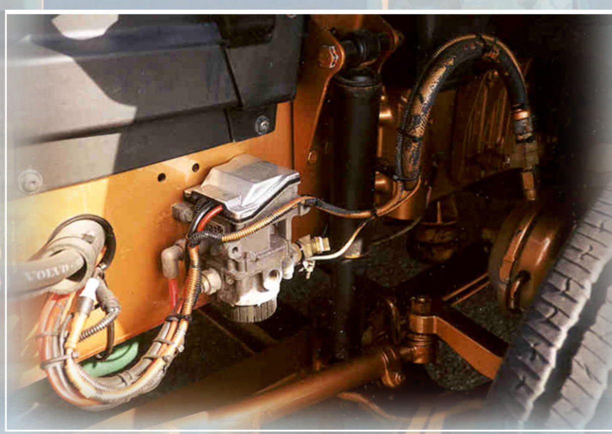
Contract No. DTFH61-96-C-00077 Task Order 7721

Final Report
Evaluation of the Volvo Intelligent Vehicle Initiative Field Operational Test
Version 1.3

U.S. Department of Transportation
Federal Highway Administration



for

U. S. Department of Transportation

Washington, D. C.

by

Battelle

505 King Avenue

Columbus, Ohio 43201-2693

January 5, 2007

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DISCLAIMER

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CONFIGURATION CONTROL REVISIONS

This document is Version 1.3 of the final report.

CC#	Description of Change	Revision Date
1.1	Changes in response to client and internal review comments, based on Draft Version 1.0, prepared July 28, 2005.	July 14, 2006
1.2	Changes in response to client comments, based on Draft Version 1.1, prepared July 14, 2006.	September 8, 2006
1.3	Changes in response to client comments, based on Version 1.2, prepared September 8, 2006.	January 5, 2007

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EXECUTIVE SUMMARY

This report presents the final results of an independent evaluation of the Volvo Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT), sponsored by the U.S. Department of Transportation (USDOT). The intent of the overall IVI program, a major component of the Intelligent Transportation System (ITS) program, is to improve the safety and efficiency of motor vehicle operations significantly by reducing the probability of motor vehicle crashes. These safety improvements could also show secondary benefits such as increased transportation mobility, productivity, or other operational improvements. In 1999, USDOT entered into a cooperative agreement with a partnership led by Volvo Trucks North America and US Xpress to test collision warning, adaptive cruise control, and advanced electronic braking systems in a Generation 0 FOT of advanced intelligent vehicle safety systems (IVSS). These systems, which were in or nearing commercial production at the time of the FOT, were designed for use in commercial trucks.

An important activity of the IVI program is to evaluate the effectiveness of IVSS as they are deployed in the FOTs and estimate the societal benefits and costs, if the IVSS were to be deployed across the entire national fleet of heavy vehicles. Thus, the USDOT contracted with Battelle to perform an independent evaluation of the Volvo IVI FOT.

The Volvo IVI FOT

Volvo Trucks North America, Inc., a leading U.S. manufacturer and distributor of heavy vehicles, tested three systems for commercial vehicles:

- Collision Warning System (CWS)
- Adaptive Cruise Control (ACC)
- Advanced Braking System (AdvBS).

These three systems constituted the IVSS being evaluated in the Volvo IVI FOT.

For purposes of conducting this FOT, the Volvo Partnership included US Xpress Enterprises, Inc. (affiliated with US Xpress Leasing, Inc.), the fleet operator; the USDOT; and several technology and supplier participants, including Eaton VORAD, Eaton Bosch, and Aberdeen Test Center.

The systems are designed to assist commercial vehicle drivers in reducing the occurrence and severity of rear-end crashes as well as lane change/merge crashes.

The CWS is based on forward radar sensors. The forward sensor transmits a radar beam out from the front bumper and receives signal reflections to measure the following distance between the host (or subject) vehicle and the lead (or target) vehicle. If the system detects a potential crash, a warning system notifies the driver to take corrective action through in-cab visual displays and audible alarms.

ACC helps maintain a fixed distance, dependent on road speed, between the host vehicle and the target vehicle ahead. When there is no detected vehicle ahead, ACC maintains a given preset speed similar to conventional cruise control (CCC). The ACC system does not actuate the service braking system to maintain the gap setting. ACC can be bundled with CWS as an integrated, complementary package.

AdvBS, which includes air disc brakes and an Electronically Controlled Braking System (ECBS), is designed to enhance the tractor's stopping performance, and therefore has the potential to reduce the frequency of rear-end crashes by reducing the stopping distance of the vehicle. However, there is potential that the improved braking could also increase drivers' aggressiveness.

As the independent evaluator, Battelle and a team of subcontractors—including Charles River Associates, CJI Research Corp., Foster Miller, J. Bret Michael, and the American Trucking Associations—analyzed the data collected during the Volvo FOT to estimate the safety benefits of the IVSS, assess driver acceptance of the new technology, and study the benefits and costs anticipated from widespread deployment. Data collected from an onboard data acquisition system (DAS) on each tractor were combined with historical crash data and data from other sources. This independent evaluation report was prepared separately from the report prepared by the Volvo Partnership and submitted to DOT in February 2005 (Volvo 2005).

Evaluation Goals and Methods

The primary goal of the IVI program is to determine the extent to which the IVSS can help drivers drive more safely and, thus, reduce the number of truck crashes, bodily injuries, and fatalities involving the subject vehicle population. The results of the FOT were extended to estimate the safety benefits to society if all similar vehicles and eventually all large commercial vehicles operating in the U.S. were to be equipped with the technologies tested. The evaluation also assessed the benefits of these IVSS technologies in areas pertaining to other national ITS goals such as public mobility, efficiency and productivity, and environmental quality. A societal benefit-cost analysis was performed to determine if the costs to deploy, maintain, and operate these systems can be economically justified based on the total benefits to society. Driver perceptions of system performance and usefulness were also evaluated.

The general goal areas with results included in this report are as follows:

- **Safety Benefits (Goal A).** The primary safety benefit expected from the deployment of the IVSS is a reduction in the number and severity of large truck crashes and the resulting injuries and fatalities. This goal area is divided into three objectives:
  - Determine if vehicles with CWS, ACC and AdvBS will have fewer conflicts and crashes than vehicles without the systems
  - Determine if drivers drive more safely with the IVSS than without it

– Determine the number of crashes, injuries, and fatalities that could be avoided if all large trucks operating in the United States were equipped with forward-looking CWS, ACC, and AdvBS.

- **Driver Acceptance (Goal B).** The perceptions of drivers were evaluated through surveys, interviews, and related human factors methods. The goal was to determine the drivers' acceptance of the IVSS, and the effects that the IVSS were perceived to have on the drivers' day-to-day activities while on the job. Results from this goal are reported in a separate document (Battelle 2004) and summarized in this report.
- **Benefit-Cost Analysis (Goal C).** The total cost of installing, operating, and maintaining the IVSS technologies in targeted fleets of trucks was compared to the total economic benefits attributable to deployment of IVSS. The primary benefits are those derived from the reductions in crashes, injuries, and fatalities—including impacts on property damage, mobility, and the environment. This benefit-cost analysis was performed to determine the extent to which further investment in these technologies is economically justified at a societal level.

Findings

Safety Benefits (Goal A)

The estimated safety benefits of deploying a specific combination of IVSS technologies were determined using a statistical model that estimates crash rates based on the frequency and severity of rear-end driving conflicts (safety-critical situations) that were encountered by drivers who participated in the FOT. Conflicts are safety-critical situations that, although they did not result in crashes in the FOT, could potentially have resulted in a crash if the driver did not react quickly or sufficiently. The estimated crash reduction rate for each combination of technologies was determined by comparing the estimated crash rates for drivers that used the IVSS with the corresponding rates for drivers that did not use the IVSS. Crash reduction rates were calculated for three combinations of IVSS technologies: CWS, ACC + AdvBS (relative to CWS alone), and the bundled system (CWS + ACC + AdvBS).

Two different methodologies were employed in the calculations of the safety benefits. One uses a straightforward Kinetic Motion Equation (KME) definition of a conflict and the other uses the Restricted Kinetic Motion Equation (RKME) definition. In the KME conflict definition, driving events were classified as conflicts if they exceeded the conservative KME threshold. Thus, a conflict occurs when a driver must begin braking within 1.5 seconds with a deceleration of at least 8 ft/s^2 in order to avoid a rear-end crash. In the RKME definition, events were considered conflicts if they met the conservative KME threshold and satisfied an additional criterion that the conflict would have resulted in a collision if the driver had waited to react. The RKME Conflict Definition uses a kinematic algorithm to determine the additional time a driver could have waited to react without a collision. Although the RKME definition results in fewer conflicts, the rationale for considering this approach is that it results in a comparison of more severe conflicts that might be mitigated by the use of the IVSS technologies. To present a more complete and robust picture of the potential safety benefits, results are presented using data derived from both definitions.

