of their lanes more. A possible explanation for this result is that, at lower speeds, drivers are less reliant on the LDWS feedback because they feel “safer” than at higher speeds. If curve-cutting is a significant portion of the drivers’ behavior in curves, then the data would not be expected to indicate an effect of the LDWS on PTOL in curves.

5.1.3 Objective 1A.3. What Are the Decreases in Crashes, Injuries, and Fatalities if These IVSS are Deployed Nationwide?

This section presents estimates of the potential safety benefits—in the form of reductions of crashes, injuries, and fatalities—under different deployment scenarios for the LDWS. The approach follows from the safety-benefits-estimation methodology for Objective 1A.3, which was summarized in Section 4.3.

Overview

The goal of this analysis was to extrapolate the estimated safety benefits of the LDWS tested in this FOT to different populations of trucks for which the systems might be deployed. Each year approximately 31,000 large trucks (i.e., trucks with gross vehicle weight over 10,000 lbs.) are involved in SVRD crashes and 2,000 are involved in untripped rollover crashes, which represents approximately 8 percent of all large truck crashes according to statistics from the General Estimates System of the National Automotive Sampling System (NASS; GES; FARS). Another 12 percent (52,000 trucks) are involved in lane-change/merge crashes. Since the LDWS alerts drivers about lane departures when turn signals are not used, it is expected that the LDWS will help avoid some portion of lane-change/merge crashes; however, these benefits were not evaluated in this FOT.

When the findings from a single field test are being extrapolated to a larger fleet there is a degree to which the findings are applicable to the target population. When performing the calculations to estimate the potential safety benefits of deploying these technologies in various target populations, considerations should be given to the types of trucks; driver demographics (age, gender, experience, safety record, etc.); carrier operational characteristics (long- or short-haul, familiarity with routes, types of cargo, etc.); and many other factors that might influence the use, performance, or benefits of the IVSS.

The population of approximately 8 million large trucks represents the largest population of interest for projecting safety benefits. Given the large variation in truck sizes and configurations within this broad category, it is useful to estimate safety benefits for additional target populations, such as all tractors pulling tankers and the fleet of all class 7 and 8 tractors pulling trailers and all tractors pulling HAZMAT tanker-trailers. This section describes the calculation of the potential safety benefits under various deployment scenarios and discusses how some of these factors might impact the benefits. However, it was beyond the scope of this study to evaluate how these different factors might alter the effectiveness of these technologies.

The safety benefit (B) of an IVSS technology for reducing the number of crashes preceded by a particular type of conflict scenario (S) is estimated using the equation:

$$B = N_{wo} \times P\left(S_i \middle| C\right) \times (1 - CRR_i),$$

where N_{wo} is the average annual number of SVRD or rollover crashes for trucks without the LDWS, $P(S_i|C)$ is the conditional probability that driving conflict S_i was the first harmful event given that a crash has occurred, and CRR_i is the estimated crash reduction ratio for the particular conflict type. The conditional probabilities $[P(S_i|C)]$ are estimated in GES by the relative frequency of driving conflicts determined from actual crash investigations (Table 6 and Table 7 above). After summing the benefits across all conflict types for each crash type (rollover and SVRD), the overall benefit of the LDWS for avoiding each crash type is estimated by:

$$B = N_{wo} \times Eff,$$

where *Eff* is the estimated overall efficacy or percentage reduction of a particular crash type that is attributable to deployment of the technology. This calculation was performed for each crash type and summed to obtain the overall benefit. The estimated reduction in the number of fatalities or injuries was calculated in the same manner using the number of fatalities or injuries for the term N_{wo}.

The primary focus of the safety benefits analysis was on driving conflicts where the truck traveled over the edge of the road while driving at a constant speed or where the driver loses control due to excessive speed. As shown in Table 6 and Table 7 previously, these types of conflicts account for approximately 58 percent of large truck SVRD crashes and 50 percent of large truck rollover crashes. For tractors pulling tanker-trailers, these conflicts account for 65 percent of the SVRD crashes and 90 percent of the rollovers.

The remainder of this section shows the benefits equation applied to the McKenzie Tank Lines fleet. Then, the results are extrapolated to the four operational scenarios consisting of all large trucks, tractor-trailer combinations, tractors pulling tanker-trailers, and tractors pulling tanker-trailers containing HAZMAT.

Characteristics of the McKenzie Tank Lines Fleet

As noted in Section 2.2, McKenzie Tank Lines, Inc., headquartered in Tallahassee, FL, operates a fleet of 585 tractors and approximately 1,000 trailers out of 30 locations, and serves customers across the United States and Canada. Almost all of the trailers are stainless steel, aluminum, high pressure, dry bulk, or specialized tankers. Approximately 65 percent of the deliveries involve HAZMAT. The average power unit travels approximately 75,000 miles per year. In this FOT, the average truck mileage was nearly 105,000 miles per year.

Examination of carrier information from the SafeStat system shows that McKenzie Tank Lines has a very good safety rating (USDOT 2005a). Over the past 30 months, nearly 1,200 roadside inspections were performed on McKenzie Tank Lines vehicles with less than 4 percent placed out-of-service (OOS). The national average OOS rate for vehicle inspections is 23 percent. During this same period, 2 percent of the 1,400 McKenzie Tank Lines drivers inspected received OOS orders, compared to the national average of 6.8 percent. McKenzie Tank Lines has an Inspection Selection System (ISS) rating of 28, which places it in the “Pass” category, since ISS recommends that trucks from carriers with ISS ratings of 1 to 49 be allowed to bypass an inspection station. Trucks from carriers with a rating of 75 to 100 are in the category to be inspected, while trucks from carriers with ISS ratings of 50 to 74 are in the optional category for inspections.

McKenzie Tank Lines’ SafeStat Safety Evaluation Area (SEA) scores for vehicle and driver inspections and violations were 23.4 and 26.6, respectively. The SEA score represents a percentile of the distribution of safety measures among motor carriers. For example, the vehicle SAE score of 23.4 means that this carrier’s vehicle OOS rate is lower than more than 75 percent of the carriers in the country.

SafeStat identified a total of 56 state-reported crashes involving McKenzie Tank Lines trucks that occurred within the last 30 months. These crashes produced 41 injuries and 6 deaths. At 44 million vehicle miles traveled (MVMT) per year, the rates of 0.51 crashes/MVMT, 0.37 injuries/MVMT, and 0.055 deaths/MVMT compare favorably with national averages. According to the FMCSA, the average large truck crash-rate, based on state-reported data, is 0.71 crashes/MVMT (Gruberg, 2005). From GES, the average injury and fatality rates for tractors with tanker-trailers are 0.50 injuries/MVMT and 0.05 deaths/MVMT.

For this evaluation, McKenzie Tank Lines provided a complete set of truck accidents and incident reports that occurred since 2002. Each of the nearly 1,000 reports contained a brief description of the incident. A detailed review of these reports identified 18 SVRD crashes, 3 rollover crashes, and 12 lane-change/merge (LCM) crashes that occurred during a three-year period from 2002 to 2004. The corresponding crash rates of 0.023 rollovers/MVMT, 0.136 SVRDs/MVMT, and 0.091 LCMs/MVMT are comparable to the national rates for tractors with tanker-trailers (0.006, 0.140, and 0.091, respectively) obtained from GES. No injuries or fatalities were reported in any of the McKenzie Tank Lines SVRD or rollover crashes during the period 2002 to 2004. It should be noted that classification criteria and available data used by the independent evaluator were very different from those used in GES; therefore, a statistical comparison of these rates is not meaningful. The above comparison simply demonstrates that McKenzie Tank Lines' accident rates are generally comparable with their industry.

Safety Benefits for the McKenzie Tank Lines Fleet

Section 5.1.1 described estimates of the efficacy of the LDWS for preventing SVRD and rollover crashes. The best estimates of the efficacies of the LDWS for preventing rollover and SVRD crashes involving tractor-trailer units are 23.9 percent and 23.5 percent, respectively. That is, 23.9 percent of the rollover crashes and 23.5 percent of the SVRD crashes involving tractor-trailers could be avoided through the deployment of LDWS (Table 32). The corresponding efficacies involving tractors pulling tanker trailers are 46.6 percent for rollovers and 21.9 percent for SVRD crashes. According to McKenzie Tank Lines, 97 percent of their fleet consists of tractors pulling tanker-trailers.

Based on the analysis of the crash reports provided by McKenzie Tank Lines for the three-year period from 2002 to 2004, McKenzie Tank Lines could be expected to experience an average of one rollover crash and 6 SVRD crashes per year. Therefore, the deployment of the LDWS to all McKenzie Tank Lines trucks could help avoid an estimated 0.466 rollovers per year (or approximately one rollover every two years) and 1.74 SVRD crashes per year (or over three SVDR crashes every two years).

Extrapolation of Safety Benefits to Other Fleets

Before estimating the potential safety benefits of IVSS technologies for other populations of trucks, the effect of characteristic differences between the McKenzie Tank Lines fleet and other target populations on the efficacy estimates obtained in this FOT should be considered. If the FOT had been conducted in such a way as to permit investigation of the effects of factors such as driver age and gender, carrier type, and truck type, the statistical analysis of the FOT driving data could be used to establish relationships between the levels of the characteristic of interest and the effectiveness of the safety system. However, this FOT was performed with one type of carrier and one type of truck (tractor pulling a tanker-trailer). Although the safety benefits for other populations of trucks can be calculated using the efficacy estimates from this FOT, the efficacy may or may not be the same for all truck types and carrier types. Nevertheless, separate estimates of average annual numbers of crashes, injuries, and fatalities without IVSS for each target population were obtained, and the estimated safety benefits took these different rates into account.

Table 38 shows the average annual number of trucks involved in rollover and SVRD crashes and the associated injuries and fatalities for four target fleets of trucks: all large trucks (>10,000 lbs GVW), tractor-trailer combinations, truck-tractors pulling tanker-trailers, and truck-tractors with HAZMAT tanker-trailers. The numbers of trucks involved in crashes and the numbers of injuries within each combination of truck fleet and conflict type, as well as the distribution of fatalities among conflict types for each fleet, were estimated from GES crash statistics for the five-year period from 1999 through 2003. The total numbers of fatalities for each combination of truck type and fleet were obtained from the FARS database. The FARS data were used because they are obtained from a census of all fatal accidents involving large trucks, rather than from estimates derived from sampled crashes as with GES.

Approximately 45 percent of the untripped rollovers among large trucks, including tractor-trailers, occurred while turning or in curved roadways. For tractors with tanker-trailers, almost 90 percent of the rollovers involved turns or curves where most of these crashes were attributable to driving at excessive speeds. Most of the remaining untripped rollovers involved vehicle failures or another vehicle encroaching or being present in the lane. The conflicts that led to SVRD crashes were more evenly divided among the two conflict categories (going straight and turning or in a curve) and the “other” category that included vehicle failures and encroaching vehicles.

The evaluation of the FOT driving data involved various conditional analyses of conflict rates and crash probabilities, which included an analysis to determine if the efficacy of the LDWS is related to driver age or years of experience. The analysis did not find a statistically significant relationship between driver age or experience and the efficacy of the LDWS. The implication of these findings was that adjustments were not necessary to the efficacy-estimate obtained in this FOT as the benefits were extrapolated to other populations of drivers.

The most applicable extension of safety benefits from this FOT to a larger fleet was to consider the impact of deploying these technologies to the fleet of all truck-tractors pulling tanker-trailers. Nationwide, there are approximately 112,000 tractors pulling tanker-trailers, with approximately 70 percent (78,500) carrying HAZMAT, according to the National Tank Truck Carriers, Inc. To illustrate the potential safety benefits of wider deployment, the safety benefits estimated in this FOT were also extrapolated to two larger populations, including the 1.8 million tractor-trailer units and the 8 million large trucks over 10,000 lbs. Although there is no evidence that the efficacies of the systems studied in this FOT are applicable to this diverse population of trucks, this calculation was performed to obtain an upper bound on the potential benefits for truck applications. Further discussions of the various fleet populations used in the safety-benefits calculations and the benefit-cost analysis are presented in Sections 4.2.4 and 5.9.2, respectively.

Table 38. Average Numbers of Untripped Rollover and Single Vehicle Roadway Departure Crashes and Associated Injuries and Fatalities, (1999-2003) by Crash Type and Conflict Category

Units	Fleet	Untripped Rollovers Going Straight[1]	Untripped Rollovers Turning or in Curve[1]	Untripped Rollovers Other[2]	Untripped Rollovers Total	Single Vehicle Roadway Departures Going Straight	Single Vehicle Roadway Departures Turning or in Curve	Single Vehicle Roadway Departures Other	Single Vehicle Roadway Departures Total
Trucks in Crashes	Large Trucks	121	929	1,018	**2,068**	7,087	11,026	13,225	**31,338**
Trucks in Crashes	Tractor-Trailers	80	736	747	**1,562**	3,266	7,492	5,879	**16,638**
Trucks in Crashes	Tanker-Trailers[5]		43	5	**48**	230	459	377	**1,067**
Trucks in Crashes	HAZMAT Tanker-Trailers[6]		6.5	2.2	**8.6**	49	163	99	**311**
Fatalities	Large Trucks	12	78		**90**	191	148	120	**458**
Fatalities	Tractor-Trailers	8.2	52		**60**	143	96	80	**319**
Fatalities	Tanker-Trailers		13		**13**	10	35	0.5	**46**
Fatalities	HAZMAT Tanker-Trailers		6.2		**6.2**	4.2	14	0.2	**19**
Injuries	Large Trucks	110	693	725	**1,528**	2,516	2,435	3,513	**8,463**
Injuries	Tractor-Trailers	76	608	503	**1,187**	1,329	1,417	1,580	**4,326**
Injuries	Tanker-Trailers		14	3	**17**	92	286	165	**543**
Injuries	HAZMAT Tanker-Trailers		2.1	0.9	**3.0**	27	124	59	**210**

[1] Includes traveling over lane line or road edge and loss of control due to excessive speed.
[2] Other conflicts include vehicle failures or another vehicle encroaching or present in the lane.
[3] Over 10,000 lbs GVW.
[4] Class 7 or 8 tractor with at least one trailer.
[5] Tractor pulling a tanker-trailer.
[6] Tanker-trailers with HAZMAT placard.

Table 39 illustrates how the CRRs estimated for each conflict type were applied to the average annual numbers of SVRD crashes involving tractor-trailers. For this illustration, the “best estimate” CRRs was used, which included the estimated PRs that were not statistically significant. The total numbers of crashes predicted with the LDWS within each conflict type were summed and compared to the total number of crashes without the LDWS to determine the total number of crashes avoided and the percentage reduction in crashes.

Table 39. Estimated Annual Numbers of Tractor-Trailer SVRD Crashes Avoided Due to the Deployment of LDWS Using the “Best Estimate” Crash Reduction Ratios

SVRD Conflict Type	Total Tractor-Trailer Crashes	Percent of Total	Crash Reduction Ratio	Crashes with LDWS
Going Straight	3,266	19.6%	1.2	3,957
Turning or in Curve	7,492	45.0%	0.4	2,883
Other	5,879	35.3%	1.0	5,879
Total	**16,638**	**100%**		**12,719**
Crashes Avoided	**3,919**		**%of Total Crashes**	**23.6%**

The same approach was used in Table 40 to calculate the numbers of injuries and fatalities avoided with the deployment of LDWS to each of the other scenarios. Also, Table 41 shows the results using the “Conservative” crash reduction ratios, using the default values of 1 for the PRs.

Table 40. Estimated Annual Numbers of Trucks in Crashes, Injuries, and Fatalities Based on “Best Estimate” Efficacies of LDWS

Units per Year	Fleet	Rollover Reduction	% of Total	SVRD Reduction	% of Total
Trucks in crashes	All Large Trucks[1]	470	23%	5,282	17%
Trucks in crashes	Truck-Tractor with Trailer[2]	374	24%	3,917	24%
Trucks in crashes	Truck-Tractor with Tanker-Trailer[3]	23	47%	234	22%
Trucks in crashes	Truck-Tractor with HAZMAT Tanker-Trailer[4]	3.4	39%	90	29%
Fatalities	All Large Trucks[1]	39	43%	51	11%
Fatalities	Truck-Tractor with Trailer[2]	26	43%	29	9%
Fatalities	Truck-Tractor with Tanker-Trailer[3]	6.6	52%	19	43%
Fatalities	Truck-Tractor with HAZMAT Tanker-Trailer[4]	3.2	52%	8.0	43%
Injuries	All Large Trucks[1]	348	23%	965	11%
Injuries	Truck-Tractor with Trailer[2]	308	26%	590	14%
Injuries	Truck-Tractor with Tanker-Trailer[3]	7.3	43%	156	29%
Injuries	Truck-Tractor with HAZMAT Tanker-Trailer[4]	1.1	36%	70	33%

[1] Over 10,000 lbs GVW.
[2] Class 7 or 8 tractor with at least one trailer.
[3] Tractor pulling a tanker-trailer.
[4] Tanker-trailers with HAZMAT placard.

Table 41. Annual Numbers of Trucks in Crashes, Injuries, and Fatalities Avoided Based on "Conservative" Estimates of LDWS Efficacies

Units per Year	Fleet	Rollover Reduction	% of Total	SVRD Reduction	% of Total
Trucks in crashes	All Large Trucks[1]	349	17%	5,912	19%
Trucks in crashes	Truck-Tractor with Trailer[2]	272	17%	3,532	21%
Trucks in crashes	Truck-Tractor with Tanker-Trailer[3]	15	30%	226	21%
Trucks in crashes	Truck-Tractor with HAZMAT Tanker-Trailer[4]	2.2	25%	70	23%
Fatalities	All Large Trucks[1]	30	33%	109	24%
Fatalities	Truck-Tractor with Trailer[2]	20	33%	77	24%
Fatalities	Truck-Tractor with Tanker-Trailer[3]	4.3	34%	15	33%
Fatalities	Truck-Tractor with HAZMAT Tanker-Trailer[4]	2.1	34%	6.1	33%
Injuries	All Large Trucks[1]	266	17%	1,603	19%
Injuries	Truck-Tractor with Trailer[2]	227	19%	891	21%
Injuries	Truck-Tractor with Tanker-Trailer[3]	4.7	28%	125	23%
Injuries	Truck-Tractor with HAZMAT Tanker-Trailer[4]	0.7	23%	50	24%

[1] Over 10,000 lbs GVW.
[2] Class 7 or 8 tractor with at least one trailer.
[3] Tractor pulling a tanker-trailer.
[4] Tanker-trailers with HAZMAT placard.

5.1.4 Objective 1A.4. Will Drivers Using LDWS Have Less Severe Crashes?

Because no crashes occurred during the FOT, it was not possible to measure crash severity directly. Alternatively, surrogate measures of crash severity were used to compare large lane excursions that occurred with and without the use of the LDWS.

Using the computer simulation model, the point when the driver initiated a recovery maneuver was estimated for each LEX file. The lateral velocity of the truck at this point was calculated using the following equation:

$$V_{LAT,R} = V \cdot \sin\theta_R \text{, ft/s}$$

where $V =$ forward speed in ft/s and $\theta_R =$ yaw angle of tractor in radians. The parameter $V_{LAT,R}^2$ was selected as a surrogate measure of crash severity based on the following assumptions:

1. The severity of a crash into a roadside feature (e.g., guardrail, light pole) generally increases with the "lateral" kinetic energy ($KE_{LAT,R}$) of the truck, where

$$KE_{LAT,R} = 1/2 \cdot m \cdot V_{LAT,R}^2 \text{, ft-lbf}$$

and m is the mass of the truck in lbf-sec^2/ft.

2. The potential severity of a crash is related to the speed and heading of the truck just before the driver begins a recovery maneuver.

3. The LDWS may reduce crash severity by alerting the driver and enabling him or her to initiate a recovery maneuver sooner than if the LDWS were not active. This is because the tractor yaw angle should be smaller.

Using a similar rationale, a second surrogate measure, the square of the lateral velocity at hypothetical impact, $V_{LAT,I}^2$, was calculated by assuming that the driver did not initiate a recovery maneuver, and the truck continued to move out of the lane at a value of constant yaw rate estimated just before the recovery maneuver was initiated in the measured LEX event.

A summary is provided in Table 42, which compares the potential crash severities for trucks with and without the LDWS on the basis of the surrogate measures $V_{LAT,R}^2$ and $V_{LAT,I}^2$. The results indicate that there is no significant difference in potential crash severity for drivers with and without an active LDWS interface. These results reveal that the LDWS is designed to reduce exposure to driving conflicts associated with SVRDs and rollovers, and not to reduce the consequences of a driving conflict that has already occurred.

Table 42. Comparison of Potential Crash Severities

Driver ID	Truck ID	$V^2_{LAT,R}$ (ft/s)^2 Without LDWS	$V^2_{LAT,R}$ (ft/s)^2 With LDWS	$V^2_{LAT,I}$ (ft/s)^2 Without LDWS	$V^2_{LAT,I}$ (ft/s)^2 With LDWS
146	6101	0.26	0.36	2.43	2.69
192	6106 / 6112	0.50	0.66	2.66	2.46
194	6120	0.33	0.05	2.44	2.29
199	6102	0.39	0.30	2.79	2.21
204	6115	0.52	0.26	1.33	2.39
205	6134	0.51	0.52	2.58	3.18
All	All	0.37	0.39	2.56	2.60

5.2 Goal 1B. Assess Mobility Benefits

Goal 1B involves evaluating the effects of IVSS on mobility, and measuring any mobility benefits to the general public that will accrue from the deployment of IVSS. Mobility is measured by the net benefits to travelers or other transportation consumers from a transportation improvement. Mobility benefits, in the form of reduced costs to society from avoided delays caused by crashes, were applied to the benefit-cost analysis outlined in Section 5.9.

5.3 Goals 1C and 1D. Assess Efficiency and Productivity Benefits

Goals 1C and 1D involve evaluating the efficiency and productivity benefits from using the IVSS. In economics, "efficiency" means maximizing total net benefits from an investment or policy. To an economist, "efficiency" includes *all* of the IVSS goals that have a dollar value to society. However, engineers more narrowly define "efficiency" as *more output per unit of input*. Measures of achieving the engineering efficiency goal do not enter into a benefit-cost analysis (BCA), because increased output per unit of input is best measured in transportation as increased throughput or capacity (e.g., vehicles per hour). Converting this benefit to a dollar value to society falls under the productivity goal in the form of cost savings. Thus, the efficiency and productivity goals were combined for purposes of this evaluation.

"Productivity" means *lower costs to produce a given level of output*. Cost savings are the most important measure of achievement of the IVSS productivity goal (e.g., cost per vehicle mile traveled, reduced truck transit time, etc.). This benefit includes the savings that result from IVSS, primarily through reduced numbers and severity of crashes. These cost savings have value to society, enter into the calculation of the net worth of IVSS investments, and were used as crash cost avoidance inputs to a formal benefit-cost analysis, which is summarized in Section 5.9.

5.4 Goal 1E. Assess Environmental Quality Benefits

Environmental benefits from lower costs for responding to and recovering from HAZMAT incidents, with or without releases of HAZMAT, were included in the analysis. A summary of environmental benefits is presented in Section 5.9.

5.5 Goal 2. Assess Driver Acceptance and Human Factors

Driver acceptance and human factors were assessed through the use of surveys. Because only six drivers responded to the surveys, it is not possible to say with a high degree of statistical confidence that these findings are representative of all truck drivers' opinions about the LDWS. However, the surveys provided a range of reactions to driving with the LDWS in the FOT. The results of the driver acceptance study can be summarized as follows:

- ♦ Surveys of drivers to determine their perceptions of the LDWS had mixed results; some drivers believed that driving with an active LDWS interface helped their driving, and others believed that it hindered their driving. In general, drivers thought that the LDWS was easy to use and understand, but that formal training was needed to ensure proper operation. Positive comments noted that the LDWS helped maintain alertness (especially in late-night driving), improved concentration on the driving task, and helped the driver to drive in a straighter path. Negative comments noted that the location of the LDWS on the dash obscured the view; the alert tones were annoying, startling, and sometimes difficult to distinguish from tones from other systems in the truck; and the LDWS contributed to general "information overload."

- ♦ Drivers were surveyed to evaluate their opinions on whether or not they drive more safely with the LDWS. The majority felt that driving with the LDWS improved their lane-keeping ability, but it did not change other aspects of their safety-related driving, such as:
    - Turn signal usage
    - Risk-taking as a result of a greater awareness of safety hazards
    - Anticipation of a need to brake
    - Maintaining safe speeds
    - Frequency of rest stops
    - Alertness and focus on the driving task

Yet, for each of these aspects, at least one out of six drivers believed that his or her safe driving improved with the LDWS.

In the following sections, the results from the post-activation survey are organized according to the four study objectives under Goal 2. Since the baseline data collection contained too few cases to support a separate analysis of these data, findings from the limited baseline "before" data are noted where appropriate in comparison to the "after" data. Since the CWS was standard equipment on McKenzie Tank Lines' tractor fleet, McKenzie Tank Lines drivers were used to normally driving with an active CWS before driving with a LDWS in the FOT. Therefore, the results may be biased, since the survey included drivers' responses to the same questions for both the newly introduced LDWS and the more familiar CWS. In several questions, the surveyed drivers were asked to compare these systems, despite the fact that the CWS was not evaluated in this FOT; therefore, the results are likely skewed and not a true reflection of drivers only using the LDWS.

Also, due to the small number of responses, findings from these surveys may not be relevant to all truck drivers. Since statistically meaningful conclusions cannot be drawn from the survey results, the results simply reveal examples of the range of reactions to driving with the LDWS as provided by a small number of drivers in the FOT.

5.5.1 Background

IVSS are relatively new technologies that require drivers to be able to interpret and make appropriate driving responses to the information provided by these systems in order to enhance their overall driving safety. In the survey, drivers were asked whether they have access to a home computer and how much time they spend using those computers. The intent was to provide a measure of their exposure to computing technology and an indirect indicator of their level of comfort with new electronic technologies. The presumption was that drivers who regularly interact with computers are more likely to feel comfortable with similar technologies in their truck than those who do not use computers. Note that the survey questions use the name of the manufacturers, VORAD for the CWS and SafeTRAC for the LDWS, to reference the different IVSS.

As shown in Table 43, seven of the drivers who answered this question had access to a computer at home and used it a few hours a week on average. Due to the low number of responses, additional inquiry would be needed to completely understand driver comfort with on-board technology.

Table 43. Computer Use by Drivers at Home

Question	Yes	No	Skipped or Missing	N/A	N/A	N/A	Response N=14
Do you have access to a computer at home?	7	3	4				14
Question	**No time**	**1—2**	**3—4**	**5—6**	**7+**	**Skipped or Missing**	**Response N=14**
How much time do you spend using a computer at home? (Hours per week)	0	4	2	1	0	7	14

The drivers who responded to these surveys were experienced drivers, as shown in Figure 33. On average, these drivers had more than 18 years of truck-driving experience; however, the respondents' experience ranged widely from one driver with less than 1 year to four drivers with 30 or more years of experience.

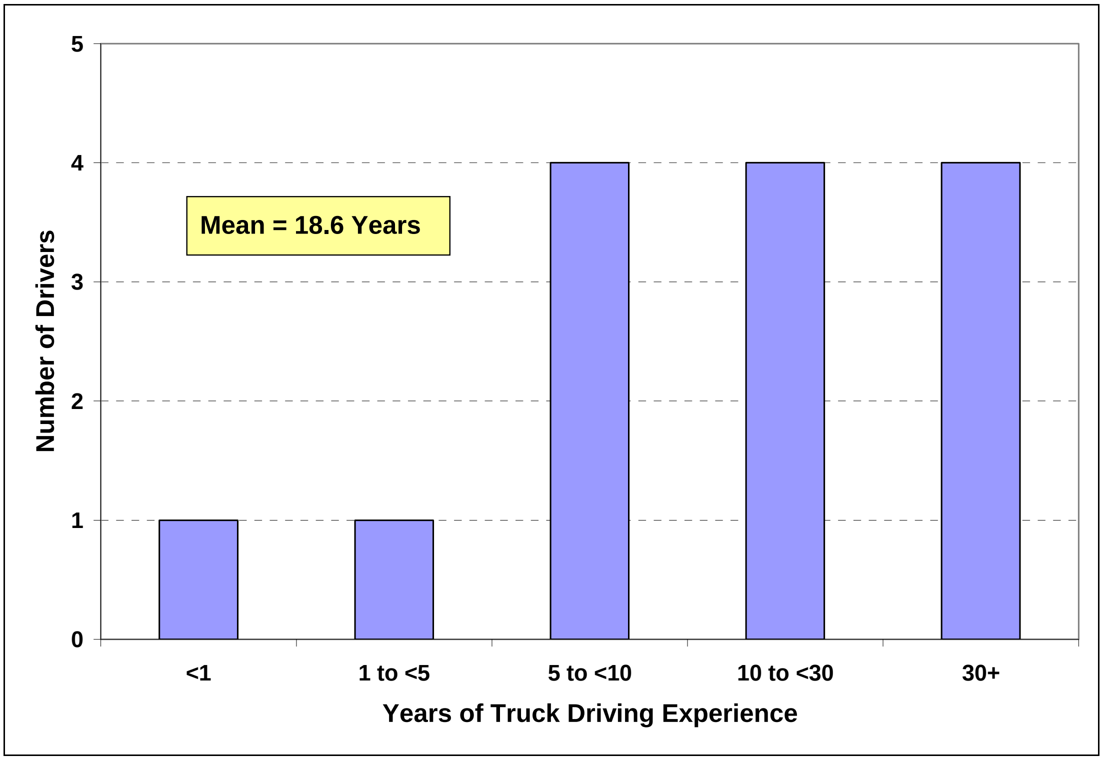

Figure 33. Years of Truck Driving Experience

Also, drivers were asked to report the number of years that they had been driving for McKenzie Tank Lines. As shown in Figure 34, the drivers responding to these surveys had driven an average of nine and a half years for McKenzie Tank Lines, ranging from less than 1 year to 20 years or more. These data indicated that most of these respondents are very experienced truck drivers.

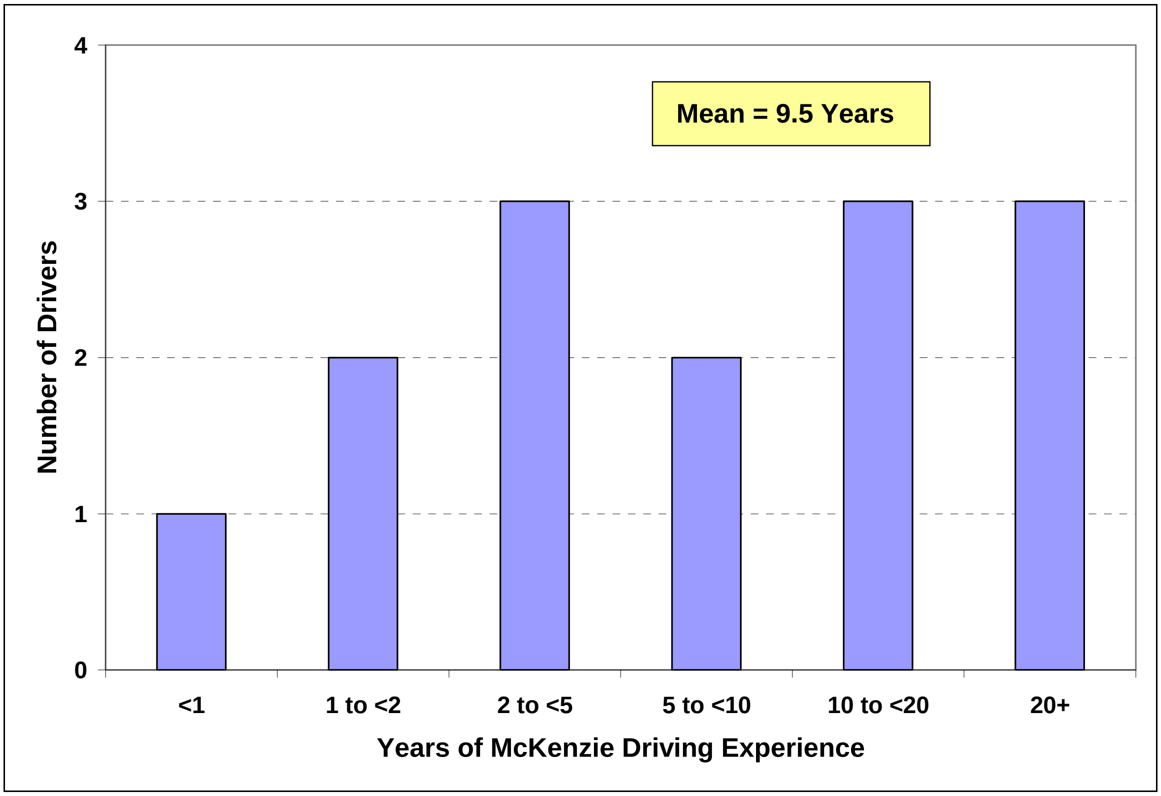

Figure 34. Years of Experience Driving for McKenzie Tank Lines

In addition to general driving experience, it was important to know how long these drivers had driven a truck with an active CWS. The respondents to the survey reported they had between 1 and 5 years of driving experience using the CWS, whether for McKenzie Tank Lines or any other company. The average for those responding was 2.3 years of experience using the CWS.

Less driving experience with an active LDWS was expected; therefore, this experience was measured in weeks. The result for 11 drivers was 54.6 weeks or just over 1 year of experience on average using the LDWS, as shown in Figure 35. The experience using the LDWS ranged from 6 weeks for two drivers to 3 years for one of the drivers.

Three of the drivers stated that they had *never* driven a truck with the LDWS activated. These respondents were instructed to skip the remaining questions regarding perceptions and uses of the LDWS.

The drivers who had driven with the active LDWS were asked to estimate the percentage of activated time that the LDWS worked properly. As shown in Figure 36, two drivers said it *never* worked properly, and for more than half the remaining drivers, the LDWS did not work properly for a significant portion of their driving experience with this technology.

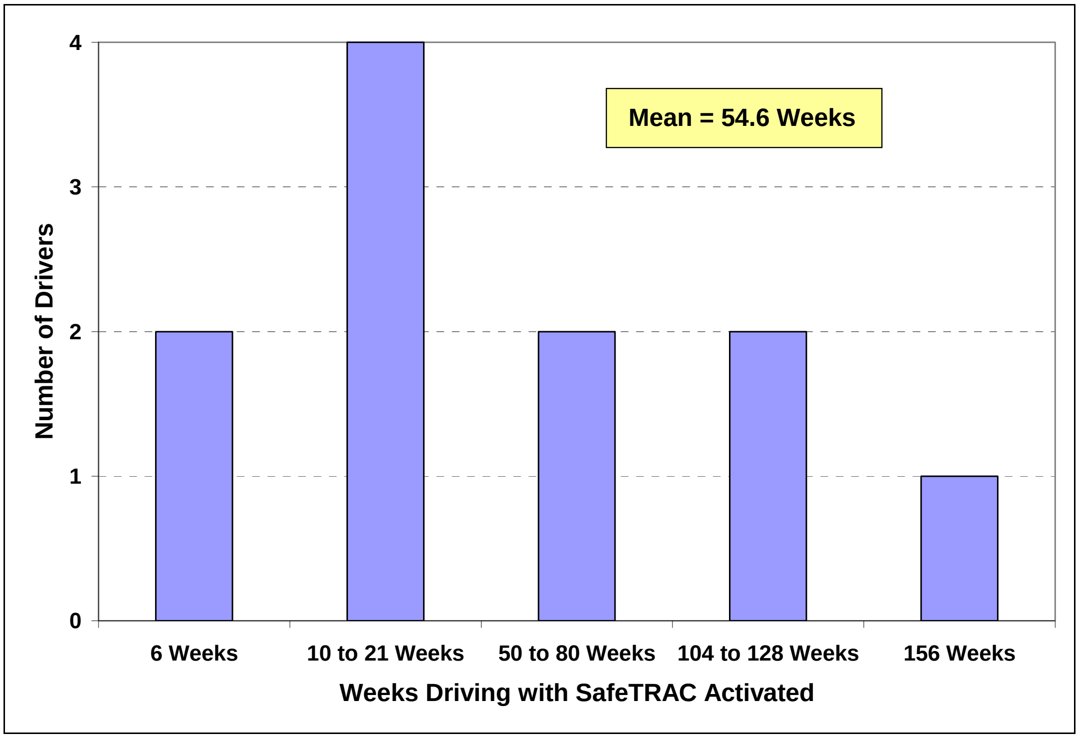

Figure 35. Weeks Driving with the LDWS Activated

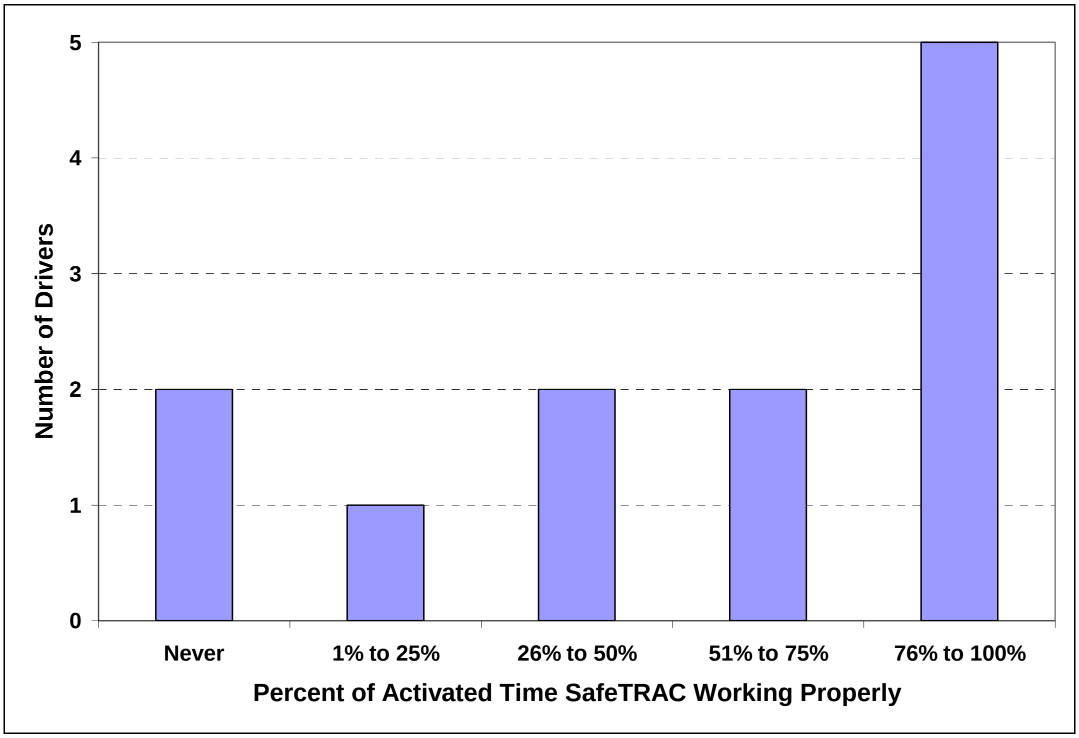

Figure 36. Percentage of Time the LDWS Was Working Properly

The drivers who reported that the LDWS sometimes did not work properly in their trucks were asked to briefly describe the problems in their own words. Table 44 shows these comments that are grouped by the indications of the percentage of time that the LDWS worked properly.

Table 44. Driver Comments Describing Problems with LDWS

Percentage of Time Working Properly	Driver Comments
1% to 25%	♦ "Alarms go off when truck is not moving. And it is very distracting."
26% to 50%	♦ "Just didn't come on." ♦ "Electrical"
51% to 75%	♦ "No problem, just buzzers going off."
76% to 100%	♦ "Misjudging where the lanes are. Unable to see road at dusk and dawn." ♦ "The center bar sometimes sticks to the outer bar and will not come off, even if you reset. Sometimes you can be driving in the center of your lane and it shows you on the edge." ♦ "Did not always go off due to the stripes on the road that were poorly maintained. Also keeps beeping (single) while there was no lane changing or other activity going on to make it go off." ♦ "Cable to camera."

5.5.2 Objective 2.1. Usability of IVSS Technologies

The survey also focused on how IVSS are used and understood by the drivers. It examined usability under normal driving conditions in terms of ease of learning and adequacy of training, the understandability of signals and controls, and factors affecting usability, such as driver understanding and use of system components.