Results are also presented for three different KME threshold levels: conservative, medium, and aggressive. They represent levels of increasing severity in the definition of a conflict. The aggressive KME criterion requires that a driver react within 0.5 second with a deceleration of at least 12 ft/s^2. Varying the threshold criteria limits the conflicts to a set that is increasingly closer to a crash, but also reduces the number of conflicts to be studied.

Table ES-1 and corresponding Figures ES-1 and ES-2 illustrate the range of results expressed in terms of the predicted percent reduction in rear-end crashes that might be attributable to the deployment of selected IVSS technologies. A statistically significant benefit is achieved when the 95-percent confidence interval (the mean plus or minus two standard errors) does not contain zero. Negative percent reduction estimates indicate that deployment of the given technology might lead to increased numbers of rear-end crashes. None of the negative percent reduction estimates in Table ES-1 are statistically significant.

Table ES-1. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

Kinetic Motion Equation (KME) Conflict Definition Method

Threshold[1]	Estimate ± 95% Confidence Limit		
	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System[2]
Conservative	10.1 ± 14.0 %	2.2 ± 14.2 %	11.7 ± 13.6 %
Medium	21.6 ± 22.6 %	4.7 ± 30.6 %	23.4* ± 21.8 %
Aggressive	26.5 ± 42.4 %	-8.1 ± 68.4 %	19.5 ± 49.2 %

Restricted Kinetic Motion Equation (RKME) Conflict Definition Method

Threshold	Estimate ± 95% Confidence Limit		
	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System
Conservative	-1.9 ± 20.8 %	9.4 ± 12.4 %	7.2 ± 16.8 %
Medium	20.7 ± 24.2 %	12.0 ± 28.4 %	28.1* ± 21.0 %
Aggressive	25.3 ± 44.0 %	9.8 ± 53.6 %	29.9 ± 39.6 %

* Denotes statistically significant results at the 95-percent confidence limit

[1] Conflict threshold levels are as follows: Conservative (1.5 second reaction time with 8 ft/s^2 deceleration), Medium (1.0 sec., 10 ft/s^2), Aggressive (0.5 sec., 12 ft/s^2)

[2] CWS + ACC + AdvBS

Overall, the two calculation methods produce consistent results. For example, using the medium KME threshold criteria (1.0 second reaction time with 10 ft/s^2 deceleration), both methods find that there is a statistically significant reduction in rear-end crashes associated with the deployment of the bundled system. The RKME method estimates that the bundled system will help reduce rear-end crashes by 28 percent, while the KME method estimates a 23-percent crash reduction. The difference between these estimates is not statistically significant. Both methods indicate that the majority of this benefit (21 percent or 22 percent) comes from the effect of the CWS. Although not significant at the 95-percent confidence level, the percent reduction in crashes associated with the CWS (as calculated using the medium threshold criterion) is statistically significant at the 90-percent confidence level using either method. This is illustrated in Table ES-2, which lists the confidence levels for stating that there is a real safety benefit associated with each system. These figures aid in evaluating results that are not significant at the 95-percent confidence level. The safety benefit is estimated by a crash reduction ratio for each combination of conflict definition method and conflict threshold level.

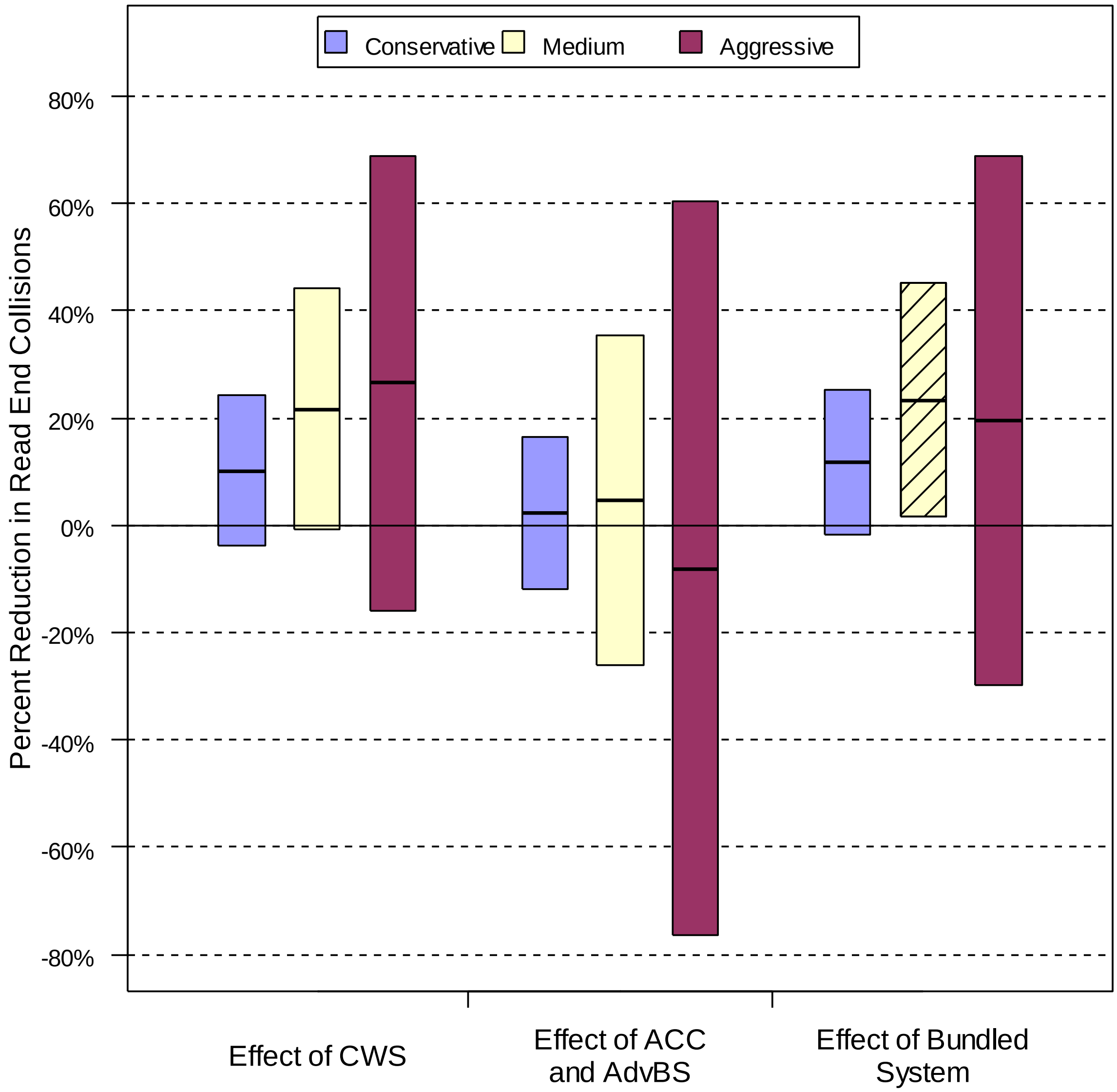

Figure ES-1. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies using the Kinetic Motion Equation (KME) Conflict Definition Method

(Error Bars Represent Approximate 95-Percent Confidence Intervals, Hatched Columns Represent Significant Results)