The Evaluation Plan's nine hypotheses under Objective 2.1 are shown in Table 45, yet tests of statistical significance were not meaningful for these data, given the small number of respondents to the surveys. Therefore, formal statistical tests of these hypotheses were not performed. Instead, the open-ended responses were informally assessed.

Table 45. Usability of IVSS Technologies

Evaluation Hypotheses	Informal Assessment	Sections
Drivers find the IVSS and components easy to learn.	Yes, for the most part	Training and Learning
Drivers believe that they are adequately trained to use these systems.	Most said “no”	Training and Learning
Drivers find the IVSS and components easy to use and control.	Insufficient data to answer	Understandability
Drivers understand the IVSS capabilities.	Most appear to understand	Understandability
Drivers understand the signals and controls.	Most lack a full and accurate understanding	Understandability
Drivers perceive that the IVSS signals are recognizable and easy to see or hear.	Mostly yes	Usability
Drivers understand how to use information from the IVSS.	Yes, for CWS Mixed for LDWS	Usability
Drivers believe that the IVSS messages are unambiguous and clearly understood.	Most appear to understand	Usability
Drivers have reasons for using the IVSS under specific, if not all, driving conditions.	Insufficient data to answer	Usability

Training and Learning

Table 46 presents survey results regarding the helpfulness of training and ease of learning for both the CWS and LDWS. First, drivers were asked whether they received training or not for each of these technologies. Only three drivers received training for both of the IVSS technologies, and they stated that the training was generally helpful to them.

Overall, the drivers stated that it was easy to learn how to use the CWS and LDWS, whether or not they received training. Four drivers stated that it was less than “very easy” for them to learn how to use the LDWS. The drivers cited that training, or a “proper explanation of functions” would be an aid in learning how to use these systems.

Table 46a. Driver Training and CWS and LDWS Usage—Questions 1 and 2

Question	Yes	No	Skipped or Missing	Response N=14
Did you receive CWS training?	3	9	2	14
Did you receive SafeTRAC training?	3	11	0	14

Table 46b. Driver Training and CWS and LDWS Usage—Questions 3 and 4

Question	Very helpful: 5	4	3	2	Not at all helpful: 1	Skipped or Missing	Response N=14
How helpful would you say CWS training was for you?	1	2	0	0	0	11	14
How helpful would you say SafeTRAC training was for you?	1	0	1	0	0	12	14

Table 46c. Driver Training and CWS and LDWS Usage—Questions 5 and 6

Question	Very easy: 5	4	3	2	Not at all easy: 1	Skipped or Missing	Response N=14
Overall how easy is it to learn how to use the CSW system?	8	2	1	0	0	3	14
Overall how easy is it to learn how to use the SafeTRAC system?	5	1	3	0	0	5	14

In summary, these surveyed drivers report that both the LDWS and CWS were easy to learn to use but that training should be improved.

Understandability

In order to use IVSS effectively and to derive their full benefits, drivers need to understand the capabilities of these systems and how they work. As described previously, the LDWS provided alerts using different combinations of tones, depending on the driving situation. To assess driver understanding of these aspects of the LDWS, drivers were asked to describe in their own words the meaning of the alerts and index score.[2] Based on the results presented in Table 47, it is apparent that some of these drivers lacked an accurate understanding of this system, primarily due to a lack of training. There was equivalent misunderstanding in the baseline results.

Table 47. Driver Understanding of the LDWS Alerts and Index Score

SafeTRAC can give two different alert tones or beeps, either a single short beep or a multi-tone sequence of 4 beeps. What does the short beep indicate?	SafeTRAC can give two different alert tones or beeps, either a single short beep or a multi-tone sequence of 4 beeps. What does the multi-tone sequence indicate?	SafeTRAC can also provide the driver a driving index score. What does this index score mean, and how should the driver respond to it?
"You're getting too close to either shoulders of the road."	"You're off the shoulder for a long length of time."	"The higher the score, the better steering control you have. The lower the score the less control you have."
"Never been trained."	"Never been trained. All I know that it beeps when something gets close."	"Don't know – never been trained but I see 95 upon screen."
"Don't know. I shut it off. It is a very irritating and distracting system."		"?"
"Don't know (no training)."	"Don't know (no training)."	"Don't know (no training)."
"Crossing a broken line without indicating."	"Crossing a solid line without indicating."	"Provides an indication of performance and level of concentration."
"You have crossed over outer line which is not a solid line/hash line."	"You have crossed the outer lines of the lane you are traveling in that has a solid line."	"If it's a high score, you're staying in your lane. If it's a low score, you're crossing the outer lines of your lane. Which means you're getting drowsy or you're driving in a lot of road construction."
"Lane changes."	"Drowsy driver alert."	
"Approaching object."	"Too close."	"Percent of time in your lane."
"Crossing a solid line."	"Crossing a dash line."	"It tells the driver how well he is staying in his lane and holding a straight line. If the driver is all over the lane, the score will be lower."

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[2] Although the "alertness score" was not evaluated in the Mack FOT, this feature could be viewed by the drivers in the FOT; therefore, the survey included some questions relating to this feature of the SafeTRAC LDWS.

In addition to the CWS and LDWS in the drivers' trucks, other automated systems on their trucks, such as a backup warning or a left-side-blind-spot warning system, could provide separate alerts or other sounds that could be confused with the SafeTRAC LDWS. Of the 10 drivers who answered this question, five drivers indicated that the following systems were also in their trucks:

- "Left side warning"
- "Blind spot warning system"
- "Geocell – Tells driver of potential dangerous intersections by highway number and name, (crash intersections) curves (rollovers), hazardous areas (construction), and long crash area"
- "Right side warning"
- "Satellite"

As shown in Table 48, several drivers noted that the LDWS audible alerts could not be easily distinguished from other systems' audible alerts.

Table 48. Ease of Distinguishing the LDWS Alerts from Other Alerts

Question	Very easy: 5	4	3	2	Very hard: 1	Skipped or Missing	Response N=14
On a scale from 1 to 5, where 1 is **very hard** and 5 is **very easy**, how easily distinguishable are the **SafeTRAC** audible alerts from other systems in your truck(s), including **VORAD**?	1	1	3	2	3	4	14

The drivers were also asked to indicate why or under what conditions these different alerts might not be easily distinguished from each other. Specifically with regard to the LDWS versus the CWS, drivers stated:

- "Similar beeps"
- "VORAD keeps warning you where SafeTRAC doesn't"
- "Different sound"
- "If a car cuts close in front of you and you move to miss and you crossed the lane"

With regard to LDWS versus any other system, drivers said:

- "QUALCOMM"
- "When the Satellite has a message it will beep one time like you had crossed the lane"
- "My QUALCOMM has a very similar tone and they are pretty well next to each other. I have to actually look at them to see which one is beeping" (From baseline survey)

In summary, several of the surveyed drivers lacked a clear understanding of the SafeTRAC LDWS. Other drivers understood the purpose and capabilities of IVSS despite the lack of training and the inability to distinguish alerts from multiple systems.

Usability

Usability relates to the ability of drivers to understand how to use these systems properly and effectively. Figure 37 shows the surveyed drivers' perception of whether or not they had a good understanding about how to use the LDWS and CWS. Even though their understanding of the meaning of the SafeTRAC LDWS alerts was incomplete, most of the respondents stated that they had a good understanding of how to use these systems. In contrast, there was solid agreement among drivers that they understood how to use the CWS.

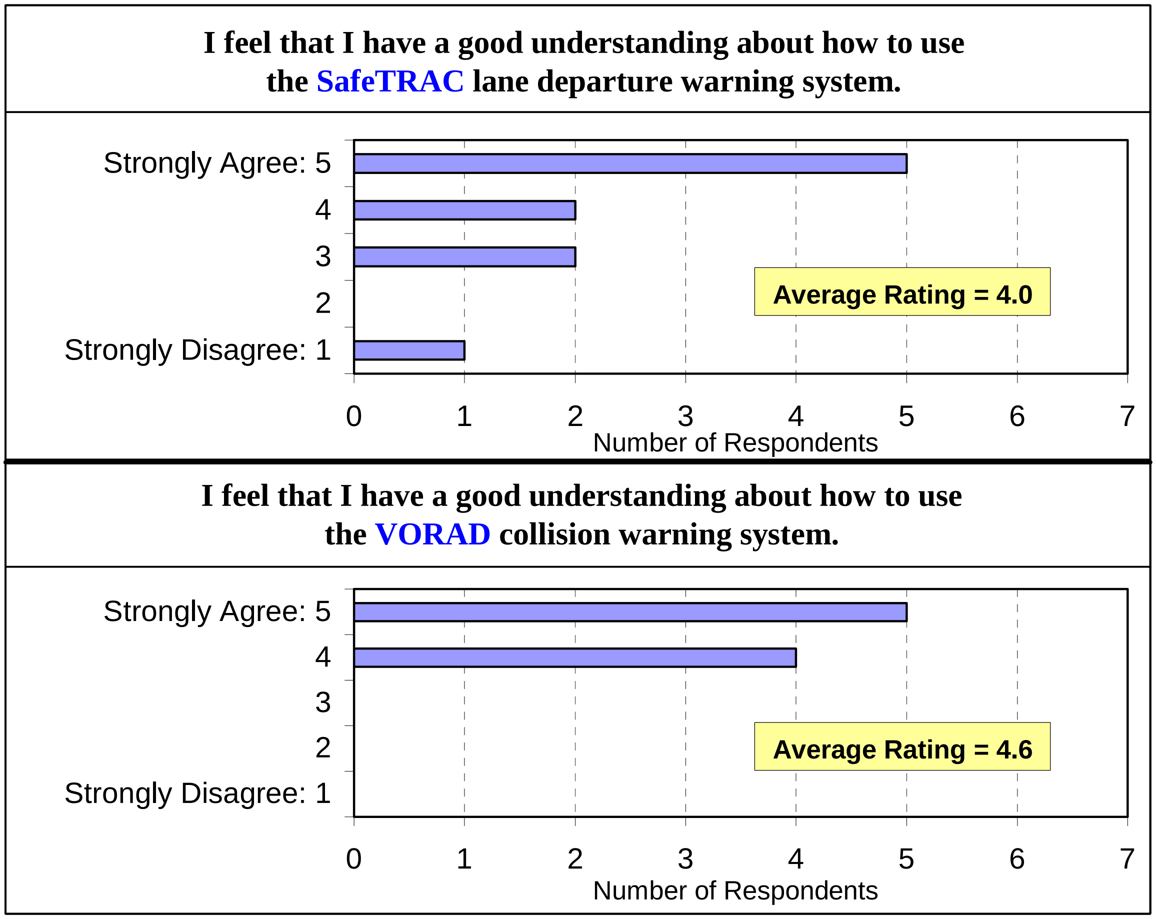


Figure 37. Driver Understanding of How to Use the LDWS and CWS

To understand whether drivers thought that the LDWS signals were recognizable and easy to see or hear, drivers were asked to rate (on a 5-point scale from "very hard" to "very easy") how easy or hard it was to distinguish the two LDWS warning tones from each other in practice (usability). As shown in Table 49, none of the nine respondents said that it was hard to tell the difference.

Table 49. Ease of Distinguishing Different LDWS Alert Tones

Question	Very easy: 5	4	3	2	Very hard: 1	Skipped or Missing	Response N=14
SafeTRAC gives two different warning tones, one for lane departures and another for a drowsy driver alert. On a scale from 1 to 5, where 1 is **very hard** and 5 is **very easy**, how easy is it to distinguish these two warning tones from each other?	3	4	2	0	0	0	14

When the drivers were asked to indicate why, or under what conditions, these tones might not be easily distinguished from each other, they reported the following reasons:

- "Believe me, I know what it is. I hate the sound—very distracting and a view blocker because it is mounted on the dash."
- "I don't know which one is which and try to ignore them."
- "Other similar tones and beeps in cab (indicators, QUALCOMM, etc.)"
- "If you were drowsy and did not pick up on alert"
- "Short tones long tones"
- "There are a lot of tones in the unit with SafeTRAC and VORAD and Satellite. One warning system for all would be nice"

5.5.3 Objective 2.2. Driver Distraction, Stress, Workload, and Acceptance

This section focuses on how drivers experience IVSS in their day-to-day driving. It examines potential distraction effects of the systems, effects on driving stress and fatigue, effects on the workload or level of focus and concentration required in their driving tasks under various driving conditions, and their effect on driver satisfaction, trust in the systems, and perceived effectiveness of the IVSS.

The Evaluation Plan's eight hypotheses under Objective 2.2 are shown in Table 50. Tests of statistical significance were not meaningful for these data given the small number of respondents to the surveys; therefore, an informal assessment is shown.

Table 50. Driver Distraction, Perceived Stress, Workload, and Acceptance

Evaluation Hypotheses	Informal Assessment	Sections
Drivers perceive that IVSS do not distract them or interfere with their other tasks.	Some say they distract; some don't	Driver Distraction and False Alerts
Drivers perceive that IVSS false positive alarms are a nuisance.	Yes, but more for LDWS than CWS	Driver Distraction and False Alerts
Drivers perceive that IVSS false negative alarms degrade their confidence in the systems.	Yes, but more so for LDWS than CWS	Driver Distraction and False Alerts
Drivers perceive that the IVSS reduce their levels of stress or fatigue.	No for LDWS, yes for CWS	Stress and Fatigue
Drivers perceive that SafeTRAC reduces their driving workload.	Yes for all conditions	Driver Workload
SafeTRAC increases job satisfaction of drivers.	Does for some, not for others	Driver Acceptance
Drivers trust the IVSS and perceive that they are useful.	More trust in CWS than in LDWS	Driver Acceptance
Drivers perceive that SafeTRAC is effective under specific (if not all) driving conditions.	Yes (conditions noted in text)	Driver Acceptance

Driver Distraction and False Alerts

IVSS should assist drivers under a variety of difficult driving conditions without distracting them or interfering with their driving tasks. As shown in Table 51, drivers were asked to indicate whether the LDWS's visual and auditory warnings diverted their attention from their driving tasks or helped focus their attention on those tasks. Three of the nine drivers who responded to these questions said the LDWS's visual and audible alerts distracted them "a lot". The remaining six drivers found the audible alerts to be less distracting and focused their attention on the driving task more than on the visual alerts.

When asked to explain how the LDWS's visual display and audible alerts were distracting and to indicate how often this happens, the drivers provided the comments shown in Table 52. The varied driver reactions included a belief that technology is not needed by experienced drivers, the audible tones are loud and irritating, and the LDWS tends to interfere with driving concentration. On the other hand, some drivers felt that the LDWS aided their attention.

Table 51. LDWS Visual and Audible Alerts

Question	Helps focus 5	4	3	2	Distracts a lot 1	Skipped or Missing	Response N=14
Considering the **visual warnings** provided by **SafeTRAC**, please mark how much **SafeTRAC**'s visual display distracts your attention away from your driving tasks or helps focus your attention on your driving tasks.	1	1	3	1	3	4	14
Considering the audible warnings provided by **SafeTRAC**, please mark how much **SafeTRAC**'s auditory warning (beep) distracts your attention away from your driving tasks or helps focus your attention on your driving tasks.	2	4	0	0	3	5	14

As shown in Table 5.5-10, for a few drivers these distractions are perceived to occur all the time, while for other drivers they occur only occasionally.

Table 52a. Driver Descriptions Distraction Effects—Visual Warnings

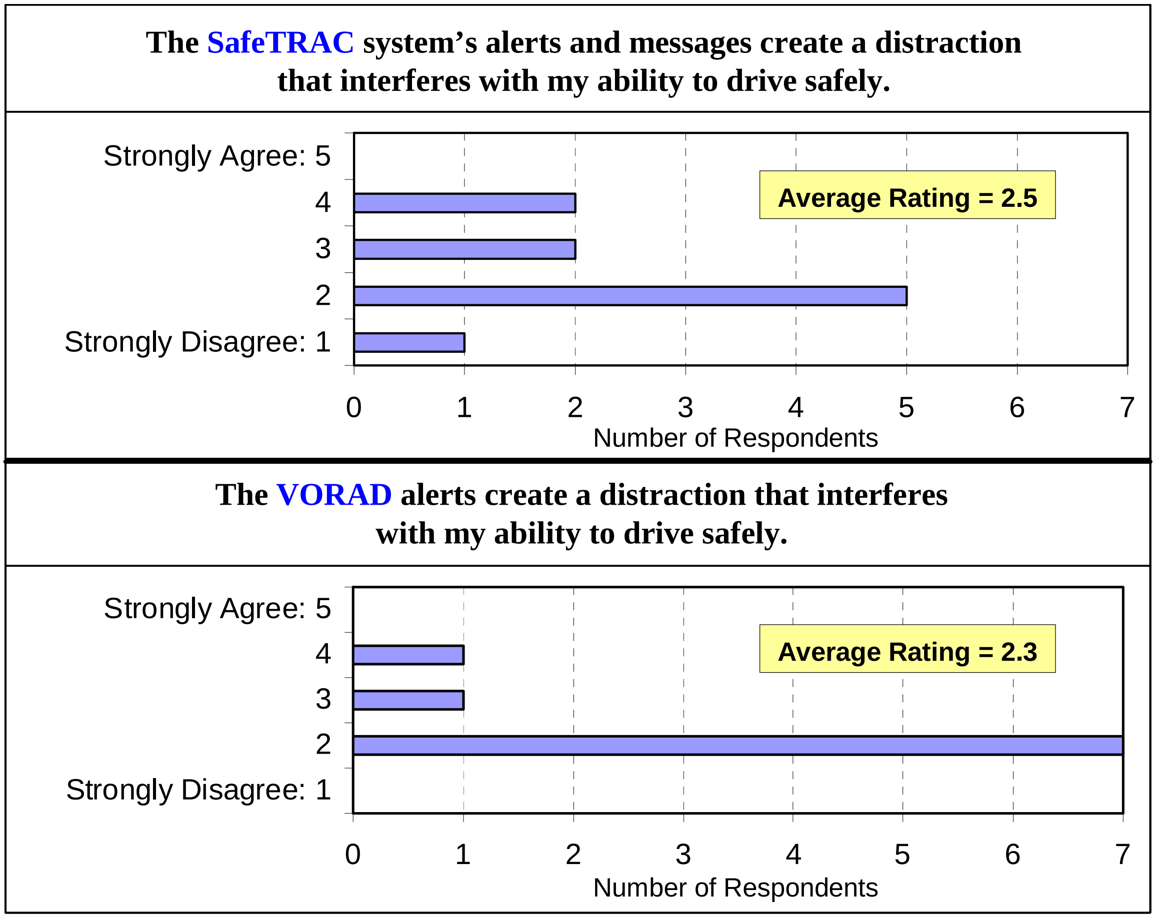
* Question/Observation	Helps Focus a Lot: 5	4	3	2	Distracts a Lot: 1	Skipped or Missing	How often does this happen?
How does SafeTRAC's visual display distract (or might distract) your attention from your driving tasks?					✓		"All the time because of where it is mounted."
"Irritating tone. I can see the road; I don't need a computer telling me where I am."					✓		"All the time, 'till I shut it off."
"Using number scale for performance [and] looking at unit every time to see why it beeped."					✓		"All the time."
"If you are watching the display you are not doing your job."				✓			"You have to not pay attention to it."
"Didn't ever distract me."			✓				Skipped or Missing
"When alerts go off."			✓				"Normal"
"When it hangs up and will not separate from outer bar and you keep eye on it too much."		✓					"Not often because it doesn't happen much."

Table 52b. Driver Descriptions Distraction Effects—Auditory Warnings

* Question/Observation	Helps Focus a Lot: 5	4	3	2	Distracts a Lot: 1	Skipped or Missing	How often does this happen?
How does SafeTRAC's auditory warning distract (or might distract) your attention from your driving tasks?						✓	
"Has the loud and annoying sound – too loud – sometimes startles me."					✓		
"As I said before, it's 'information overload.' You're trying to concentrate on driving and there are all these distracting alarms going off."					✓		
"Reset tone is annoying. Other tones are similar to other instruments."					✓		"Very often – every time I come to a stop and pull away."
"When it beeps at you and you are driving in the center of your lane. No reason really."		✓					"Not often."
"Sometimes take eyes off road."		✓					"Normal"
"I like the beeps. It lets me know to watch the road, not what is walking down the street or what is on the road beside me."	✓						

*The rankings are explained, with full results, as shown in Table 51.

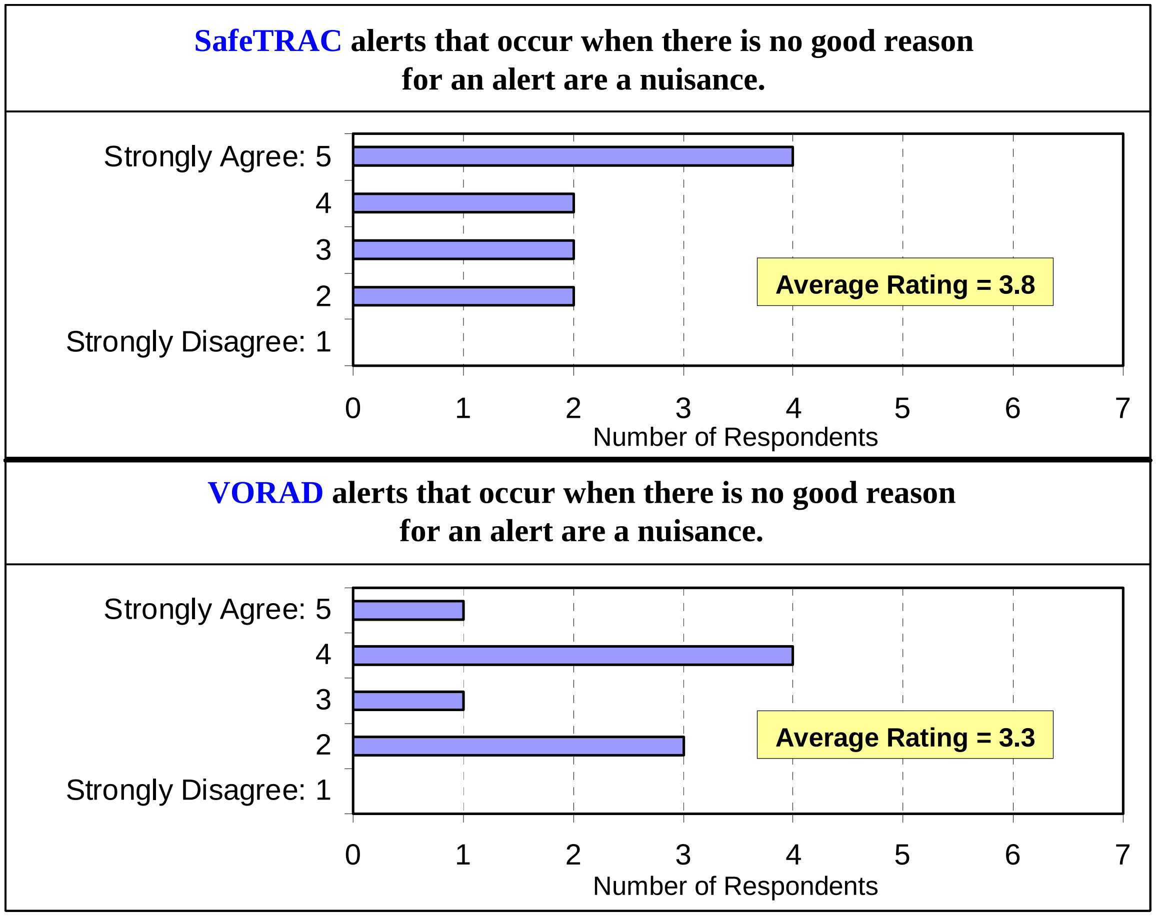
As shown in Figure 38, none of the surveyed drivers agreed strongly that IVSS interfere with their ability to drive safely. Although several drivers reported distraction effects, they did not strongly indicate that those distractions jeopardized their ability to drive safely.


The **SafeTRAC** system's alerts and messages create a distraction that interferes with my ability to drive safely.

The **VORAD** alerts create a distraction that interferes with my ability to drive safely.

Figure 38. Driver Perceptions of the Distraction Effects

False alerts can either be "false positive" or "false negative". A "false positive" alert occurs when an IVSS issues an alert when in reality there was no cause for the alert. A "false negative" alert occurs when an IVSS should have given an alert but did not. Drivers in the survey were asked whether they thought that false positive alerts were a nuisance. The results are shown graphically in Figure 39. The responding drivers tended to agree that false positive alerts from the LDWS and CWS were a nuisance. Drivers were not asked how frequently false positive alerts occurred in practice; however, in other survey questions they indicated that "false positives" do sometimes occur.



SafeTRAC **alerts that occur when there is no good reason for an alert are a nuisance.**

VORAD **alerts that occur when there is no good reason for an alert are a nuisance.**

Figure 39. Driver Perceptions of the Nuisance Effects

To assess the effects of false negative alerts, drivers were asked whether they tend to lose confidence in an IVSS when it fails to give an alert or when the driver thought it should have done so. As shown in Figure 40, more surveyed drivers agreed with this statement with regard to the LDWS. For the CWS, the drivers were equally divided between “agree” and “disagree.” Similar to the occurrence of false positives, it was unknown how frequently drivers experienced false negative alerts.

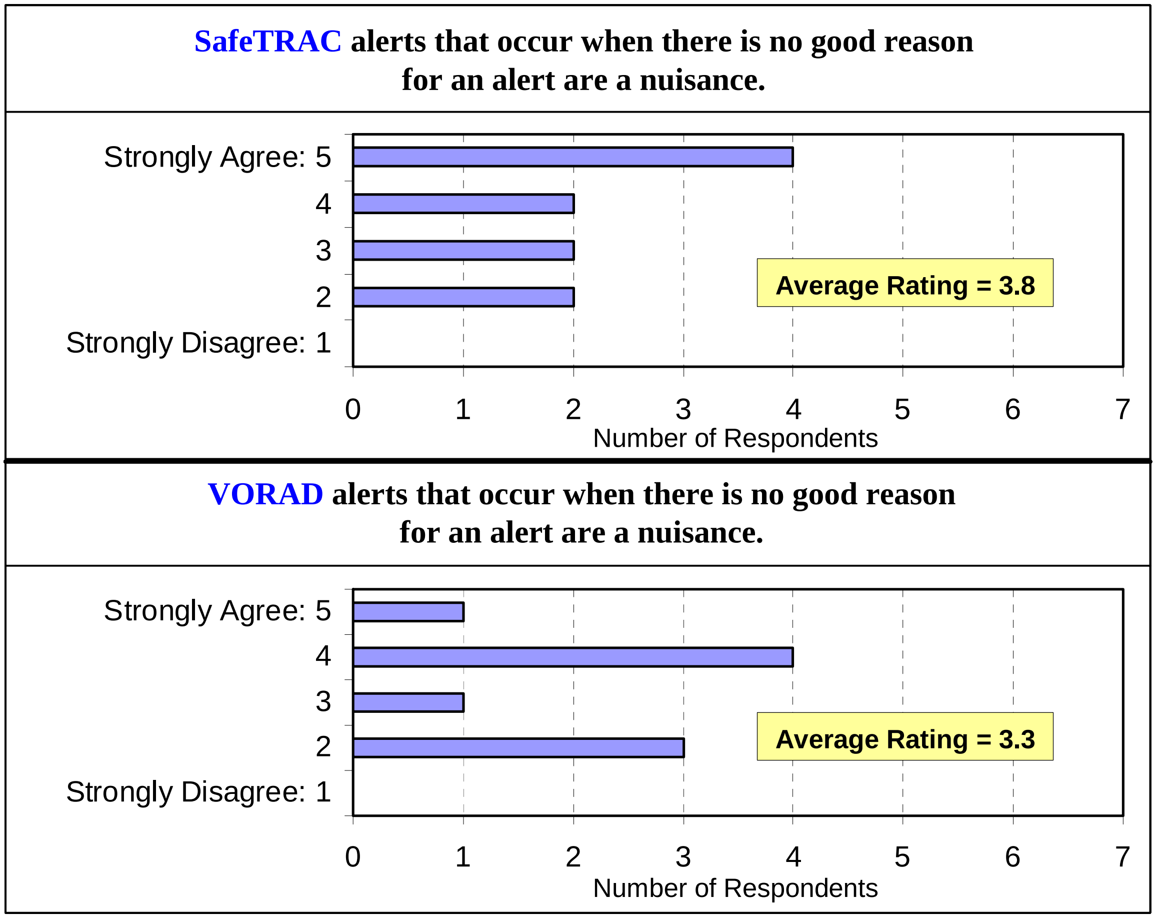
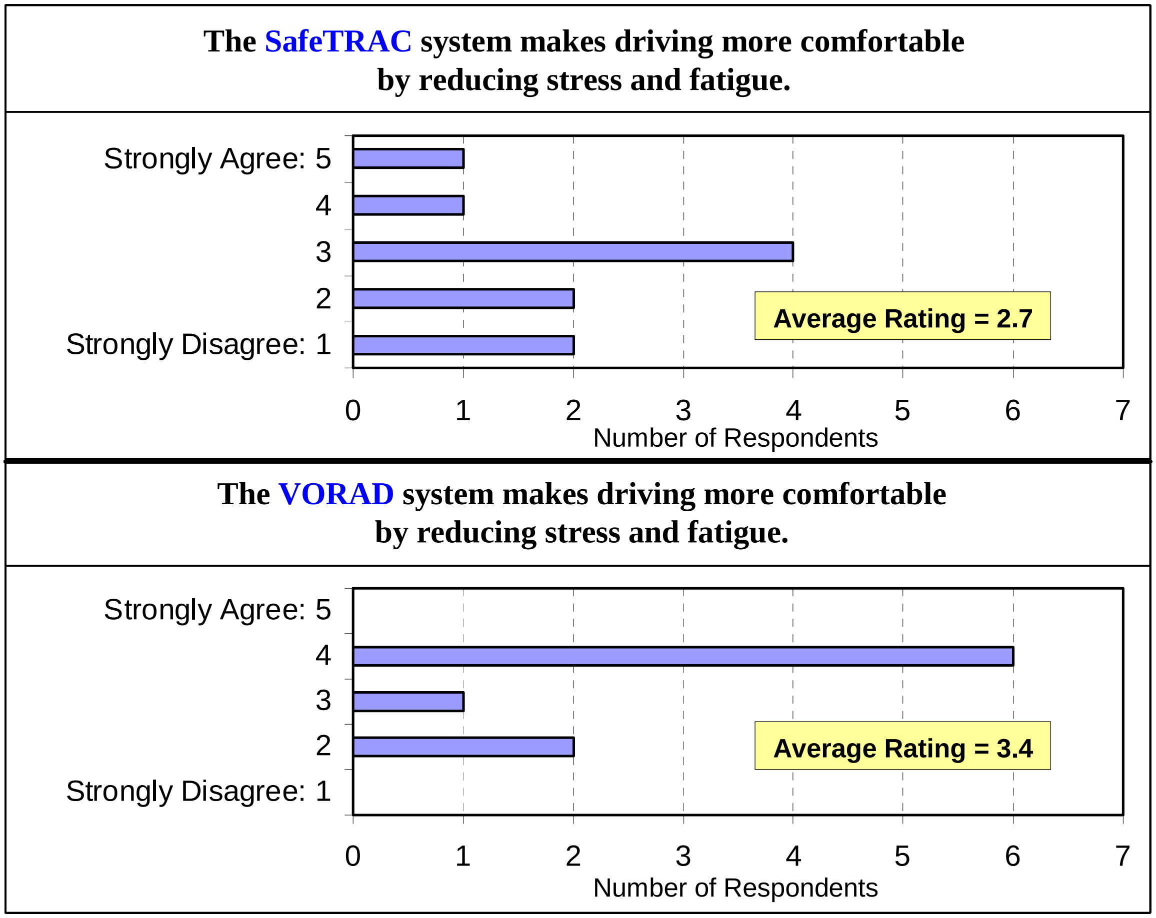


Figure 40. Driver Perceptions of the Loss of Confidence in the LDWS and CWS

Stress and Fatigue

Although IVSS were developed to increase driving safety by reducing driving stress, the visual and audible alerts from the IVSS may increase driving stress. The drivers were asked whether they agreed or disagreed that the LDWS and CWS made their driving more comfortable by reducing stress and fatigue. As shown in Figure 41, drivers on average tend to disagree that the LDWS reduced stress and fatigue, while they were in mild agreement that the CWS reduced stress. There was more disparity of responses for the LDWS, where drivers reported both strong agreement and strong disagreement. Overall, more surveyed drivers agreed that the CWS helped to reduce stress and fatigue (six out of nine agreed) than the LDWS (two out of 10 agreed).


The SafeTRAC system makes driving more comfortable by reducing stress and fatigue.

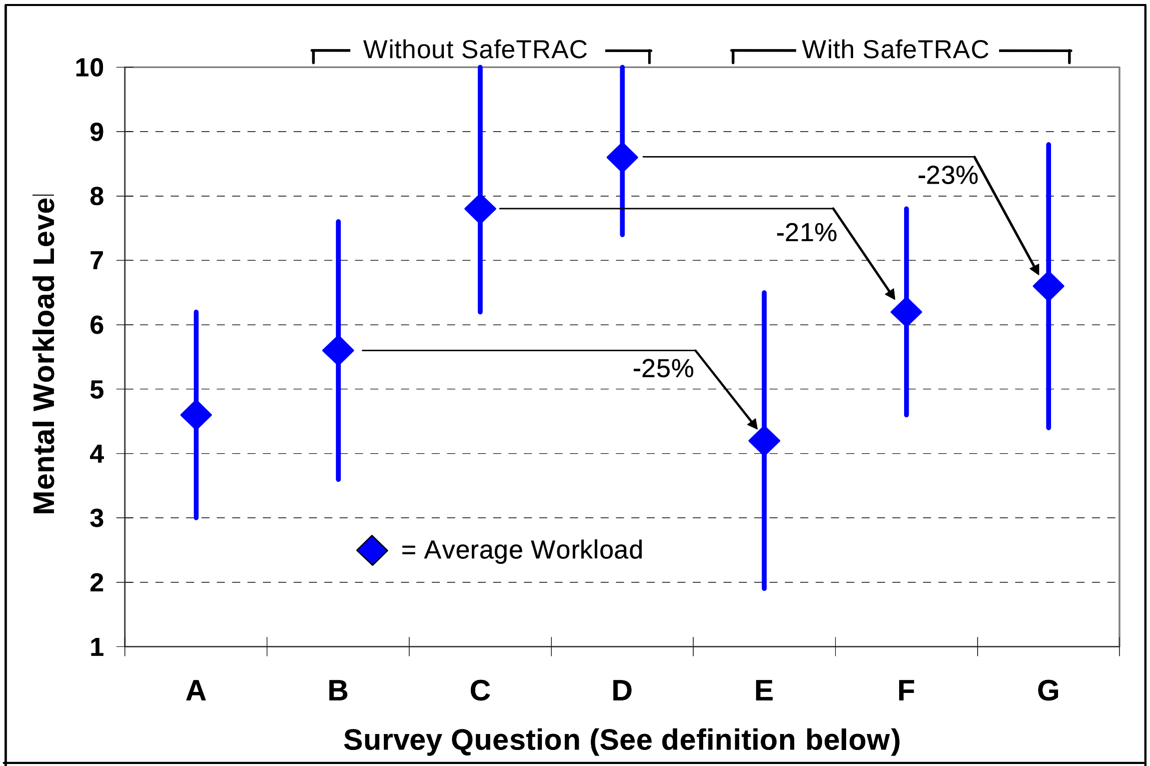
The VORAD system makes driving more comfortable by reducing stress and fatigue.

Figure 41. Level of Driver Agreement that IVSS Reduce Stress and Fatigue

Driver Workload

Mental workload refers to the amount of mental effort it takes a driver to perform his or her driving tasks. Drivers were asked to think in terms of their level of concentration, amount of mental effort, or degree of mental focus, and to rate their assessment of the mental workload required under various driving conditions, using a scale that ranges from 1 to 10, where 1 means the lowest level of mental workload and 10 means the highest level. The results, shown in Figure 42, indicate the average reported workload level under each of seven driving situations, along with the standard deviation around the average, which reflects where about two-thirds (68 percent) of the driver responses clustered.

These data support the hypothesis that the LDWS will reduce the level of reported mental workload under a variety of driving conditions; however, due to the small number of only 10 drivers responding to this question, the differences shown between the with-LDWS feedback and without-LDWS feedback conditions were not statistically significant.



A = Personal automobile; normal conditions
B = Truck; good conditions; light to moderate traffic; without SafeTRAC feedback
C = Truck; heavy traffic; without SafeTRAC feedback
D = Truck; low visibility; without SafeTRAC feedback
E = Truck; good conditions; light to moderate traffic; with SafeTRAC feedback
F = Truck; heavy traffic; with SafeTRAC feedback
G = Truck; low visibility; with SafeTRAC feedback

Figure 42. Reported Level of Average Mental Workload

As shown in Figure 42, driving a truck under light to moderate traffic conditions without LDWS feedback entailed greater concentration and effort (average 5.6) than driving a personal automobile (average 4.6). Substantial mental effort was required for driving a truck without LDWS feedback under heavy traffic conditions (average 7.8) or low-visibility conditions (average 8.6).

Using the LDWS resulted in a substantial reduction, between 20 percent and 25 percent, in all reported workload levels. Even driving a truck in light to moderate traffic with the LDWS required no additional mental effort compared to driving a personal automobile. Also, by using the LDWS in the most difficult and stressful driving conditions, the reported level of mental workload was reduced. The surveyed drivers reported a 21 percent reduction in mental workload using the LDWS when driving in heavy traffic, and 23 percent when driving in low-visibility driving conditions (fog, rain, snow, night).

Driver Acceptance

If truck drivers do not accept IVSS, then they will either not use them or they will reluctantly use them, thereby not receiving all of the benefits. As shown in Figure 43, drivers were asked whether having these IVSS increased their overall driving satisfaction. While 4 of the 10 drivers agreed that the LDWS increased their satisfaction, three of the drivers stated that they strongly disagreed, and the remainder neither agreed nor disagreed, indicating widely differing opinions on this question. Driver satisfaction with the CWS was only slightly more positive.

In order to gain additional perspective on driver acceptance, the surveyed drivers were asked what they liked the most and least about the LDWS. As shown in Table 53, the drivers who agreed that the LDWS has increased their driving satisfaction did not indicate any dissatisfaction about the system. Yet, among the drivers who disagreed that the LDWS had increased their driving satisfaction, most drivers positively stated what they specifically liked and did not like about the system. In summary, driver acceptance of the LDWS and its ability to increase their driving satisfaction was mixed among the small number of surveyed drivers.

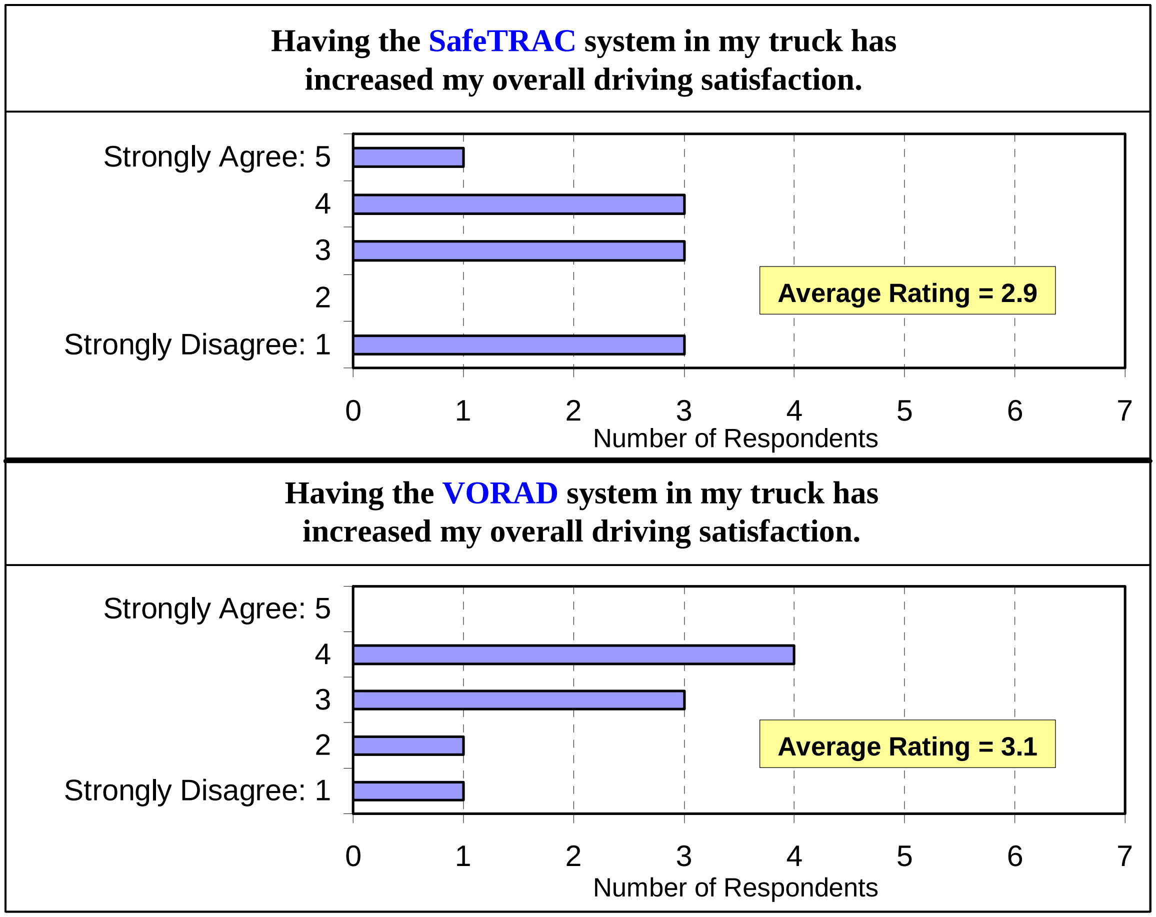


Figure 43. Drivers' Perceived Overall Driving Satisfaction from IVSS

Table 53. Driver Opinions About the LDWS

Driving satisfaction* 1 = Strongly Disagree 5 = Strongly Agree	What do you like most about the SafeTRAC lane departure warning system?	What do you like least about the SafeTRAC lane departure warning system?
1	"I like the fact it slows things down if someone cuts in front of me."	
1		"It needs an on-off switch."
1	"Helps you keep that space cushion between you and others around you."	"Beeps when not necessary."
3	"Drowsy driver warning."	"Similar sounds to other instruments."
3	"It keeps you alert and attentive."	"It has no leeway for State and County roads, which lots of times are narrower than interstates."
4	"It gives you a score for better handling the vehicle."	
4	"Helps with keeping your attention."	
4	"Keeps you on your toes – which is good."	
5	"It helps keep me focused on working (driving)."	

*The rankings and results are shown in Figure 43.

Another aspect of driver acceptance is the usefulness and reliability of IVSS. Figure 44 shows that the surveyed drivers had a higher degree of trust that the CWS will work properly. There was a wide diversity of opinion expressed on the degree of trust relating to the LDWS. Figure 44 also shows the results from asking drivers if they feel less safe driving in a truck that does not have either of these systems installed. These survey respondents clearly do not feel less safe without LDWS. Comparing trust and confidence in these two systems, these respondents say they feel safer and are more likely to trust the CWS to work properly than the LDWS. However, the sample size was too small to generalize these findings to other drivers based on these survey results.

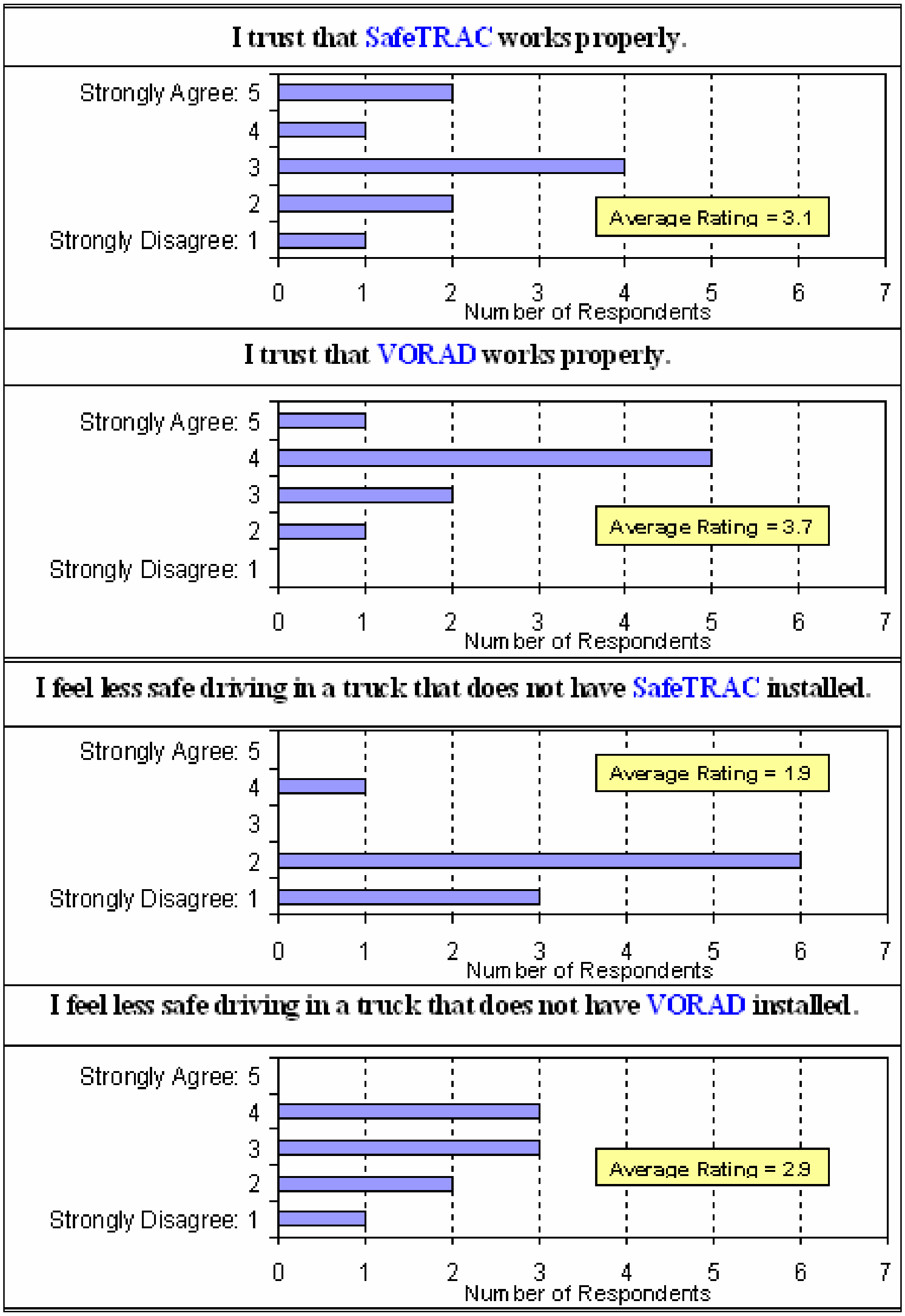


Figure 44. Driver Perceptions of IVSS Safety

To assess whether drivers perceived the IVSS to be useful, they were asked to rate whether the LDWS hinders or helps them in their job as a truck driver. As shown in Table 54, these respondents are about evenly divided on this issue.

Table 54. LDWS Usefulness

Question	Help: 5	4	3	2	Hinder: 1	Skipped or Missing	Response N=14
On a scale from 1 to 5, where 1 is **hinder** and 5 is **help**, does **SafeTRAC** hinder you or help you in your job as a truck driver? Think in terms of advantages and disadvantages of this system.	3	2	1	2	2	2	14

These drivers' explanations about how the LDWS helps or hinders them are shown in Table 55. Advantages of the LDWS included maintaining alertness, enhancing concentration, and aiding driving under poor driving conditions. Disadvantages included the distracting alerts and the location of the unit on the dash.

A closely related question was whether the LDWS helped the driver carry out his or her driving tasks. The results, shown in Table 56, indicate that the surveyed drivers were almost evenly divided on this issue. The drivers provided the following comments about how the LDWS helped them:

- "Makes driving more interesting and more alert."
- "Keeps you on your Ps and Qs. You notice what's going on around you more."
- "Keeps driver alert at all times."
- "It helps me stay focused on the road."
- "In bad weather is really the time that it is a benefit because in the rain and stuff like that when the visibility is real low." (from baseline survey)

Table 55. Driver Explanations on LDWS Advantages and Disadvantages

Help or Hinder* 1 = Hinder 5 = Help	Tell me how SafeTRAC helps or hinders you in your driving?	What do you think are the biggest advantages and disadvantages of SafeTRAC?
1	“Disadvantage is the unit is on top of dash – direct view hindered – needs to be a more pleasant tone. Also hinders your sleep.”	
1	“It is called information overload. There are a lot of distractions on the road, more alarms and indicators are just more distractions.”	“I cannot see any advantages to either system. The VORAD system seems to be bad for the engine (cutting power under a load then putting it back on in cruise).”
2	“When alerted makes me jerk back into lane; makes me jumpy.”	“Beeping drives me mad. Softer type of alert might be more helpful.”
3	“Helps on poorly marked roads during heavy rain or fog.”	
4	“Helps you stay alert and drive in a straighter path.”	
4	“Helps especially in late night driving, say, 2 a.m. to 5 a.m., when you might be getting tired or sleepy.”	“If I notice my score lower than normal, it makes me focus more on my driving to raise the score. Also lets me know it’s time to stop truck and rest.”
5	“Makes you concentrate more on the road.”	
5	“Keeps you alert.”	
5	“If something distracts you and you start to cross the lane, it will bring you back. If you cannot hold a straight line, it will let you know.”	“It helps keep you centered on what you are doing.”

*The rankings are shown in Table 54.

Table 56. Utility of LDWS in Supporting Driving Tasks

Question	Yes	No	Not Sure	Skipped or Missing	Response N=14
Does the **SafeTRAC** system help you carry out your driving tasks?	4	5	1	4	14

As shown in Figure 45, drivers were asked whether or not the LDWS helps or hinders their driving under specific traffic and weather conditions. The drivers were also asked to specify any other condition not listed. On average, these respondents said that using the LDWS was most helpful at night, in heavy rain or snow conditions, in fog, and on open highway with light to moderate traffic, in that order. The LDWS was least helpful in heavy traffic and urban traffic. One driver noted that the LDWS hindered driving in road construction zones. Another driver noted that the LDWS hindered driving up a hill when the LDWS cut power to the engine; however, this driver mistakenly thought that the LDWS took control of the vehicle in this situation.

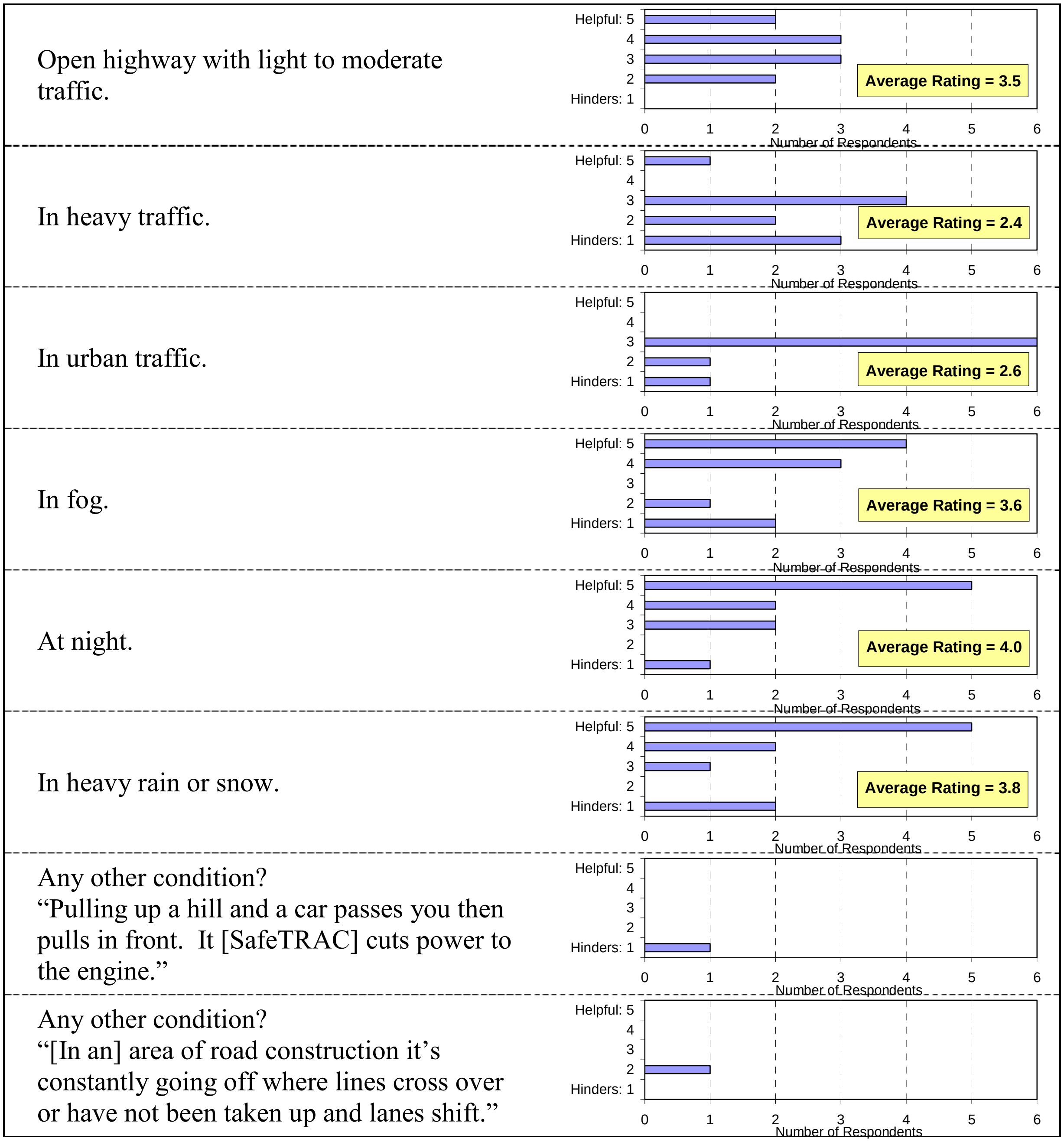


Figure 45. Conditions of LDWS Usefulness

5.5.4 Objective 2.3. Driver Risk and Vigilance

This section addresses drivers' perceptions about how the use of IVSS may affect driver risk and behavior. The intent of an IVSS is to enhance safety and reduce crashes; however, the opposite effect might occur if drivers become dependent on an IVSS, reduce their driving vigilance, or take greater driving risks, because an IVSS will warn them of potentially dangerous situations within time to respond.

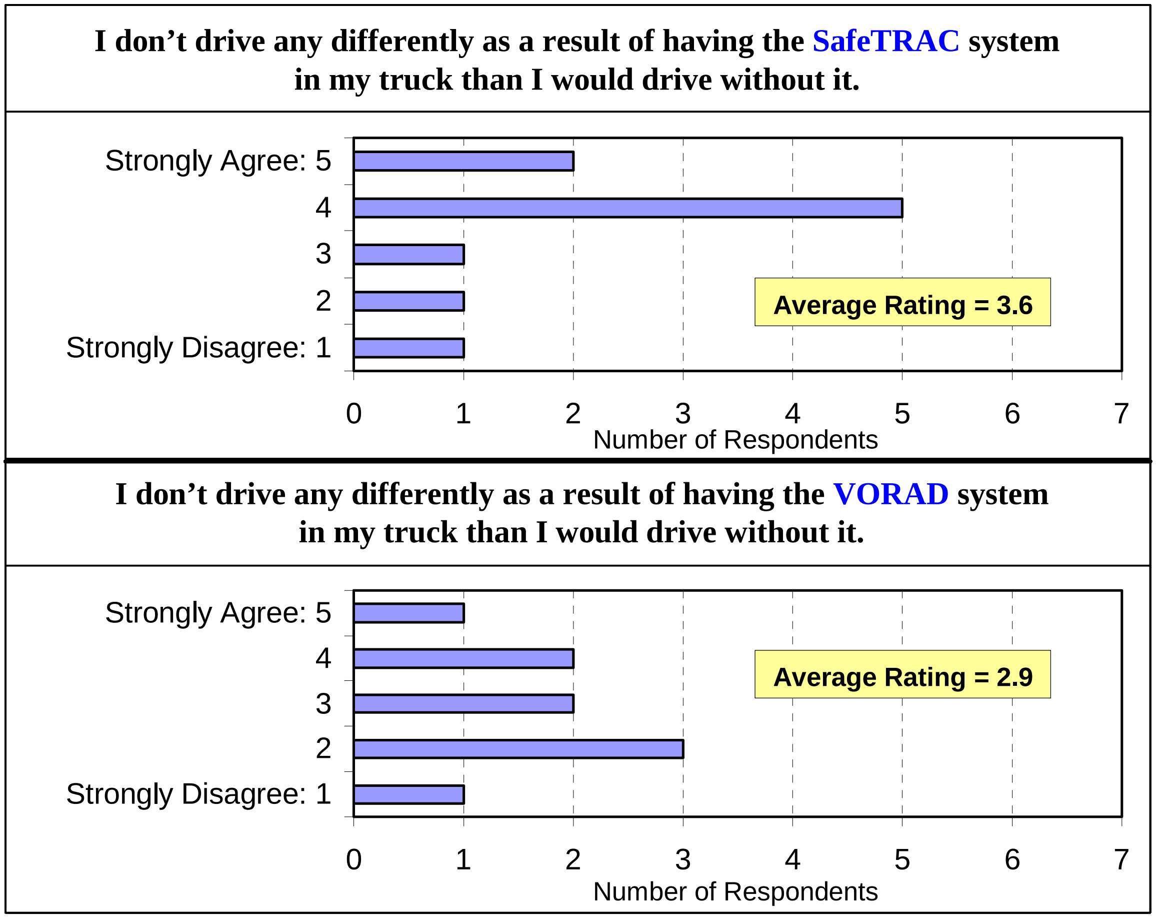
Table 57 provides an informal assessment of each hypothesis of Objective 2.3.

Table 57. Perceived Impacts of IVSS on Driver Risk and Vigilance

Evaluation Hypotheses	Informal Assessment	Sections
Drivers are aware that they modify their driving behavior (speed, following distance, braking, turn signal usage) for particular reasons in response to the IVSS.	The majority do not	Driving Behavior
Drivers with the systems become more dependent on the systems over time, which degrades their safety-related driving performance when driving vehicles without the systems.	Definitely not for LDWS; less clear for CWS	Driving Behavior
Drivers with the systems are aware that they take fewer risks than drivers without the systems because they have greater awareness of potential safety hazards.	No for LDWS; mixed for CWS	Risk Taking
Drivers with the IVSS are aware that they are more vigilant in their following-distance behavior than those without the system, because of the feedback provided by the system.	Yes for CWS; less so for LDWS	Risk Taking

Driving Behavior

Figure 46 shows the extent to which drivers perceive that they drive differently as a result of using the IVSS. The respondents agreed that they do not drive differently as a result of the LDWS, but they are about evenly divided on whether having the CWS leads them to drive differently. Further information is provided in Table 58 regarding specific driving habits that may be affected by using the LDWS.


I don't drive any differently as a result of having the SafeTRAC system in my truck than I would drive without it.

I don't drive any differently as a result of having the VORAD system in my truck than I would drive without it.

Figure 46. Driver Behavior Modification Using IVSS

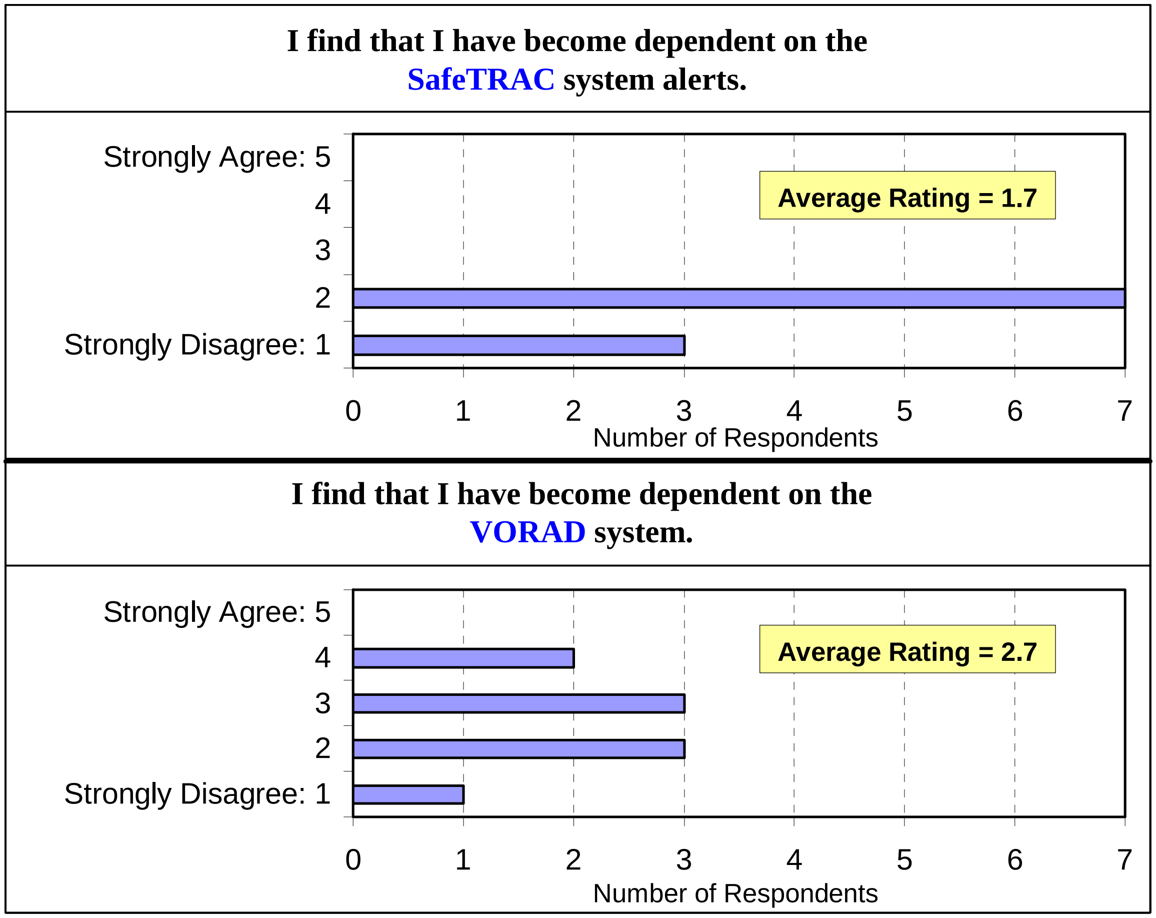
Among the six specified driver behaviors listed in Table 58 that might be affected by LDWS, "using care in lane keeping" is the only one that the drivers do more now than before they had the LDWS. None of the surveyed drivers reported doing any of these behaviors less than before having the LDWS, and they reported that they do these behaviors about the same now as before having the LDWS. One interesting finding was that only 2 out of 10 respondents said they "maintain overall alertness" more than before having LDWS.

In summary for this hypothesis, the main behavioral effect of the LDWS was increased attentiveness to lane keeping on the part of some drivers, which constitutes a major safety objective of this technology.

Table 58. Drivers' Reported Changes in Driving with LDWS

Question	More Than Before	The Same as Before	Less than Before	Skipped or Missing	Response N=14
Watch your speed.	1	9	0	4	14
Use your turn signals.	3	7	0	4	14
Use care in lane keeping.	6	4	0	4	14
Anticipate your braking needs.	3	7	0	4	14
Take rest stops or coffee breaks.	1	9	0	4	14
Maintain overall alertness.	2	8	0	4	14
Other behaviors (as specified): Maintain driving focus.	1	2	0	11	14

The second hypothesis related to driving behavior addressed drivers' perceptions that they become more dependent on the IVSS over time, which could degrade their safe driving performance in vehicles not equipped with these technologies. In the survey, drivers were asked whether they have become dependent on the LDWS and CWS. As shown in Figure 47, these respondents uniformly disagreed that they had become dependent on the LDWS. While on average the respondents disagreed that they had become dependent on the CWS, about half the drivers either agreed or disagreed.



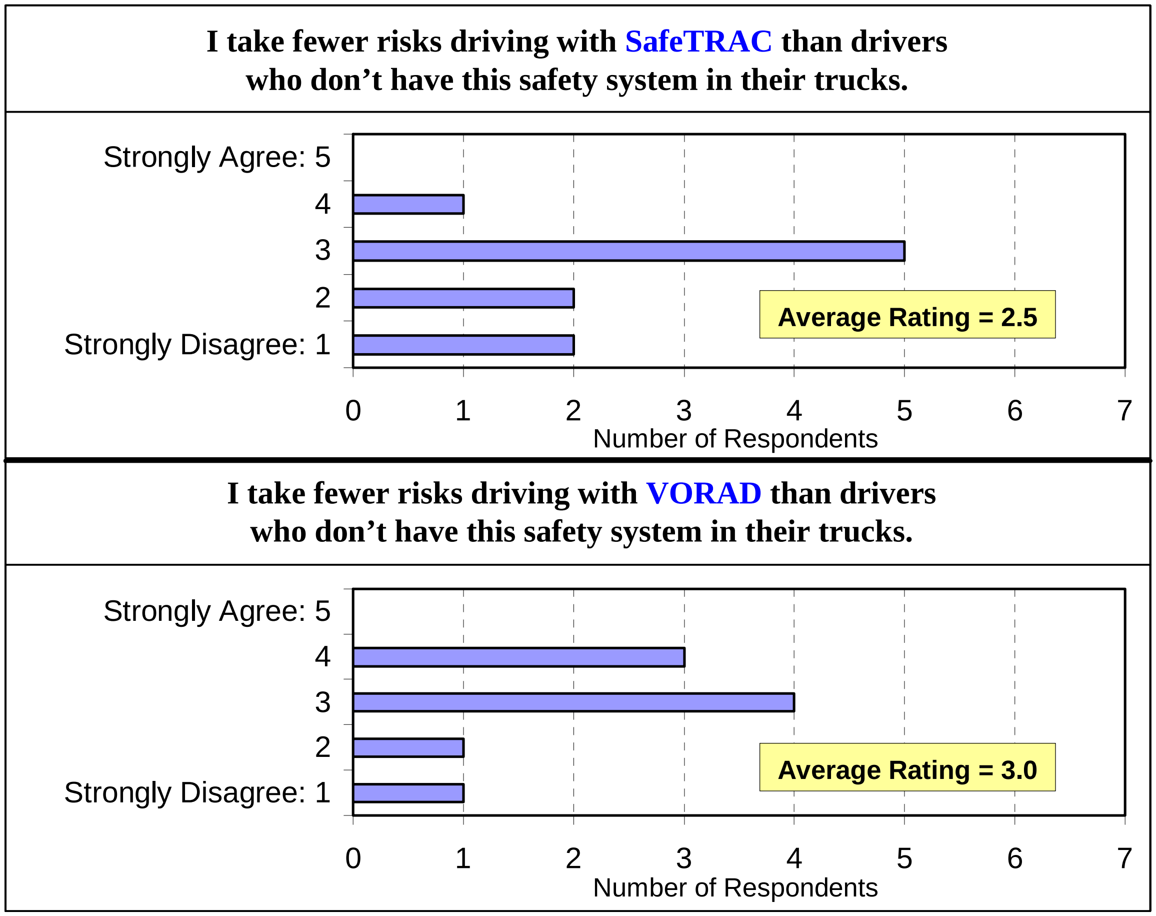
I find that I have become dependent on the SafeTRAC system alerts.

I find that I have become dependent on the VORAD system.

Figure 47. Perceived Dependence on IVSS

Risk Taking

The hypothesis relative to risk-taking behavior was that drivers using IVSS take fewer risks than drivers without these safety systems, because they become more sensitized to the risks and hazards of truck driving, and for that reason they are less inclined to be risk-takers in their driving. As shown in Figure 48, the surveyed drivers were asked whether they take fewer risks with using LDWS and CWS than drivers who do not have these systems. With regard to the LDWS, these respondents on balance disagreed that they take fewer risks. The responses were somewhat more balanced between agreeing and disagreeing that they take fewer risks when using the CWS.

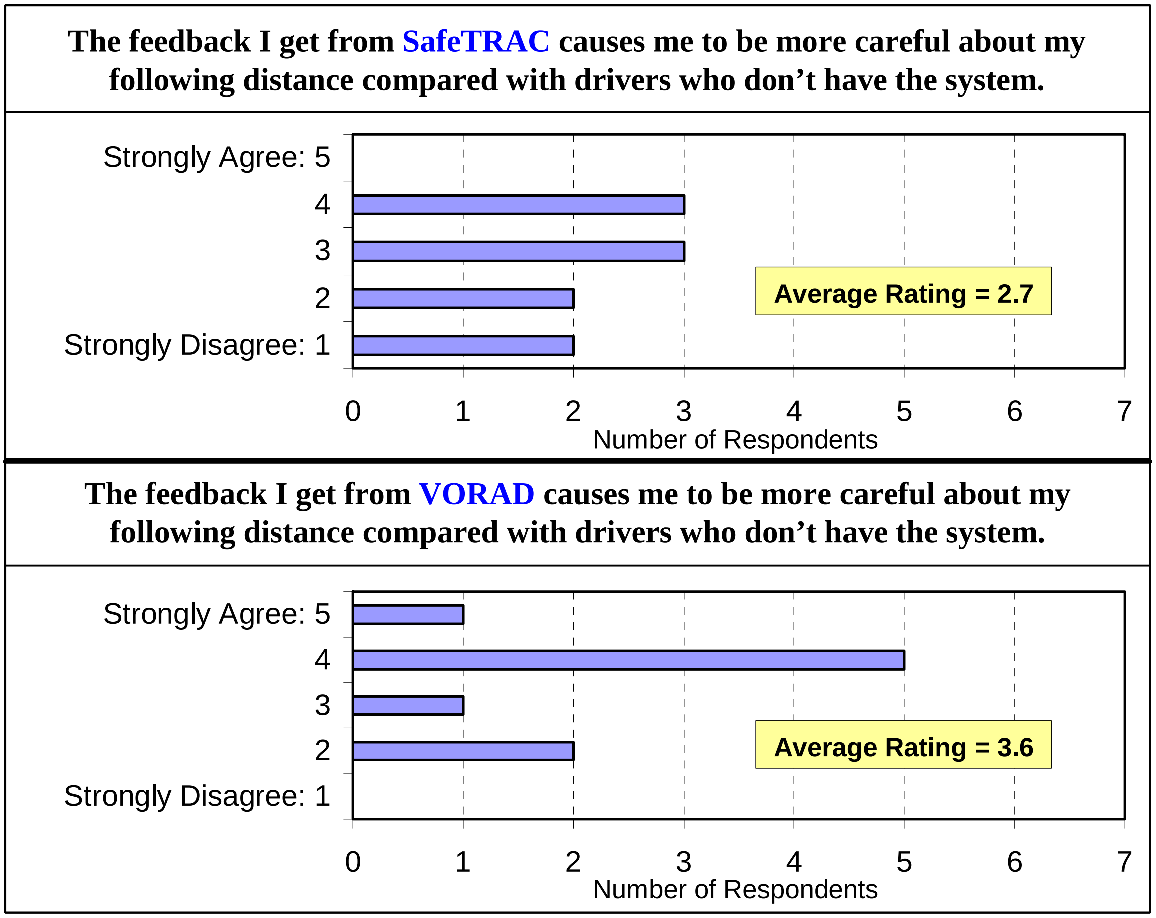


I take fewer risks driving with SafeTRAC than drivers who don't have this safety system in their trucks.

I take fewer risks driving with VORAD than drivers who don't have this safety system in their trucks.

Figure 48. Reported Risk-Taking with IVSS

The final hypothesis under Objective 2.3 addresses the effects of IVSS on driver vigilance in maintaining a safe following distance between their truck and the vehicle in front of them. As shown in Figure 49, drivers were asked whether the feedback they got from the LDWS and CWS caused them to be more careful about their following distance compared with drivers who do not have the system. Since the CWS is designed to alert drivers regarding unsafe driving distance to the vehicle in front, while SafeTRAC is focused primarily on lane-keeping behavior, these respondents were more in agreement that the CWS helps in this regard compared with the LDWS.



The feedback I get from SafeTRAC causes me to be more careful about my following distance compared with drivers who don't have the system.

The feedback I get from VORAD causes me to be more careful about my following distance compared with drivers who don't have the system.

Figure 49. Driver Following Distance Behavior with IVSS

5.5.5 Objective 2.4. Product Quality and Maturity

This section provides information about drivers' perspectives on the quality and maturity of the IVSS technologies, based on driving experiences using these safety systems. The survey addressed driver perceptions of system performance and functionality, and solicited driver recommendations for any changes that could improve the systems or make them easier to use.

The Evaluation Plan identified two hypotheses under Objective 2.4, as shown in Table 59. These hypotheses addressed whether or not drivers have recommendations for changes or improvements in the IVSS.

Table 59. Product Quality and Maturity

Evaluation Hypotheses	Assessment	Sections
Drivers have recommendations for changes that might make it easier to use or learn how to use the IVSS.	Mostly more training	Changes to Improve Ease of Use or Learning
Drivers have recommendations for changes that might improve the performance or functionality of SafeTRAC.	Some offered suggestions	Recommended Performance Changes

Recommended Changes to Improve Ease of Use or Learning

Regarding ease of learning, only a few drivers offered recommendations related to additional training to make it easier to learn how to use the LDWS and CWS, as shown in Table 60.

Table 60. Driver Recommendations for Learning How to Use the LDWS

What would make SafeTRAC easier to learn?	What would make VORAD easier to learn?
"If someone would train me I could tell you."	"Training"
"Training"	
"Proper explanation of functions."	
"Remove the display with the line going back and forth between the lines. Just have a light that will light when you cross the lane and tone."	

Recommended Performance Changes

Drivers were given the opportunity to offer recommendations for any changes that might improve the performance or functionality of the LDWS. Those who provided suggestions said the following:

- "Change warning tones so they are different and less shocking from truck control tones."
- "Overall it is a very good system. Take 'Clean Window' message off. You clean window at a truck stop and soon as I pulled out it tells me to clean window."

- "Take out all moving displays and only beep when you cross a line in the road, not at start up or at transition. Change the display to light and numbers and only beep when you cross a lane without turning your blinker on or when your score is below the set limit."
- "Get rid of it."

At the end of the post-activation survey, drivers were asked whether they had any additional comments that they would like to make. Responses included:

- "I like the VORAD system, especially in the rain and fog conditions. It did give some false reading sometimes. My SafeTRAC never worked properly. It would go off prematurely; when I touched the line it would beep. I was told by shop it was supposed to beep when the truck went 18 inches over the center line or right line without using turn signal."
- "Warning systems do no harm in trucks. Keeps you more alert longer even when you get tired."
- "SafeTRAC will make a difference in safety. All tractors should have SafeTRAC and VORAD systems installed. They should also work with QUALCOMM or Satellite system. But the Onvoy system is a piece of junk. Thank you for letting me be a part of this."
- "VIP system [fleet management-to-driver messaging system] does not work and has been removed for 6 months."
- "There are enough distractions outside the cab of a truck; we don't need any more inside the cab. I pay more attention to the engine gauges and warning lights than the VORAD or SafeTRAC systems. And if you drove using the VORAD as it is intended to be used, you never get anywhere. You give the following distance that VORAD wants, you will have 10 cars pull in front of you on any busy highway in the country."
- "SafeTRAC does not work in my truck!!"

5.6 Goal 3. Assess Performance and Capability Potential

The focus of this goal was to understand and quantify the performance of the LDWS from the perspectives of functionality, capability, and reliability.

5.6.1 Functionality

Drift Alerts

During the Mack FOT, the LDWS was assessed to determine the consistency and repeatability of drift alerts. For the commercially purchased SafeTRAC LDWS, a drift alert is issued when the truck approaches a lane boundary. For the FOT, all LDWS were programmed to issue a drift alert when a front tire was just over the lane boundary. This is confirmed in Figures 50 and 51. In Figure 50, the number of drift alerts per OPS file (i.e., per 15 minutes) is plotted against number of lane excursions with the turn signals off, per OPS file. As indicated, the frequency of drift alerts is directly proportional to the frequency of lane excursions. These data indicate that the LDWS drift alert is strongly related to lane excursions.

In Figure 51, statistics are presented on the position of the truck at the time a drift alert is issued. The average tire position among the seven FOT trucks ranged from -10 to -4 inches, where a negative value indicates distance out of the lane. The standard deviation of tire position at the time of drift alert ranged from -3 to +3 inches. These data reflect the repeatability and consistency of the issuance of drift alerts. The extreme values shown in the box plots in Figure 51, particularly the large values of tire position for trucks 6101 (1 case) and 6120 (2 cases), were situations where a drift alert was issued in a maneuver that was a lane change. When the LDWS identifies a maneuver as a lane change it shifts its reference to the new lane. During this shift, it generates large, artificial estimates of lane position. In these cases, the turn signals were not used during the lane change, and the LDWS issued a drift alert.

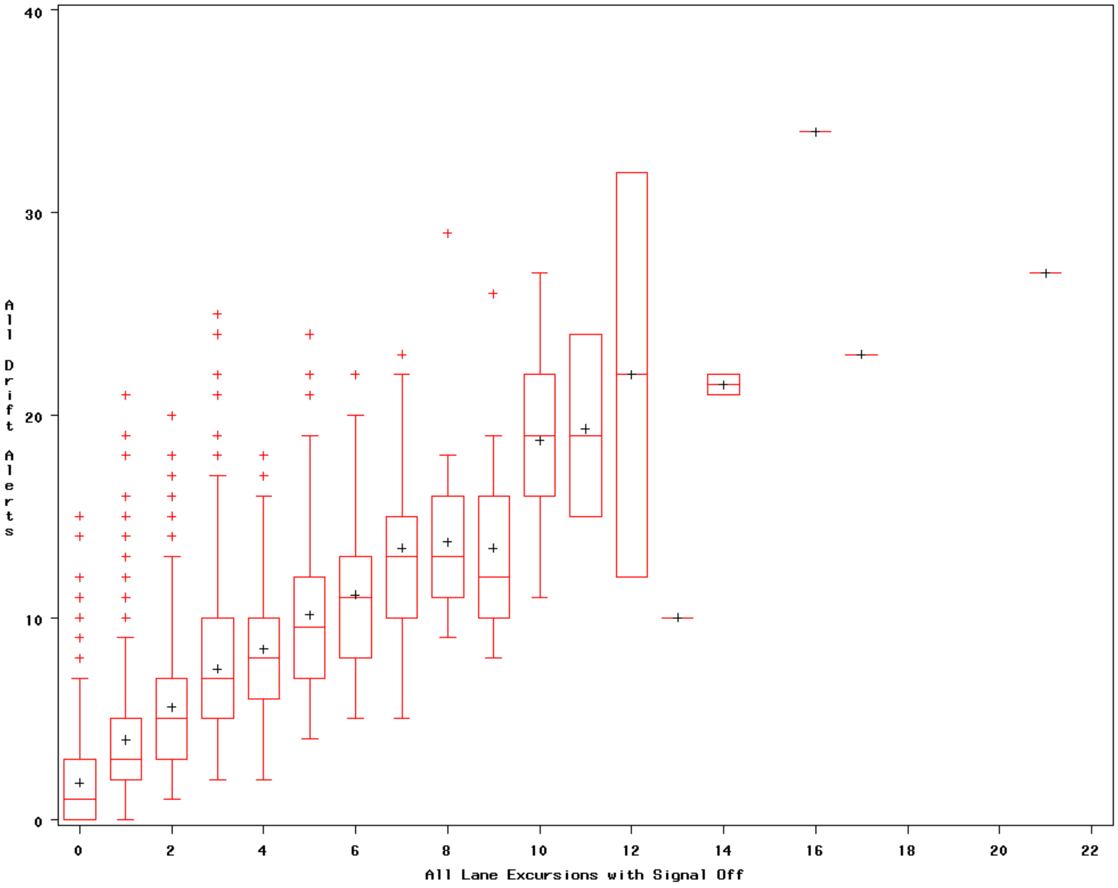


Figure 50. Correlation of the Frequency of LDWS Drift Alerts to the Frequency of Lane Excursions

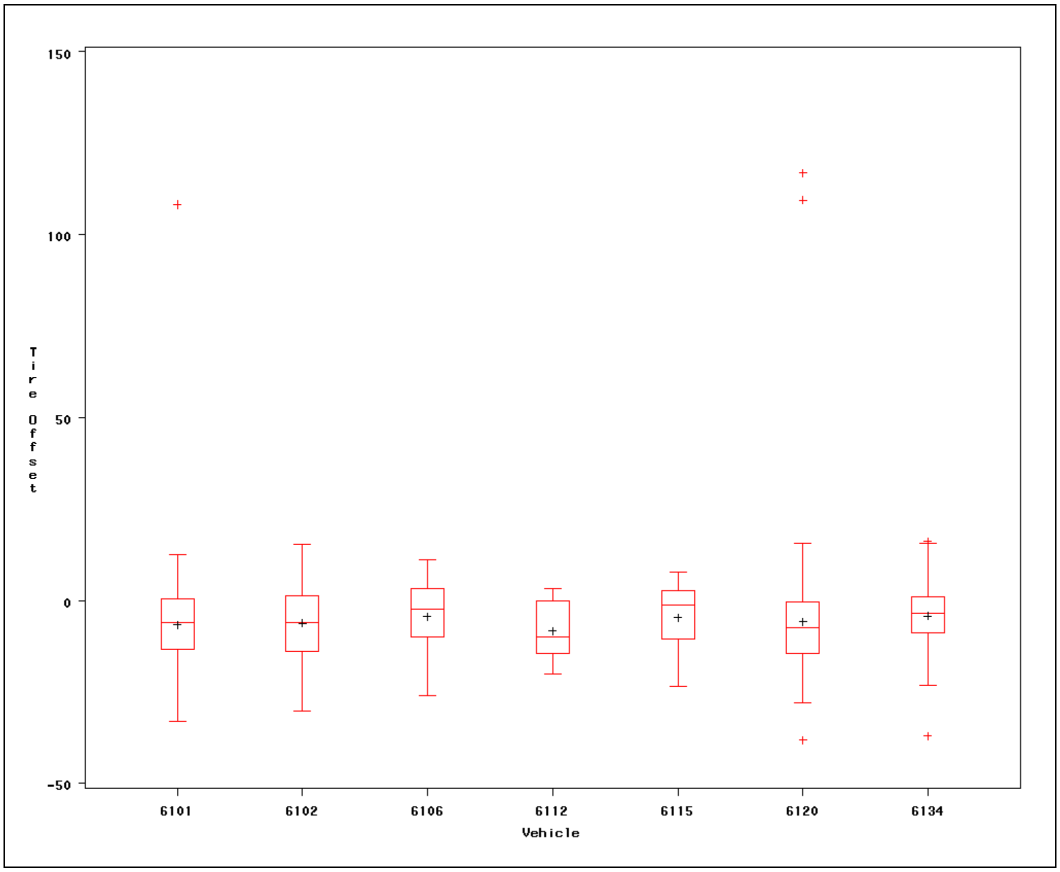


Figure 51. Tire Offset Distance for Seven FOT Trucks

Availability

The availability of the LDWS is indicated by the amount of time that alerts are enabled as a percentage of total time moving at speeds greater than 35 mph. To evaluate availability, data from the OPS files were used. Because a functional LDWS was required to generate an OPS file, availability was evaluated only for functional LDWS; systems that malfunctioned were not considered. As shown in Table 61, the availability for seven trucks in the FOT ranged from about 82 percent to about 97 percent.