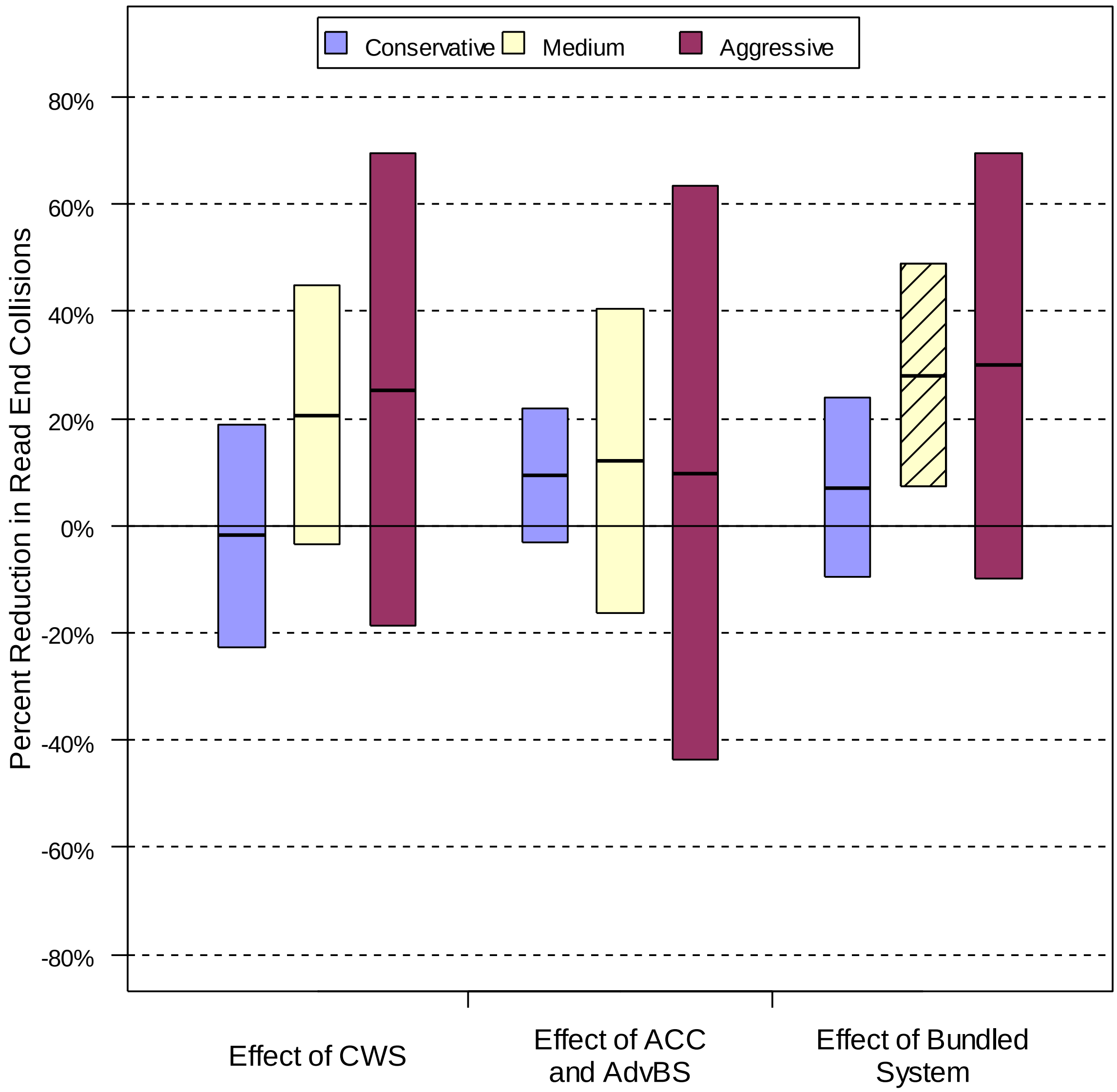

Figure ES-2. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies using the Restricted Kinetic Motion Equation (RKME) Conflict Definition Method

(Error Bars Represent Approximate 95-Percent Confidence Intervals, Hatched Columns Represent Significant Results)

Table ES-2. Approximate Statistical Confidence that the Indicated Safety Benefit is Different from Zero

Threshold	Kinetic Motion Equation (KME) Conflict Definition Method		
	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System
Conservative	85.1%	23.8%	91.5%
Medium	94.5%	24.1%	96.9%
Aggressive[2]	N/A	N/A	N/A

Threshold	Restricted Kinetic Motion Equation (RKME) Conflict Definition Method		
	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System
Conservative	14.6%[1]	86.9%	60.6%
Medium	91.2%	60.0%	99.3%
Aggressive[2]	N/A	N/A	N/A

[1] Estimated effect of the technology indicates a disbenefit at the level of significance indicated.

[2] The percent reduction in rear-end crashes for the aggressive threshold is not normally distributed. Thus, confidence levels based on normality were not calculated. See Appendix D10 for a complete discussion.

In general, the estimated safety benefits using the medium and aggressive threshold levels are consistent with each other, whereas the conservative threshold tends to produce consistently lower benefits estimates. This may be due to the fact that the conservative threshold produces a comparison of the frequencies of a broader range of driving events, some of which might not be true conflicts. In any case, using the conservative threshold, the estimated safety benefit for any combination of systems is not statistically significant, even though the estimate is based on a larger number of "conflicts" and, therefore, has narrower confidence bounds.

The statistical uncertainty in the estimated crash reduction rates, represented by the 95-percent confidence bounds, increases as the severity level of the conflict definition increases. This is expected because there are fewer conflicts that meet the tighter threshold levels. Both calculation methods produce very similar results that demonstrate a significant safety benefit of the bundled system at the medium sensitivity threshold. The RKME Conflict Definition results based on the medium threshold level were used in the benefit-cost analysis; the RKME Conflict Definition and the conservative threshold level were used in the conditional analysis. The analysis of the KME method gives added confidence that the results are insensitive to the calculation methodology.

For the most part, the safety benefit is achieved by helping drivers avoid safety-critical driving scenarios, or conflicts, that typically precede rear-end crashes. There is some evidence that these systems will help drivers avoid crashes once they are involved in conflicts; but analysis of the data indicates that most of the benefit comes from the reduced exposure to conflicts.

In particular, it was estimated that CWS will help eliminate 52 percent of the conflicts in which the truck is driving along at a constant speed and encounters another vehicle in the same lane driving more slowly. Adding the ACC and AdvBS will help reduce another 9 percent of the same type of conflicts for a total of 61 percent reduction of conflicts. These types of conflicts were found to precede 40 percent of all tractor-trailer rear-end crashes and 36 percent of rear-end crashes involving large trucks.

Analyses of the driving conditions under which these systems were used revealed that the systems are most effective at helping to avoid rear-end crashes when the truck is operating at highway speeds. It was found that drivers using the CWS tended to maintain greater following distances than drivers without the system. As shown in Figure ES-3, the average following distance for drivers using CWS is approximately 15 feet greater than for drivers without CWS. This finding is supported by the results of the driver interviews, as discussed below. Drivers using CWS along with ACC and AdvBS have slightly shorter following distances than drivers with CWS alone. Drivers using the ACC and AdvBS were less likely to operate the truck in a manner that would result in very short times to collision (0.5 to 1.0 second) than drivers without these systems—regardless of whether they were using CWS.

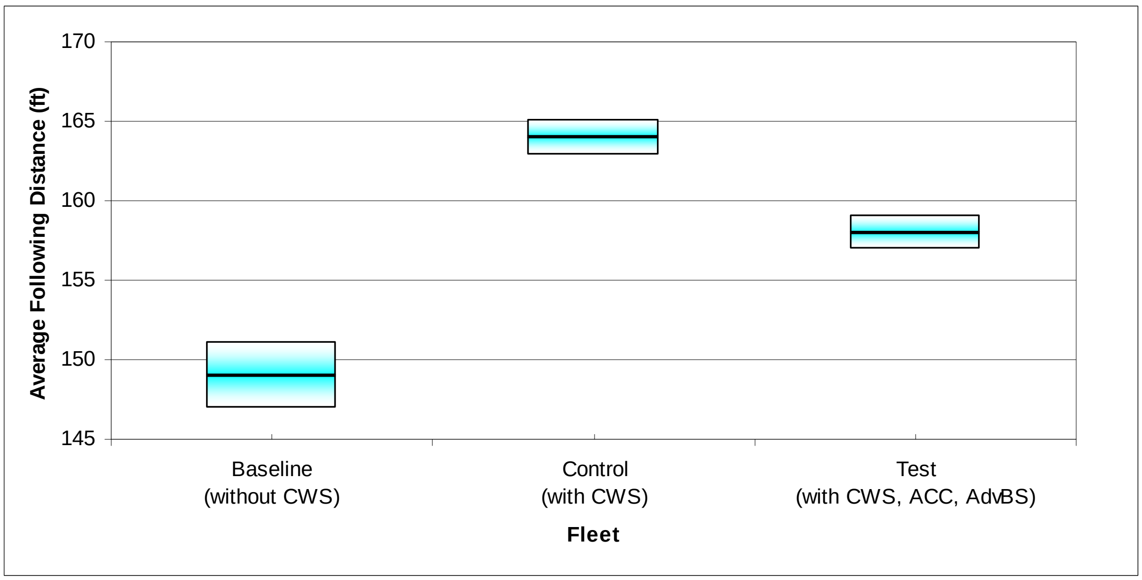

Figure ES-3. Average Following Distance (Feet) with 95-Percent Confidence Interval for Trucks in Three Test Fleets

The safety results observed in this FOT were used to estimate the benefits (reductions in crashes, injuries, and fatalities) that could be achieved if the IVSS were deployed on all tractor-trailers, as well as all large trucks over 10,000 pounds. Data from the USDOT's General Estimates System (GES) and Fatality Analysis Reporting System (FARS) for the five-year period from 1999 through 2003 were examined to determine the average annual numbers of trucks involved in rear-end crashes as well as the numbers of injuries and fatalities. The approximately 1.8 million tractor-trailer units in the U.S. are responsible for 23,000 rear-end crashes each year along with 12,000 associated injuries and 304 fatalities. Because the US Xpress trucks involved in this FOT were also tractor-trailer units, it is reasonable to project that, if the same IVSS technologies (CWS + ACC + AdvBS) were deployed in the larger fleet, approximately 6,500 crashes, 3,400 injuries, and 122 fatalities could be avoided each year. More fatalities are avoided than the 28.1 percent predicted in Table ES-1 due to the distribution of fatalities in GES among various conflict types. Deployment of the CWS alone is projected to result in 4,700 fewer crashes, 2,500 fewer injuries, and 96 fewer fatalities.