Table 61. Availability of the LDWS during the FOT

Truck	% Time
6101	96.86%
6102	83.25%
6106	96.83%
6112	93.82%
6115	94.38%
6120	91.60%
6134	81.68%

5.6.2 Capability

The operating limits of the LDWS are reflected in its Alert System Status codes. The LDWS provides lane-departure warnings to the driver whenever the code = 1. Otherwise, the warnings are intentionally disabled. The list of Alert System Status codes is provided in Table 62.

Table 62. Description of the LDWS Alert System Status Codes

Code	Description	Value*
ENABLED	Code used to indicate the alert system is enabled	1
LOW CONFIDENCE	The system's recent confidence is currently low.	2
EXTENDED LOW CONFIDENCE	If the system's confidence has been low for an extended period of time.	3
MISSING BOUNDARIES	If both land boundaries are MISSING, then this suppression code will be used to indicate alerts are suppressed.	4
HIGH LATERAL VELOCITY	If the vehicle's lateral velocity is too high, something weird is going on. Maybe driver did a lane change, or is executing an evasive maneuver so suppress alerts.	5
RESET	If the vision system resets, probably due to a lane change, suppress alerts for a while.	6
LOW VELOCITY	If the vehicle velocity is below threshold now or has been recently, then suppress alerts. The character displayed is 's' if velocity is currently below threshold, and 'S' if velocity is above threshold now, but was below threshold recently	7
APPARENTLY STOPPED	If SafeTRAC does not know real vehicle velocity, it tries to determine if the vehicle is stopped by checking if the vehicle's lateral offset has remained constant for an extended period of them. If so, alerts are suppressed. Uses 's' if vehicle is apparently stopped now and 'S' if it was apparently stopped recently. This condition is mutually exclusive with the low velocity condition above, since low velocity suppression is only triggered is SafeTRAC knows the vehicle's real velocity.	8
NO VELOCITY	If there has not been a valid velocity estimate yet (probably because GPS has not acquired lock), disable alerts unless the default vehicle velocity is greater than minimum velocity threshold. Will only occur on units with the GPS option.	9
DRIVER INTERFACE	Driver has hit a button on the Interface Unit recently, so suppress alerts to prevent false alarms when camera is moving.	10
VEHICLE SIGNAL	If one of the vehicle signals is active ('t') or has been active recently ('T') suppress alerts. Will only occur on units with the vehicle signal option.	11
STARTUP SUPPRESSION	Right after startup, there is a fixed short period of suppression	12
EXTENDED STARTUP SUPPRESSION	If confidence isn't high or one of the boundaries is missing shortly after startup, SafeTRAC suppresses alerts for an extended period.	13
TURNED OFF	If the alert system is turned off (by setting the threshold to zero) alerts are suppressed.	14
WEIRD CONDITION	If a weird environmental condition is detected, alerts are momentarily suppressed.	15

* The Alert System Status field of the output message can take one of the 15 values described in the table. An alert system status of other than '1' means drift and drowsy alerts are disabled for the reason associated with the status code. The number in the 'Value' column is the number displayed on the system's video output for each status condition.

Occurrences of each value of Alert System Status code for seven trucks are reported in Table 63. These data were taken from the first and last 10 seconds of driving in the 635 LEX files that were used in the safety benefits calculations.

Alert System Status Codes 7, 8, 10, 11, 12, and 14 would be issued in situations where the driver may not need nor expect an LDWS warning.

As indicated in the table, during the sampled driving periods warnings were enabled about 86 percent of the time, with a range of about 78 percent to 91 percent. Further, warnings were disabled in situations where they could be expected about 5.9 percent of the time.

Table 63. Frequencies of Alert System Status Codes—by Truck

Alert System Status Code	6101 %	6101 Count	6102 %	6102 Count	6106 %	6106 Count	6112 %	6112 Count	6115 %	6115 Count	6120 %	6120 Count	6134 %	6134 Count	All Trucks %	All Trucks Count
1[1]	84.86	3598	89.41	3138	90.56	1449	83.82	285	78.33	188	79.59	1544	86.41	1544	85.99	10921
2	0.73	31	0.87	31	0.50	8	0.29	1	6.25	15	1.02	23	0.51	23	0.89	113
3	3.28	139	3.76	134	1.75	28	2.94	10	8.33	20	4.74	92	3.21	92	3.53	448
4	0.94	40	0.87	31	0.88	14	0.29	1	0.42	1	0.21	4	2.69	4	0.88	112
5	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
6	0.38	16	0.42	15	0.50	8	0.59	2	1.25	3	0.93	18	0.38	18	0.51	65
7	2.92	124	0.73	26	1.75	28	0.00	0	0.00	0	5.00	97	2.05	97	2.29	291
8	0.00	0	0.62	22	0.00	0	0.00	0	0.00	0	0.57	11	0.00	11	0.26	33
9	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
10	0.19	8	0.00	0	0.00	0	0.00	0	1.25	3	0.00	0	0.00	0	0.09	11
11	6.67	283	3.06	129	4.00	64	12.06	41	4.17	10	7.73	150	4.62	150	5.46	693
12	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
13	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
14	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
15	0.02	1	0.25	9	0.06	1	0.00	0	0.00	0	0.05	1	0.13	1	0.10	12
All Codes	100.00	4240	100.00	3560	100.00	1600	100.00	340	100.00	240	100.00	1940	100.00	1940	100.00	12700
2-15[2]	15.14	642	10.59	377	9.44	151	16.18	55	21.67	52	20.41	396	13.59	396	14.01	1779
2-6, 9, 13, 15[3]	5.35	227	6.18	220	3.69	59	4.12	14	16.25	39	7.11	138	6.92	138	5.91	751

[1] LDWS warnings enabled.

[2] All codes for which LDWS warnings are disabled.

[3] All codes for which LDWS warnings are disabled but would be expected and/or needed.

NOTE. Factors may not add up exactly because of rounding in source worksheets.

5.6.3 Reliability

The reliability of the LDWS was determined in terms of availability and history of malfunctions.

Availability

The availability of the LDWS was indicated by the amount of time that alerts were enabled as a percentage of total time moving at speeds greater than 35 mph. To evaluate availability, data from the OPS files were used. Because a functional LDWS was required to generate an OPS file, availability was evaluated only for functional LDWS; systems that malfunctioned were not considered. As shown in Table 61, the availability for seven trucks in the FOT ranged from about 82 percent to about 97 percent. The availability for each truck is plotted by month in Figure 52. As shown in the figure, the availability decreased substantially in the final month of the FOT for trucks 6102, 6112, and 6120, while availability remained relatively constant throughout the FOT for the other four trucks reported in the figure. The sudden drop in availability was caused by failures in the data acquisition/transmission systems and/or malfunctions in the LDWS. Low availability of the LDWS could be a contributing factor to many of the negative responses of the surveyed drivers.

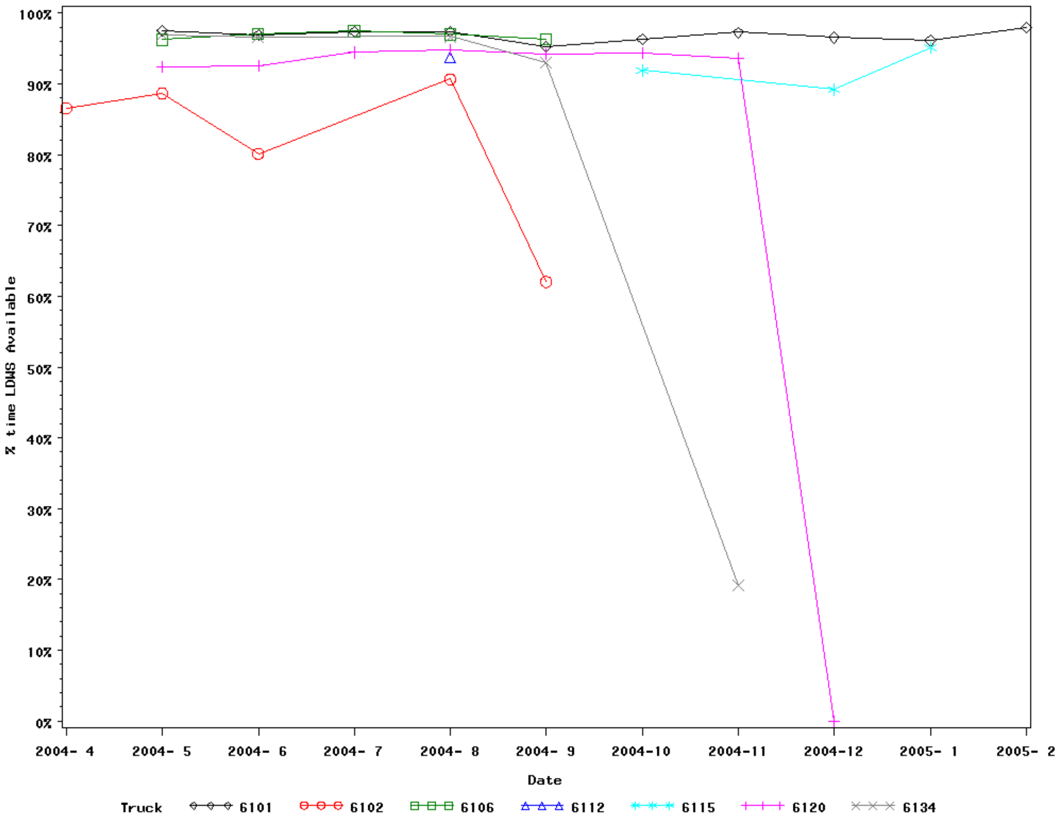


Figure 52. Monthly Availability of the LDWS for Seven Trucks

Malfunctions, Maintenance and Repair

During the FOT, malfunctions occurred in some of the LDWS units. According to the manufacturer, six units were inadvertently set to ‘silent mode’ and one unit failed due to external physical damage. Other problems occurred with the installation of some cameras due to wire splicing. Furthermore, there were connection problems with the Onvoy data collection system. Because the LDWS units in the Mack FOT were considered “first generation” and “prototypes” by the supplier their malfunctions may not be representative of the current commercial units.

5.7 Goal 4. Assess Product Maturity for Deployment

The SafeTRAC LDWS unit manufactured by AssistWare Technology, Inc., was tested in Mack trucks operated by McKenzie Tank Lines as a prototype of the version of this LDWS currently on the market. Wider deployment of a more mature and improved SafeTRAC LDWS has occurred following the Mack FOT, since the prototype LDWS required improvements to withstand the environment of trucks that typically log over 1,000,000 lifetime miles.

From the time that these units were deployed in a small number for the FOT, to the wider deployment that exists now, the LDWS has continued to undergo modifications and refinement. Throughout the FOT, issues have been rectified through ongoing modification of the technology. Aspects of the unit design and installation have also been addressed as the system has evolved. According to AssistWare, the LDWS hardware is now entirely different from the beta hardware used in the FOT.

The current systems now include functionality that was not part of the FOT prototype, including a capability to store data and limited video capture on the unit. This latter capability can be beneficial to the fleets because it provides video documentation of crash situations that often are not the fault of the operator. Other added features include greater capability for the operators to customize the units within parameters set by their fleet managers. Although the core algorithms have not changed, the system is more user-friendly and reliable. Since the core algorithms are the same, the safety benefits predicted for the functioning test units would be similar to those for the current versions.

Installation of the LDWS is relatively straightforward. The manufacturer provides installation service, training, or a combination of both. AssistWare reported that about half the time they do the fleet installations and half the time the fleets do their own installations. The first unit installation takes approximately 2 hours, in order to understand the particular tractor requirements of the fleet; the second installation takes approximately 1 hour to complete, and then it typically averages a half-hour per installation. Field installations currently cost approximately $75 per hour plus travel.

For the LDWS, maintenance requirements are minimal. The manufacturer specifies no preventive maintenance requirements and only suggests the importance of keeping the windshield clean in order to maintain a clear camera view. The biggest issue is cracked windshields, which require the camera mount to be removed to allow for windshield replacement. After remounting the camera, about 2 minutes of driving time is typically required to recalibrate the unit. In normal operations, the system recalibrates itself. There are very few user-serviceable parts. If the camera is not aimed correctly it can be easily adjusted. If the wiring becomes disconnected it can be easy to reconnect. The deployment of AssistWare LDWS units began in 2002, and the manufacturer claimed that they tend not to have any problems. Also, the manufacturer expects the commercial off-the-shelf LDWS units to have a service life of 5 to 7 years.

While exact figures are proprietary, the cost to a fleet is well under $1,000 per unit. The cost to manufacture these units has dropped dramatically since the initial production runs. Units provided through an OEM may be subject to additional mark-up. Some manufacturers, such as Volvo, are keeping costs down by pre-wiring their tractors for plug-and-play installation. AssistWare sees these systems as being very viable in the marketplace at this time, and their business strategy is to make the next-generation systems better rather than to change the system in any fundamental way. For example, future versions are expected to have the capability to wirelessly transmit stored data from the vehicles to a central storage and processing unit.

Some trucking industry representatives with LDWS experience believe that these systems require more hardening to withstand the rigors of trucks that typically log over 1,000,000 lifetime miles, experience occasional voltage spikes, significant vibration, and generally hard use. Other issues and concerns relate to the system interface in the truck cab. One fleet manager reported that his company had to make its own housing for the units, and that the off-the-shelf version did not blend in a presentable way in the truck. They would prefer an easy panel-mount.

Further issues involve system validation. One fleet manager reported that, in order to validate the system, his company needed to take the vehicle on a test ride and conduct controlled lane excursions to validate performance on the highway. Another concern is the perceived difficulty of obtaining parts for faulty systems. Finally, there are reports that a fleet operator has had to modify the system's algorithms to ensure proper performance. The conclusion is that a more mature system would have private testing facilities for establishing calibration and performance settings.

In summary, there are differences of opinion on the degree of the LDWS maturity for deployment, as is typical for any relatively new technology. There is a high-level interest in the LDWS, along with other technologies such as collision-warning systems and rollover-stability systems, to enhance safety in the trucking industry. The ATA is actively involved in assessing the value of these systems for their members. Some fleets have shown a willingness to deploy LDWS in their fleet, while others are more inclined to wait and see how the systems perform over time. Although the SafeTRAC LDWS is currently in use, full acceptance and large-scale deployment will require significant awareness-building and a longer track record.

5.8 Goal 5. Assess Institutional and Legal Issues

Institutional issues cover a range of "nontechnical" issues that may be faced in the deployment of any technology. These issues include an understanding of the relevant organizations that can be considered stakeholders, their roles and responsibilities in the IVI program, and their perspectives on the kinds of institutional issues that are expected to be critical for program success. These organizations include the manufacturers as well as regulators, legislative bodies, unions, insurers, and organizations representing the carriers and the public interest.

Institutional issues were identified through several telephone interviews with AssistWare and Mack Trucks, and discussions with knowledgeable persons in the IVI program. Because the LDWS is advisory, leaving the vehicle operator in full control at all times, the institutional and legal issues are less significant than might be the case with safety technologies that may control some truck functions. Legal issues generally involve regulatory matters and liability risks associated with technology deployment and how those issues can best be anticipated and prevented or mitigated. Legal issues can arise in conjunction with such aspects as product failures, driver distractions, loss of vehicle control, property damage, and tort liability. There may also be concerns in employee relations pertaining to privacy or supervision. Institutional and legal issues are addressed with regard to this LDWS in the following sections.

5.8.1 Institutional Issues

When considering the introduction of new safety technologies into their trucks, the major fleets are aware of the importance of attending to potential institutional issues that can affect the success of the technology and ultimately their operational performance. Most carriers want to ensure proper adherence to standards and compliance with applicable rules and laws. They continually monitor the relevant requirements and laws to be sure that their companies are in compliance and aware of changes in requirements.

IVSS are in an early stage of deployment and not yet mandated, so enforcement is not an issue now, but standardization is important to both manufacturers and carriers. First, it is important that the human factors aspects of the control layouts and driver interface be carefully considered early on. Some drivers are in the same truck every day and become very familiar with all the safety devices, controls, and alerts, while other drivers rotate frequently from one vehicle to another where equipment configurations may differ. Standardization across the industry helps ensure that IVSS are logical and intuitive. Standardization can provide a straightforward way to determine the system's operational status, including its calibration settings and its drift from those settings at any time.

Motor carriers operate in a highly competitive environment; as a result, the trucking industry generally supports voluntary adoption of IVSS. Technologies that can help them improve their operational productivity and have a short payback period are more likely to facilitate deployment. Also, the regulatory community is well aware of its duties and responsibilities. Safety and economic analyses must be performed as part of any rulemaking. New technologies must have a basis in sound science and engineering to ensure that the applications are well understood and that the results are predictable and repeatable.

From the perspective of the OEM and the fleet operator, there are several important steps in ensuring acceptance of new safety technologies. The OEM (e.g., Mack Trucks) wants to introduce effective technologies that will provide real safety benefits to the fleet operator (e.g., McKenzie Tank Lines) and will be accepted and used correctly by the drivers. To this end, many OEMs hold quality reviews with their major customers who operate fleets, which include representatives from engineering, product marketing, dealers, district and regional sales, and service and maintenance.

Many of the new safety technologies, including LDWS such as SafeTRAC, generate data that could be used for management to evaluate driver performance. There is a recognition that the possibility always exists that some drivers can subvert the safety system but, on balance, drivers accept technologies that enhance their safety and help protect good drivers from liability in crashes.

Due to recently increased security awareness, many carriers consider it to be their responsibility to demand safe and secure performance. HAZMAT haulers, for example, are heavily investing in technologies that allow for real-time, continuous monitoring of driver performance, and the drivers understand the reasons. Concerns about company use of technology for driver-performance monitoring may be a lesser issue in fleets where good driving behavior and monitored performance offer a basis for driver rewards, good assignments, and safe driving bonuses.

To be successful in the long run, new safety technologies have to pay for themselves. The carriers' perspective is that the insurance companies have not offered the trucking industry adequate incentives for safety advances, as they have for passenger cars with airbags or anti-lock brake systems (ABS). Insurance companies assess premium adjustments for IVI devices typically only after they have demonstrated that they reduce claims over a sustained period of years. The LDWS has not been in use long enough yet to demonstrate the required safety benefit. Also, the industry has long noted that the Federal Excise Tax (FET) is applied on the entire vehicle, including the cost of safety devices, making it more difficult for carriers to recover costs.

Considering the different roles and perspectives of LDWS manufacturers, owner/operators, drivers, and independent fleets, institutional issues are important. AssistWare plans to proceed with refinements and improvements to the SafeTRAC LDWS, because they believe it to be beneficial from a safety perspective, as well as affordable and acceptable to drivers.

5.8.2 Legal Issues

The concern with the legal liability risk is that the cost of defending against lawsuits and associated settlements will outweigh the benefit of the technology from the perspective of the manufacturer or the fleet operator. This concern may limit or delay deployment of safety-enhancing technology.

Product Liability. Manufacturers and operators face product liability exposure where it is not necessary to prove negligence or fault, but rather only that the product was placed into the stream of commerce and that it contributed to the cause of the injury.

Scenarios of potential liability risk:

- The device fails to operate as designed, and the failure is deemed to be a cause of the injury.
- The operator relies on the device in a way that it was not designed to work, but a jury determines that the use could have and should have been foreseen.
- Plaintiffs' attorneys may seek to attribute crashes or incidents to the technology whether a causal link exists or not.
- If the device proves over time to be an effective means of reducing crashes or other incidents, then creative lawyers may charge negligence on the part of manufacturers or fleet operators who fail to equip their vehicles with the device.

Manufacturers and insurers would like to see some statutory protection from liability exposure to encourage development and deployment of safety enhancing technology. Risks that are particularly hard to predict and manage include awards for punitive damages and for pain and suffering. However, it is difficult to make a case for liability shields with legislatures in that manufacturers are unwilling to admit that they may fail to deploy or delay deployment of safety devices due to fear of exposure to product liability suits.

Intellectual Property. The LDWS is being developed to prevent SVRD events and crashes. It records data regarding vehicle operations that could be useful in documenting such events and tracking driver performance with regard to lane-keeping. Collection and archiving of such data raises a number of questions, such as:

- How might the data be used as a "black box," similar to data recorders in commercial aviation, to reconstruct crash events in assessing responsibility?
- Can, or will, data be used to assess driver performance and support disciplinary action outside of actual incidents?
- Absent a statutory shield from such use, will information from the technology be available by discovery to plaintiffs in personal injury suits, disclosing the frequency and severity of warnings regarding individual driver's performance? The "reasonable person" test is likely to be applied to employers regarding their liability for actions in employee supervision or retention in light of such information.

Mitigation Strategies. Actions that may reduce the risk associated with the issues discussed above include:

- Emphasis on human factors research to assess how the vehicle operator uses the technology and the potential for misuse, and take the potential for misuse into effect in designing the user interface.
- Care in the development of instructions for use and training procedures to ensure proper use and proper maintenance.
- Involvement with legal counsel responsible for defending product liability suits as technology is developed to ensure documentation of due diligence.

- Collaboration with insurance companies and regulating agencies as the device is developed and tested to demonstrate its effectiveness and to ensure that the process of deployment and regulatory oversight proceeds in a timely and effective way.
- Determination of policies regarding data collection, storage and use in consultation with regulators, risk managers, and employee representatives.

It is critical for acceptance and use that development and deployment of new technology be applied, in both appearance and deed, to focus on safety improvement rather than assessment of blame.

Summary of Real World Experience to Date. The fleets that use LDWS tend to be attentive to legal requirements, and they seek to comply with all the laws pertaining to the use of safety technologies such as SafeTRAC. Their focus is on being responsive to their customers' and operators' needs and meeting the technical requirements. Their legal departments provide oversight and guidance. They have not faced legal problems so far using this approach. The new safety technologies that automatically record performance data actually can serve to protect the carriers and their drivers in situations that receive close scrutiny, assuming the driver has not been negligent. The unions, that can be expected to be particularly sensitive to legal and privacy issues, have been generally accepting of industry's position with regard to the deployment of these technologies. Overall, legal and regulatory issues associated with LDWS have not constituted any legal problems to date.

5.9 Benefit-Cost Analysis

An important objective of this evaluation of the Mack IVI system was to conduct a BCA to determine the net economic benefits of deploying the IVSS technologies. The general approach was to leverage the work that was done in the Freightliner and Volvo IVI FOT Evaluations (Battelle, 2003 and 2005), and in the earlier Commercial Vehicle Information Systems and Networks (CVISN) Model Deployment Initiative evaluation (Battelle, 2002). In the Mack IVI FOT evaluation, the cost assumptions were updated and modified appropriately for the LDWS evaluation.

5.9.1 Benefit-Cost Analysis Approach

The BCA approach in the Mack IVI FOT evaluation was to provide a general, high-level analysis of all identifiable benefits and all costs at the societal level, rather than an analysis targeted specifically to the motor carrier industry, truck manufacturers, or other private-sector entities. The BCA, as applied to the Mack IVI FOT, is a public-sector evaluation tool that compares all of a project's benefits to society to all of the deployment and maintenance costs, if the benefit-cost ratio (BCR) is greater than 1, and the project is considered to be *economically feasible* or *justified.* By contrast, *industry* feasibility, the analogous private-sector criterion, is much narrower in the benefits and costs it compares. Benefits and costs are restricted to industry revenue outlays, industry costs, and industry avoided costs.

Objective 1D.1 Determine Costs to Deploy and Maintain IVSS Technologies.

Costs to deploy and maintain IVSS technologies include one-time costs and recurring costs. Examples of one-time costs are purchase and installation costs, one-time software development and consulting costs, and any other capital investments required to deploy the system initially. Examples of recurring costs are annual operations and maintenance (O&M) costs, such as consumable supplies, repair parts, or labor to keep the IVSS adjusted, calibrated, and in running order. Other recurring costs would be for capital equipment, such as costs required to replace equipment or components of the system periodically. Training costs for drivers have both one-time and recurring elements. Assuming a widespread deployment, all drivers in each operational scenario under consideration at the time of deployment would be trained to use the LDWS. Also, as drivers leave and new drivers enter the occupation through normal turnover the new drivers would also need to be trained.

The best available quantitative information on costs estimated to be incurred during real-world deployment and operation of the LDWS was obtained from the FOT partners and other industry sources. Actual cost values tend to be closely held, due to competitive markets and confidentiality among suppliers, OEMs, dealers, and end-users. The estimated costs in this BCA can be updated with cost elements for related IVSS deployments in the future, as better data become available.

Objective 1D.2 Estimate Cost Savings Potential.

The deployment of the LDWS is expected to result in cost savings through the avoided costs of prevented crashes. No other major cost savings to fleet operators or to society are anticipated. It is possible that long-range savings may be realized through enhanced driver satisfaction (resulting in reduced rates of driver turnover and increased savings of funds normally devoted to recruitment, driver training, etc.), reduced insurance rates, and other benefits. These kinds of indirect savings were not evaluated in the Mack FOT.

The numbers of crashes, injuries, and fatalities prevented through the deployment of LDWS were determined through statistical modeling and analysis based on national historical crash statistics and engineering data from the FOT, as described under Goal 1A. The costs associated with each crash, injury, and fatality were determined through literature reviews.

Objective 1D.3. Conduct Comprehensive Benefit-Cost Analysis.

The purpose of the BCA was to sum up and compare all available monetary elements derived from the other measures in the evaluation (safety, crash avoidance, deployment cost, operating cost, mobility cost to society, etc.). Although there are differences in the costs and benefits of the IVSS technologies being tested in the three IVI truck FOTs (Freightliner, Mack, Volvo), certain types of data and analyses required for the BCA are common to all three FOTs. Examples include the average costs of truck crashes, the value of mobility and environmental benefits, and analyses of truck populations and characteristics. Therefore, the BCA was coordinated among the three FOTs. The specific hypothesis that was tested in this BCA was that the total cost to society of deploying and maintaining each of the IVSS is less than the combined value of all the benefits.

All of the benefits and costs considered in a BCA must have some inherent value to society. While the actual summing of the benefits and costs in a BCA is straightforward, identifying the right inputs and observing or estimating their values is not. In particular, for a benefit or cost to be included in a BCA, it must be quantifiable, monetizable, and not duplicative. Benefits must be quantifiable in order to attach a monetary value to them; however, not all quantifiable benefits have economic value to society.

All of the categories of benefits and costs included in the BCA are derived from the hypothetical impacts of each of the IVI FOTs. The FOTs are expected to alter the operation of commercial vehicles in various ways, but the net economic benefits cannot be assessed until the impacts are translated into the measures listed in the tables that follow. The process of identifying the appropriate set of benefits is further complicated by the way values are customarily placed on such benefits as crashes that are avoided, travel time saved, truck "productivity," etc. The estimates in the literature include a wide range of benefit elements. The elements that make up these valuations in the literature were explicitly identified in order to avoid double counting or omitting a benefit.

Finally, to test the hypothesis that the IVI systems yield net benefits to society, all present and future discounted costs must be subtracted from their properly discounted present and future benefits to society. Each of the benefits and costs in a BCA is discounted to a present value over the economic life of a project. For the FOTs, benefits are assumed to begin immediately with one-time start-up costs in the year 2005 and extend for a 20-year period through 2024. This assumption allows 20 years of economic returns for the project, which includes replacement cycles for IVSS equipment at a 5-year interval, as described below.

Each of the benefits and costs occurring each year between 2005 and 2024 were discounted back to 2005 using both a 4 percent and a 7 percent real discount rate to calculate the present values of the benefits and costs in 2005 dollars. The use of a 4 percent discount rate in these kinds of benefit-cost calculations has been recommended by economists in both the public and private sectors. The use of a 7 percent discount rate is usually a more stringent test and has been required for two decades for use in BCAs of Federal programs by the U.S. Office of Management and Budget (U.S. OMB, 1992 and 2000). Results shown in this section are based on the 4 percent discount rate; results for undiscounted, 4 percent, and 7 percent rates are included in Appendix D.

Table 64 shows the benefits that were to be measured in the IVI FOTs, and Table 65 shows the costs. For each benefit or cost, these tables present the measurable values to be sought, along with the sources of information.

Table 64. Benefits Related to IVSS Deployment

Benefit	Measure	Source(s)
Safety	Reduced numbers of crashes	Crash avoidance analysis (statistical modeling)
Safety	Crash severity	
Safety	– Change in severity	Derived from driving data
Safety	– Effect on injury/fatality rates	Literature search
Safety	Dollar value of a crash	Literature search, plus constituent factors below
Safety	– Avoided fatalities, personal injury, property damage, and infrastructure damage per crash	Literature search (included in $ value of crash)
Safety	– Avoided costs of emergency responder services (police, fire, EMS) per crash	Literature search
Environment	– Avoided costs of HAZMAT response (release and non-release) per HAZMAT crash	Literature search
Mobility	– Improved public mobility (reduced traffic delays and congestion from crash)	Literature search

Table 65. Costs Related to IVSS Deployment

Cost	Measure	Source(s)
One-Time Start-Up	Dollar value of capital equipment and software	Interviews and site visits
One-Time Start-Up	Dollar value of initial driver/staff training	Interviews and site visits
One-Time Start-Up	Dollar value of start-up services, installation, consultants, administration, etc.	Interviews and site visits
Recurring	Dollar value of annual O&M	Interviews, site visits, and fleet records
Recurring	Dollar value of ongoing driver/staff training	Interviews and site visits
Recurring	Dollar value of recurring replacement hardware items	Interviews and site visits
Recurring	Expected service life (years) of capital equipment (used to determine recurring capital costs)	Interviews, site visits, and literature search

Figure 53 depicts the flow of dollar cost values and population counts that were combined in the BCA. The benefits, in terms of crash cost avoidance, are shown on the left, and the costs, in terms of equipment purchases and driver training, are shown on the right. In general, unit costs were summed with similar per-crash, per-truck, or per-driver cost elements, and then multiplied by population numbers (e.g., trucks, crashes, injuries, drivers, hours) to provide total annual costs, which were summed and discounted over a 20-year deployment life cycle. Appendix B presents the spreadsheet model used to combine, sum, and discount the various unit costs in the BCA. The appendix also presents tables showing annual cash flows throughout the life cycle being modeled.

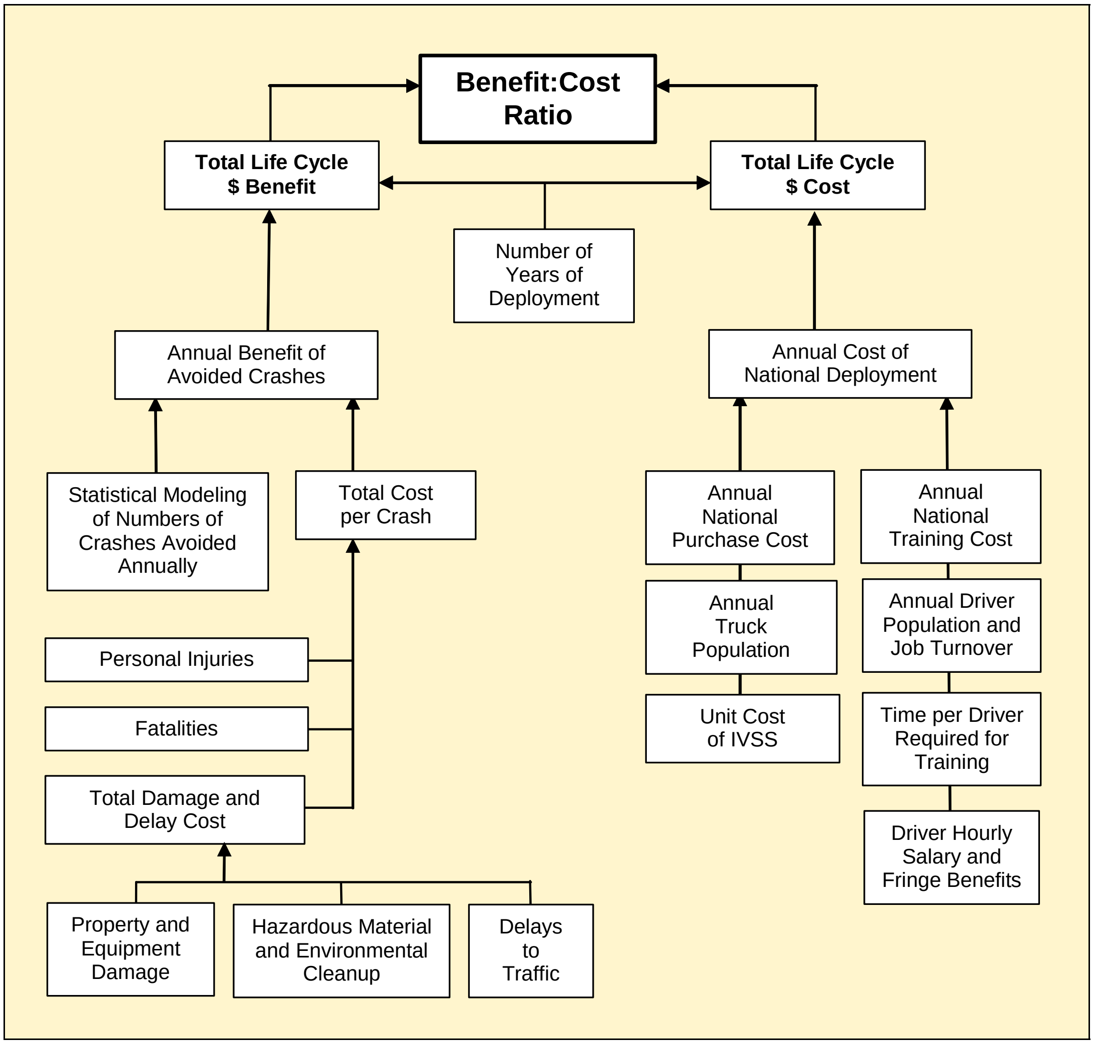


Figure 53. Combining Data Elements to Determine the Benefit-Cost Ratio

The main benefit of the LDWS is increased safety in the form of the reduced numbers of crashes involving large trucks; as a result, the crash-rate reduction and the monetary values of the truck crashes were estimated. Values of truck crashes have been estimated in a number of studies reported in the literature and summarized in related USDOT-sponsored projects (e.g., Pacific Institute, 2000 and 2002). The best available relevant estimates of the costs of a truck crash were used in the analysis.

5.9.2 Benefit-Cost Assumptions

Scenarios Modeled. A total of 16 scenarios were modeled in all, determined as follows:

(4 operational configurations) ×
(2 equipment cost assumptions) ×
(2 crash reduction efficacy assumptions) = 16 BCA scenarios

In the Mack IVI FOT, the truck populations in the four scenarios were (1) all trucks of more than 10,000 pounds; (2) all truck-tractors pulling trailers; (3) all truck-tractors pulling tanker-trailers; and (4) all truck-tractors pulling tanker-trailers with placarded HAZMAT. Scenarios for the Mack FOT benefit-cost analysis are shown in Table 66.

Cost-Side Assumptions. As noted above, component developers, suppliers, OEMs, and dealers tend to be reluctant to disclose actual costs for individual components in a highly competitive market. Conventional wisdom is that the costs that are quoted in public are often higher than the actual costs agreed to in private purchase negotiations, because of volume discounts and other interrelated factors that determine the actual price paid to a dealer by an end-user when buying a commercial vehicle.

First (Installed) Cost. The costs used in this evaluation report are based on an informal survey of publications related to IVSS, plus engineering estimates, plus contacts with industry sources. Table 67 lists the component-cost estimates used as sources for the cost values used in this report.

Because the LDWS has entered the marketplace relatively recently, costs may fluctuate upward or downward as the market evolves and as supply and demand vary. For example, as the product matures and as production volumes rise, economies of scale in manufacturing and distribution may allow initial costs to decline over time. For the BCA scenarios, low and high installed cost estimates were used in the benefit-cost modeling, based on the informal survey described above. The low-cost assumption per tractor was $750 and the high-cost assumption was $1,500. The manufacturer of the LDWS estimates that commercial off-the-shelf units are expected to have a service life of 5 to 7 years. For the BCA, the more conservative value of 5 years was used for replacement life, assuming purchases for every truck in each operational scenario in years 2005, 2010, 2015, and 2020. Because future cost-estimates are not available, the replacement cost per tractor was assumed to be the same as the year-1 purchase cost. No purchase in the final year of the 20-year life cycle analysis (2024) was modeled.

Table 66. Truck Populations Used in the Benefit-Cost Analysis by Year[1]

Population	2002	2003	2004	2005	Sources and Comments
All Large Trucks (>10,000 pounds GWV)	—	**7,912,018**	8,147,796	8,390,600	Number of single-unit, 2-axle, 6-tire or more, and combination trucks registered in 2003, USDOT FHWA Highway Statistics, Table VM-1[2]
Truck-Tractors Pulling Trailers	—	**1,757,288**	1,809,655	1,863,583	Number of private and commercial truck-tractors registered in 2003, USDOT FHWA Highway Statistics, Table MV-9 [3]
Truck-Tractors Pulling Tanker-Trailers	**108,900**	112,145	115,487	118,929	Number of truck-tractors with body type = tank: dry bulk (28,300) + liquids or gases (80,600) in 2002, U.S. Census Bureau Economic Census, Vehicle Inventory and Use Survey, Table 3a [4]
Truck-Tractors Pulling HAZMAT Tanker-Trailers	76,230	78,502	80,841	83,250	Estimated proportion (70%) of tank-trucks laden with HAZMAT as defined by the USDOT, per The National Tank Truck Carriers, Inc., web site. (108,900 * 0.7 = 76,230) [5]

[1] Earliest year shown was taken from the source indicated in the last column, and inflated to 2005 population values using annual truck growth rate of **2.98 percent,** based on the American Trucking Associations' U.S. Freight Transportation Forecast, comparison of populations of Class 8 trucks in 1998 (2,298,000) to those forecast in 2008 (3,081,000).

[2] http://www.fhwa.dot.gov/policy/ohim/hs03/pdf/vm1.pdf, published December 2004.

[3] http://www.fhwa.dot.gov/policy/ohim/hs03/pdf/mv9.pdf, published October 2004.

[4] http://www.census.gov/prod/ec02/ec02tv-us.pdf, published December 2004.

[5] http://www.tanktruck.org/links/index.html, August 2005. Coincidentally, McKenzie Tank Lines reported that approximately 65 percent of their tanker deliveries involve HAZMAT.

Table 67. SafeTRAC LDWS Installed Cost Estimates per Tractor

Estimated Cost, $	Source
<1,000	"Well under $1,000 per unit for a fleet operator," per Mike Formica, CEO of AssistWare, the system vendor. Interview with Chris Cluett and Jeff Hadden of Battelle, June 11, 2005.
<1,000	"Volume pricing for end-users is under $1,000," per AssistWare web site, www.assistware.com, August 2005.
1,000 to 2,000	T. Barton, "On the Safer Side," Overdrive, www.etrucker.com, August 2003.
1,000 to 1,500	Gary Woodward, Hurley's Auto Audio, McLean, VA, www.hurleysaudio.com, independent retailer/dealer who installs SafeTRAC equipment in aftermarket configuration. Interview with Vincent Brown of Battelle, August 8, 2005.

First cost (installed cost) values were the only cost elements varied to model different cost ranges for deployment of the IVSS. Other cost values, such as annual operating and maintenance costs and the costs for driver labor for time spent training to use the new systems, were held constant across all scenarios modeled in all years.

Annual Operating, Maintenance, and Training Cost

Some of the units used in the FOT experienced problems that required repair and/or component replacement. However, these problems occurred on what the manufacturer considers a prototype version and may not be representative of those that would be experienced by current versions of the LDWS. Further, the expected life of the test units was about 2 years, and many of the units had been installed in trucks for more than 2 years by the end of the FOT. According to the manufacturer, preventive maintenance is not required during the operation of the LDWS. Therefore, annual operating and maintenance costs were assumed to be $0.

Driver training was a topic in the driver interviews, with some drivers expressing an opinion that more training would have helped. For the BCA, 1 hour per driver for paid training on the LDWS was assumed. The training cost was assumed to be paid at the prevailing driver hourly rate (national average including fringe benefits). This cost was assumed to be a one-time training cost per driver for all drivers in the first year. In subsequent years, it was assumed to include training for every driver upon hire, with an assumed 20-percent annual turnover rate through the 20-year course of the deployment. This 20-percent turnover estimate for drivers of all trucks across the industry in the United States was provided by the American Transportation Research Institute. Some carriers report a higher annual turnover rate, even as high as 100 percent annually.

The numbers of drivers to be trained in a given year was determined by a calculation of the ratio of drivers to tractors in a given fleet that same year, taken to be 0.42:1. This ratio was derived from the population of trucks (7,392,582), as given in an FHWA truck population study, compared with the total number of drivers in the same year (3,136,170), as given in the Bureau of Labor Statistics National Occupational Employment and Wage Estimates. Thus, as the population of trucks modeled in each fleet increased each year, the assumed population of drivers, and the dollar costs of training them, increased commensurately. The ratio of drivers to trucks was assumed to remain constant throughout the life cycle being modeled.

Benefit-Side (Crash Avoidance) Assumptions

The numbers of crashes, injuries, and fatalities were derived from the statistical modeling described earlier in Chapter 5 (Sections 5.1.1 and 5.1.3). Corresponding dollar costs per crash, injury, and fatality were derived from a literature review, based largely on sources similar to those used in the Freightliner and Volvo IVI FOT reports (Battelle, 2003 and 2005). Where updated crash-cost values were readily available, they were applied to the BCA. A detailed, updated literature review was not performed. Instead, where updated values were not available, the values documented in the earlier reviews were consistently inflated to year 2005 dollars using the U.S. Department of Labor, Bureau of Labor Statistics Consumer Price Index (CPI) web site, http://www.bls.gov/cpi/home.htm. Specifically, the "Inflation Calculator" available on that web site was used.

Table 68 compares the values used in the earlier Freightliner IVI FOT report with those that were modified for use in this report, and describes the modifications that were applied. It is noteworthy that the per-crash costs for personal injury and delays to other traffic went down sharply from the earlier Freightliner report. The personal injury cost-factor in the Freightliner report had been based on data from Pacific Institute (2000) Table 10, Costs Per Crash. However, for this FOT, it was determined to be more accurate to draw data from Pacific Institute (2002) Table 9, Costs Per Victim Injured, because the statistical modeling expressed injury reductions in terms of the numbers of victims injured, not in terms of number of injury crashes. As the following table shows, this change resulted in each injury being counted as approximately $100,000 less expensive than in the Freightliner report, affecting the BCRs.

The property damage cost-estimates used in the Freightliner report were based on an informal industry survey by the American Trucking Associations for the costs of rollover and single-vehicle road-departure crashes. Because these were the same crash types considered in this FOT, the same survey results were used in the modeling and adjusted for inflation.

For the delay costs, the revised Pacific Institute report (2002) made three refinements over the previous Pacific Institute report (2000):

- Used a newer, broader survey of police departments to update the hours-of-delay ratio from 40:130:385 in the 2000 report to 49:86:233 in the 2002 report, for delays due to property damage only, injury, and fatality crashes, respectively. This resulted in fewer delay-hours, and thus dollars, per crash in the revised report.
- Used data on the average number of people killed or injured in a heavy vehicle crash.
- Assumed that only police-reported crashes delay traffic (2002, p. 11).

Table 68. Comparison of Relevant Cost Values

Description	Freightliner Report	Mack Report	Comments*
Dollars/injury (truck-tractor, 1 trailer)	162,095	61,779	Freightliner used Pacific Institute dollars/crash (Table 10). Mack uses revised Pacific Institute dollars /victim, Table 9, inflated using CPI from 2000 dollars to the year 2005 dollars.
Dollars/injury (all trucks)	156,558	51,861	Freightliner used Pacific Institute dollars/ crash (Table 10). Mack uses revised Pacific Institute dollars/victim, Table 9, inflated using CPI from 2000 dollars to the year 2005 dollars.
Dollars/fatality	3,358,240	3,022,840	Freightliner used Pacific Institute Table 10. Mack uses Revised Pacific Institute Table 9, cost per fatality (minus delays and property damage). Inflated using CPI from 2000 dollars to the year 2005 dollars.
Property damage dollars/crash (truck-tractor, 1 trailer)	13,854 (SVRD) or 25,223 (Rollover)	16,209 (SVRD) or 29,511 (Rollover)	Freightliner used ATA/American Transportation Research Institute (ATRI) informal survey results; Mack uses previous ATA survey results, inflated to the year 2005 dollars.
Property damage dollars/crash (all trucks)	6,350	7,430	Freightliner used ATA/ATRI informal survey results; Mack uses previous ATA survey results, inflated to the year 2005 dollars.
Delays to other traffic, dollars/ crash (truck-tractor, 1 trailer)	9,064	5,280	Freightliner used previous Pacific Institute report (2000); Mack uses revised Pacific Institute report Table 11 ($4,677 in 2000 dollars, inflated to the year 2005 dollars).
Delays to other traffic, dollars/ crash (all trucks)	9,355	5,419	Freightliner used previous Pacific Institute report (2000); Mack uses revised Pacific Institute report Table 11 ($4,800 in 2002 dollars, inflated the year 2005 dollars).
HAZMAT environmental damage	12,246	13,608	Freightliner used FMCSA 2001 Comparative Risks report, inflated to 1999 dollars; Mack uses FMCSA values inflated to the year 2005 dollars.
Annual average driver wage	40,800	45,288	Freightliner used ATA year 2000 Driver Compensation Study. Mack uses that value, inflated using CPI from 2000 dollars to the year 2005 dollars.

*All inflation factors were calculated using the "Inflation Calculator" at the U.S. Department of Labor, Bureau of Labor Statistics CPI web site, http://www.bls.gov/cpi/home.htm.

These changes resulted in the aggregated per-crash delay costs used in this BCA (approximately $5,000) being less than the aggregated per-crash delay costs that had been used in the Freightliner BCA (approximately $9,000).

The national truck population, based on FHWA *Highway Statistics* data, was forecasted to account for an estimated annual 2.98 percent rate of growth in the truck fleet over the period under analysis (2005 to 2024), based on the U.S. Freight Transportation Forecast to 2008, published by the American Trucking Associations, and covering the years 1998 to 2008. This growth rate was assumed to remain constant over the life cycle being modeled.

5.9.3 Benefit-Cost Results

Table 69 shows the societal BCRs, expressed in present (year 2005) dollars at a 4 percent discount rate over a 20-year deployment window for each of the 16 scenarios modeled. As noted, BCR values of more than 1 indicate an economic return on the investment required to deploy the IVSS. BCR values of less than 1 indicate that the deployment does not appear to be economically justified based on the assumptions used in this analysis. Tables of annual cash flows for benefits and costs, plus details of all values that were factored into the BCA model, are presented in Appendix D.

The table shows that ten of the 16 scenarios offer BCRs of more than 1, while the remaining six scenarios do not appear to be economically justified. None of the “all trucks” scenarios is economically justified according to the assumptions used in this BCA. This may be because of the much larger numbers of all large trucks, which greatly increases the deployment cost. The scenarios involving tractor-trailers pulling tankers are the most economically favorable over the 20-year life cycle, with BCRs ranging from 1.95 to 5.11. The HAZMAT tanker scenarios are the next best, with BCRs ranging from 1.19 to 3.20. The tractor-trailer scenarios with low equipment costs are marginally economically justified (BCRs = 1.10 and 1.54), while the high equipment-cost scenarios pull the two remaining tractor-trailer BCRs below 1.

The benefit-cost ratios for the two larger fleets (all trucks and tractor-trailers) are higher for the conservative scenarios than for the best-estimate scenarios. This is contrary to the results for the two smaller fleets (tractor-tankers and HAZMAT tankers) where the best-estimate scenarios yield higher BCRs. This is because the larger fleets and smaller fleets have different conflict rates (Table 6), and the crash-reduction ratios (Table 31) are different for rollover crashes under conservative and best-estimate scenarios.

For the two larger fleets, approximately 5 percent of rollover crashes are preceded by conflicts in straight roads. For these 5 percent of rollover crashes, the best estimate actually projects a slight (but statistically insignificant) increase in crashes, while the conservative efficacy assumption projects a decrease in rollover crashes.

By contrast, for the two smaller fleets, there are no rollover crashes preceded by conflicts in straight roads. Therefore, the conservative efficacy-scenarios yield BCRs that are lower than the best-estimate scenarios.

Table 69. Net Present (2005) Dollar Values and Benefit-Cost Ratios

Population	Cost Category	Efficacy	$ Benefits	Costs	BCR
All Trucks	Low	Best Estimate	$7,251,667,932	$22,976,455,388	0.32
All Trucks	Low	Conservative	$10,496,874,747	$22,976,455,388	0.46
All Trucks	High	Best Estimate	$7,251,667,932	$45,482,640,586	0.16
All Trucks	High	Conservative	$10,496,874,747	$44,864,469,080	0.23
Tractor-Trailers	Low	Best Estimate	$5,594,230,595	$5,103,154,919	**1.10**
Tractor-Trailers	Low	Conservative	$7,851,485,875	$5,103,154,919	**1.54**
Tractor-Trailers	High	Best Estimate	$5,594,230,595	$10,101,861,106	0.55
Tractor-Trailers	High	Conservative	$7,851,485,875	$10,101,861,106	0.78
Tanker Trailers	Low	Best Estimate	$1,664,500,391	$325,670,019	**5.11**
Tanker Trailers	Low	Conservative	$1,255,285,771	$325,670,019	**3.85**
Tanker Trailers	High	Best Estimate	$1,664,500,391	$644,674,393	**2.58**
Tanker Trailers	High	Conservative	$1,255,285,771	$644,674,393	**1.95**
HAZMAT Tankers	Low	Best Estimate	$730,015,944	$227,968,192	**3.20**
HAZMAT Tankers	Low	Conservative	$535,833,540	$227,968,192	**2.35**
HAZMAT Tankers	High	Best Estimate	$730,015,944	$451,270,449	**1.62**
HAZMAT Tankers	High	Conservative	$535,833,540	$451,270,449	**1.19**

Figure 54 illustrates the 16 scenarios graphically, showing which configurations of fleet, equipment cost, and crash-reduction efficacy yield a positive societal return on the investment required to deploy IVSS on all trucks in each fleet. The break-even point at 1 is shown by the dark horizontal line. As can be seen in the figure, the best return is obtained by equipping tractors with tanker-trailers and tractors with HAZMAT tanker-trailers.

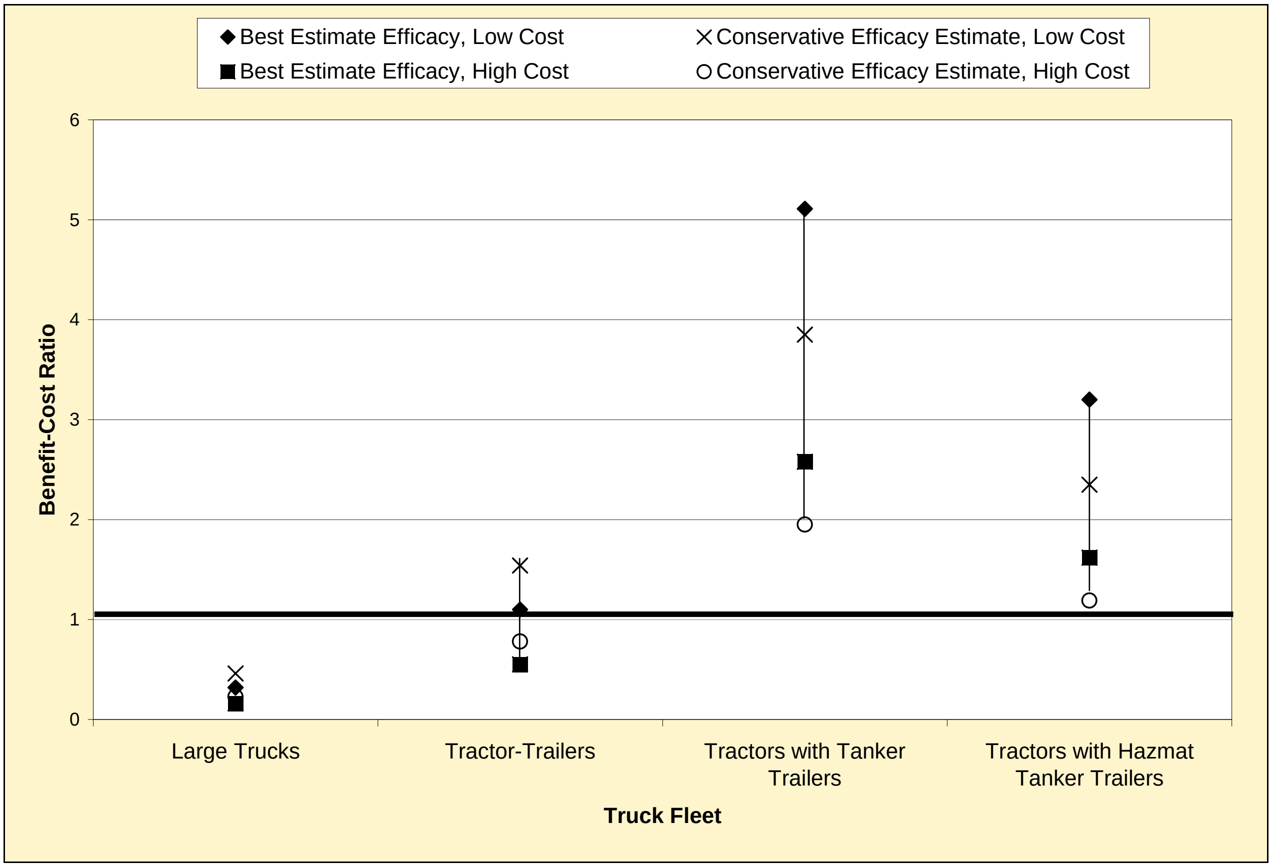


Figure 54. LDWS Benefit-Cost Analysis Results

6.0 IMPLICATIONS OF LESSONS LEARNED AND FINDINGS

This section summarizes the lessons learned and findings of the independent evaluation in the context of the benefits of an LDWS installed on large trucks.

6.1 Lessons Learned

Several lessons were learned from the Mack FOT independent evaluation which can be valuable lessons to apply in future FOTs of IVSS. This FOT revealed that a risk-based independent evaluation plan developed prior to the FOT is vital to prevent problems that may occur, such as those described below.

As shown in this FOT, it is critical that a risk-based independent evaluation plan includes comprehensive and quantitative criteria that can be developed and applied to ensure that the IVSS proposed for an FOT are acceptable, have been demonstrated in system verification tests, and are ready for deployment in an FOT. The focus of the Mack FOT was on “Generation Zero” systems that were commercially available for deployment on trucks. Although the LDWS was commercially available for trucks, the version supplied to the Mack Partnership for this FOT was considered a prototype by the manufacturer. Since the functionality of the test units related to issuing warnings and displaying information to the driver was virtually identical to the current commercial version of the LDWS, conclusions could be drawn about the safety benefits of the commercial version. However, conclusions about the reliability of the commercial version could not be drawn from the FOT data on the prototypes.

At the initiation of the FOT, it is vital that the risk-based independent evaluation plan include specific contingency plans to be in place to mitigate the effects of unexpected events. These plans should include the availability of additional trucks, drivers, and spare hardware; alternative methods for obtaining driver feedback; and options to adjust to changes in fleet operations that may impact the conduct of the FOT.

Proper planning by the independent evaluator should be in place and should be followed in a risk-based independent evaluation plan to ensure that driver training and driver surveys are performed successfully. Responding to driver surveys should be a major part of driver training prior to FOT data collection. The plan for training drivers on the operation of the LDWS involved providing them with an informational brochure. Another important element of the plan was to install the LDWS and data acquisition systems on all trucks in the test fleet during a specific 1-to-2-month period at McKenzie Tank Lines’ Tallahassee maintenance facility, and to provide driver training during this time. However, delays caused by the need to complete the development and verification of the on-board systems resulted in losing this window of opportunity, which could not be rescheduled because it would have disrupted McKenzie Tank Lines’ operations. Instead, brochures were distributed to the several McKenzie Tank Lines terminals where the test drivers were based, and the brochure distribution and personal training was delegated to the terminal managers. Consequently, the amount of training provided to the test drivers was inconsistent and varied widely, as reflected in some of the responses to the driver surveys.

As outlined in a risk-based independent evaluation plan, it is vital that the independent evaluator understand the day-to-day operations of the fleet participating in the FOT and adjust the experimental design and test plan to ensure adequate data collection. The amount of data used to estimate safety benefits in the Mack FOT was a small fraction of the total data acquired. This was attributable to two primary factors. First, malfunctions of the instrumentation and data acquisition systems resulted in some of the data files containing poor quality data. Second, the need to operate harmoniously with McKenzie Tank Lines' normal business operations meant that driver/truck assignments could not be controlled, which in turn resulted in the inability to ensure that the data acquired for any particular driver had roughly equal amounts of VMT for the LDWS active and inactive interface (a requirement for the evaluation method). With a better up-front understanding of the nature of McKenzie Tank Lines' fleet operations and better anticipation of the problems that eventually occurred, it might have been possible to adjust the experimental design and test plan to ensure the adequacy of the data acquired.

Ensuring the collection of sufficient quantity and quality of data is essential to the success of the FOT. For example, in the Mack FOT, the following additions to the on-board measurement system could have improved the ability to identify driving conflicts and analyze driving behavior:

- A steering wheel angle-sensor to provide a better indication of the driver's reactions in a lane departure scenario
- An accelerometer mounted on the front-axle assembly to indicate lateral acceleration more accurately
- A tilt sensor with a higher frequency response than the one installed in the VES box, to indicate roll response more accurately

Likewise, in the Mack FOT, the following refinements to the periodic operational data summaries (known as OPS files) would have aided in the data quality and completeness checks and the data processing:

- A count of the triggered events that occurred during each OPS file-check to verify that no potential driving conflict files (LEX files) were missing
- Odometer readings at the beginning and end of each OPS file to provide a more accurate measure of VMT
- System status
- Independent verification that the driver is – or is not – receiving the audible and visual alerts from the LDWS

During the FOT, the participating truck fleet's desire for minimal disruption of normal operations needs to be balanced by the independent evaluator's need to execute the experimental design. Lengthy delays in the development and verification of the on-board systems, coupled with McKenzie Tank Lines' need to deploy trucks to meet their business needs, forced significant changes in the initial research plan. As a result, the inability to control the VMT in the baseline, active, and post-active periods resulted in a reduced amount of data that could be used in the safety-benefits estimate. Also, many of the challenges encountered in contacting drivers and checking and servicing test equipment could probably have been avoided if the drivers and vehicles had not been based at many widely dispersed terminals.

By following a risk-based independent evaluation plan, the expectations and levels of commitment required to accomplish the goals of the FOT could be communicated in advance and agreed upon by all FOT participants. For a successful FOT, it is important that all participants be aware of the effects of changes in the plan, schedule, roles, and responsibilities. If all FOT participants follow a risk-based independent evaluation plan, many problems could be solved in a timely manner.

6.2 Implications of Findings

The Mack FOT independent evaluation revealed that the use of the LDWS could reduce crashes, injuries, and fatalities in crashes involving large trucks. These findings were primarily based upon improved driver lane-keeping behavior and the reduction in the frequency of driving conflicts in the FOT. These results indicated that the LDWS is effective in reducing the number of situations where an SVRD or rollover crash could result, since the LDWS provides advance information that the driver can use to avoid a potential hazard. Using the LDWS, the truck driver is warned about a lane departure when the front tire of the truck is at the lane edge. The amount of time and space that a given driver has to recover from a lane departure will likely vary widely, depending on factors such as truck speed and heading, driver reaction time, shoulder width, and roadside characteristics. Based on the conflict criteria used in the Mack FOT evaluation (e.g., drift alert issued when truck goes at least 18 inches out of the lane), the results indicated that the LDWS is effective for driving conditions typical of the McKenzie Tank Lines fleet.

Based on the conditions in the FOT, a vision-based LDWS such as SafeTRAC, could potentially lower the numbers of SVRD and rollover crashes by reducing the types of driving conflicts that are precursors to these crashes. The FOT results showed that under the conditions observed in the FOT, the LDWS can reduce driving conflicts by 31 percent on straight roads and 34 percent on curves. Also, under similar conditions as the Mack FOT, the deployment of the LDWS would result in an approximate 21 percent to 23 percent reduction in single vehicle roadway departure crashes and 17 percent to 24 percent reduction in rollover crashes. During the FOT, the LDWS was most effective in reducing lane departures at night and on straight roads at highway speeds.

The results also indicated that the system can improve safety-related driving behavior, even with experienced drivers, such as those drivers participating in this FOT. For example, during the FOT period, drivers of trucks with active interface systems not only had fewer driving conflicts, but also received fewer drift alerts than drivers of trucks with inactive interface systems. This implies that one benefit of using the system was a decrease in the number of unintended times the truck headed out of its lane.

Because the LDWS used in the FOT were prototypes and many units had been installed on trucks without the driver interface activated for several months prior to the start of the FOT data collection, conclusions about reliability and performance of the current commercial version could not be drawn. However, the FOT data indicated that the LDWS issued alerts consistently under the conditions for which it was designed.

The findings were inconclusive with regard to driver acceptance of the LDWS. Limited feedback was received from a small set of the drivers from a questionnaire, and the results were mixed. These drivers generally believed that the LDWS improved their lane-keeping ability and was relatively easy to use and understand. These drivers felt that it helped to maintain alertness, and reduced driver workload. Yet, they also cited that it was difficult to distinguish the SafeTRAC warning from other warnings (e.g., VORAD), the false alarms caused a loss of confidence in the system, and the warnings and displays could be annoying or distracting. Due to the small number of drivers who provided feedback, statistically significant conclusions could not be drawn from this information. The criticisms of the warnings and displays could be addressed by design changes such as providing drivers with the ability to adjust the volume, tone, and timing of the lane-departure warnings. Further, confidence and acceptance of the system could be increased through more formal driver training on how to operate the system. One of the most significant implications of the drivers' feedback was the importance of effectively integrating multiple IVSS so that all warnings are interpreted correctly and the driver takes appropriate action.

From a societal benefit-cost perspective, the system was economically justified for tractors pulling tanker-trailers and for tractors pulling HAZMAT tanker-trailers under conditions similar to the FOT. Advantages of the LDWS included improvements in aiding alertness, concentration, and driving under poor driving conditions. Disadvantages included the distracting alerts and the location of the unit on the dash. The main behavioral effect of the LDWS was increased attentiveness to lane keeping, which constituted a major safety objective of this technology.

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APPENDIX A:

DATABASE SPECIFICATIONS: GES AND FARS VARIABLES

Coding Scheme Used in Historical Crash Data Analysis (GES and FARS)

This appendix explains how the General Estimates System (GES) and Fatality Analysis Reporting System (FARS) data sets were used in the analysis of historical crash statistics. Only crash data from 1999 to 2003 were used in this analysis. Similar variables in the GES and the FARS data sets were used whenever possible to define categories of interest for analysis. Sometimes, multiple variables were necessary to define a category.

The tables in this document all have the same general format. Both the name and alphanumeric name are given for the GES variables, while the Statistical Analysis System (SAS) software names are given for the FARS variables. For each variable, the coded SAS values that were utilized – and a text description of what they represent – are provided. Beginning in 2002, there were some significant changes made to the GES and FARS coding schemes. The changes are indicated in the tables. One important change in FARS involves the "manner of collision" variable. Prior to 2002, the manner of collision variable was defined in terms of the direction of travel of the vehicles involved – as determined by the pre-crash condition direction of travel. Beginning in 2002, the manner of collision was defined in terms of the points of impact.

The analysis focused on large trucks classes 3 through 8 (over 10,000 lbs gross vehicle weight). Additional breakdowns of the large truck category included tractor-trailer combinations, tractors pulling tanker-trailers, and tractors puling tanker-trailers containing HAZMAT. The method used to define the truck categories from the GES and FARS data is provided in Table 70.

Five crash types were determined from the GES and FARS data sets. Table 71 displays the variables used to determine the crash types. Classifying the crashes into these categories for the GES data was straightforward given the crash-type diagrams supplied in the GES User's Manual. Since FARS did not have an accident type variable similar to GES, several variables were identified to determine the crash type.

The crash types were further broken down into predominant driving conflicts based on the "critical event" and "movement prior to the critical event" variables in GES data. FARS does not provide such detail. Tables 72 and 73 describe the process used to determine predominant driving conflicts for SVRD and rollover crashes, respectively.

Table 70. Determination of Truck Category Variables

Data Source	Category	Hot-Deck Imputed Body Type V5H	Tailing Units V13	Cargo Body Type V33	HAZMAT Placard V34
GES	Large Truck	60 – Step Van	All	All	All
		64 – Single Unit Straight Truck	All	All	All
		66 – Truck-Tractor	All	All	All
		78 – Unknown Medium/Heavy Truck	All	All	All
GES	Tractor-Trailer	66 – Truck Tractor	2,3,4,5 – Trailing units	All	All
GES	Tractor with Tanker-Trailer	66 – Truck Tractor	2,3,4,5 – Trailing units	03 – Cargo Tank	All
GES	HAZMAT Tanker-Trailer	66 – Truck Tractor	2,3,4,5 – Trailing units	03 – Cargo Tank	1 – Yes
Data Source	**Category**	**Body_typ**	**Tow_veh**	**Cargo_bt**	**Haz_carg**
FARS	Large Truck	60 – Step Van	All	All	All
		61 – Single Unit Straight Truck low GVWR	All	All	All
		62 – Single Unit Straight Truck med GVWR	All	All	All
		63 – Single Unit Straight Truck high GVWR	All	All	All
		64 – Single Unit Straight Truck	All	All	All
		66 – Truck-Tractor	All	All	All
		71 – Med. Single Unit Straight Truck or Combination Truck	All	All	All
		72 – Heavy Single Unit Straight Truck or Combination Truck	All	All	All
		78 – Unknown Medium/Heavy Truck	All	All	All
		79 – Unknown Truck	1,2,3,4 – Trailing units	All	All
FARS	Tractor-Trailer	66 – Truck Tractor	1,2,3,4 – Trailing units	All	All
FARS	Tractor with Tanker-Trailer	66 – Truck Tractor	1,2,3,4 – Trailing units	02 – Cargo Tank	All
FARS	HAZMAT Tanker-Trailer	66 – Truck Tractor	1,2,3,4 – Trailing units	02 – Cargo Tank	1 – Placard

Table 71. Determination of Crash Type (Changes made due to variable recoding in 2002 in parenthesis)

Crash Type	GES Accident Type V23	GES Rollover V30	GES Univariate Imputed Vehicle Role V22I	FARS Man_col*	FARS Rel_road	FARS Rollover	FARS Impacts	FARS J_knife
SVRD	1-10	All	All	3 – Rear to rear	2 – Shoulder	All	All	All
				3 – Rear to rear	4 – Roadside	All	All	All
				3 – Rear to rear	6 – Off roadway	All	All	All
				6 – Sideswipe (Opp Dir.)	2, 4, or 6	All	All	All
				9 – Unknown	2, 4, or 6	All	All	All
				2 – Head On	2, 4, or 6	All	Not 2 – Omit Struck	All
Rear-End	20-43	All	Not 2 – Omit Struck	1 – Rear End (Front-to-Rear)	All	All	All	All
Lane Change/ Merge	44-49	All	Not 2 – Omit Struck	4 (3,4,5,6) – Angle	All	All	Not 2 – Omit Struck	All
				5 (7) – Side Swipe (Same Dir.)	All	All	Not 2 – Omit Struck	All
Untripped Rollover	98 – Other	10 – Untripped Rollover	All	3 (10) – Rear to Rear	None	1 – First Event	All	Not 2 – Omit First Event
				(9) – Rear to Side	None	1 – First Event	All	Not 2 – Omit First Event
				6 (8) – Sideswipe (Opp Dir.)	None	1 – First Event	All	Not 2 – Omit First Event
				(11) – Other	None	1 – First Event	All	Not 2 – Omit First Event
				9 (99) – Unknown	None	1 – First Event	All	Not 2 – Omit First Event
Other*								

*Everything not categorized above

*Prior to 2002 the manner of collision was dependent on the direction of travel of the vehicles involved, where this was determined by the pre-crash condition direction of travel. In 2002 the manner of collision was dependent on the points of impact.

Table 72. Determination of SVRD Predominant Driving Conflicts from GES Data

Conflict Number	Accident Type V23	Univariate Imputed Movement Prior to Critical Event V21I	Critical Event V26	Univariate Imputed Roadway Alignment A13I
SVRD.1	1-10	01 – Going Straight	010,011,012,013 – Road Departure Over Line Edge or Road Edge	1 – Straight
SVRD.2	1-10	All	010,011,012,013 – Road Departure Over Line Edge or Road Edge	2 – Curve
SVRD.2	1-10	10,11,12 – Turning	010,011,012,013 – Road Departure Over Line Edge or Road Edge	1 – Straight
SVRD.2	1-10	14 – Negotiating a Curve	010,011,012,013 – Road Departure Over Line Edge or Road Edge	1 – Straight
SVRD.3	1-10	01 – Going Straight	006 – Loss of Control – Excessive Speed	1 – Straight
SVRD.4	1-10	All	006 – Loss of Control – Excessive Speed	2 – Curve
SVRD.4	1-10	10,11,12 – Turning	006 – Loss of Control – Excessive Speed	1 – Straight
SVRD.4	1-10	14 – Negotiating a Curve	006 – Loss of Control – Excessive Speed	1 – Straight
SVRD.5	1-10	All	001,002,003,004,008,009 – Loss of Control – Vehicle-Related	All
SVRD.6*	1-10			

* Everything Not Categorized in SVRD.1 – SVRD.5

Table 73. Determination of Untripped Rollover Conflicts from GES Data

Conflict Number	Accident Type V23	Rollover V30	Univariate Imputed Movement Prior to Critical Event V21I	Critical Event V26	Univariate Imputed Roadway Alignment A13I
Rollover.1	98 – Other	10 – Untripped Rollover	01 – Going Straight	010,011,012,013 – Road Departure Over Line or Road Edge	1 – Straight
Rollover.2	98 – Other	10 – Untripped Rollover	All	010,011,012,013 – Road Departure Over Line or Road Edge	2 – Curve
Rollover.2	98 – Other	10 – Untripped Rollover	10,11,12 – Turning	010,011,012,013 – Road Departure Over Line or Road Edge	1 – Straight
Rollover.2	98 – Other	10 – Untripped Rollover	14 – Negotiating a Curve	010,011,012,013 – Road Departure Over Line or Road Edge	1 – Straight
Rollover.3	98 – Other	10 – Untripped Rollover	01 – Going Straight	006 – Loss of Control – Excessive Speed	1 – Straight
Rollover.4	98 – Other	10 – Untripped Rollover	All	006 – Loss of Control – Excessive Speed	2 – Curve
Rollover.4	98 – Other	10 – Untripped Rollover	10,11,12 – Turning	006 – Loss of Control – Excessive Speed	1 – Straight
Rollover.4	98 – Other	10 – Untripped Rollover	14 – Negotiating a Curve	006 – Loss of Control – Excessive Speed	1 – Straight
Rollover.5	98 – Other	10 – Untripped Rollover	All	001,002,003,004,008,009 – Loss of Control – Vehicle-Related	All
Rollover.6	98 – Other	10 – Untripped Rollover	Everything Not Categorized in SVRD.1 – SVRD.5		

APPENDIX B:

DESCRIPTION OF ON-BOARD MEASUREMENTS AND DATA FILES

Table 74. Contents of LEX File—Header

Header (Cells A1-G6):
MAJOR LANE EXCURSION
WHERE: Zone: Unknown, State: Unknown
DATE: 01/29/04
TIME: 03:28:34P
FOR: 1 mins 1 secs
DRIVER: John Doe
ALERT INDEX: 88
ADVISE: NO
VEHICLE: 6123
ODOM: 2393536
WIPER: OFF

Table 75. Contents of LEX File—Definitions

Term:	***Definition:***
WHERE:	Does not relate to lane excursion event (reserved for TAZ event)
DATE:	Date of lane excursion
TIME:	Time of lane excursion, always in Eastern Standard Time (no daylight savings adjustment)
FOR:	Length of data record in minutes, seconds
DRIVER:	Driver name that is logged into system
ALERT INDEX:	SafeTRAC Drowsy Driver Index around time of data trigger (Time Offset = 0)
ADVISE:	Does not relate to lane excursion event (reserved for TAZ event)
VEHICLE:	McKenzie vehicle ID
ODOM:	Odometer reading in TENTHS of miles
WIPER:	Wiper status around time of data trigger

Table 76. Contents of LEX File—Data

Column (Rows 8–70)	**Name**	**Units**	**Definition**
A	Time Offset	(seconds)	Time, where Time Offset = 0 corresponds to TIME listed in header
B	Latitude	(degrees)	Latitudinal position of truck on the face of the Earth
C	Longitude	(degrees)	Longitudinal position of truck on the face of the Earth
D	Heading	(degrees)	Vehicle heading: 0 = Due North, 90 = Due East; 180 = Due South; 270 = Due West
E	Feet	(feet)	Distance traveled by truck over one second. Calculated as Speed × (88/60) × Time
F	Speed	(mph)	Speed of truck in miles per hour
G	RPM		Engine speed in revolutions per minute
H	Cruise		0 = Cruise control not active; 1 = Cruise control is active
I	Brake		0 = Brakes not applied; 1 = Brakes applied
J	Alarm System Status – SafeTRAC		SafeTRAC Alert System Status Code (See Table 2)

Column (Rows 8–70)	Name	Units	Definition
K	Time Offset	(seconds)	Repeat of A
L	V-Right		0 = Vorad sensor detects no vehicle on right side of truck; 1 = Vehicle is detected
M	T-Range	(ft)	Distance to vehicle in front of truck (= 4369 if no vehicle present)
N	T-Rate	(ft/s)	Difference in velocity between truck and vehicle in front of truck (+ = increasing separation; –2184.6 = no vehicle present)
O	T-Azimuth	(deg)	Angular position of vehicle in front of truck (0 = directly in front; –9.85474 = no vehicle present)
P	Yaw	(deg/s)	Yaw rate of truck (+ = CCW)
Q	LatAcc	(Gs)	Lateral acceleration under bunk near floor of truck cab (+ = to right)
R	Tilt	(deg)	Roll angle of tractor (+ = Clockwise when facing forward)
S	Signal	(left,right)	11 = no signals on; 1 = left signal on; 10 = right signal on
T	Time Offset	(seconds)	Repeat of A
U	Curve	(deg/s)	Curvature (+ to left); units are NOT deg/s as indicated
V	LWidth	(inches)	Lane width
W	Event		SafeTRAC event code. (See Table 3)
X	Confid	(%)	Percent confidence in SafeTRAC lateral position estimate
Y	Boundry	(left,right)	Lane boundary type (See Table 4)
Z	Time Offset	(seconds)	Repeat of A
AA	LatOff	(inches)	Lateral position of truck in lane (0 = centered, + = right)
AB	LatOff	(inches)	Lateral position of truck 0.2 seconds after LatOff reported in AA
AC	LatOff	(inches)	Lateral position of truck 0.4 seconds after LatOff reported in AA
AD	LatOff	(inches)	Lateral position of truck 0.6 seconds after LatOff reported in AA
AE	LatOff	(inches)	Lateral position of truck 0.8 seconds after LatOff reported in AA
AF	LatVel	(inches/s)	Lateral velocity of truck (0 = traveling parallel to centerline of lane + = right)
AG	LatVel	(inches/s)	Lateral velocity of truck 0.2 seconds after LatVel reported in AF
AH	LatVel	(inches/s)	Lateral velocity of truck 0.4 seconds after LatVel reported in AF
AI	LatVel	(inches/s)	Lateral velocity of truck 0.6 seconds after LatVel reported in AF
AJ	LatVel	(inches/s)	Lateral velocity of truck 0.8 seconds after LatVel reported in AF
AK	TCnt	(inches)	Number of targets detected by Vorad (units are incorrect – should have no units) + D10
AL	Time Offset	(seconds)	Repeat of A
AM	L-Tire	(inches)	Position of left tire with respect to left boundary (0 = on boundary line; – = outside boundary)
AN	R-Tire	(inches)	Position of left tire with respect to right boundary (0 = on boundary line; – = outside boundary)
CELL A72	SafeTRAC driver version xxx		Version of Aonix data acquisition software installed on truck

Table 77. Contents of OPS File (15-minute Data Summary)—Header Definitions

Header	Definition
Start Date (UTC): mm/dd/yy	Date on first record in file exported from website
End Date (UTC): mm/dd/yy	Date on last record in file exported from website
Begin Time: xx:xxi	Time at start of first 15-minute data summary (EST)
End Time: xx:xxi	Time at start of last 15-minute data summary (EST)

Table 78. Contents of OPS File (15-minute Data Summary)—Data

Column	Column Title	Units Indicated in File	Definition
A	Driver Name		First and Last Name of Driver
B	Vehicle		4-digit identification number for McKenzie vehicle
C	Begin Date/Time		mm/dd/yy and time at which 15-minute segment began (EST)
D	In Motion	(seconds)	Number of seconds in 15-minute period in which vehicle was moving
E	Speed > 35MPH	(seconds)	Number of seconds in 15-minute period in which vehicle was moving at a speed greater than 35 mph
F	SafeTracs Enabled	(seconds)	Number of seconds in 15-minute period in which SafeTRAC is providing data
G	SmallX Dashed SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a dashed boundary with the turn signal off
H	SmallX Dashed SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a dashed boundary with the turn signal on
I	SmallX Solid SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a solid boundary with the turn signal off
J	SmallX Solid SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a solid boundary with the turn signal on
K	SmallX Virtual SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a virtual boundary with the turn signal off
L	SmallX Virtual SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is 0–10 inches across a virtual boundary with the turn signal on
M	SmallX Dashed SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is 0–10 inches across a dashed boundary with the turn signal off
N	SmallX Dashed SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is 0–10 inches across a dashed boundary with the turn signal on
O	SmallX Solid SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is 0–10 inches across a solid boundary with the turn signal off