In addition, it is reasonable to assume that these technologies will also be effective for reducing rear-end crashes among the 8 million large trucks (over 10,000 pounds) in the U.S., which are responsible for 55,000 rear-end crashes, 28,000 associated injuries, and 395 fatalities each year. To illustrate the potential benefits, the efficacy of the bundled system estimated in this FOT was applied to this larger fleet. Under this broader deployment scenario, approximately 14,000 rear-end crashes, 7,500 injuries, and 127 fatalities could be avoided. The CWS alone could be responsible for 10,000 fewer crashes, 5,400 fewer injuries, and 96 fewer fatalities.

Driver Acceptance (Goal B)

Driver interviews were conducted during the first year of the FOT (Phase 1) and shortly after the conclusion of the FOT (Phase 2). A total of 117 drivers participated in the Phase 1 interviews and 87 participated in Phase 2. Findings are organized according to four research objectives that evaluated driver perceptions of (1) system usability (including training, ease of use, and understanding of the system), (2) impact on workload and stress, (3) impacts on driving, and (4) product quality. Key findings are as follows:

Usability

Approximately half of the drivers reported that they received formal training on the use of CWS and less than one quarter said they received training on ACC or AdvBS. Drivers demonstrated that they had a general understanding of the CWS warnings; but most did not understand the meanings of specific measures of urgency (distance to object or time to react) nor how these measures related to the various combinations of auditory and visual signals. Drivers reported that the signals were easy to see and hear and that they could distinguish them from other systems.

Workload and Stress

Most drivers said the CWS warnings rarely or never drew their attention from driving tasks; however, their chief complaint with the CWS is that there was no apparent cause for about half of the alerts. These nuisance alarms degrade the drivers' confidence in the system. Nevertheless, about half of the drivers said that driving is somewhat or a lot less stressful using CWS. Slightly more than half (56 percent) felt the same about AdvBS and less than half (38 percent) felt that driving is less stressful with ACC.

Impacts on Driving

Most drivers agree that all three IVSS technologies help them drive more safely and, as shown in Figure ES-4, most prefer to drive trucks equipped with these systems. Over 80 percent prefer trucks equipped with CWS and over 90 percent prefer trucks equipped with AdvBS. The attitudes about ACC are mixed. About half say that ACC helps them maintain safe following distances and improves reaction time, but some are uncomfortable with the system taking control away from the driver. As shown in Figure ES-5, between 40 percent and 60 percent of the drivers reported that their driving has changed because of these systems. Many drivers reported that CWS helps reduce the risk of crashes because it makes them more vigilant, helps them maintain a safe following distance, and increases their reaction time and awareness. The impact on following distance was confirmed with the data collected on board (see Figure ES-3). Drivers said that they felt more secure using AdvBS because they did not have to apply as much pressure to stop the truck. A few drivers reported that ACC makes them more relaxed.

Perceptions of Quality

Drivers were generally satisfied with the performance of all three systems. Some drivers reported performance problems with CWS (39 percent), ACC (21 percent), and AdvBS (19 percent); however, reports of frequent downtime were rare. Most drivers did not have recommendations for improvements; but of those who did (38 percent), some wanted more detailed information on CWS indicators (e.g., distances), volume controls for alerts, and better training or simpler manuals.

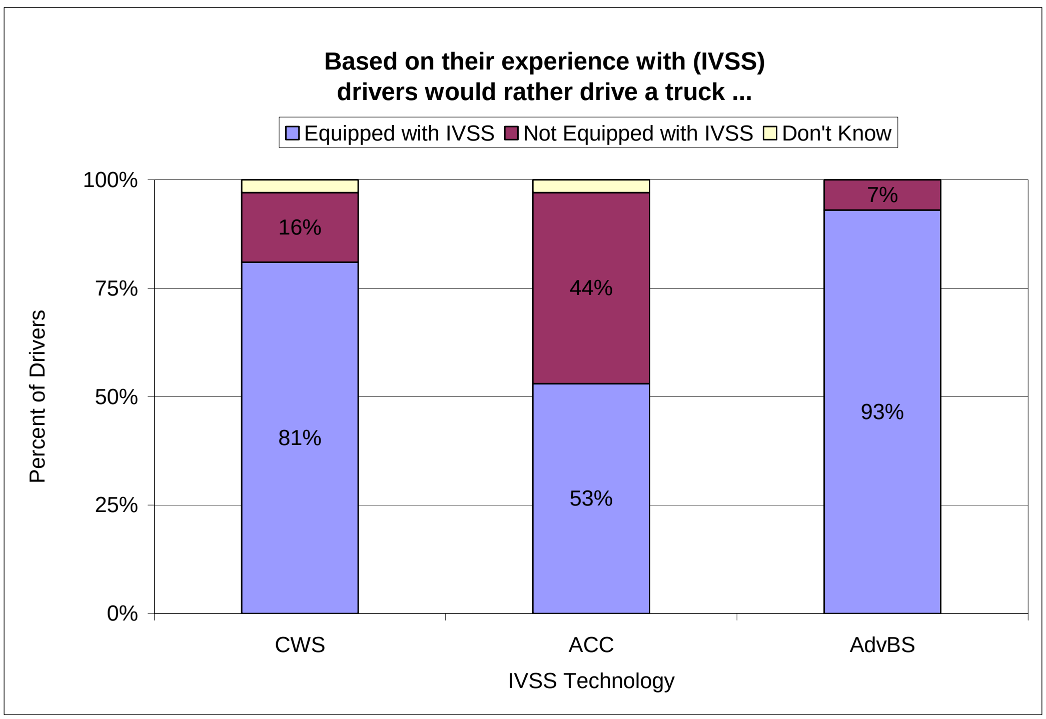

Figure ES-4. Drivers' Responses to Questions Regarding Their Preference for Driving Trucks Equipped with Selected IVSS Technologies

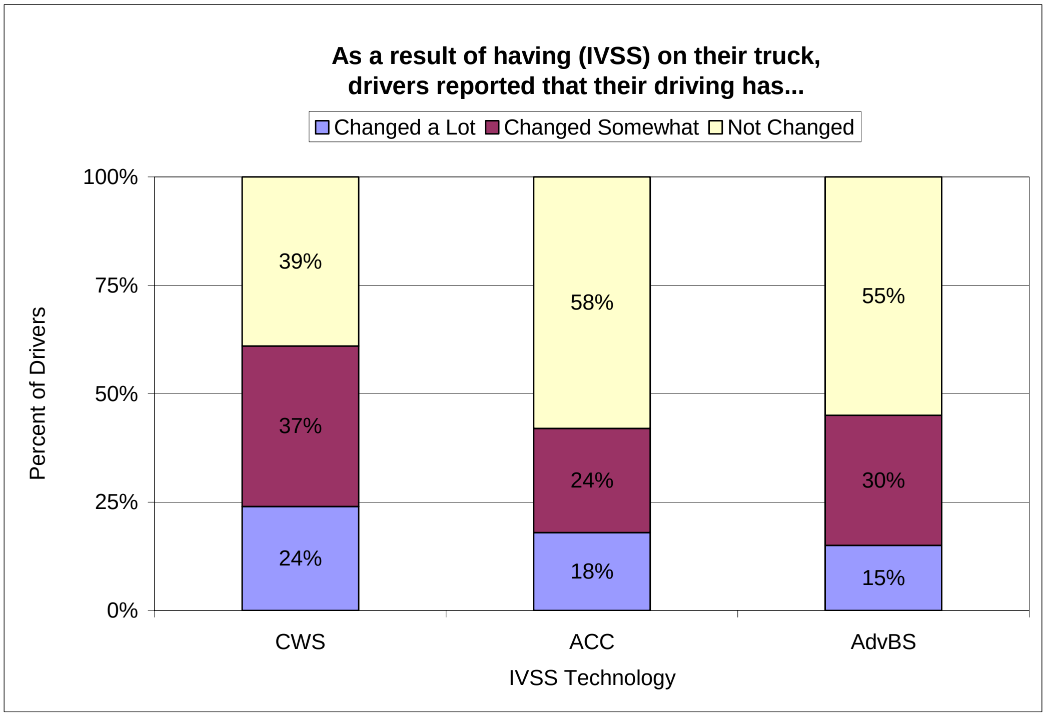

Figure ES-5. Drivers' Responses to Questions Regarding Whether Their Driving Habits Changed as a Result of Having IVSS Technologies on Their Truck

Benefit-Cost Analysis (Goal C)

A societal benefit-cost analysis was performed to determine if the costs to deploy, maintain, and operate these IVSS technologies can be economically justified based on the total benefits to society. Four different deployment options were modeled. Each option represents a unique combination of a national fleet (1.8 million tractor-trailer units or the 8 million commercial trucks over 10,000 pounds) and a set of deployed IVSS technologies (CWS alone or the bundled system: CWS + ACC + AdvBS). For each deployment option, the benefit-cost ratio (BCR), or the ratio of the total societal benefits to the total societal costs, was calculated under six different modeling scenarios. Total societal costs included property damage costs, bodily injury costs, fatality costs, medical and emergency response costs, lost productivity, lost quality of life, and legal costs, among others. Each scenario represents a unique combination of unit cost assumptions (low versus high) and three options for calculating the efficacy of the safety system. The three options are determined by specifying different threshold criteria (conservative, medium, and aggressive) for defining the severity of the driving conflicts—the safety critical events that precede a rear-end crash. Sensitivity analyses were performed to assess the impacts of modeling assumptions on the overall benefit-cost analysis.