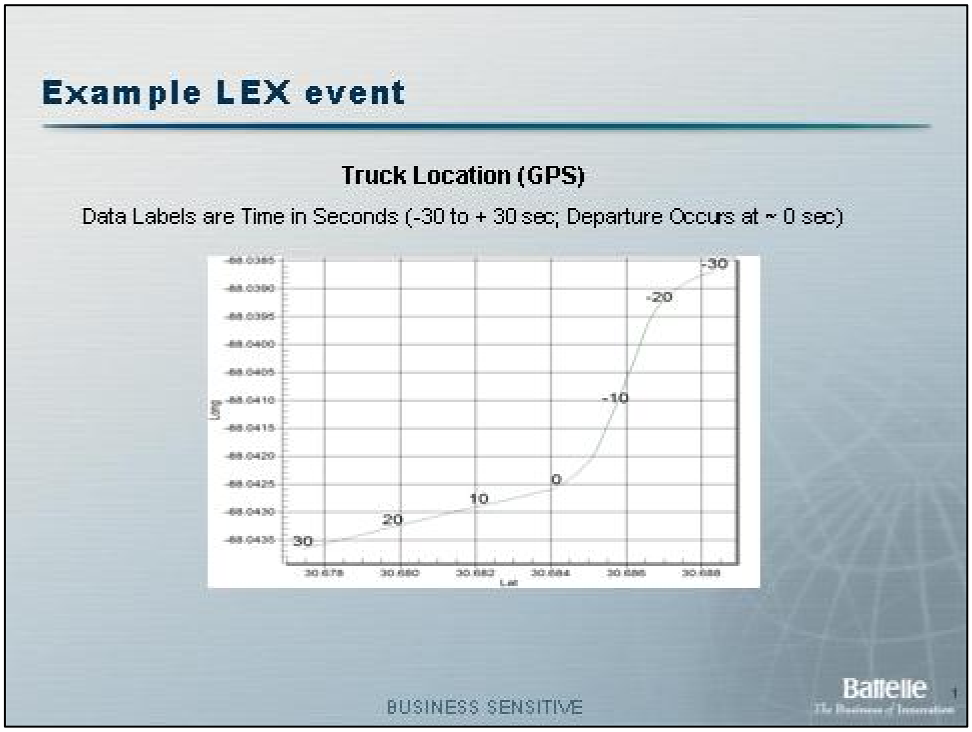
Column	Column Title	Units Indicated in File	Definition
P	SmallX Solid SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is 0–10 inches across a solid boundary with the turn signal on
Q	SmallX Virtual SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is 0–10 inches across a virtual boundary with the turn signal off
R	Cruise Active Time	(seconds)	Number of seconds in 15-minute period in which the truck's cruise control system was active
S	MedX Dashed SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a dashed boundary with the turn signal off
T	MedX Dashed SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a dashed boundary with the turn signal on
U	MedX Solid SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a solid boundary with the turn signal off
V	MedX Solid SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a solid boundary with the turn signal on
W	MedX Virtual SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a virtual boundary with the turn signal off
X	MedX Virtual SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >10 and <18 inches across a virtual boundary with the turn signal on
Y	MedX Dashed SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a dashed boundary with the turn signal off
Z	MedX Dashed SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a dashed boundary with the turn signal on
AA	MedX Solid SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a solid boundary with the turn signal off
AB	MedX Solid SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a solid boundary with the turn signal on
AC	MedX Virtual SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a virtual boundary with the turn signal off
AD	MedX Virtual SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >10 and <18 inches across a virtual boundary with the turn signal on

Column	Column Title	Units Indicated in File	Definition
AE	LargeX Dashed SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a dashed boundary with the turn signal off
AF	LargeX Dashed SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a dashed boundary with the turn signal on
AG	LargeX Solid SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a solid boundary with the turn signal off
AH	LargeX Solid SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a solid boundary with the turn signal on
AI	LargeX Virtual SigOff Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a virtual boundary with the turn signal off
AJ	LargeX Virtual SigOn Time	(seconds)	Number of seconds in 15-minute period in which the truck is >18 inches across a virtual boundary with the turn signal on
AK	LargeX Dashed SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a dashed boundary with the turn signal off
AL	LargeX Dashed SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a dashed boundary with the turn signal on
AM	LargeX Solid SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a solid boundary with the turn signal off
AN	LargeX Solid SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a solid boundary with the turn signal on
AO	LargeX Virtual SigOff Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a virtual boundary with the turn signal off
AP	LargeX Virtual SigOn Area	(square inches)	Total area of excursions in 15-minute period in which the truck is >18 inches across a virtual boundary with the turn signal on
AQ	Large Curve Left Count		Number of seconds in 15-minute period in which the calculated curve radius = 0 to –2,950 ft
AR	Small Curve Left Count		Number of seconds in 15-minute period in which the calculated curve radius = –2,950 to –8,200 ft
AS	No Curve Count		Number of seconds in 15-minute period in which the calculated curvature was < –8,200 ft or > +8,200 ft
AT	Small Curve Right Count		Number of seconds in 15-minute period in which the calculated curvature = +2,950 ft to +8,200 ft
AU	Large Curve Right Count		Number of seconds in 15-minute period in which the calculated curvature = 0 to +2,950 ft
AV	Large Curve Left Sum	(inches)	Sum of the lateral positions of the truck while in a large left curve

Column	Column Title	Units Indicated in File	Definition
AW	Small Curve Left Sum	(inches)	Sum of the lateral positions of the truck while in a small left curve
AX	No Curve Sum	(inches)	Sum of the lateral positions of the truck while on straight road
AY	Small Curve Right Sum	(inches)	Sum of the lateral positions of the truck while in a small right curve
AZ	Large Curve Right Sum	(inches)	Sum of the lateral positions of the truck while in a large right curve
BA	Large Curve Left Sum of Squares	(square inches)	Sum of the squares of the lateral positions of the truck while in a large left curve
BB	Small Curve Left Sum of Squares	(square inches)	Sum of the squares of the lateral positions of the truck while in a small left curve
BC	No Curve Sum of Squares	(square inches)	Sum of the squares of the lateral positions of the truck while on straight road
BD	Small Curve Right Sum of Squares	(square inches)	Sum of the squares of the lateral positions of the truck while in a small right curve
BE	Large Curve Right Sum of Squares	(square inches)	Sum of the squares of the lateral positions of the truck while in a large right curve
BF	SmallX Dashed SigOff Count		Number of small excursions across a dashed boundary with turn signal off
BG	SmallX Dashed SigOn Count		Number of small excursions across a dashed boundary with turn signal on
BH	SmallX Solid SigOff Count		Number of small excursions across a solid boundary with turn signal off
BI	SmallX Solid SigOn Count		Number of small excursions across a solid boundary with turn signal on
BJ	SmallX Virtual SigOff Count		Number of small excursions across a virtual boundary with turn signal off
BK	SmallX Virtual SigOn Count		Number of small excursions across a virtual boundary with turn signal on
BL	MedX Dashed SigOff Count		Number of medium excursions across a dashed boundary with turn signal off
BM	MedX Dashed SigOn Count		Number of medium excursions across a dashed boundary with turn signal on
BN	MedX Solid SigOff Count		Number of medium excursions across a solid boundary with turn signal off
BO	MedX Solid SigOn Count		Number of medium excursions across a solid boundary with turn signal on
BP	MedX Virtual SigOff Count		Number of medium excursions across a virtual boundary with turn signal off
BQ	MedX Virtual SigOn Count		Number of medium excursions across a virtual boundary with turn signal on
BR	LargeX Dashed SigOff Count		Number of large excursions across a dashed boundary with turn signal off
BS	LargeX Dashed SigOn Count		Number of large excursions across a dashed boundary with turn signal on
BT	LargeX Solid SigOff Count		Number of large excursions across a solid boundary with turn signal off
BU	LargeX Solid SigOn Count		Number of large excursions across a solid boundary with turn signal on
BV	LargeX Virtual SigOff Count		Number of large excursions across a virtual boundary with turn signal off

Column	Column Title	Units Indicated in File	Definition
BW	LargeX Virtual SigOn Count		Number of large excursions across a virtual boundary with turn signal on
BX	Drift Alert Dashed Count		Number of drift alerts issued by SafeTRAC associated with a dashed boundary
BY	Drift Alert Solid Count		Number of drift alerts issued by SafeTRAC associated with a solid boundary
BZ	Drift Alert Virtual Count		Number of drift alerts issued by SafeTRAC associated with a virtual boundary
CA	Unsignaled Lane Change Count		Number of lane changes detected by SafeTRAC with turn signal off
CB	Signaled Lane Change Count		Number of lane changes detected by SafeTRAC with turn signal on
CC	Drowsy Alert Count		Number of drowsy driver alerts issued by SafeTRAC
CD	Beginning Alertness Index		Value of driver alertness index calculated by SafeTRAC at the beginning of the 15-minute period
CE	Elapsed Miles		Cumulative distance driven in 15-minute period in miles

EXAMPLE DATA FROM A LEX FILE



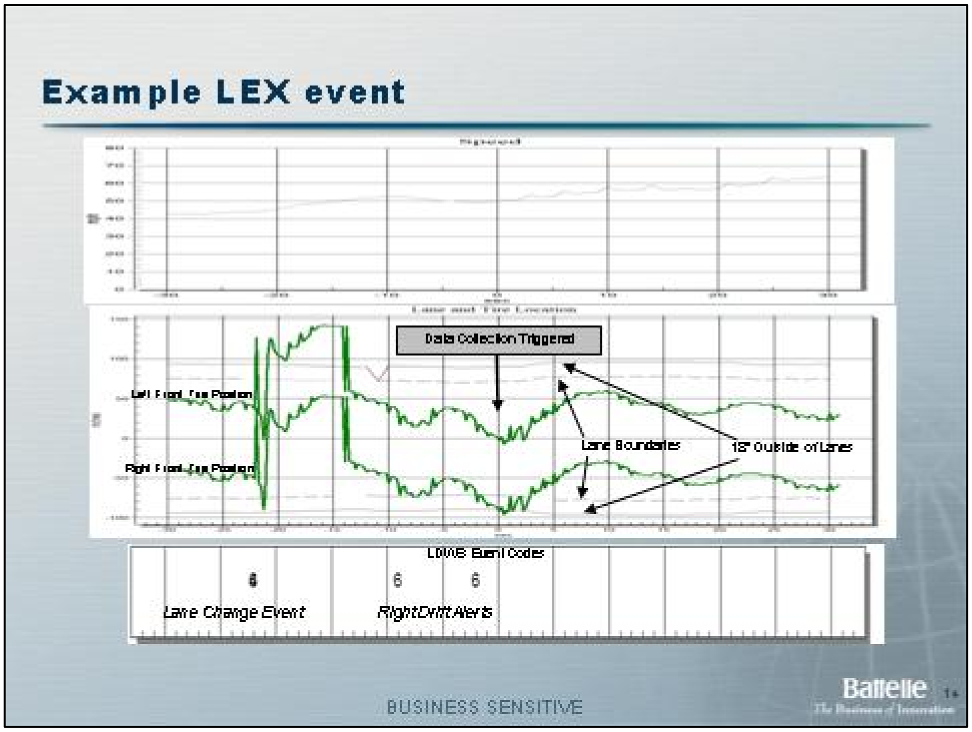
Example LEX event

Truck Location (GPS)

Data Labels are Time in Seconds (-30 to + 30 sec; Departure Occurs at ~ 0 sec)

BUSINESS SENSITIVE

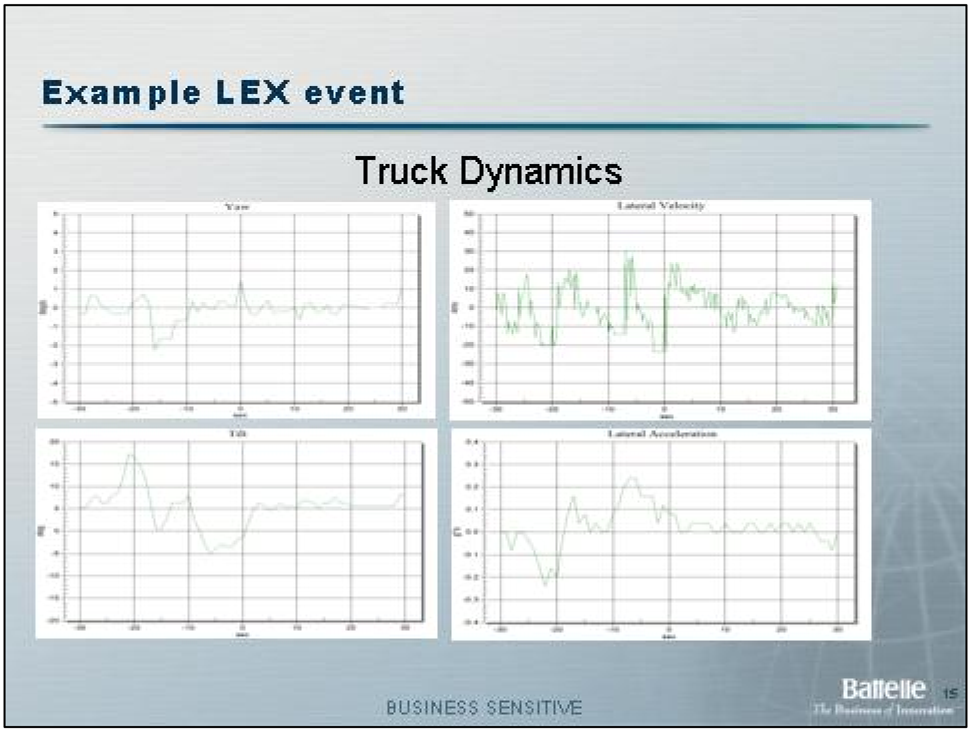
Figure 55. Example LEX Event—Truck Location (GPS)



Example LEX event

BUSINESS SENSITIVE

Figure 56. Example LEX Event—Data Collection Triggered



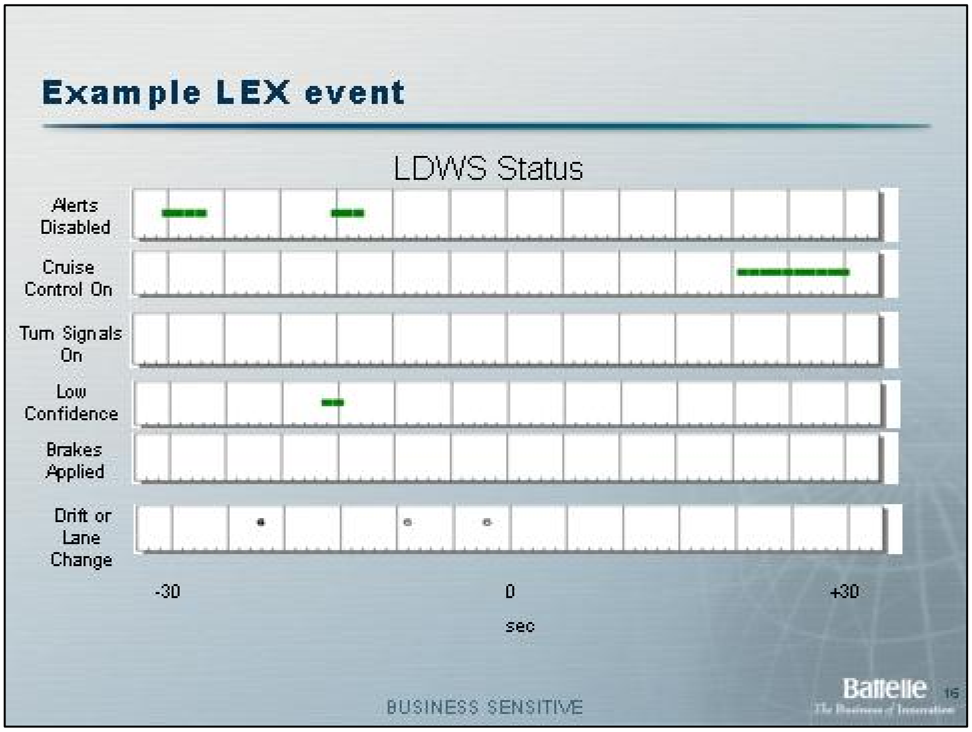
Example LEX event

Truck Dynamics

BUSINESS SENSITIVE

Battelle
The Business of Innovation

Figure 57. Example LEX Event—Truck Dynamics



Example LEX event

LDWS Status

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Figure 58. Example LEX Event—LDWS status in different circumstances

APPENDIX C:

LDWS STATUS AND EVENT CODES

As shown in Table 79, the Alert System Status field of the output message can take on one of 15 values described below. An alert system status of other than '1' means drift and drowsy alerts are disabled for the reason associated with the status code. The last column of the table is the single character that is displayed on the system's video output for each status condition.

Table 79. SafeTRAC Alert System Status Codes

Code	Description	Value
ENABLED	Code used to indicate the alert system is enabled.	1
LOW CONFIDENCE	The system's recent confidence is currently low.	2
EXTENDED LOW CONFIDENCE	The system's confidence has been low for an extended period of time.	3
MISSING BOUNDARIES	If both lane boundaries are MISSING, this suppression code will be used to indicate alerts are suppressed.	4
HIGH LATERAL VELOCITY	If the vehicle's lateral velocity is too high, something weird is going on. Maybe the driver did a lane change, or is executing an evasive maneuver, so alerts are suppressed.	5
RESET	If the vision system resets, probably due to a lane change, alerts are suppressed for awhile.	6
LOW VELOCITY	If the vehicle velocity is below threshold now or has been recently, alerts are suppressed. The character displayed is 's' if velocity is currently below threshold, and 'S' if velocity is above threshold now, but was below threshold recently.	7
APPARENTLY STOPPED	If SafeTRAC does not know the real vehicle velocity, it tries to determine if the vehicle is stopped by checking if the vehicle's lateral offset has remained constant for an extended period of time. If so, alerts are suppressed. The character displayed is 's' if vehicle is apparently stopped now and 'S' if it was apparently stopped recently. This condition is mutually exclusive with the low velocity condition above, since low velocity suppression is only triggered if SafeTRAC knows the vehicle's real velocity.	8
NO VELOCITY	If there has not been a valid velocity estimate yet (probably because GPS has not acquired lock), alerts are disabled unless the default vehicle velocity is greater than minimum velocity threshold. This will only occur on units with the GPS option.	9
DRIVER INTERFACE	If the driver has hit a button on the Interface Unit recently, alerts are suppressed to prevent false alarms when camera is moving.	10
VEHICLE SIGNAL	If one of the vehicle signals is active ('t') or has been active recently ('T') alerts are suppressed. This will only occur on units with the vehicle signal option.	11
START-UP SUPPRESSION	Right after start-up, there is a fixed short period of suppression.	12
EXTENDED START-UP SUPPRESSION	If confidence isn't high or one of the boundaries is missing shortly after start-up, alerts are suppressed by SafeTRAC for an extended period.	13
TURNED OFF	If the alert system is turned off (by setting the threshold to zero), alerts are suppressed.	14
WEIRD CONDITION	If a weird environmental condition is detected, alerts are momentarily suppressed.	15

Table 80. SafeTRAC Event Codes

Code	Description	Value
NO EVENT	No event has occurred	0
CALIBRATION STARTED	A calibration has started	1
CALIBRATION SUCCESSFUL	A calibration finished successfully	2
CALIBRATION FAILED	A calibration finished unsuccessfully	3
LEFT LANE CHANGE EVENT	The vehicle has done a lane change from right to left	4
RIGHT LANE CHANGE EVENT	The vehicle has done a lane change from left to right	5
LEFT DRIFT ALERT EVENT	The system has triggered an alert for a drift to the left	6
RIGHT DRIFT ALERT EVENT	The system has triggered an alert for a drift to the right	7
DROWSY ALERT EVENT	The system has triggered a drowsy driver alert	8
CLEAN WINDOW EVENT	The system has asked the driver to clean the window	9
LEFT BUTTON EVENT	The driver has pressed left button	10
SELECT BUTTON EVENT	The driver has pressed select button	11
RIGHT BUTTON EVENT	The driver has pressed right button	12
CALIBRATION REFINED	Refinement of calibration has just occurred	13
PARAMETERS SAVED	User-adjustable parameters have just been saved	14
IMAGE LOGGED	An image has just been logged	15
TAKE BREAK EVENT	The system has triggered a “take break” reminder	16
CALIBRATION REPORT	The system reported its calibration in output message	17
TIME REPORT	The system reported the current time in output message	18
MESSAGE CHANGE EVENT	The message on the driver display has changed	19
STARTUP EVENT	The system has just started after being turned off	20
ALERT SYSTEM STATUS CHG	The drift alert system has changed long-term status	21
IMAGE REPORT	The system reported the latest logged image following the output message	22
INVALID INPUT MESSAGE RECEIVED	The system received (and ignored) an input message with an invalid format from the client, possibly because of communication error	23

Table 81. Lane Boundary Codes

BNDRY	Left Boundary	Right Boundary
00	None	None
01	None	Dashed
02	None	Solid
03	None	Virtual
10	Dashed	None
11	Dashed	Dashed
12	Dashed	Solid
13	Dashed	Virtual
20	Solid	None
21	Solid	Dashed
22	Solid	Solid
23	Solid	Virtual
30	Virtual	None
31	Virtual	Dashed
32	Virtual	Solid
33	Virtual	Virtual

APPENDIX D:

BENEFIT-COST ANALYSIS SUMMARY DATA

This appendix presents detailed results and modeling used in the benefit-cost analysis for the Mack IVI FOT. The model covered 16 scenarios. The first set of tables (D-1 through D-8) present the 20-year total dollar costs, dollar benefits, and benefit-cost ratios (BCRs), expressed in constant 2005 dollars, using discount rates of 4 percent and 7 percent. The second set of tables (D-9 through D-24) show the annual dollar costs incurred and benefits received, for each year modeled, from 2005 to 2024. These annual tables are expressed separately in undiscounted dollars, as well as in terms of the 4 percent and 7 percent discount rates. The third set of tables (D-25 through D-34) show the unit costs used to calculate the various benefit-cost ratios, and sources of the data. This model was adapted from one originally designed by Charles River Associates.

Table 82. Benefit-Cost Comparison for Mack: All Trucks—Low Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$7,251,667,932	$5,503,146,566
Total benefits	$7,251,667,932	$5,503,146,566
Costs:		
Purchase Cost for On-board IVSS	$22,506,185,198	$18,054,289,332
Training and O&M Cost	$470,270,189	$374,905,832
Total costs	$22,976,455,388	$18,429,195,164
Total (Net Present Value)[1]	–$15,724,787,456	–$12,926,048,598
Benefit-Cost Ratio	0.32	0.30
Conservative Efficacy		
Benefits:		
Crashes avoided	$10,496,874,747	$7,965,869,474
Total benefits	$10,496,874,747	$7,965,869,474
Costs:		
Purchase Cost for On-board IVSS	$22,506,185,198	$18,054,289,332
Training and O&M Cost	$470,270,189	$374,905,832
Total costs	$22,976,455,388	$18,429,195,164
Total (Net Present Value)[1]	–$12,479,580,641	–$10,463,325,690
Benefit-Cost Ratio	0.46	0.43

[1] Present value in Year 2005 dollars

Table 83. Benefit-Cost Comparison for Mack: All Trucks—High Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$7,251,667,932	$5,503,146,566
Total benefits	$7,251,667,932	$5,503,146,566
Costs:		
Purchase Cost for On-board IVSS	$45,012,370,397	$36,108,578,664
Training and O&M Cost	$470,270,189	$374,905,832
Total costs	$45,482,640,586	$36,483,484,496
Total (Net Present Value)[1]	–$38,230,972,654	–$30,980,337,930
Benefit-Cost Ratio	0.16	0.15
Conservative Efficacy		
Benefits:		
Crashes avoided	$10,496,874,747	$7,965,869,474
Total benefits	$10,496,874,747	$7,965,869,474
Costs:		
Purchase Cost for On-board IVSS	$44,394,198,891	$35,685,679,604
Training and O&M Cost	$470,270,189	$374,905,832
Total costs	$44,864,469,080	$36,060,585,436
Total (Net Present Value)[1]	–$34,367,594,333	–$28,094,715,962
Benefit-Cost Ratio	0.23	0.22

[1] Present value in Year 2005 dollars

Table 84. Benefit-Cost Comparison for Mack: Truck-Tractors with Trailers—Low Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$5,594,230,595	$4,245,350,335
Total benefits	$5,594,230,595	$4,245,350,335
Costs:		
Purchase Cost for On-board IVSS	$4,998,706,187	$4,009,923,805
Training and O&M Cost	$104,448,732	$83,267,959
Total costs	$5,103,154,919	$4,093,191,764
Total (Net Present Value)[1]	$491,075,676	$152,158,572
Benefit-Cost Ratio	1.10	1.04
Conservative Efficacy		
Benefits:		
Crashes avoided	$7,851,485,875	$5,958,336,473
Total benefits	$7,851,485,875	$5,958,336,473
Costs:		
Purchase Cost for On-board IVSS	$4,998,706,187	$4,009,923,805
Training and O&M Cost	$104,448,732	$83,267,959
Total costs	$5,103,154,919	$4,093,191,764
Total (Net Present Value)[1]	$2,748,330,956	$1,865,144,709
Benefit-Cost Ratio	1.54	1.46

[1] Present value in Year 2005 dollars

Table 85. Benefit-Cost Comparison for Mack: Truck-Tractors with Trailers—High Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$5,594,230,595	$4,245,350,335
Total benefits	$5,594,230,595	$4,245,350,335
Costs:		
Purchase Cost for On-board IVSS	$9,997,412,374	$8,019,847,610
Training and O&M Cost	$104,448,732	$83,267,959
Total costs	$10,101,861,106	$8,103,115,568
Total (Net Present Value)[1]	–$4,507,630,510	–$3,857,765,233
Benefit/Cost Ratio	0.55	0.52
Conservative Efficacy		
Benefits:		
Crashes avoided	$7,851,485,875	$5,958,336,473
Total benefits	$7,851,485,875	$5,958,336,473
Costs:		
Purchase Cost for On-board IVSS	$9,997,412,374	$8,019,847,610
Training and O&M Cost	$104,448,732	$83,267,959
Total costs	$10,101,861,106	$8,103,115,568
Total (Net Present Value)[1]	–$2,250,375,231	–$2,144,779,096
Benefit-Cost Ratio	0.78	0.74

[1] Present value in Year 2005 dollars

Table 86. Benefit-Cost Comparison for Mack: Truck-Tractors with Tanker Trailers—Low Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$1,664,500,391	$1,263,156,242
Total benefits	$1,664,500,391	$1,263,156,242
Costs:		
Purchase Cost for On-board IVSS	$319,004,374	$255,902,865
Training and O&M Cost	$6,665,645	$5,313,944
Total costs	$325,670,019	$261,216,808
Total (Net Present Value)[1]	$1,338,830,372	$1,001,939,434
Benefit-Cost Ratio	5.11	4.84
Conservative Efficacy		
Benefits:		
Crashes avoided	$1,255,285,771	$952,611,406
Total benefits	$1,255,285,771	$952,611,406
Costs:		
Purchase Cost for On-board IVSS	$319,004,374	$255,902,865
Training and O&M Cost	$6,665,645	$5,313,944
Total costs	$325,670,019	$261,216,808
Total (Net Present Value)[1]	$929,615,752	$691,394,597
Benefit-Cost Ratio	3.85	3.65

[1] Present value in Year 2005 dollars

Table 87. Benefit-Cost Comparison for Mack: Truck-Tractors with Tanker Trailers—High Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$1,664,500,391	$1,263,156,242
Total benefits	$1,664,500,391	$1,263,156,242
Costs:		
Purchase Cost for On-board IVSS	$638,008,748	$511,805,729
Training and O&M Cost	$6,665,645	$5,313,944
Total costs	$644,674,393	$517,119,673
Total (Net Present Value)[1]	$1,019,825,998	$746,036,569
Benefit-Cost Ratio	2.58	2.44
Conservative Efficacy		
Benefits:		
Crashes avoided	$1,255,285,771	$952,611,406
Total benefits	$1,255,285,771	$952,611,406
Costs:		
Purchase Cost for On-board IVSS	$638,008,748	$511,805,729
Training and O&M Cost	$6,665,645	$5,313,944
Total costs	$644,674,393	$517,119,673
Total (Net Present Value)[1]	$610,611,378	$435,491,733
Benefit-Cost Ratio	1.95	1.84

[1] Present value in Year 2005 dollars

Table 88. Benefit-Cost Comparison for Mack: HAZMAT Tankers—Low Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$730,015,944	$553,994,581
Total benefits	$730,015,944	$553,994,581
Costs:		
Purchase Cost for On-board IVSS	$223,302,257	$179,131,360
Training and O&M Cost	$4,665,935	$3,719,747
Total costs	$227,968,192	$182,851,107
Total (Net Present Value)[1]	$502,047,752	$371,143,474
Benefit-Cost Ratio	3.20	3.03
Conservative Efficacy		
Benefits:		
Crashes avoided	$535,833,540	$406,633,417
Total benefits	$535,833,540	$406,633,417
Costs:		
Purchase Cost for On-board IVSS	$223,302,257	$179,131,360
Training and O&M Cost	$4,665,935	$3,719,747
Total costs	$227,968,192	$182,851,107
Total (Net Present Value)[1]	$307,865,348	$223,782,310
Benefit-Cost Ratio	2.35	2.22

[1] Present value in Year 2005 dollars

Table 89. Benefit-Cost Comparison for Mack: HAZMAT Tankers—High Cost Estimate

Benefits and Costs	Discounted at 4%	Discounted at 7%
Best-Estimate Efficacy		
Benefits:		
Crashes avoided	$730,015,944	$553,994,581
Total benefits	$730,015,944	$553,994,581
Costs:		
Purchase Cost for On-board IVSS	$446,604,514	$358,262,719
Training and O&M Cost	$4,665,935	$3,719,747
Total costs	$451,270,449	$361,982,467
Total (Net Present Value)[1]	$278,745,495	$192,012,114
Benefit-Cost Ratio	1.62	1.53
Conservative Efficacy		
Benefits:		
Crashes avoided	$535,833,540	$406,633,417
Total benefits	$535,833,540	$406,633,417
Costs:		
Purchase Cost for On-board IVSS	$446,604,514	$358,262,719
Training and O&M Cost	$4,665,935	$3,719,747
Total costs	$451,270,449	$361,982,467
Total (Net Present Value)[1]	$84,563,091	$44,650,950
Benefit-Cost Ratio	1.19	1.12

[1] Present value in Year 2005 dollars

Table 90. Annual Benefits and Costs for Mack FOT[1]: All Trucks—Low Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$413,595,765	$6,292,950,000	$109,982,188	$397,688,236	$6,050,913,462	$105,752,104	$386,538,098	$5,881,261,682	$102,787,092
2006	$425,902,560	$0	$22,650,955	$393,770,858	$0	$20,942,081	$371,999,791	$0	$19,784,221
2007	$438,575,552	$0	$23,324,948	$389,892,068	$0	$20,735,794	$358,008,292	$0	$19,040,106
2008	$451,625,636	$0	$24,018,996	$386,051,486	$0	$20,531,539	$344,543,035	$0	$18,323,977
2009	$465,064,033	$0	$24,733,696	$382,248,735	$0	$20,329,295	$331,584,228	$0	$17,634,783
2010	$478,902,297	$7,286,603,165	$25,469,662	$378,483,442	$5,758,708,325	$20,129,044	$319,112,822	$4,855,371,357	$16,971,511
2011	$493,152,328	$0	$26,227,528	$374,755,239	$0	$19,930,766	$307,110,485	$0	$16,333,186
2012	$507,826,378	$0	$27,007,944	$371,063,760	$0	$19,734,440	$295,559,575	$0	$15,718,869
2013	$522,937,062	$0	$27,811,582	$367,408,643	$0	$19,540,048	$284,443,113	$0	$15,127,658
2014	$538,497,374	$0	$28,639,132	$363,789,531	$0	$19,347,572	$273,744,759	$0	$14,558,683
2015	$554,520,693	$8,437,153,590	$29,491,307	$360,206,068	$5,480,614,089	$19,156,991	$263,448,787	$4,008,430,893	$14,011,108
2016	$571,020,796	$0	$30,368,839	$356,657,904	$0	$18,968,287	$253,540,062	$0	$13,484,128
2017	$588,011,869	$0	$31,272,483	$353,144,691	$0	$18,781,443	$244,004,021	$0	$12,976,968
2018	$605,508,522	$0	$32,203,014	$349,666,084	$0	$18,596,438	$234,826,644	$0	$12,488,884
2019	$623,525,798	$0	$33,161,235	$346,221,742	$0	$18,413,257	$225,994,444	$0	$12,019,158
2020	$642,079,190	$9,769,375,262	$34,147,968	$342,811,329	$5,215,949,324	$18,231,879	$217,494,436	$3,309,225,400	$11,567,098
2021	$661,184,649	$0	$35,164,061	$339,434,509	$0	$18,052,288	$209,314,127	$0	$11,132,041
2022	$680,858,603	$0	$36,210,390	$336,090,953	$0	$17,874,467	$201,441,493	$0	$10,713,348
2023	$701,117,967	$0	$37,287,852	$332,780,331	$0	$17,698,396	$193,864,960	$0	$10,310,402
2024	$721,980,161	$0	$38,397,375	$329,502,321	$0	$17,524,061	$186,573,393	$0	$9,922,611
Total	$11,085,887,234	$31,786,082,017	$677,571,155	$7,251,667,932	$22,506,185,198	$470,270,189	$5,503,146,566	$18,054,289,332	$374,905,832

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 91. Annual Benefits and Costs for Mack FOT[1]: All Trucks—Low Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$598,684,742	$6,292,950,000	$109,982,188	$575,658,406	$6,050,913,462	$105,752,104	$559,518,450	$5,881,261,682	$102,787,092
2006	$616,498,973	$0	$22,650,955	$569,987,956	$0	$20,942,081	$538,474,079	$0	$19,784,221
2007	$634,843,277	$0	$23,324,948	$564,373,361	$0	$20,735,794	$518,221,219	$0	$19,040,106
2008	$653,733,427	$0	$24,018,996	$558,814,073	$0	$20,531,539	$498,730,101	$0	$18,323,977
2009	$673,185,665	$0	$24,733,696	$553,309,546	$0	$20,329,295	$479,972,075	$0	$17,634,783
2010	$693,216,716	$7,286,603,165	$25,469,662	$547,859,240	$5,758,708,325	$20,129,044	$461,919,568	$4,855,371,357	$16,971,511
2011	$713,843,804	$0	$26,227,528	$542,462,622	$0	$19,930,766	$444,546,045	$0	$16,333,186
2012	$735,084,663	$0	$27,007,944	$537,119,163	$0	$19,734,440	$427,825,967	$0	$15,718,869
2013	$756,957,557	$0	$27,811,582	$531,828,339	$0	$19,540,048	$411,734,757	$0	$15,127,658
2014	$779,481,292	$0	$28,639,132	$526,589,631	$0	$19,347,572	$396,248,763	$0	$14,558,683
2015	$802,675,235	$8,437,153,590	$29,491,307	$521,402,527	$5,480,614,089	$19,156,991	$381,345,222	$4,008,430,893	$14,011,108
2016	$826,559,328	$0	$30,368,839	$516,266,517	$0	$18,968,287	$367,002,227	$0	$13,484,128
2017	$851,154,106	$0	$31,272,483	$511,181,099	$0	$18,781,443	$353,198,694	$0	$12,976,968
2018	$876,480,717	$0	$32,203,014	$506,145,775	$0	$18,596,438	$339,914,334	$0	$12,488,884
2019	$902,560,937	$0	$33,161,235	$501,160,050	$0	$18,413,257	$327,129,619	$0	$12,019,158
2020	$929,417,190	$9,769,375,262	$34,147,968	$496,223,437	$5,215,949,324	$18,231,879	$314,825,758	$3,309,225,400	$11,567,098
2021	$957,072,567	$0	$35,164,061	$491,335,450	$0	$18,052,288	$302,984,665	$0	$11,132,041
2022	$985,550,847	$0	$36,210,390	$486,495,613	$0	$17,874,467	$291,588,933	$0	$10,713,348
2023	$1,014,876,516	$0	$37,287,852	$481,703,450	$0	$17,698,396	$280,621,814	$0	$10,310,402
2024	$1,045,074,787	$0	$38,397,375	$476,958,491	$0	$17,524,061	$270,067,184	$0	$9,922,611
Total	$16,046,952,348	$31,786,082,017	$677,571,155	$10,496,874,747	$22,506,185,198	$470,270,189	$7,965,869,474	$18,054,289,332	$374,905,832

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 92. Annual Benefits and Costs for Mack FOT[1] All Trucks—High Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$413,595,765	$12,585,900,000	$109,982,188	$397,688,236	$12,101,826,923	$105,752,104	$386,538,098	$11,762,523,364	$102,787,092
2006	$425,902,560	$0	$22,650,955	$393,770,858	$0	$20,942,081	$371,999,791	$0	$19,784,221
2007	$438,575,552	$0	$23,324,948	$389,892,068	$0	$20,735,794	$358,008,292	$0	$19,040,106
2008	$451,625,636	$0	$24,018,996	$386,051,486	$0	$20,531,539	$344,543,035	$0	$18,323,977
2009	$465,064,033	$0	$24,733,696	$382,248,735	$0	$20,329,295	$331,584,228	$0	$17,634,783
2010	$478,902,297	$14,573,206,330	$25,469,662	$378,483,442	$11,517,416,649	$20,129,044	$319,112,822	$9,710,742,714	$16,971,511
2011	$493,152,328	$0	$26,227,528	$374,755,239	$0	$19,930,766	$307,110,485	$0	$16,333,186
2012	$507,826,378	$0	$27,007,944	$371,063,760	$0	$19,734,440	$295,559,575	$0	$15,718,869
2013	$522,937,062	$0	$27,811,582	$367,408,643	$0	$19,540,048	$284,443,113	$0	$15,127,658
2014	$538,497,374	$0	$28,639,132	$363,789,531	$0	$19,347,572	$273,744,759	$0	$14,558,683
2015	$554,520,693	$16,874,307,180	$29,491,307	$360,206,068	$10,961,228,178	$19,156,991	$263,448,787	$8,016,861,785	$14,011,108
2016	$571,020,796	$0	$30,368,839	$356,657,904	$0	$18,968,287	$253,540,062	$0	$13,484,128
2017	$588,011,869	$0	$31,272,483	$353,144,691	$0	$18,781,443	$244,004,021	$0	$12,976,968
2018	$605,508,522	$0	$32,203,014	$349,666,084	$0	$18,596,438	$234,826,644	$0	$12,488,884
2019	$623,525,798	$0	$33,161,235	$346,221,742	$0	$18,413,257	$225,994,444	$0	$12,019,158
2020	$642,079,190	$19,538,750,523	$34,147,968	$342,811,329	$10,431,898,647	$18,231,879	$217,494,436	$6,618,450,800	$11,567,098
2021	$661,184,649	$0	$35,164,061	$339,434,509	$0	$18,052,288	$209,314,127	$0	$11,132,041
2022	$680,858,603	$0	$36,210,390	$336,090,953	$0	$17,874,467	$201,441,493	$0	$10,713,348
2023	$701,117,967	$0	$37,287,852	$332,780,331	$0	$17,698,396	$193,864,960	$0	$10,310,402
2024	$721,980,161	$0	$38,397,375	$329,502,321	$0	$17,524,061	$186,573,393	$0	$9,922,611
Total	$11,085,887,234	$63,572,164,034	$677,571,155	$7,251,667,932	$45,012,370,397	$470,270,189	$5,503,146,566	$36,108,578,664	$374,905,832