For the fleet of 1.8 million tractor-trailers, the economic analysis indicates that in a competitive market (with lower costs) the deployment of CWS and the bundled system are economically justified by a small margin. In four of the 12 modeled scenarios, the economic value of the benefits exceeded the projected costs by margins of 10 percent to 30 percent (BCR = 1.1 to 1.3). The scenarios were varied according to the truck fleet, the equipment package deployed, the conflict threshold criterion used, and the installed cost of the IVSS. For the installed costs, the CWS was assumed to range from $2,000 to $3,000 per tractor. The installed cost of the bundled system (CWS + ACC + AdvBS) was estimated to range from $2,300 to $6,300 per tractor. The lower cost assumption for the bundled system was based on disregarding the added costs for the braking system. The rationale for this scenario was that the safety benefits analysis indicated that the benefits of the bundled system are largely attributable to the CWS. These costs as well as the annual operating and maintenance (O&M) costs were estimated through consultation with manufacturers and suppliers as well as engineering analysis of similar systems. Actual installed cost information is difficult to obtain, because it tends to be closely held as proprietary by vendors, OEMs, and purchasers in a competitive market.

For the larger fleet of 8 million large trucks over 10,000 pounds, none of the scenarios involving deployment on all large trucks was economically justified. That is, all of the BCRs were less than 1.0.

A sensitivity analysis was performed to gauge the effects of sharply reduced purchase and O&M costs in the future. If the future purchase costs of CWS can be reduced to $600 (from $2,000 to $3,000 currently) and the costs of the bundled system can be reduced to $1,000 (from $2,300 to $6,300), the BCRs increased markedly. These lower costs might be possible through economies of scale, reduced manufacturing costs, or other means.

Figure ES-6 summarizes the findings by presenting the BCRs across 36 scenarios representing all possible combinations of two fleet types (tractor-trailers and all large trucks), two IVSS technologies (CWS and the bundled system), three modeling assumptions concerning the severity of conflicts, and three cost assumptions (low and high current cost estimates and one corresponding to sharply reduced equipment and O&M costs in the future). To summarize these results:

- Very little difference was observed between the medium and aggressive conflict threshold criteria.
- The only positive societal returns on investment occur if the CWS or the bundled system is deployed under the low current cost assumptions. (This includes the assumption that the benefits of the bundled system are not attributable to the AdvBS.)
- Deploying these systems on all large trucks does not appear to be economically justified under any current cost assumptions.
- A clear economic benefit of deploying these systems on tractor-trailers was observed, if costs can be lowered to the future levels used in the sensitivity analysis. There is still no—or very little—economic justification for deploying these system on all large trucks under any feasible current or future cost assumptions.

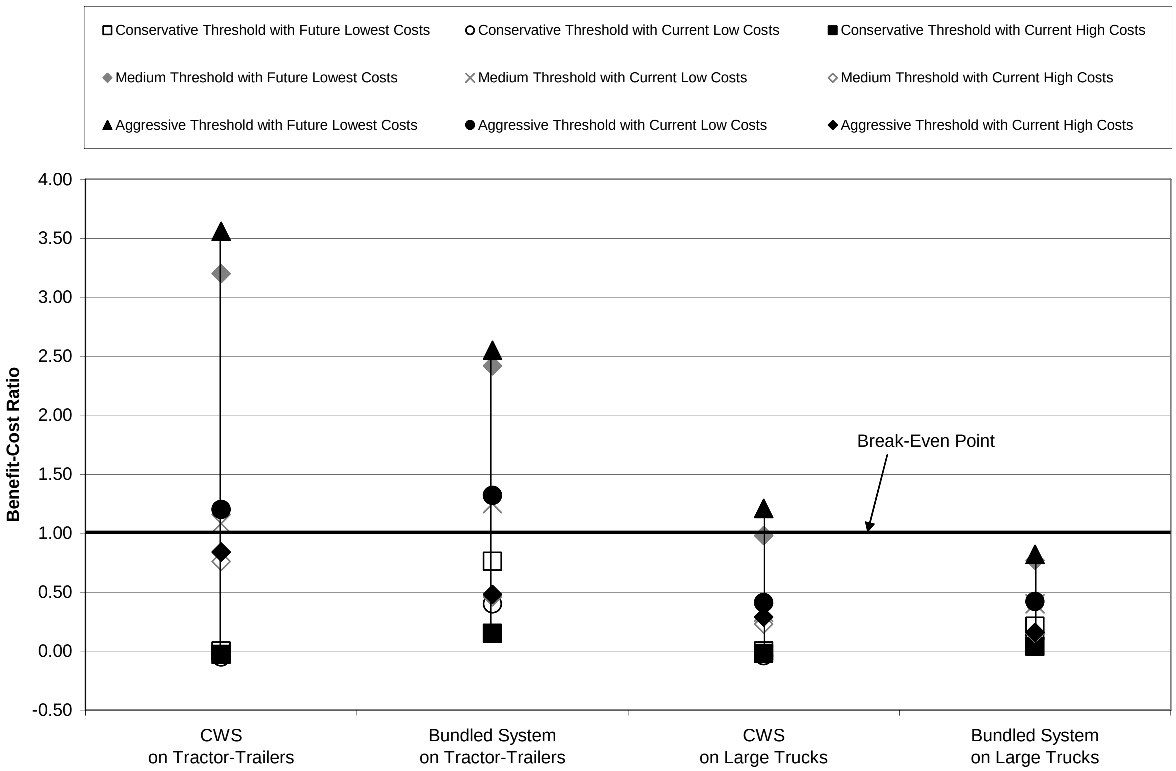

Figure ES-6. Benefit-Cost Ratios Across Four National Fleets Using Various Cost Assumptions and Conflict Threshold Criteria

Implications of Findings

From a safety perspective, the most significant finding from this FOT is that the bundled system consisting of CWS + ACC + AdvBS on a tractor-trailer unit can help reduce the number of rear-end crashes by 28 percent. It appears that most of this benefit (21 percent) is due to the use of CWS, especially while driving at highway speeds; however, the estimated benefit of the CWS is only significant at the 90-percent confidence level. If the CWS were to be deployed nationwide on all 1.8 million tractor-trailer units, approximately 4,700 rear-end crashes, 2,500 injuries, and 96 fatalities can be avoided each year. If all three systems were deployed on the same vehicles, the nation could realize reductions of 6,500 crashes, 3,400 injuries, and 122 fatalities. However, this FOT could not determine which of the two supplemental systems (ACC or AdvBS) is responsible for the additional safety benefit. This has significant implications on the costs of deployment.

Although additional studies may be needed to determine whether the ACC or AdvBS was responsible for the incremental benefits when both were added to a truck that already had CWS installed, it is clear that the cost of adding ACC (approximately $300 per truck) is substantially less than the cost of adding AdvBS (approximately $4,000 per truck). So, adding the ACC will have only a modest impact on the cost of deployment; but may produce substantial safety benefits.

The drivers participating in this FOT clearly recognized the value of the CWS—stating that it helped them to be more vigilant and maintain safer following distances. Driver feelings about the ACC were mixed, with about half of the drivers preferring to drive trucks with ACC and half preferring not to have ACC. Almost all of the drivers who used AdvBS agreed that it was beneficial.

All Large Trucks

Deployment of these systems on the larger population of 8 million large trucks (over 10,000 pounds) could result in additional crash savings; however, there are substantially fewer rear-end crashes per truck for this fleet (7 crashes per 1,000 large trucks versus 13 crashes per 1,000 tractor-trailers). Furthermore, more than three-fourths of the fatalities from rear-end crashes involving large trucks come occur when tractor-trailers are involved. Thus, the safety benefit per unit deployed is substantially smaller for the larger fleet.