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 93. Annual Benefits and Costs for Mack FOT[1]: All Trucks—High Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$598,684,742	$12,585,900,000	$109,982,188	$575,658,406	$12,101,826,923	$105,752,104	$559,518,450	$11,762,523,364	$102,787,092
2006	$616,498,973	$0	$22,650,955	$569,987,956	$0	$20,942,081	$538,474,079	$0	$19,784,221
2007	$634,843,277	$0	$23,324,948	$564,373,361	$0	$20,735,794	$518,221,219	$0	$19,040,106
2008	$653,733,427	$0	$24,018,996	$558,814,073	$0	$20,531,539	$498,730,101	$0	$18,323,977
2009	$673,185,665	$0	$24,733,696	$553,309,546	$0	$20,329,295	$479,972,075	$0	$17,634,783
2010	$693,216,716	$14,573,206,330	$25,469,662	$547,859,240	$11,517,416,649	$20,129,044	$461,919,568	$9,710,742,714	$16,971,511
2011	$713,843,804	$0	$26,227,528	$542,462,622	$0	$19,930,766	$444,546,045	$0	$16,333,186
2012	$735,084,663	$0	$27,007,944	$537,119,163	$0	$19,734,440	$427,825,967	$0	$15,718,869
2013	$756,957,557	$0	$27,811,582	$531,828,339	$0	$19,540,048	$411,734,757	$0	$15,127,658
2014	$779,481,292	$0	$28,639,132	$526,589,631	$0	$19,347,572	$396,248,763	$0	$14,558,683
2015	$802,675,235	$16,386,710,581	$29,491,307	$521,402,527	$10,644,494,724	$19,156,991	$381,345,222	$7,785,208,154	$14,011,108
2016	$826,559,328	$0	$30,368,839	$516,266,517	$0	$18,968,287	$367,002,227	$0	$13,484,128
2017	$851,154,106	$0	$31,272,483	$511,181,099	$0	$18,781,443	$353,198,694	$0	$12,976,968
2018	$876,480,717	$0	$32,203,014	$506,145,775	$0	$18,596,438	$339,914,334	$0	$12,488,884
2019	$902,560,937	$0	$33,161,235	$501,160,050	$0	$18,413,257	$327,129,619	$0	$12,019,158
2020	$929,417,190	$18,974,162,703	$34,147,968	$496,223,437	$10,130,460,594	$18,231,879	$314,825,758	$6,427,205,372	$11,567,098
2021	$957,072,567	$0	$35,164,061	$491,335,450	$0	$18,052,288	$302,984,665	$0	$11,132,041
2022	$985,550,847	$0	$36,210,390	$486,495,613	$0	$17,874,467	$291,588,933	$0	$10,713,348
2023	$1,014,876,516	$0	$37,287,852	$481,703,450	$0	$17,698,396	$280,621,814	$0	$10,310,402
2024	$1,045,074,787	$0	$38,397,375	$476,958,491	$0	$17,524,061	$270,067,184	$0	$9,922,611
Total	$16,046,952,348	$62,519,979,614	$677,571,155	$10,496,874,747	$44,394,198,891	$470,270,189	$7,965,869,474	$35,685,679,604	$374,905,832

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 94. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Trailers—Low Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$319,064,539	$1,397,687,250	$24,427,447	$306,792,826	$1,343,930,048	$23,487,930	$298,191,158	$1,306,249,766	$22,829,390
2006	$328,558,499	$0	$5,030,860	$303,770,802	$0	$4,651,313	$286,975,718	$0	$4,394,148
2007	$338,334,959	$0	$5,180,556	$300,778,546	$0	$4,605,496	$276,182,108	$0	$4,228,877
2008	$348,402,322	$0	$5,334,707	$297,815,765	$0	$4,560,130	$265,794,464	$0	$4,069,822
2009	$358,769,247	$0	$5,493,445	$294,882,169	$0	$4,515,211	$255,797,514	$0	$3,916,750
2010	$369,444,645	$1,618,381,258	$5,656,905	$291,977,469	$1,279,030,217	$4,470,734	$246,176,566	$1,078,395,767	$3,769,435
2011	$380,437,696	$0	$5,825,230	$289,101,382	$0	$4,426,696	$236,917,477	$0	$3,627,660
2012	$391,757,853	$0	$5,998,563	$286,253,626	$0	$4,383,091	$228,006,637	$0	$3,491,218
2013	$403,414,847	$0	$6,177,054	$283,433,921	$0	$4,339,916	$219,430,948	$0	$3,359,908
2014	$415,418,703	$0	$6,360,856	$280,641,991	$0	$4,297,167	$211,177,804	$0	$3,233,537
2015	$427,779,741	$1,873,922,723	$6,550,127	$277,877,562	$1,217,264,468	$4,254,838	$203,235,073	$890,287,187	$3,111,918
2016	$440,508,589	$0	$6,745,030	$275,140,365	$0	$4,212,926	$195,591,081	$0	$2,994,874
2017	$453,616,191	$0	$6,945,733	$272,430,129	$0	$4,171,427	$188,234,592	$0	$2,882,232
2018	$467,113,818	$0	$7,152,407	$269,746,591	$0	$4,130,337	$181,154,792	$0	$2,773,827
2019	$481,013,076	$0	$7,365,232	$267,089,486	$0	$4,089,652	$174,341,275	$0	$2,669,499
2020	$495,325,914	$2,169,814,037	$7,584,389	$264,458,555	$1,158,481,454	$4,049,367	$167,784,024	$734,991,085	$2,569,095
2021	$510,064,640	$0	$7,810,067	$261,853,540	$0	$4,009,479	$161,473,402	$0	$2,472,467
2022	$525,241,925	$0	$8,042,460	$259,274,185	$0	$3,969,985	$155,400,133	$0	$2,379,474
2023	$540,870,820	$0	$8,281,768	$256,720,237	$0	$3,930,879	$149,555,289	$0	$2,289,978
2024	$556,964,762	$0	$8,528,198	$254,191,447	$0	$3,892,158	$143,930,279	$0	$2,203,848
Total	$8,552,102,788	$7,059,805,268	$150,491,036	$5,594,230,595	$4,998,706,187	$104,448,732	$4,245,350,335	$4,009,923,805	$83,267,959

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 95. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Trailers—Low Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$447,806,124	$1,397,687,250	$24,427,447	$430,582,812	$1,343,930,048	$23,487,930	$418,510,396	$1,306,249,766	$22,829,390
2006	$461,130,869	$0	$5,030,860	$426,341,410	$0	$4,651,313	$402,769,560	$0	$4,394,148
2007	$474,852,100	$0	$5,180,556	$422,141,788	$0	$4,605,496	$387,620,761	$0	$4,228,877
2008	$488,981,615	$0	$5,334,707	$417,983,534	$0	$4,560,130	$373,041,733	$0	$4,069,822
2009	$503,531,562	$0	$5,493,445	$413,866,240	$0	$4,515,211	$359,011,045	$0	$3,916,750
2010	$518,514,452	$1,618,381,258	$5,656,905	$409,789,503	$1,279,030,217	$4,470,734	$345,508,073	$1,078,395,767	$3,769,435
2011	$533,943,167	$0	$5,825,230	$405,752,924	$0	$4,426,696	$332,512,969	$0	$3,627,660
2012	$549,830,972	$0	$5,998,563	$401,756,106	$0	$4,383,091	$320,006,632	$0	$3,491,218
2013	$566,191,529	$0	$6,177,054	$397,798,658	$0	$4,339,916	$307,970,678	$0	$3,359,908
2014	$583,038,905	$0	$6,360,856	$393,880,193	$0	$4,297,167	$296,387,415	$0	$3,233,537
2015	$600,387,584	$1,873,922,723	$6,550,127	$390,000,326	$1,217,264,468	$4,254,838	$285,239,816	$890,287,187	$3,111,918
2016	$618,252,484	$0	$6,745,030	$386,158,677	$0	$4,212,926	$274,511,497	$0	$2,994,874
2017	$636,648,965	$0	$6,945,733	$382,354,870	$0	$4,171,427	$264,186,686	$0	$2,882,232
2018	$655,592,844	$0	$7,152,407	$378,588,532	$0	$4,130,337	$254,250,208	$0	$2,773,827
2019	$675,100,411	$0	$7,365,232	$374,859,294	$0	$4,089,652	$244,687,457	$0	$2,669,499
2020	$695,188,436	$2,169,814,037	$7,584,389	$371,166,790	$1,158,481,454	$4,049,367	$235,484,375	$734,991,085	$2,569,095
2021	$715,874,194	$0	$7,810,067	$367,510,658	$0	$4,009,479	$226,627,436	$0	$2,472,467
2022	$737,175,468	$0	$8,042,460	$363,890,541	$0	$3,969,985	$218,103,621	$0	$2,379,474
2023	$759,110,575	$0	$8,281,768	$360,306,084	$0	$3,930,879	$209,900,400	$0	$2,289,978
2024	$781,698,375	$0	$8,528,198	$356,756,934	$0	$3,892,158	$202,005,715	$0	$2,203,848
Total	$12,002,850,632	$7,059,805,268	$150,491,036	$7,851,485,875	$4,998,706,187	$104,448,732	$5,958,336,473	$4,009,923,805	$83,267,959

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 96. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Trailers—High Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$319,064,539	$2,795,374,500	$24,427,447	$306,792,826	$2,687,860,096	$23,487,930	$298,191,158	$2,612,499,533	$22,829,390
2006	$328,558,499	$0	$5,030,860	$303,770,802	$0	$4,651,313	$286,975,718	$0	$4,394,148
2007	$338,334,959	$0	$5,180,556	$300,778,546	$0	$4,605,496	$276,182,108	$0	$4,228,877
2008	$348,402,322	$0	$5,334,707	$297,815,765	$0	$4,560,130	$265,794,464	$0	$4,069,822
2009	$358,769,247	$0	$5,493,445	$294,882,169	$0	$4,515,211	$255,797,514	$0	$3,916,750
2010	$369,444,645	$3,236,762,517	$5,656,905	$291,977,469	$2,558,060,433	$4,470,734	$246,176,566	$2,156,791,533	$3,769,435
2011	$380,437,696	$0	$5,825,230	$289,101,382	$0	$4,426,696	$236,917,477	$0	$3,627,660
2012	$391,757,853	$0	$5,998,563	$286,253,626	$0	$4,383,091	$228,006,637	$0	$3,491,218
2013	$403,414,847	$0	$6,177,054	$283,433,921	$0	$4,339,916	$219,430,948	$0	$3,359,908
2014	$415,418,703	$0	$6,360,856	$280,641,991	$0	$4,297,167	$211,177,804	$0	$3,233,537
2015	$427,779,741	$3,747,845,446	$6,550,127	$277,877,562	$2,434,528,936	$4,254,838	$203,235,073	$1,780,574,373	$3,111,918
2016	$440,508,589	$0	$6,745,030	$275,140,365	$0	$4,212,926	$195,591,081	$0	$2,994,874
2017	$453,616,191	$0	$6,945,733	$272,430,129	$0	$4,171,427	$188,234,592	$0	$2,882,232
2018	$467,113,818	$0	$7,152,407	$269,746,591	$0	$4,130,337	$181,154,792	$0	$2,773,827
2019	$481,013,076	$0	$7,365,232	$267,089,486	$0	$4,089,652	$174,341,275	$0	$2,669,499
2020	$495,325,914	$4,339,628,074	$7,584,389	$264,458,555	$2,316,962,908	$4,049,367	$167,784,024	$1,469,982,170	$2,569,095
2021	$510,064,640	$0	$7,810,067	$261,853,540	$0	$4,009,479	$161,473,402	$0	$2,472,467
2022	$525,241,925	$0	$8,042,460	$259,274,185	$0	$3,969,985	$155,400,133	$0	$2,379,474
2023	$540,870,820	$0	$8,281,768	$256,720,237	$0	$3,930,879	$149,555,289	$0	$2,289,978
2024	$556,964,762	$0	$8,528,198	$254,191,447	$0	$3,892,158	$143,930,279	$0	$2,203,848
Total	$8,552,102,788	$14,119,610,536	$150,491,036	$5,594,230,595	$9,997,412,374	$104,448,732	$4,245,350,335	$8,019,847,610	$83,267,959

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 97. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Trailers—Low Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$447,806,124	$2,795,374,500	$24,427,447	$430,582,812	$2,687,860,096	$23,487,930	$418,510,396	$2,612,499,533	$22,829,390
2006	$461,130,869	$0	$5,030,860	$426,341,410	$0	$4,651,313	$402,769,560	$0	$4,394,148
2007	$474,852,100	$0	$5,180,556	$422,141,788	$0	$4,605,496	$387,620,761	$0	$4,228,877
2008	$488,981,615	$0	$5,334,707	$417,983,534	$0	$4,560,130	$373,041,733	$0	$4,069,822
2009	$503,531,562	$0	$5,493,445	$413,866,240	$0	$4,515,211	$359,011,045	$0	$3,916,750
2010	$518,514,452	$3,236,762,517	$5,656,905	$409,789,503	$2,558,060,433	$4,470,734	$345,508,073	$2,156,791,533	$3,769,435
2011	$533,943,167	$0	$5,825,230	$405,752,924	$0	$4,426,696	$332,512,969	$0	$3,627,660
2012	$549,830,972	$0	$5,998,563	$401,756,106	$0	$4,383,091	$320,006,632	$0	$3,491,218
2013	$566,191,529	$0	$6,177,054	$397,798,658	$0	$4,339,916	$307,970,678	$0	$3,359,908
2014	$583,038,905	$0	$6,360,856	$393,880,193	$0	$4,297,167	$296,387,415	$0	$3,233,537
2015	$600,387,584	$3,747,845,446	$6,550,127	$390,000,326	$2,434,528,936	$4,254,838	$285,239,816	$1,780,574,373	$3,111,918
2016	$618,252,484	$0	$6,745,030	$386,158,677	$0	$4,212,926	$274,511,497	$0	$2,994,874
2017	$636,648,965	$0	$6,945,733	$382,354,870	$0	$4,171,427	$264,186,686	$0	$2,882,232
2018	$655,592,844	$0	$7,152,407	$378,588,532	$0	$4,130,337	$254,250,208	$0	$2,773,827
2019	$675,100,411	$0	$7,365,232	$374,859,294	$0	$4,089,652	$244,687,457	$0	$2,669,499
2020	$695,188,436	$4,339,628,074	$7,584,389	$371,166,790	$2,316,962,908	$4,049,367	$235,484,375	$1,469,982,170	$2,569,095
2021	$715,874,194	$0	$7,810,067	$367,510,658	$0	$4,009,479	$226,627,436	$0	$2,472,467
2022	$737,175,468	$0	$8,042,460	$363,890,541	$0	$3,969,985	$218,103,621	$0	$2,379,474
2023	$759,110,575	$0	$8,281,768	$360,306,084	$0	$3,930,879	$209,900,400	$0	$2,289,978
2024	$781,698,375	$0	$8,528,198	$356,756,934	$0	$3,892,158	$202,005,715	$0	$2,203,848
Total	$12,002,850,632	$14,119,610,536	$150,491,036	$7,851,485,875	$9,997,412,374	$104,448,732	$5,958,336,473	$8,019,847,610	$83,267,959

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 98. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Tanker-Trailers—Low Cost Estimate—Best-Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$94,934,065	$89,196,750	$1,558,896	$91,282,755	$85,766,106	$1,498,938	$88,723,425	$83,361,449	$1,456,912
2006	$97,758,886	$0	$321,056	$90,383,585	$0	$296,835	$85,386,397	$0	$280,423
2007	$100,667,761	$0	$330,610	$89,493,273	$0	$293,911	$82,174,880	$0	$269,876
2008	$103,663,192	$0	$340,447	$88,611,731	$0	$291,016	$79,084,153	$0	$259,725
2009	$106,747,754	$0	$350,577	$87,738,873	$0	$288,149	$76,109,673	$0	$249,957
2010	$109,924,099	$103,280,865	$361,009	$86,874,612	$81,624,368	$285,311	$73,247,068	$68,820,401	$240,555
2011	$113,194,958	$0	$371,751	$86,018,865	$0	$282,500	$70,492,131	$0	$231,508
2012	$116,563,143	$0	$382,813	$85,171,547	$0	$279,717	$67,840,810	$0	$222,800
2013	$120,031,550	$0	$394,203	$84,332,575	$0	$276,962	$65,289,210	$0	$214,421
2014	$123,603,163	$0	$405,933	$83,501,868	$0	$274,234	$62,833,580	$0	$206,356
2015	$127,281,050	$119,588,854	$418,012	$82,679,343	$77,682,639	$271,533	$60,470,310	$56,815,803	$198,595
2016	$131,068,376	$0	$430,450	$81,864,921	$0	$268,858	$58,195,926	$0	$191,125
2017	$134,968,396	$0	$443,259	$81,058,521	$0	$266,210	$56,007,086	$0	$183,937
2018	$138,984,463	$0	$456,448	$80,260,064	$0	$263,587	$53,900,571	$0	$177,018
2019	$143,120,030	$0	$470,030	$79,469,473	$0	$260,991	$51,873,285	$0	$170,360
2020	$147,378,655	$138,471,865	$484,016	$78,686,669	$73,931,261	$258,420	$49,922,249	$46,905,211	$163,953
2021	$151,763,997	$0	$498,418	$77,911,576	$0	$255,875	$48,044,595	$0	$157,786
2022	$156,279,827	$0	$513,249	$77,144,117	$0	$253,354	$46,237,562	$0	$151,852
2023	$160,930,029	$0	$528,521	$76,384,219	$0	$250,858	$44,498,494	$0	$146,140
2024	$165,718,600	$0	$544,247	$75,631,806	$0	$248,387	$42,824,835	$0	$140,644
Total	$2,544,581,993	$450,538,334	$9,603,945	$1,664,500,391	$319,004,374	$6,665,645	$1,263,156,242	$255,902,865	$5,313,944

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 99. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Tanker-Trailers—Low Cost Estimate—Best-Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$71,594,685	$89,196,750	$1,558,896	$68,841,043	$85,766,106	$1,498,938	$66,910,920	$83,361,449	$1,456,912
2006	$73,725,028	$0	$321,056	$68,162,933	$0	$296,835	$64,394,295	$0	$280,423
2007	$75,918,762	$0	$330,610	$67,491,503	$0	$293,911	$61,972,324	$0	$269,876
2008	$78,177,771	$0	$340,447	$66,826,686	$0	$291,016	$59,641,447	$0	$259,725
2009	$80,503,998	$0	$350,577	$66,168,418	$0	$288,149	$57,398,238	$0	$249,957
2010	$82,899,444	$103,280,865	$361,009	$65,516,635	$81,624,368	$285,311	$55,239,400	$68,820,401	$240,555
2011	$85,366,168	$0	$371,751	$64,871,271	$0	$282,500	$53,161,759	$0	$231,508
2012	$87,906,290	$0	$382,813	$64,232,265	$0	$279,717	$51,162,261	$0	$222,800
2013	$90,521,996	$0	$394,203	$63,599,553	$0	$276,962	$49,237,968	$0	$214,421
2014	$93,215,533	$0	$405,933	$62,973,074	$0	$274,234	$47,386,050	$0	$206,356
2015	$95,989,218	$119,588,854	$418,012	$62,352,766	$77,682,639	$271,533	$45,603,786	$56,815,803	$198,595
2016	$98,845,436	$0	$430,450	$61,738,568	$0	$268,858	$43,888,556	$0	$191,125
2017	$101,786,643	$0	$443,259	$61,130,420	$0	$266,210	$42,237,838	$0	$183,937
2018	$104,815,366	$0	$456,448	$60,528,262	$0	$263,587	$40,649,206	$0	$177,018
2019	$107,934,212	$0	$470,030	$59,932,036	$0	$260,991	$39,120,325	$0	$170,360
2020	$111,145,860	$138,471,865	$484,016	$59,341,684	$73,931,261	$258,420	$37,648,948	$46,905,211	$163,953
2021	$114,453,073	$0	$498,418	$58,757,146	$0	$255,875	$36,232,912	$0	$157,786
2022	$117,858,695	$0	$513,249	$58,178,366	$0	$253,354	$34,870,135	$0	$151,852
2023	$121,365,652	$0	$528,521	$57,605,287	$0	$250,858	$33,558,614	$0	$146,140
2024	$124,976,961	$0	$544,247	$57,037,854	$0	$248,387	$32,296,422	$0	$140,644
Total	$1,919,000,792	$450,538,334	$9,603,945	$1,255,285,771	$319,004,374	$6,665,645	$952,611,406	$255,902,865	$5,313,944

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 100. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Tanker-Trailers—High Cost Estimate—Best-Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$94,934,065	$178,393,500	$1,558,896	$91,282,755	$171,532,212	$1,498,938	$88,723,425	$166,722,897	$1,456,912
2006	$97,758,886	$0	$321,056	$90,383,585	$0	$296,835	$85,386,397	$0	$280,423
2007	$100,667,761	$0	$330,610	$89,493,273	$0	$293,911	$82,174,880	$0	$269,876
2008	$103,663,192	$0	$340,447	$88,611,731	$0	$291,016	$79,084,153	$0	$259,725
2009	$106,747,754	$0	$350,577	$87,738,873	$0	$288,149	$76,109,673	$0	$249,957
2010	$109,924,099	$206,561,730	$361,009	$86,874,612	$163,248,736	$285,311	$73,247,068	$137,640,803	$240,555
2011	$113,194,958	$0	$371,751	$86,018,865	$0	$282,500	$70,492,131	$0	$231,508
2012	$116,563,143	$0	$382,813	$85,171,547	$0	$279,717	$67,840,810	$0	$222,800
2013	$120,031,550	$0	$394,203	$84,332,575	$0	$276,962	$65,289,210	$0	$214,421
2014	$123,603,163	$0	$405,933	$83,501,868	$0	$274,234	$62,833,580	$0	$206,356
2015	$127,281,050	$239,177,708	$418,012	$82,679,343	$155,365,279	$271,533	$60,470,310	$113,631,606	$198,595
2016	$131,068,376	$0	$430,450	$81,864,921	$0	$268,858	$58,195,926	$0	$191,125
2017	$134,968,396	$0	$443,259	$81,058,521	$0	$266,210	$56,007,086	$0	$183,937
2018	$138,984,463	$0	$456,448	$80,260,064	$0	$263,587	$53,900,571	$0	$177,018
2019	$143,120,030	$0	$470,030	$79,469,473	$0	$260,991	$51,873,285	$0	$170,360
2020	$147,378,655	$276,943,730	$484,016	$78,686,669	$147,862,522	$258,420	$49,922,249	$93,810,423	$163,953
2021	$151,763,997	$0	$498,418	$77,911,576	$0	$255,875	$48,044,595	$0	$157,786
2022	$156,279,827	$0	$513,249	$77,144,117	$0	$253,354	$46,237,562	$0	$151,852
2023	$160,930,029	$0	$528,521	$76,384,219	$0	$250,858	$44,498,494	$0	$146,140
2024	$165,718,600	$0	$544,247	$75,631,806	$0	$248,387	$42,824,835	$0	$140,644
Total	$2,544,581,993	$901,076,669	$9,603,945	$1,664,500,391	$638,008,748	$6,665,645	$1,263,156,242	$511,805,729	$5,313,944

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 101. Annual Benefits and Costs for Mack FOT[1]: Truck-Tractors with Tanker-Trailers—High Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$71,594,685	$178,393,500	$1,558,896	$68,841,043	$171,532,212	$1,498,938	$66,910,920	$166,722,897	$1,456,912
2006	$73,725,028	$0	$321,056	$68,162,933	$0	$296,835	$64,394,295	$0	$280,423
2007	$75,918,762	$0	$330,610	$67,491,503	$0	$293,911	$61,972,324	$0	$269,876
2008	$78,177,771	$0	$340,447	$66,826,686	$0	$291,016	$59,641,447	$0	$259,725
2009	$80,503,998	$0	$350,577	$66,168,418	$0	$288,149	$57,398,238	$0	$249,957
2010	$82,899,444	$206,561,730	$361,009	$65,516,635	$163,248,736	$285,311	$55,239,400	$137,640,803	$240,555
2011	$85,366,168	$0	$371,751	$64,871,271	$0	$282,500	$53,161,759	$0	$231,508
2012	$87,906,290	$0	$382,813	$64,232,265	$0	$279,717	$51,162,261	$0	$222,800
2013	$90,521,996	$0	$394,203	$63,599,553	$0	$276,962	$49,237,968	$0	$214,421
2014	$93,215,533	$0	$405,933	$62,973,074	$0	$274,234	$47,386,050	$0	$206,356
2015	$95,989,218	$239,177,708	$418,012	$62,352,766	$155,365,279	$271,533	$45,603,786	$113,631,606	$198,595
2016	$98,845,436	$0	$430,450	$61,738,568	$0	$268,858	$43,888,556	$0	$191,125
2017	$101,786,643	$0	$443,259	$61,130,420	$0	$266,210	$42,237,838	$0	$183,937
2018	$104,815,366	$0	$456,448	$60,528,262	$0	$263,587	$40,649,206	$0	$177,018
2019	$107,934,212	$0	$470,030	$59,932,036	$0	$260,991	$39,120,325	$0	$170,360
2020	$111,145,860	$276,943,730	$484,016	$59,341,684	$147,862,522	$258,420	$37,648,948	$93,810,423	$163,953
2021	$114,453,073	$0	$498,418	$58,757,146	$0	$255,875	$36,232,912	$0	$157,786
2022	$117,858,695	$0	$513,249	$58,178,366	$0	$253,354	$34,870,135	$0	$151,852
2023	$121,365,652	$0	$528,521	$57,605,287	$0	$250,858	$33,558,614	$0	$146,140
2024	$124,976,961	$0	$544,247	$57,037,854	$0	$248,387	$32,296,422	$0	$140,644
Total	$1,919,000,792	$901,076,669	$9,603,945	$1,255,285,771	$638,008,748	$6,665,645	$952,611,406	$511,805,729	$5,313,944

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 102. Annual Benefits and Costs for Mack FOT[1]: HAZMAT Tankers—Low Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$41,636,146	$62,437,500	$1,091,223	$40,034,756	$60,036,058	$1,049,253	$38,912,286	$58,352,804	$1,019,835
2006	$42,875,055	$0	$224,739	$39,640,398	$0	$207,784	$37,448,733	$0	$196,295
2007	$44,150,828	$0	$231,426	$39,249,926	$0	$205,737	$36,040,227	$0	$188,912
2008	$45,464,563	$0	$238,312	$38,863,299	$0	$203,710	$34,684,698	$0	$181,807
2009	$46,817,389	$0	$245,403	$38,480,481	$0	$201,704	$33,380,151	$0	$174,969
2010	$48,210,469	$72,296,345	$252,705	$38,101,434	$57,136,852	$199,717	$32,124,671	$48,174,107	$168,388
2011	$49,645,001	$0	$260,225	$37,726,121	$0	$197,749	$30,916,412	$0	$162,055
2012	$51,122,219	$0	$267,968	$37,354,504	$0	$195,802	$29,753,597	$0	$155,960
2013	$52,643,391	$0	$275,941	$36,986,549	$0	$193,873	$28,634,517	$0	$150,094
2014	$54,209,828	$0	$284,152	$36,622,217	$0	$191,963	$27,557,528	$0	$144,449
2015	$55,822,874	$83,711,896	$292,607	$36,261,475	$54,377,652	$190,072	$26,521,045	$39,770,919	$139,016
2016	$57,483,918	$0	$301,314	$35,904,286	$0	$188,200	$25,523,547	$0	$133,787
2017	$59,194,387	$0	$310,280	$35,550,615	$0	$186,346	$24,563,566	$0	$128,755
2018	$60,955,752	$0	$319,512	$35,200,428	$0	$184,510	$23,639,692	$0	$123,912
2019	$62,769,528	$0	$329,020	$34,853,691	$0	$182,693	$22,750,566	$0	$119,252
2020	$64,637,274	$96,929,956	$338,810	$34,510,369	$51,751,696	$180,893	$21,894,881	$32,833,530	$114,767
2021	$66,560,596	$0	$348,891	$34,170,429	$0	$179,112	$21,071,380	$0	$110,450
2022	$68,541,147	$0	$359,273	$33,833,837	$0	$177,347	$20,278,852	$0	$106,296
2023	$70,580,631	$0	$369,963	$33,500,562	$0	$175,600	$19,516,132	$0	$102,298
2024	$72,680,800	$0	$380,972	$33,170,569	$0	$173,871	$18,782,100	$0	$98,450
Total	$1,116,001,796	$315,375,698	$6,722,737	$730,015,944	$223,302,257	$4,665,935	$553,994,581	$179,131,360	$3,719,747

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 103. Annual Benefits and Costs for Mack FOT[1]: HAZMAT Tankers—Low Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$30,561,036	$62,437,500	$1,091,223	$29,385,611	$60,036,058	$1,049,253	$28,561,716	$58,352,804	$1,019,835
2006	$31,470,398	$0	$224,739	$29,096,152	$0	$207,784	$27,487,465	$0	$196,295
2007	$32,406,819	$0	$231,426	$28,809,544	$0	$205,737	$26,453,618	$0	$188,912
2008	$33,371,104	$0	$238,312	$28,525,759	$0	$203,710	$25,458,655	$0	$181,807
2009	$34,364,081	$0	$245,403	$28,244,770	$0	$201,704	$24,501,115	$0	$174,969
2010	$35,386,606	$72,296,345	$252,705	$27,966,548	$57,136,852	$199,717	$23,579,590	$48,174,107	$168,388
2011	$36,439,556	$0	$260,225	$27,691,068	$0	$197,749	$22,692,724	$0	$162,055
2012	$37,523,837	$0	$267,968	$27,418,300	$0	$195,802	$21,839,215	$0	$155,960
2013	$38,640,382	$0	$275,941	$27,148,220	$0	$193,873	$21,017,807	$0	$150,094
2014	$39,790,150	$0	$284,152	$26,880,800	$0	$191,963	$20,227,295	$0	$144,449
2015	$40,974,130	$83,711,896	$292,607	$26,616,014	$54,377,652	$190,072	$19,466,514	$39,770,919	$139,016
2016	$42,193,341	$0	$301,314	$26,353,836	$0	$188,200	$18,734,348	$0	$133,787
2017	$43,448,829	$0	$310,280	$26,094,241	$0	$186,346	$18,029,719	$0	$128,755
2018	$44,741,676	$0	$319,512	$25,837,203	$0	$184,510	$17,351,593	$0	$123,912
2019	$46,072,992	$0	$329,020	$25,582,697	$0	$182,693	$16,698,972	$0	$119,252
2020	$47,443,922	$96,929,956	$338,810	$25,330,698	$51,751,696	$180,893	$16,070,898	$32,833,530	$114,767
2021	$48,855,645	$0	$348,891	$25,081,181	$0	$179,112	$15,466,446	$0	$110,450
2022	$50,309,374	$0	$359,273	$24,834,122	$0	$177,347	$14,884,728	$0	$106,296
2023	$51,806,360	$0	$369,963	$24,589,496	$0	$175,600	$14,324,890	$0	$102,298
2024	$53,347,890	$0	$380,972	$24,347,281	$0	$173,871	$13,786,109	$0	$98,450
Total	$819,148,127	$315,375,698	$6,722,737	$535,833,540	$223,302,257	$4,665,935	$406,633,417	$179,131,360	$3,719,747

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 104. Annual Benefits and Costs for Mack FOT[1]: HAZMAT Tankers—High Cost Estimate—Best Estimate Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$41,636,146	$124,875,000	$1,091,223	$40,034,756	$120,072,115	$1,049,253	$38,912,286	$116,705,607	$1,019,835
2006	$42,875,055	$0	$224,739	$39,640,398	$0	$207,784	$37,448,733	$0	$196,295
2007	$44,150,828	$0	$231,426	$39,249,926	$0	$205,737	$36,040,227	$0	$188,912
2008	$45,464,563	$0	$238,312	$38,863,299	$0	$203,710	$34,684,698	$0	$181,807
2009	$46,817,389	$0	$245,403	$38,480,481	$0	$201,704	$33,380,151	$0	$174,969
2010	$48,210,469	$144,592,690	$252,705	$38,101,434	$114,273,703	$199,717	$32,124,671	$96,348,215	$168,388
2011	$49,645,001	$0	$260,225	$37,726,121	$0	$197,749	$30,916,412	$0	$162,055
2012	$51,122,219	$0	$267,968	$37,354,504	$0	$195,802	$29,753,597	$0	$155,960
2013	$52,643,391	$0	$275,941	$36,986,549	$0	$193,873	$28,634,517	$0	$150,094
2014	$54,209,828	$0	$284,152	$36,622,217	$0	$191,963	$27,557,528	$0	$144,449
2015	$55,822,874	$167,423,792	$292,607	$36,261,475	$108,755,303	$190,072	$26,521,045	$79,541,838	$139,016
2016	$57,483,918	$0	$301,314	$35,904,286	$0	$188,200	$25,523,547	$0	$133,787
2017	$59,194,387	$0	$310,280	$35,550,615	$0	$186,346	$24,563,566	$0	$128,755
2018	$60,955,752	$0	$319,512	$35,200,428	$0	$184,510	$23,639,692	$0	$123,912
2019	$62,769,528	$0	$329,020	$34,853,691	$0	$182,693	$22,750,566	$0	$119,252
2020	$64,637,274	$193,859,912	$338,810	$34,510,369	$103,503,392	$180,893	$21,894,881	$65,667,059	$114,767
2021	$66,560,596	$0	$348,891	$34,170,429	$0	$179,112	$21,071,380	$0	$110,450
2022	$68,541,147	$0	$359,273	$33,833,837	$0	$177,347	$20,278,852	$0	$106,296
2023	$70,580,631	$0	$369,963	$33,500,562	$0	$175,600	$19,516,132	$0	$102,298
2024	$72,680,800	$0	$380,972	$33,170,569	$0	$173,871	$18,782,100	$0	$98,450
Total	$1,116,001,796	$630,751,395	$6,722,737	$730,015,944	$446,604,514	$4,665,935	$553,994,581	$358,262,719	$3,719,747

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 105. Annual Benefits and Costs for Mack FOT[1]: HAZMAT Tankers—High Cost Estimate—Conservative Efficacy

Year	Undiscounted Avoided Crashes Benefit	Undiscounted Purchase Cost for IVSS	Undiscounted Training Cost Plus Operating/ Maintenance	Discounted 4% Avoided Crashes Benefit	Discounted 4% Purchase Cost for IVSS	Discounted 4% Training Cost Plus Operating/ Maintenance	Discounted 7% Avoided Crashes Benefit	Discounted 7% Purchase Cost for IVSS	Discounted 7% Training Cost Plus Operating/ Maintenance
2005	$30,561,036	$124,875,000	$1,091,223	$29,385,611	$120,072,115	$1,049,253	$28,561,716	$116,705,607	$1,019,835
2006	$31,470,398	$0	$224,739	$29,096,152	$0	$207,784	$27,487,465	$0	$196,295
2007	$32,406,819	$0	$231,426	$28,809,544	$0	$205,737	$26,453,618	$0	$188,912
2008	$33,371,104	$0	$238,312	$28,525,759	$0	$203,710	$25,458,655	$0	$181,807
2009	$34,364,081	$0	$245,403	$28,244,770	$0	$201,704	$24,501,115	$0	$174,969
2010	$35,386,606	$144,592,690	$252,705	$27,966,548	$114,273,703	$199,717	$23,579,590	$96,348,215	$168,388
2011	$36,439,556	$0	$260,225	$27,691,068	$0	$197,749	$22,692,724	$0	$162,055
2012	$37,523,837	$0	$267,968	$27,418,300	$0	$195,802	$21,839,215	$0	$155,960
2013	$38,640,382	$0	$275,941	$27,148,220	$0	$193,873	$21,017,807	$0	$150,094
2014	$39,790,150	$0	$284,152	$26,880,800	$0	$191,963	$20,227,295	$0	$144,449
2015	$40,974,130	$167,423,792	$292,607	$26,616,014	$108,755,303	$190,072	$19,466,514	$79,541,838	$139,016
2016	$42,193,341	$0	$301,314	$26,353,836	$0	$188,200	$18,734,348	$0	$133,787
2017	$43,448,829	$0	$310,280	$26,094,241	$0	$186,346	$18,029,719	$0	$128,755
2018	$44,741,676	$0	$319,512	$25,837,203	$0	$184,510	$17,351,593	$0	$123,912
2019	$46,072,992	$0	$329,020	$25,582,697	$0	$182,693	$16,698,972	$0	$119,252
2020	$47,443,922	$193,859,912	$338,810	$25,330,698	$103,503,392	$180,893	$16,070,898	$65,667,059	$114,767
2021	$48,855,645	$0	$348,891	$25,081,181	$0	$179,112	$15,466,446	$0	$110,450
2022	$50,309,374	$0	$359,273	$24,834,122	$0	$177,347	$14,884,728	$0	$106,296
2023	$51,806,360	$0	$369,963	$24,589,496	$0	$175,600	$14,324,890	$0	$102,298
2024	$53,347,890	$0	$380,972	$24,347,281	$0	$173,871	$13,786,109	$0	$98,450
Total	$819,148,127	$630,751,395	$6,722,737	$535,833,540	$446,604,514	$4,665,935	$406,633,417	$358,262,719	$3,719,747

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 106. Annual Benefits and Costs for Mack FOT[1]: All Trucks—Low Cost Estimate—Best Estimate Efficacy—Annual Numbers of Trucks in Crashes, Injuries, and Fatalities (by Crash Type/Conflict Category)

Units per Year	Fleet	RO Loss of Control (Straight)	RO Loss of Control (Curve)	RO Other	RO Total	SVRDs Loss of Control (Straight)	SVRDs Loss of Control (Curve)	SVRDs Other	SVRDs Total	Lane Changes and Merges
Trucks in crashes	All Large Trucks 3	121	929	1,018	**2,068**	7,087	11,026	13,225	**31,338**	**51,856**
Trucks in crashes	Truck-Tractor with Trailer 4	80	736	747	**1,562**	3,266	7,492	5,879	**16,638**	**25,593**
Trucks in crashes	Truck-Tractor with Tanker-Trailer 5	0	43	5.0	**48**	230	459	377	**1,067**	**997**
Trucks in crashes	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	6.5	2.2	**8.6**	49	163	99	**311**	**339**
Fatalities	All Large Trucks 3	12	78	0	**90**	191	148	120	**458**	**1,197**
Fatalities	Truck-Tractor with Trailer 4	8.2	52	0	**60**	143	96	80	**319**	**778**
Fatalities	Truck-Tractor with Tanker-Trailer 5	0	13	0	**13**	10	35	0.5	**46**	**75**
Fatalities	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	6.2	0	**6.2**	4.2	14	0.2	**19**	**28**
Injuries	All Large Trucks 3	110	693	725	**1,528**	2,516	2,435	3,513	**8,463**	**11,008**
Injuries	Truck-Tractor with Trailer 4	76	608	503	**1,187**	1,329	1,417	1,580	**4,326**	**6,414**
Injuries	Truck-Tractor with Tanker-Trailer 5	0	14	3.0	**17**	92	286	165	**543**	**328**
Injuries	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	2.1	0.9	**3.0**	27	124	59	**210**	**69**

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 107a. Reductions in Crashes, Injuries, and Fatalities—by Crash Type/Conflict Category (Best Estimate)

Units per Year	Fleet	ROs Loss of Control (Straight)	ROs Loss of Control (Curve)	ROs Other	ROs Total	SRVDs Loss of Control (Straight)	SRVDs Loss of Control (Curve)	SRVDs Other	SRVDs Total	Lane Changes and Merges	RO % Reduction	SVRD % Reduction	LC/M % Reduction
Trucks in crashes	All Large Trucks 3	–13	483	0	**470**	–1,500	6,783	0	**5,282**	**0**	22.7%	16.9%	0.0%
Trucks in crashes	Truck-Tractor with Trailer 4	–8.6	382	0	**374**	–691	4,609	0	**3,917**	**0**	23.92%	23.55%	0.0%
Trucks in crashes	Truck-Tractor with Tanker-Trailer 5	0	23	0	**23**	–49	283	0	**234**	**0**	46.6%	21.9%	0.0%
Trucks in crashes	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	3.4	0	**3.4**	–10	100	0	**90**	**0**	39.0%	28.8%	0.0%
Fatalities	All Large Trucks 3	–1.3	41	0	**39**	–40	91	0	**51**	**0**	43.4%	11.0%	0.0%
Fatalities	Truck-Tractor with Trailer 4	–0.9	27	0	**26**	–30	59	0	**29**	**0**	43.4%	9.1%	0.0%
Fatalities	Truck-Tractor with Tanker-Trailer 5	0	6.6	0	**6.6**	–2.1	22	0	**19**	**0**	51.9%	42.6%	0.0%
Fatalities	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	3.2	0	**3.2**	–0.9	8.9	0	**8.0**	**0**	51.9%	42.6%	0.0%
Injuries	All Large Trucks 3	–12	360	0	**348**	–533	1,498	0	**965**	**0**	22.8%	11.4%	0.0%
Injuries	Truck-Tractor with Trailer 4	–8.2	316	0	**308**	–281	871	0	**590**	**0**	25.9%	13.6%	0.0%
Injuries	Truck-Tractor with Tanker-Trailer 5	0	7.3	0	**7.3**	–19	176	0	**156**	**0**	42.7%	28.8%	0.0%
Injuries	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	1.1	0	**1.1**	–5.8	76	0	**70**	**0**	36.0%	33.4%	0.0%