Thus, from an economic benefit-cost perspective, the deployment of the bundled system on the fleet of all large trucks cannot be justified at a societal level under any scenario considered. This is partially driven by the high cost of the AdvBS. Even under the most optimistic future cost assumptions, the economic benefits from deployment of the CWS alone on all large trucks (without the expense of the AdvBS) would be only approximately equal to the cost of deployment.

Tractor-Trailers

It appears that in a competitive market, the deployment of CWS on all tractor-trailers, on the other hand, can produce safety benefits that exceed the cost of deployment. Interviews with drivers also indicate that deployment of CWS will have positive effects on driver morale. Deployment of ACC might produce additional safety benefits at a relatively small cost. However, the relative benefits and costs of deploying AdvBS require additional study. The drivers appear convinced that these braking systems improve driving safety; however, it was not possible to fully document these benefits in this FOT. Also, the future cost assumptions necessary to make these systems economically feasible ($1,000 per truck) may be overly optimistic in the near term. Targeting the deployment to specific segments of the national truck population (other than tractor-trailers) was not considered in this analysis.

Organization of This Report

This report is arranged in six main chapters as follows:

1. Introductory material and background
2. Description of IVI systems, plans, and operational issues
3. Discussion of evaluation goals, objectives, and hypotheses
4. Evaluation methods, in terms of data collected and analyses performed
5. Independent evaluation results
6. Implications of the findings in the context of the larger safety issue

References to bibliographic sources and a series of appendices giving more detailed information related to this FOT evaluation are included at the end of the report.

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ABBREVIATIONS

Term	Definition
ABS	Antilock braking system
ACC	Adaptive cruise control
AdvBS	Advanced electronic braking system (ECBS + disc brakes)
ATA	American Trucking Associations, Inc.
ATC	Aberdeen Test Center (U.S. Army)
ATH	Abbreviated time history
ATRI	American Transportation Research Institute
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
CATI	Computer-aided telephone interview
CCC	Conventional cruise control
CDL	Commercial driver license
CPI	Consumer Price Index
CPU	Central processing unit
CRR	Crash reduction ratio
CWS	Collision warning system
DAS	Data acquisition system
DDU	Driver display unit
EBS	Electronically controlled braking system
ECBS	Electronically controlled braking system
ECU	Electronic control unit
ER	Exposure ratio
EST	Eastern Standard Time
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standard
FOT	Field operational test
FTA	Federal Transit Administration
FTP	File transfer protocol
g	Acceleration due to gravity, 9.8 m/s^2
GES	General Estimates System
GMT	Greenwich Mean Time
GPS	Global Positioning System
GVW	Gross vehicle weight

Term	Definition
Hz	Hertz, cycles or counts per second
ID	Identification
IEEE	Institute of Electrical & Electronics Engineers
ISS	Inspection Selection System
IT	Information technology
ITS	Intelligent Transportation System
IVI	Intelligent Vehicle Initiative
IVSS	Intelligent Vehicle Safety System(s)
KME	Kinetic motion equation
LVCS	Lead vehicle constant speed
LVD	Lead vehicle decelerating
LVS	Lead vehicle stopped
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
O&M	Operating and maintenance
OEM	Original equipment manufacturer
OMB	Office of Management and Budget
OOS	Out of service
P	Principal data source
PAR	Police accident report
PCMCIA	Personal Computer Memory Card International Association
PR	Prevention ratio
PST	Pacific Standard Time
S	Supplemental data source
SEA	Safety Evaluation Area (USDOT SafeStat system)
SQL	Structured Query Language
SVRD	Single-vehicle road (or roadway) departure
TH	Time history
USDOT	United States Department of Transportation
VIN	Vehicle identification number
VMT	Vehicle miles traveled
VORAD®	Vehicle On-Board Radar
VTNA	Volvo Trucks North America

1.0 INTRODUCTION

This report presents the final results of an independent evaluation of the Volvo Intelligent Vehicle Initiative (IVI) Field Operational Test (FOT), sponsored by the U.S. Department of Transportation (USDOT). The IVI is a cooperative effort among the motor carrier industry and four agencies housed within 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, a major component of the Intelligent Transportation System (ITS) program, is to improve the safety and efficiency of motor vehicle operations significantly. These improvements are brought about by reducing both the number and the consequences of motor vehicle crashes on U.S. highways. Crash reductions, in turn, are achieved by accelerating the development, testing, deployment, and use of new vehicle-based technologies known as intelligent vehicle safety systems (IVSS). IVSS are information technology (IT)-enabled systems and smart technologies designed to reduce crashes and prevent injuries by increasing vehicle performance, enhancing vehicle crashworthiness capabilities, and assisting drivers. These safety improvements may also yield secondary benefits, such as increased transportation mobility, productivity, and other operational improvements.

In 1999, USDOT entered into a cooperative agreement with Volvo Trucks North America, Inc., in partnership with US Xpress, to test a collision warning system, 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.

The Volvo Partnership has performed an FOT to demonstrate and evaluate advanced technologies. As part of this effort, the USDOT selected a Battelle-led team to work with the partnership to perform an independent evaluation of the technologies being tested. This report covers the independent evaluation of the Volvo IVI FOT.

1.1 The Volvo IVI Field Operational Test

The USDOT entered into a Cooperative Agreement with Volvo Trucks North America (VTNA), in partnership with US Xpress Enterprises, Inc., (US Xpress), the fleet operator, to test three Generation 0 advanced safety systems, described below. As described in the final FOT report (Volvo 2005), the objectives of the FOT were to evaluate the performance of the IVSS in a real-world environment; to accelerate the deployment of the IVSS; to help forge strategic partnerships in the transportation industry as a model for public-private cooperation; and to assess the state of the art in safety benefits analysis for vehicle systems.

US Xpress is the fifth largest publicly owned truckload carrier in the United States and specializes in time-definite and expedited service. The company provides truckload and dedicated services throughout North America, with regional capabilities in the West, Midwest, and Southeastern United States. Its fleet approaches 4,800 truck tractors and 9,500 dry van trailers. More than 6,500 of the 8,000 employees are drivers. US Xpress utilizes one of the largest team-operated fleets in the industry, with more than 1,000 teams of drivers.

The Volvo-led team was responsible for the integration of the technologies on new Volvo tractors, for instrumentation of the vehicles, for operating the vehicle in revenue-generating service, and for data collection and data transfer to the independent evaluator.

Vendors/suppliers and other participants in the Volvo FOT included the following:

Eaton® VORAD® (Galesburg, MI) provided the EVT-300 CWS and Adaptive Cruise Control system. Eaton® Bosch provided the ECBS. The U.S. Army Aberdeen Test Center (ATC, in Aberdeen MD) provided integrated onboard data acquisition systems (DAS) for the Volvo trucks. PAR Technology Corp./Rome Research Corp. (New Hartford, NY) performed detailed engineering analysis of driving data to determine safety benefits.

US Xpress leased 100 Volvo VN770 tractors for their normal revenue-generating service, beginning in January 2001. Fifty of these vehicles were equipped with the three safety systems ("IVI" Test vehicles) and 50 were to serve as Control vehicles. The Control vehicles were broken down further into two groups. One group would have no IVS systems activated for the first 18 months and only the Eaton® VORAD® CWS active for the remaining time (20 "Baseline" vehicles). The other Control group would have the CWS operational for the entire FOT (30 "Control" vehicles). All vehicles, both Test and Control units, were to be instrumented for data collection by the ATC. Figure 2.2-1, presented in Section 2, illustrates the study design and overall schedule.

Three commercially available IVSS were under test:

1. Collision Warning System (CWS)
2. Adaptive Cruise Control (ACC)
3. Advanced Braking System (AdvBS).

These systems have been developed to reduce the occurrence and severity of rear-end crashes. In most applications, the CWS is based on forward radar sensors. The forward sensor transmits a radar beam out from the front bumper and receives radar returns to measure the following distance between the host (or subject) vehicle and the target (or lead) vehicle. If the system detects a potential collision, a warning is given to the driver to take corrective action through in-cab visual displays and audible alarms.

ACC helps maintain a fixed distance, dependent on road speed, between the host vehicle and the target vehicle ahead. When there is no detected vehicle ahead, ACC maintains a given preset speed, similar to conventional cruise control (CCC). ACC can be bundled with CWS as an integrated, complementary package. If the following distance and speed become a potential threat, the vehicle can be slowed automatically using the ACC. CWS can also be installed as a stand-alone system, as was the case for control trucks in this FOT.

AdvBS, which includes air disc brakes and an Electronically Controlled Braking System (EBS or ECBS), is designed to enhance the tractor's stopping performance, and therefore has the potential to reduce the frequency of rear-end crashes by reducing the stopping distance of the vehicle.

Independent from the testing performed by the Volvo team itself, a Battelle-led team was engaged by the USDOT to conduct an evaluation of the Volvo IVI FOT. This final report documents the objectives, methods, and results of the independent evaluation.