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 107b. Parameters for Reductions in Crashes, Injuries, and Fatalities (Best Estimate)

Parameters	ROs Loss of Control (Straight)	ROs Loss of Control (Curve)	ROs Other	ROs Total	SRVD Loss of Control (Straight)	SRVD Loss of Control (Curve)	SRVD Other	SRVD Total	Lane Changes and Merges
Exposure Ratio	0.6869	0.6647	1		0.6869	0.6647	1		1
Prevention Ratio	1.6120	0.7230	1		1.7640	0.5790	1		1
CRR	1.1073	0.4806	1	0	1.2117	0.3849	1	0	1
Percent Reduction	–10.7%	51.9%	0.0%		–21.2%	61.5%	0.0%		0.0%

Table 108a. Reductions in Crashes, Injuries, and Fatalities—by Crash Type/Conflict Category (Assuming PR = 1.0 “Conservative”)

Units per Year	Fleet	ROs Loss of Control (Straight)	ROs Loss of Control (Curve)	ROs Other	ROs Total	SVRDs Loss of Control (Straight)	SVRDs Loss of Control (Curve)	SVRDs Other	SVRDs Total	Lane Changes and Merges	RO % Reduction	SVRD % Reduction	LC/M % Reduction
Trucks in crashes	All Large Trucks 3	38	311	0	**349**	2,219	3,697	0	**5,916**	**0**	16.9%	18.9%	0.0%
Trucks in crashes	Truck-Tractor with Trailer 4	25	247	0	**272**	1,023	2,512	0	**3,535**	**0**	17.40%	21.25%	0.0%
Trucks in crashes	Truck-Tractor with Tanker-Trailer 5	0	15	0	**15**	72	154	0	**226**	**0**	30.1%	21.2%	0.0%
Trucks in crashes	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	2.2	0	**2.2**	15	54	0	**70**	**0**	25.1%	22.5%	0.0%
Fatalities	All Large Trucks 3	3.9	26	0	**30**	60	50	0	**109**	**0**	33.2%	23.8%	0.0%
Fatalities	Truck-Tractor with Trailer 4	2.6	17	0	**20**	45	32	0	**77**	**0**	33.2%	24.1%	0.0%
Fatalities	Truck-Tractor with Tanker-Trailer 5	0	4.3	0	**4.3**	3.2	12	0	**15**	**0**	33.5%	32.7%	0.0%
Fatalities	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	2.1	0	**2.1**	1.3	4.8	0.0	**6.1**	**0**	33.5%	32.7%	0.0%
Injuries	All Large Trucks 3	34	232	0	**267**	788	816	0	**1,604**	**0**	17.5%	19.0%	0.0%
Injuries	Truck-Tractor with Trailer 4	24	204	0	**228**	416	475	0	**891**	**0**	19.2%	20.6%	0.0%
Injuries	Truck-Tractor with Tanker-Trailer 5	0	4.7	0	**4.7**	29	96	0	**125**	**0**	27.6%	23.0%	0.0%
Injuries	Truck-Tractor with HAZMAT Tanker-Trailer 6	0	0.7	0	**0.7**	8.6	42	0	**50**	**0**	23.2%	23.8%	0.0%

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 108b. Parameters for Reductions in Crashes, Injuries, and Fatalities—(Assuming PR = 1.0 “Conservative”)

Parameters	ROs Loss of Control (Straight)	ROs Loss of Control (Curve)	ROs Other	ROs Total	SVRDs Loss of Control (Straight)	SVRDs Loss of Control (Curve)	SVRDs Other	SVRDs Total	Lane Changes and Merges
Exposure Ratio	0.6869	0.6647	1		0.6869	0.6647	1		1
Prevention Ratio	1.000	1.000	1		1.000	1.000	1		1
CRR	0.687	0.665	1	0	0.687	0.665	1	0	1
Percent Reduction	31.3%	33.5%	0.0%		31.3%	33.5%	0.0%		0.0%

Table 109. Annual Benefits and Costs for Mack FOT: Value of Crash Reductions[1]— Low Cost Estimate—Best Estimate Efficacy

Scenario	Fleet	Crash Type	Damages	Persons Injured in Crashes	Persons Killed in Crashes	Total Value
AT	All Large Trucks	Rollovers	$6,033,273	$18,053,049	$118,479,922	$142,566,244
AT	All Large Trucks	SVRDs	$67,874,695	$50,065,875	$153,088,951	$271,029,521
AT	All Large Trucks	Rollovers + SVRDs	$73,907,968	$68,118,924	$271,568,873	$413,595,765
TT	Truck-Tractors with Trailers	Rollovers	$13,003,026	$18,998,620	$78,637,116	$110,638,762
TT	Truck-Tractors with Trailers	SVRDs	$84,180,386	$36,452,832	$87,792,558	$208,425,777
TT	Truck-Tractors with Trailers	Rollovers + SVRDs	$97,183,412	$55,451,453	$166,429,675	$319,064,539
TK	Truck-Tractors with Tanker-Trailers	Rollovers	$784,818	$448,372	$20,097,655	$21,330,845
TK	Truck-Tractors with Tanker-Trailers	SVRDs	$5,024,440	$9,665,747	$58,913,034	$73,603,220
TK	Truck-Tractors with Tanker-Trailers	Rollovers + SVRDs	$5,809,257	$10,114,119	$79,010,689	$94,934,065
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers	$162,150	$66,647	$9,734,802	$9,963,599
HM	Truck-Tractors with HAZMAT Tanker-Trailers	SVRDs	$3,142,775	$4,347,130	$24,182,643	$31,672,547
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers + SVRDs	$3,304,925	$4,413,777	$33,917,444	$41,636,146

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 110. Annual Benefits and Costs for Mack FOT: Value of Crash Reductions[1]— Low Cost Estimate—Conservative Efficacy

Scenario	Fleet	Crash Type	Damages	Persons Injured in Crashes	Persons Killed in Crashes	Total Value
AT	All Large Trucks				$90,794,642	$109,113,839
AT	All Large Trucks	SVRDs	$76,014,139	$83,193,335	$330,363,429	$489,570,903
AT	All Large Trucks	Rollovers + SVRDs	$80,503,591	$97,023,080	$421,158,071	$598,684,742
TT	Truck-Tractors with Trailers	Rollovers	$9,455,827	$14,059,790	$60,261,930	$83,777,548
TT	Truck-Tractors with Trailers	SVRDs	$75,959,081	$55,058,965	$233,010,530	$364,028,577
TT	Truck-Tractors with Trailers	Rollovers + SVRDs	$85,414,909	$69,118,755	$293,272,461	$447,806,124
TK	Truck-Tractors with Tanker-Trailers	Rollovers	$506,620	$289,435	$12,973,546	$13,769,601
TK	Truck-Tractors with Tanker-Trailers	SVRDs	$4,860,994	$7,702,929	$45,261,161	$57,825,084
TK	Truck-Tractors with Tanker-Trailers	Rollovers + SVRDs	$5,367,614	$7,992,364	$58,234,707	$71,594,685
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers	$104,672	$43,022	$6,284,061	$6,431,755
HM	Truck-Tractors with HAZMAT Tanker-Trailers	SVRDs	$2,454,455	$3,096,008	$18,578,817	$24,129,280
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers + SVRDs	$2,559,127	$3,139,031	$24,862,878	$30,561,036

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 111. Annual Benefits and Costs for Mack FOT: Reductions from LDW— Low Cost Estimate—Best Estimate

Scenario	Fleet	Crash Type	Trucks in Crashes	Persons Injured in Crashes	Persons Killed in Crashes
AT	All Large Trucks				
AT	All Large Trucks	Rollovers	470	348	39
AT	All Large Trucks	SVRDs	5,282	965	51
TT	Truck-Tractors with Trailers	Rollovers + SVRDs	5,752	1,313	90
TT	Truck-Tractors with Trailers	Rollovers	374	308	26
TT	Truck-Tractors with Trailers	SVRDs	3,917	590	29
TK	Truck-Tractors with Tanker-Trailers	Rollovers + SVRDs	4,291	898	55
TK	Truck-Tractors with Tanker-Trailers	Rollovers	23	7.3	6.6
TK	Truck-Tractors with Tanker-Trailers	SVRDs	234	156	19
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers + SVRDs	256	164	26
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers	3.4	1.1	3.2
HM	Truck-Tractors with HAZMAT Tanker-Trailers	SVRDs	90	70	8.0
AT	All Large Trucks	Rollovers + SVRDs	93	71	11

Table 112. Annual Benefits and Costs for Mack FOT: Reductions from LDW— Low Cost Estimate—Best Estimate

Scenario	Fleet	Crash Type	Trucks in Crashes	Persons Injured in Crashes	Persons Killed in Crashes
AT	All Large Trucks	Rollovers	349	267	30
AT	All Large Trucks	SVRDs	5,916	1,604	109
AT	All Large Trucks	Rollovers + SVRDs	6,265	1,871	139
TT	Truck-Tractors with Trailers	Rollovers	272	228	20
TT	Truck-Tractors with Trailers	SVRDs	3,535	891	77
TT	Truck-Tractors with Trailers	Rollovers + SVRDs	3,807	1,119	97
TK	Truck-Tractors with Tanker-Trailers	Rollovers	15	4.7	4.3
TK	Truck-Tractors with Tanker-Trailers	SVRDs	226	125	15
TK	Truck-Tractors with Tanker-Trailers	Rollovers + SVRDs	241	129	19
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers	2.2	0.7	2.1
HM	Truck-Tractors with HAZMAT Tanker-Trailers	SVRDs	70	50	6.1
HM	Truck-Tractors with HAZMAT Tanker-Trailers	Rollovers + SVRDs	72	51	8.2

Table 113. Value of Damages Associated with Truck Crashes, Excluding Injuries and Fatalities

Type of Damage	Fleet	Rollover	SVRD
Property damage[1]	All Large Trucks	$7,430	$7,430
Property damage[1]	Tractors with Trailing Units	$29,511	$16,209
Property damage[1]	Tractor-Tankers	$29,511	$16,209
Property damage[1]	HAZMAT Tankers	$29,511	$16,209
Delays to other traffic[2]	All Large Trucks	$5,419	$5,419
Delays to other traffic[2]	Tractors with Trailing Units	$5,280	$5,280
Delays to other traffic[2]	Tractor-Tankers	$5,280	$5,280
Delays to other traffic[2]	HAZMAT Tankers	$5,280	$5,280
Hazardous Materials Costs[3]	All Large Trucks	$0	$0
Hazardous Materials Costs[3]	Tractors with Trailing Units	$0	$0
Hazardous Materials Costs[3]	Tractor-Tankers	$0	$0
Hazardous Materials Costs[3]	HAZMAT Tankers	$13,608	$13,608
Total damages	**All Large Trucks**	**$12,849**	**$12,849**
Total damages	**Tractors with Trailing Units**	**$34,791**	**$21,489**
Total damages	**Tractor-Tankers**	**$34,791**	**$21,489**
Total damages	**HAZMAT Tankers**	**$48,399**	**$35,097**

[1] From Battelle (2003) Freightliner Report, inflated to the year 2005 dollars using BLS CPI Calculator

[2] From Zaloshnja (2002), Table 11, inflated to the year 2005 dollars

[3] From Battelle FMCSA Report (2001), Comparative Risks of Hazardous Materials, Tables 30, 33, 38

[1] Present value in Year 2005 dollars

NOTE. Factors may not add up exactly because of rounding in source worksheets.

Table 114a. Additional Costs for Hazardous Materials Tanker-Truck Crashes—HAZMAT Category/Division 2.1, Flammable Gases (Table 30)

Material	HAZMAT Release	Crashes/Yr	Cost Cleanup	Cost Environ Damage	Cost Evacuation	TOTAL
HAZMAT	No	229	$0	$0	$2,135	$2,135
HAZMAT	Yes (Total Rel.)	47	$1,443	$2,742	$4,251	$8,436
Total		**276**				
Weighted Average	**– Cost/Crash**		$246	$467	$2,495	**$3,208**

Table 114b. Additional Costs for Hazardous Materials Tanker-Truck Crashes—HAZMAT Category/Division 3.0, Flammable Liquids (Table 33)

Material	HAZMAT Release	Crashes/Yr	Cost Cleanup	Cost Environ Damage	Cost Evacuation	TOTAL
HAZMAT			$0	$0	$28	$28
HAZMAT	Yes (Total Rel.)	490	$31,877	$3,672	$135	$35,684
Total		**1,379**				
Weighted Average	**– Cost/Crash**		$11,327	$1,305	$66	**$12,698**

Table 114c. Additional Costs for Hazardous Materials Tanker-Truck Crashes—HAZMAT Category/Division 8.0, Corrosives (Table 38)

Material	HAZMAT Release	Crashes/Yr	Cost Cleanup	Cost Environ Damage	Cost Evacuation	TOTAL
HAZMAT			$0	$0	$1,877	$1,877
HAZMAT	Yes (Total Rel.)	73	$15,584	$726	$12,100	$28,410
Total		**257**				
Weighted Average	**– Cost/Crash**		$4,427	$206	$4,781	**$9,414**

Table 114d. Additional Costs for Hazardous Materials Tanker-Truck Crashes—Combined Results

	Totals
Total Number of Crashes in Model	1,912
Grand Weighted Average in 1996 Dollars	$10,886
Grand Weighted Average in the year 2005 dollars, Inflated Using CPI[1]	**$13,608**

[1] CPI factor: $1 in 1996 = $1.25 in 2005

Dollars Per Crash (in constant 1996 US dollars except as noted)

HAZMAT Release Scenarios, including Fire or Explosion Crashes

From Greenberg FMCSA Report, 3/2001, Tables 30, 33, and 38 of “Comparative Risks of Hazardous Materials and Non-Hazardous Materials Truck Shipment Accidents/Incidents”

Table 115. Cost Elements for Mack IVSS

	Cost Element	Cost per Vehicle	Source
A	Purchase Cost for LDW (Low Cost Assumption)	$750.00	Battelle
B	Purchase Cost for LDW (High Cost Assumption)	$1,500.00	Battelle
C	Total cost for vehicles without additional cost	$2,250.00	A + B (not used)
D	Current percent of vehicles with additional cost	0.00%	Assumption
E	Weighted average purchase cost for LDW (Low)	$750.00	A × (1 – D)
E	Weighted average purchase cost for LDW (High)	$1,500.00	B × (1 – D)
F	Annual wage	$45,288.00	ATA 2000 Driver Compensation study (Dan Stock email 12/9/02); inflated by CPI to the year 2005 dollars
G	Hourly wage	$21.77	F/2,080 hours
H	Assumed markup for fringe benefits	41.90%	BLS National Compensation Survey
I	Assumed hourly wage with fringe benefits	$30.90	G × (1 + H)
J	Assumed hours required for training	1.00	Battelle, per driver
K	Assumed driver turnover (industry) – all trucks	20.00%	CRA assumption
L	Total trucks	7,392,582.00	Trucks >10,000 lbs., figure supplied by Battelle (as of 1999)
M	Total drivers	3,136,170.00	BLS National National Occupational Employment and Wage Estimates (as of 1999)
N	Ratio of drivers to trucks	0.42	N/M
O	Annual O&M per truck for CWS ($)	$0.00	Battelle
P	Annual O&M per truck for Bundled System ($)	$0.00	Battelle

[1] Present value in Year 2005 dollars

Note: Factors may not add up exactly because of rounding in source worksheets.

Note: Training cost = new drivers × cost per driver, where:

- new drivers = total trucks × driver/truck ratio × turnover rate
- cost per new driver = assumed hours required for training × hourly wage

Table 116. Forecast of U.S. Truck Population[1]—by Fleet

Year	HAZMAT Trucks	Tankers	Tractor and Trailer	Trucks > 10,000lbs.
2005	83,250	118,929	1,863,583	8,390,600
2006	85,727	122,468	1,919,035	8,640,267
2007	88,278	126,112	1,976,137	8,897,364
2008	90,905	129,864	2,034,938	9,162,110
2009	93,610	133,729	2,095,489	9,434,735
2010	96,395	137,708	2,157,842	9,715,471
2011	99,263	141,805	2,222,050	10,004,561
2012	102,217	146,025	2,288,168	10,302,252
2013	105,259	150,370	2,356,254	10,608,802
2014	108,391	154,844	2,426,366	10,924,474
2015	111,616	159,452	2,498,564	11,249,538
2016	114,937	164,196	2,572,910	11,584,275
2017	118,357	169,082	2,649,468	11,928,972
2018	121,879	174,113	2,728,305	12,283,926
2019	125,505	179,294	2,809,487	12,649,442
2020	129,240	184,629	2,893,085	13,025,834
2021	133,086	190,123	2,979,171	13,413,425
2022	137,046	195,780	3,067,818	13,812,550
2023	141,123	201,606	3,159,103	14,223,551
2024	145,323	207,605	3,253,104	14,646,781
2025	149,647	213,782	3,349,902	15,082,605

[1] Based on an Average Annual Growth Rate of 2.98%. Growth rate is extrapolated from the increase in Class 8 trucks from 2,298,000 in 1998 to 3,081,000 in 2008.

Table 117a. Benefits as Percent of Base Pay—Wages and Salaries

Series ID	Compensation Component	Employer/Employee Characters	Sector
CCU520000123000D, CCU520000123000P	Wages and salaries	Transportation and material moving occupations	Private service producing
Year	**Period**	**Cost of compensation (Cost per hour worked)**	**Percent of total compensation**
1992	Annual	$10.67	68.4
1993	Annual	$10.65	68.0
1994	Annual	$11.15	68.1
1995	Annual	$11.35	68.7
1996	Annual	$11.46	69.7
1997	Annual	$11.56	70.6
1998	Annual	$11.99	70.8
1999	Annual	$12.20	71.1
2000	Annual	$12.67	70.4
2001	Annual	$12.79	70.4
2002	Qtr1	$13.37	70.2
2002	Qtr2	$13.34	70.1

Benefits as a percent of base pay 2001: 41.9%

Source: U.S. Bureau of Labor Statistics, National Compensation Survey, Compensation Cost Trends (http://www.bls.gov/ncs/ect/home.htm)

Table 117b. Benefits as Percent of Base Pay—Total Benefits

Series ID:	Compensation Component:	Employer/Employee Characters:	Sector:
CCU530000123000D, CCU530000123000P	Total benefits	Transportation and material moving occupations	Private service producing
Year	**Period**	**Cost of compensation (Cost per hour worked)**	**Percent of total compensation**
1992	Annual	$4.92	31.6
1993	Annual	$5.01	32.0
1994	Annual	$5.23	31.9
1995	Annual	$5.18	31.3
1996	Annual	$4.98	30.3
1997	Annual	$4.82	29.4
1998	Annual	$4.94	29.2
1999	Annual	$4.97	28.9
2000	Annual	$5.33	29.6
2001	Annual	$5.36	29.5
2002	Qtr1	$5.67	29.8
2002	Qtr2	$5.70	29.9

Benefits as a percent of base pay 2001: 41.9%

Source: U.S. Bureau of Labor Statistics, National Compensation Survey, Compensation Cost Trends (http://www.bls.gov/ncs/ect/home.htm)

APPENDIX E:

HISTOGRAMS OF COVARIATES FOR CONDITIONAL ANALYSES

This appendix contains histograms showing the distribution of the covariates used in the conditional analyses. The covariates for the conditional analysis of exposure ratios and the "Drivers Drive More Safely" objective were the same. Each of these histograms is based on data from the 17,472 OPS files. The histograms for the covariates involved in the conditional analysis of the prevention ratio are based on values from the 635 LEX files that were identified as conflicts.

Histograms for Exposure Ratio and "Drivers Drive More Safely" Conditional Analyses:

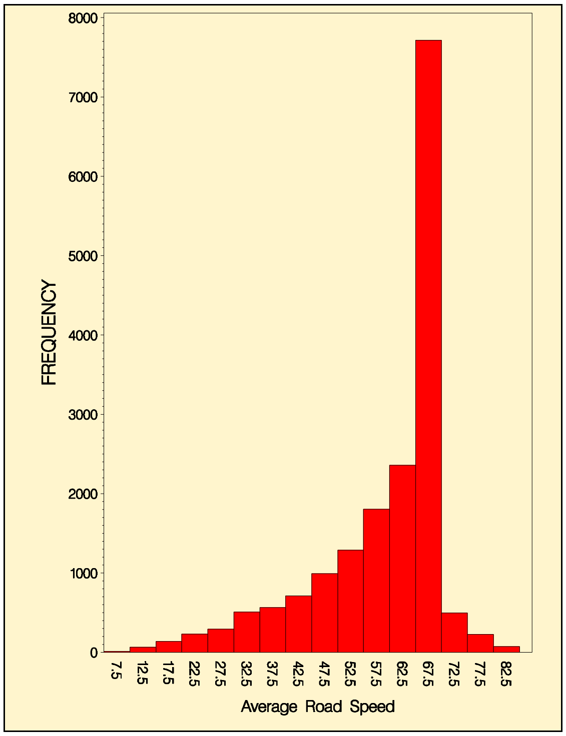

Figure 59. Histogram for Exposure Ratio—Average Road Speed

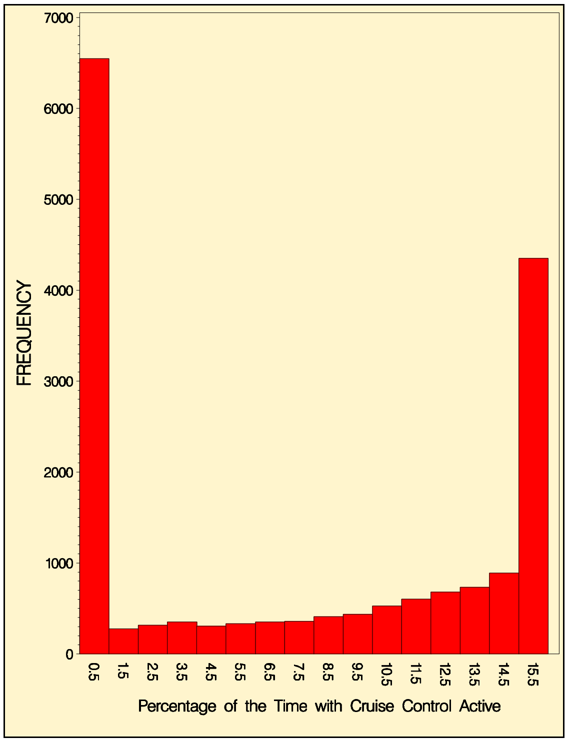

Figure 60. Histogram for Exposure Ratio—Percentage of the Time with Cruise Control Active

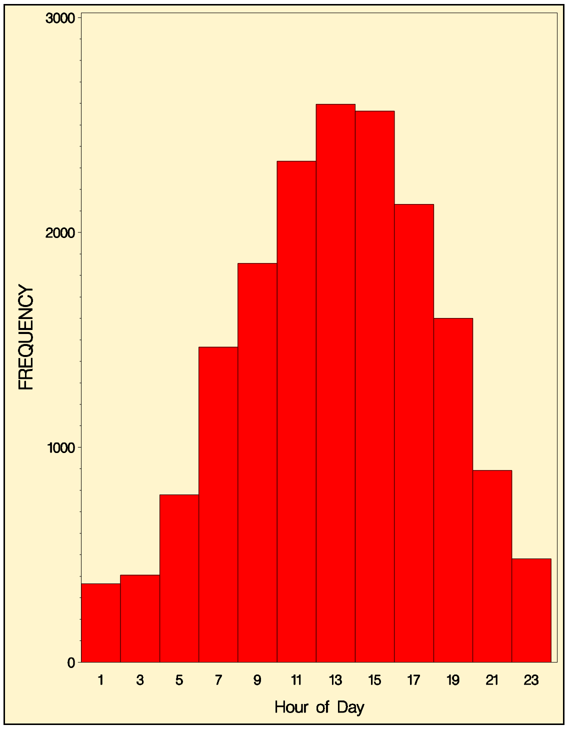

Figure 61. Histogram for Exposure Ratio—Hour of Day

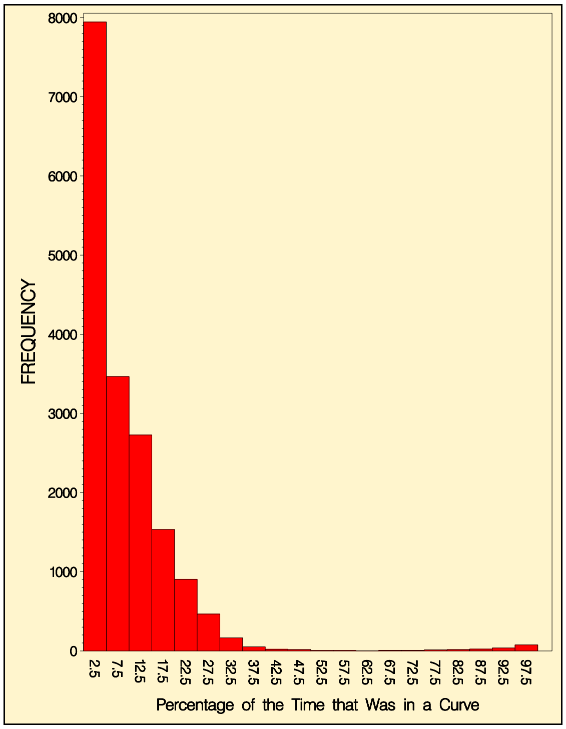

Figure 62. Histogram for Exposure Ratio—Percentage of the Time that Was in a Curve

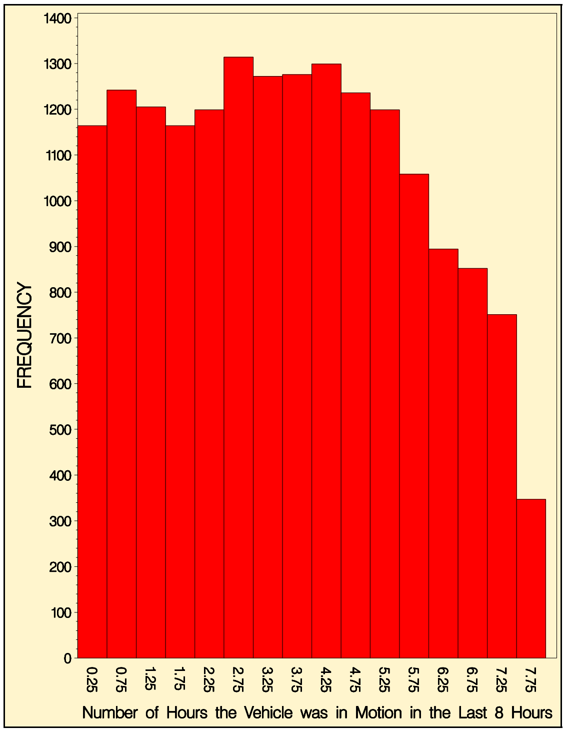

Figure 63. Histogram for Exposure Ratio—Hours in Motion in the Last 8 Hours

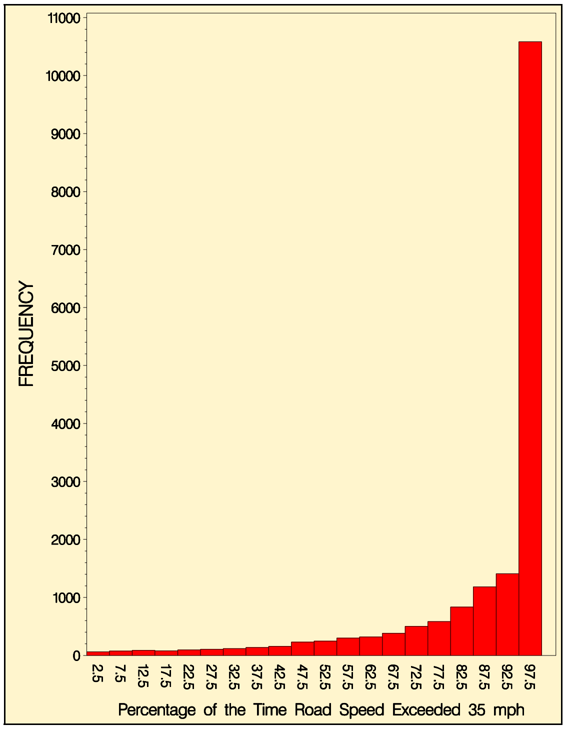

Figure 64. Histogram for Exposure Ratio—Percentage of the Time Road Speed Exceeded 35 mph

Histograms for Prevention Ratio Conditional Analysis:

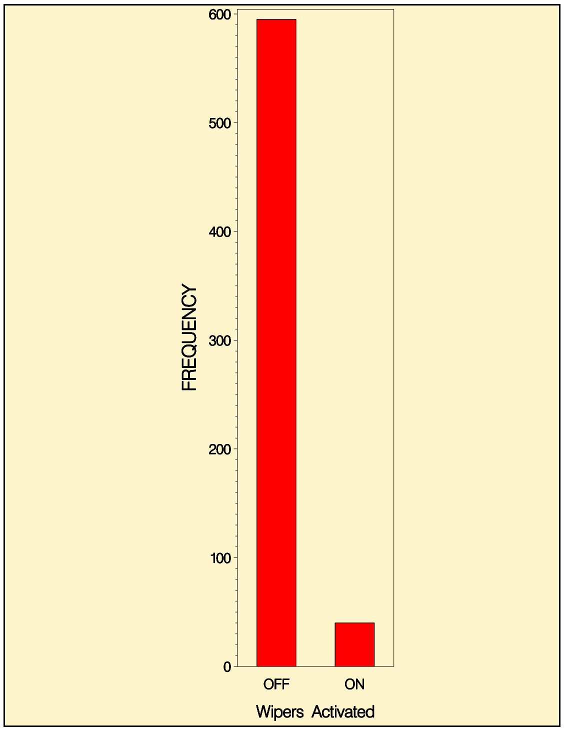

Figure 65. Histogram for Prevention Ratio—Wipers Activated

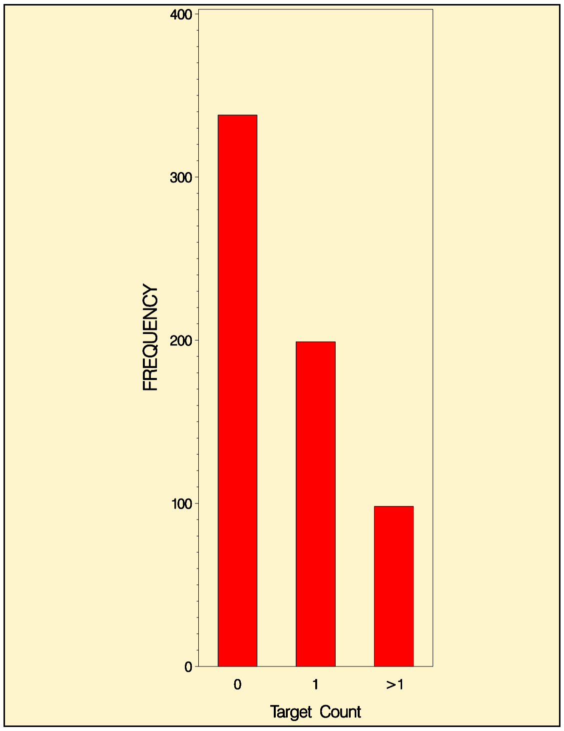

Figure 66. Histogram for Prevention Ratio—Target Count

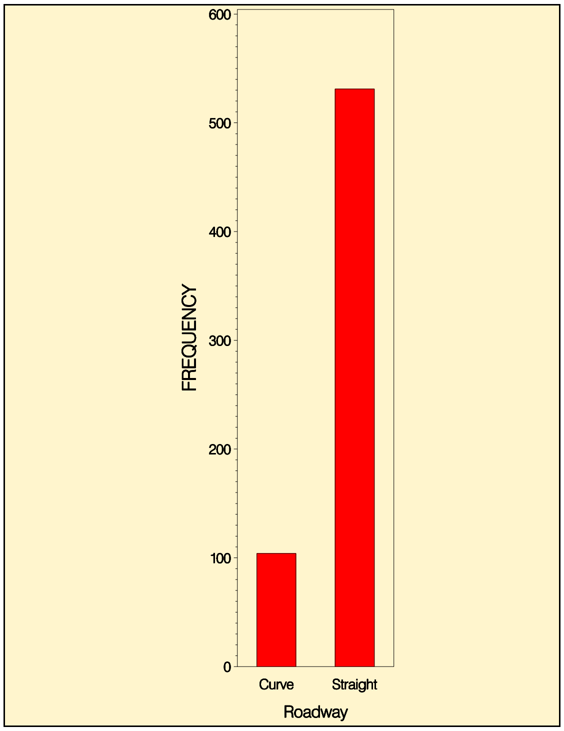

Figure 67. Histogram for Prevention Ratio—Roadway

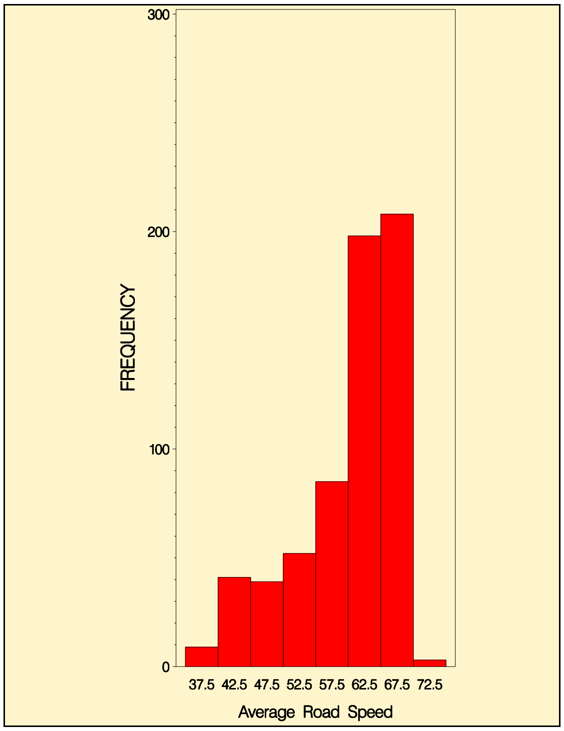

Figure 68. Histogram for Prevention Ratio—Average Road Speed

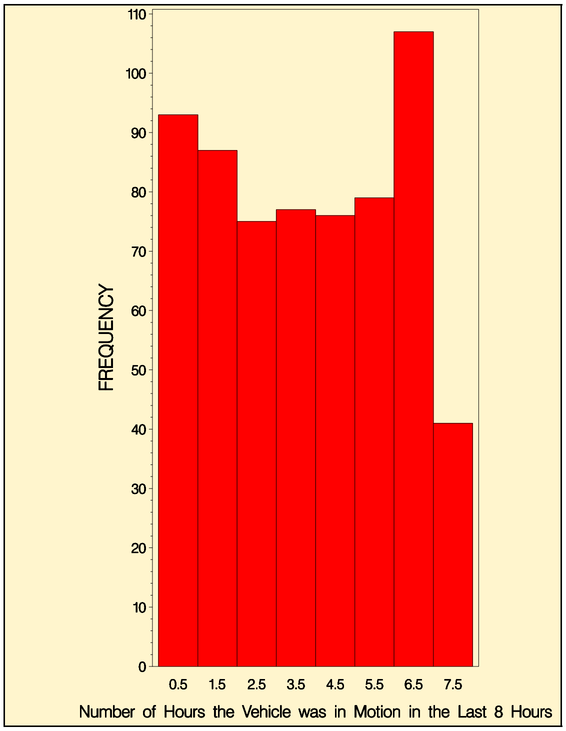

Figure 69. Histogram for Prevention Ratio—Hours in Motion in the Last 8 Hours

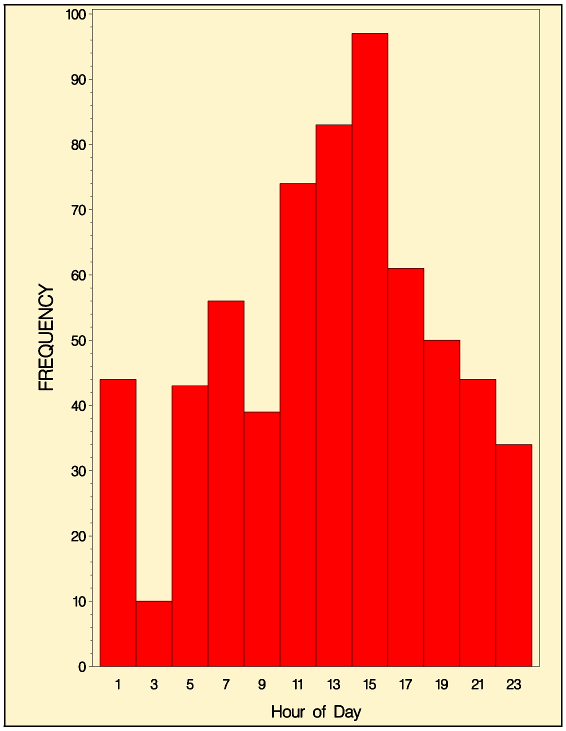

Figure 70. Histogram for Prevention Ratio—Hour of Day

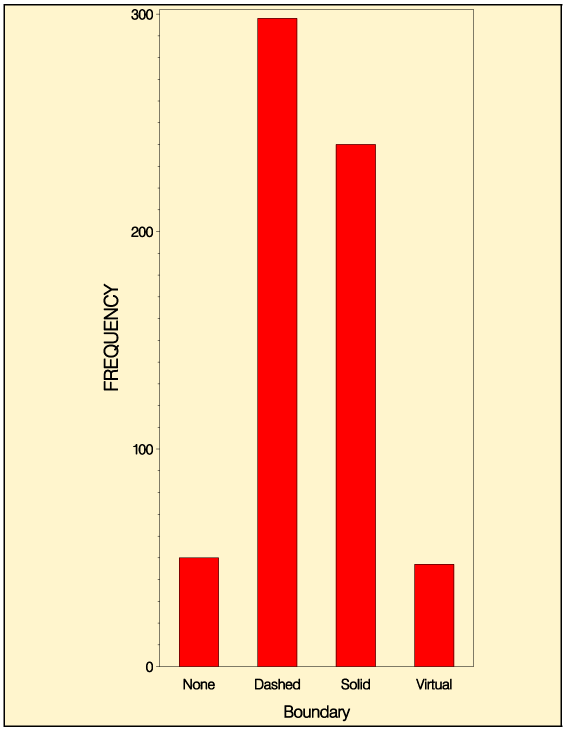

Figure 71. Histogram for Prevention Ratio—Boundary

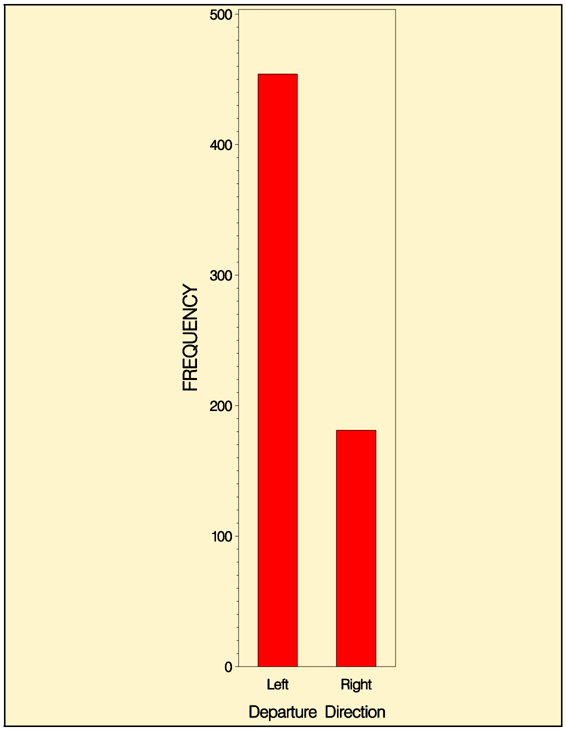

Figure 72. Histogram for Prevention Ratio—Departure Direction

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

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