1.2 Organization of this Document

This report is arranged in six main chapters as follows:

1. Introductory material and background
2. Description of IVI systems, plans, and operational issues
3. Discussion of evaluation goals, objectives, and hypotheses
4. Evaluation methods, in terms of data collected and analyses performed
5. Independent evaluation results
6. Implications of the findings in the context of the larger safety issue.

References to bibliographic sources and a series of appendices giving more detailed information related to this FOT evaluation are included at the end of the report.

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2.0 DESCRIPTION OF THE IVI TECHNOLOGIES AND THE FOT

Following a research plan developed by the Volvo Partnership, new Volvo tractors were equipped with IVSS technologies and instrumented for data collection before being leased and placed in normal service operations by US Xpress.

This chapter provides technical background on the safety systems under evaluation, on elements of the final research plan, and on operational issues that are instrumental to the independent evaluation of the technologies. Further information on the methods and data sources used in the independent evaluation—including the relationship between the IVSS and the operational and other data collected in the course of the FOT—is presented in Chapters 3 and 4.

2.1 Description of the IVI Technologies

The Volvo Partnership field tested a safety package comprised of three IVSS technologies (Figure 2.1-1):

- Collision Warning System (CWS)
- Adaptive Cruise Control (ACC)
- Advanced Braking System (AdvBS).

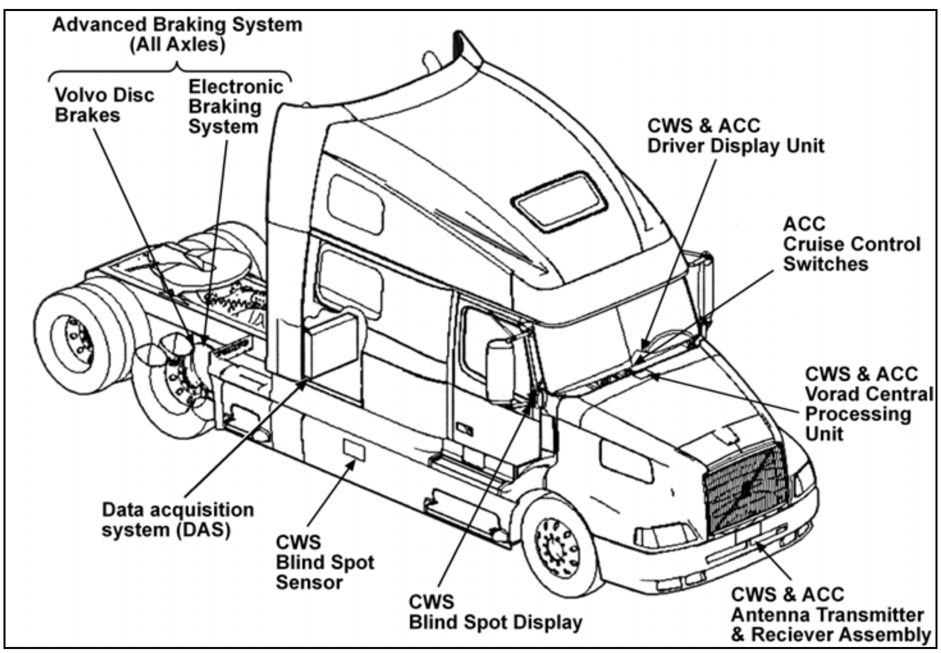

Figure 2.1-1. IVSS Technologies Under Evaluation in the Volvo IVI FOT

These systems were bundled by the Volvo Partnership as a safety package and functioned simultaneously, but independently of each other. However, the CWS and ACC shared common sensor inputs because of their design characteristics.

Heavy vehicle crashes can be broadly classified into four categories: rear-end crashes, single vehicle roadway departures (SVRDs), lane change/merge crashes, and rollovers. IVSS are designed to mitigate one or more of these crash types. The three IVSS under evaluation in the Volvo IVI FOT are primarily designed to mitigate rear-end crashes by:

- Notifying drivers when they enter a situation that could lead to a rear-end crash, such as when they follow another vehicle too closely (CWS)
- Warning drivers of impending dangers, hence giving drivers more time to react and allowing them to avoid a rear-end crash through avoidance maneuvers (CWS)
- Helping drivers maintain a safe following distance, hence assisting them in avoiding situations that could lead to a crash (ACC)
- Enhancing the braking capabilities of their tractors (AdvBS), thus helping drivers control their vehicles better in difficult situations.

Typically, crashes are preceded by a set of conditions, referred to as a driving conflict. Driving conflicts are safety-critical driving situations encountered by trucks such as "*truck is going straight at constant speed and encounters a slower moving vehicle ahead.*" Such driving conflicts can be resolved by either a crash or by some corrective action taken by the driver, where the corrective action avoids a crash and removes the safety-critical driving situation. IVSS can provide safety benefits by reducing the occurrence of driving conflicts, by assisting the driver in taking the corrective action, or both.

2.1.1 Collision Warning System

The collision warning system (CWS) is designed to prevent or reduce the severity of rear-end crashes by:

- Alerting drivers of potential hazards ahead of the truck, hence giving drivers more time to react and allowing them to avoid or reduce the severity of rear-end crashes through avoidance maneuvers
- Assisting drivers in identifying dangerous situations known to lead to rear-end crashes, hence conditioning them to maintain safer following distances by increasing awareness of vehicles and objects ahead and in the blind spots of the vehicle.

The CWS uses radar technology to monitor vehicles ahead of the vehicle, and communicates the information collected to the driver in the form of visual and/or audible alerts.

2.1.1.1 Forward-Sensing Technology

A front-end mounted radar antenna mounted near the center of the front bumper of the vehicle transmits high-frequency, low-power monopulse radar signals which, when they reflect off objects, are received back at the antenna assembly. The transmitted and received signals are compared and forwarded in digital format to an onboard electronic control unit, the Central Processing Unit (CPU).

2.1.1.2 Central Processing Unit

The CPU combines the information received from the antenna assembly with additional vehicle information available from the engine control unit, the speedometer, the optional side sensor, and the brake and turn signal circuits to identify potential threats or collisions and to generate visual and audible alerts at the driver display unit (DDU).

Proprietary algorithms are continuously used by the CPU to:

- Determine the distances and relative velocities separating the host vehicle from all detected targets
- Select an individual target as the “primary target,” i.e., the vehicle or object ahead of the host vehicle that poses the highest potential risk or the most imminent hazard
- Define the danger level of the hazard.

The primary target and associated danger level are determined using threshold values defined by VORAD®. These values correspond to various potentially dangerous situations, when the other vehicles are within given predefined distances or time headways. The different warnings are a function of the potential for problems or the need for the truck driver to take evasive action.

Once the danger level of the imminent hazard has been determined by the CPU, this level is communicated to the driver by a combination of lights and audible tones emitted through the Driver Display Unit.

2.1.1.3 Driver Display Unit

The driver display unit for the forward radar sensor, shown in Figure 2.1-2, contains:

- Light indicators to communicate
    - Various warning alerts to the driver
    - Information related to system operation (system power up light, system failure light, ACC enabled)
- A speaker to
    - Sound audible warning alerts to the driver
    - Provide audible tones indicative of the system operation (e.g., system failure)

- Control knobs giving the driver the ability to
    - Adjust the volume of the audible alerts
    - Control headway threshold values (operates only if the vehicle is equipped with ACC as an add-on technology)
- A light sensor that controls the brightness of the visual indicators.

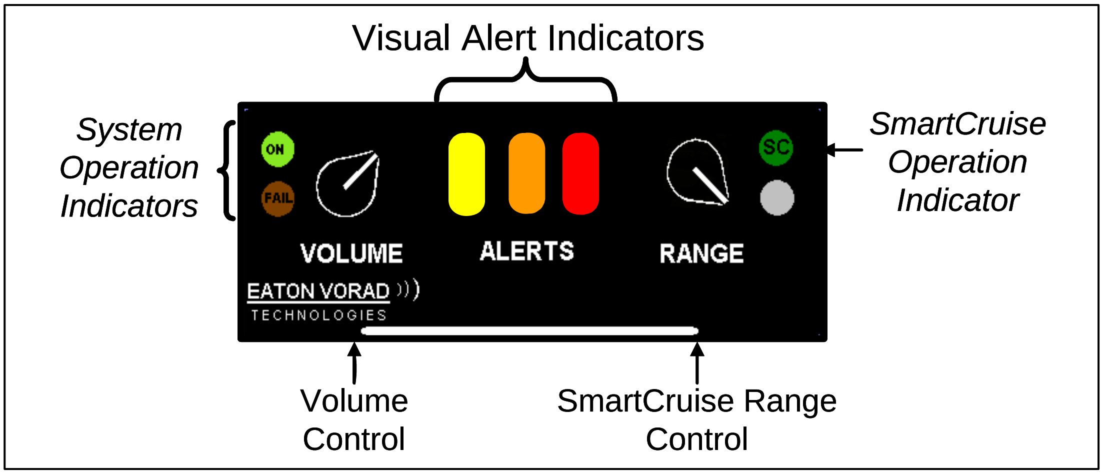

Figure 2.1-2. Eaton® VORAD® Driver Display Unit for the Forward Sensor

2.1.1.4 Alert Triggers

Table 2.1-1 lists each of the VORAD® alerts and, for each, the set of conditions that trigger them and the combination alerts communicated to the drivers. The "alert numbers" shown in the table were defined by Eaton® VORAD® and are intended to indicate increasing levels of alarm or potential severity, while the "alert name" and "alert description" in the table provide a high-level identification of the type of situation.

The conditions triggering alerts are principally based on the value of the following interval, defined as the following distance (range) divided by the velocity of the host. Conditions are also refined by criteria such as:

- Absolute values of the host vehicle speed (e.g., host speed > 10 mph),
- Relative values of the host/target vehicle speeds (e.g., target speed < 1.05 * host speed),
- The range or position of the target vehicle (e.g., in the host vehicle lane), and/or
- The status of driver intervention (e.g., brakes are applied or vehicle is turning sharply).

The driver alerts may be both visual and audible. The colors of the dots shown in the "Visual Alarms" column represent which combination of the three visual alert indicators is lit at each alert level. Figure 2.1-2 above shows the configuration of the yellow, orange, and red indicator lights. The alarm bell icons (🔔) in the "Audible Alarms" column identify which type of audible tones, if any, are generated by each level of alert.

Table 2.1-1. Levels of VORAD® Alerts (Forward Radar) Based on Following Interval, Defined by Range/Host Velocity

Alerts Name, Number & Description			Triggering Conditions: Following Interval (Note 1)	Triggering Conditions: Additional Criteria	Driver Alerts: Visual Alarms	Driver Alerts: Audible Alarms
Detect	**1**	**Object detected**		Notes 2-3	🟡	
Follow	**3**	**Opening/Closing**	2-3 seconds	Notes 2-4	🟡🟠	
	4	**Opening**	1-2 seconds	Notes 2-4, 7	🟡🟠	
	5		<1 second	Notes 2-4, 8	🟡🟠🔴	
	6	**Closing**	1-2 seconds	Notes 2-5, 10	🟡🟠🔴	🔔
	7		<1 second	Notes 2-5, 11	🟡🟠🔴	🔔🔔
½ second	**10**	**Opening/Closing**	< ½ second	Notes 2-4, 5	🟡🟠🔴	🔔🔔🔔🔔
Stationary	**8**	**Stationary Target**	3 seconds	Notes 2, 4, 5, 6, 9	🟡🟠🔴	🔔🔔
Slow moving	**9**	**Slow moving Target**		Notes 2, 5, 6, 12		
Creep	**2**	**Closing**		Notes 14-16	🟡	🔔🔔

Note 1: Following interval is defined as range/host velocity speed.
Note 2: Target is in same lane as host vehicle.
Note 3: $R < R_{max}$.
Note 4: Host speed $V_F > 10$ mph.
Note 5: Audible alarm is disabled if brakes are applied or in a hard turn (≥5 degrees/s).
Note 6: R is < 220 ft or R_{max}, whichever is smaller.
Note 7: $V_L > 101\% * V_F$.
Note 8: $V_L > 105\% * V_F$.
Note 9: $V_L < 3.4$mph.
Note 10: $V_L < 101\% * V_F$.
Note 11: $V_L < 105\% * V_F$.
Note 12: $V_F > 1.25 * V_L$.
Note 13: $V_F > 35$ mph.
Note 14: R < 15 feet.
Note 15: $V_F < 2$ mph.
Note 16: $V_F - V_L < 0.5$mph.

Following Interval = range / host velocity speed

R = Range, distance (target to host)
R_{max} = Maximum VORAD® range,
= 350 feet, or
= [2 x Turn radius x sin(6°)]
V_L = Target or lead vehicle speed
V_F = Host or following vehicle speed

2.1.1.5 Product Specifications

The CWS evaluated in the Volvo IVI FOT was the EVT-300, commercially available from Eaton® VORAD® Technologies. The forward radar antenna assembly can monitor up to 20 objects, moving or stationary, within a 350-foot range. The radar beam reflects only off objects with sufficiently large surface area, and which are within the beam field (±6° azimuth and ±2.5° elevation). Specifications of the forward radar are listed in Table 2.1-2. On US Xpress trucks, the CPU was installed in the dashboard, at the centerline of the vehicle under the cup holder, and the driver display unit for the forward sensor was mounted on the dashboard. Figure 2.1-3 is a top view of a tractor illustrating the location of the forward radar system components (antenna assembly, CPU, DDU) and interconnecting harness.

Table 2.1-2. Eaton® VORAD® CWS Specifications

Description	Value	
	English	Metric
Temperature range	-40 to +185°F	-40 to +85°C
Vehicle closing rate (1%±0.2mph)	0.25 to 100 mph	0.4 to 160 km/h
Host vehicle speed	0.5 to 120 mph	0.8 to 190 km/h
Operating range (±5%, ±3ft)	3 to 350 feet	0.9 to 110 meters
Azimuth radar field	-6° to +6°	
Elevation radar field (±0.2%)	-2.5° to +2.5°	
Frequency	24.725 GHz	

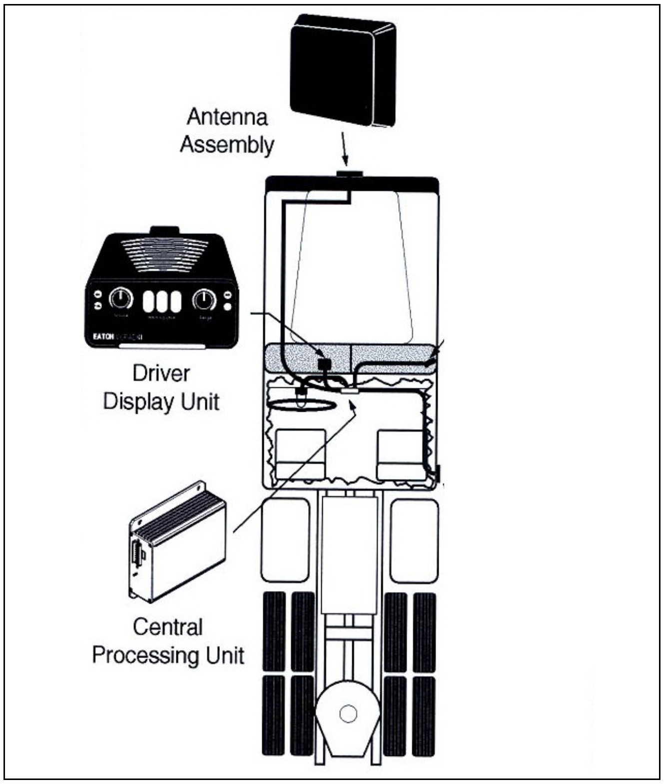

Figure 2.1-3. Location of the Components of the VORAD® CWS

(Courtesy of Eaton® VORAD®)

The CWS is designed to prevent or reduce the severity of rear-end crashes by alerting drivers of potential hazards ahead of the truck. Depending on the severity of the hazard identified and communicated to the drivers, the alerts generated by the CWS have the potential to

- Reduce the occurrence of driving situations known to lead to rear-end crashes (i.e., driving conflicts) and
- Assist drivers in avoiding a crash or reduce its severity with enhanced avoidance maneuvers if drivers enter such driving conflicts.

As such, the safety benefits of the forward-sensing technology were evaluated by comparing the following parameters, among groups of vehicles equipped and those not equipped with the CWS technology:

- The frequency of occurrence of selected driving conflicts
- The resolution of driving conflicts if they occur.

2.1.2 Adaptive Cruise Control

The Adaptive Cruise Control (ACC) system is designed to avoid rear-end crashes and prevent injuries by helping drivers maintain safe following distances. By keeping safe following distances, the drivers are more likely to avoid situations known to lead to rear-end crashes.

Eaton® VORAD® Adaptive Cruise Control, or SmartCruise®, is an optional safety feature available with the EVT-300 CWS: it combines the forward collision warning radar with conventional cruise control. Illustrated in Figure 2.1-4, the system's principle of operation is such that

- If a target vehicle is identified ahead within the radar's operational range and in the same lane as the host vehicle, the technology maintains a minimum following interval[1] between the target vehicle and the host vehicle
- When no target is identified by the radar system, then the vehicle maintains a set speed, like conventional cruise control.

[1] The following interval, expressed in seconds, is equal to the distance separating the target and the host vehicles divided by the speed of the host vehicle.

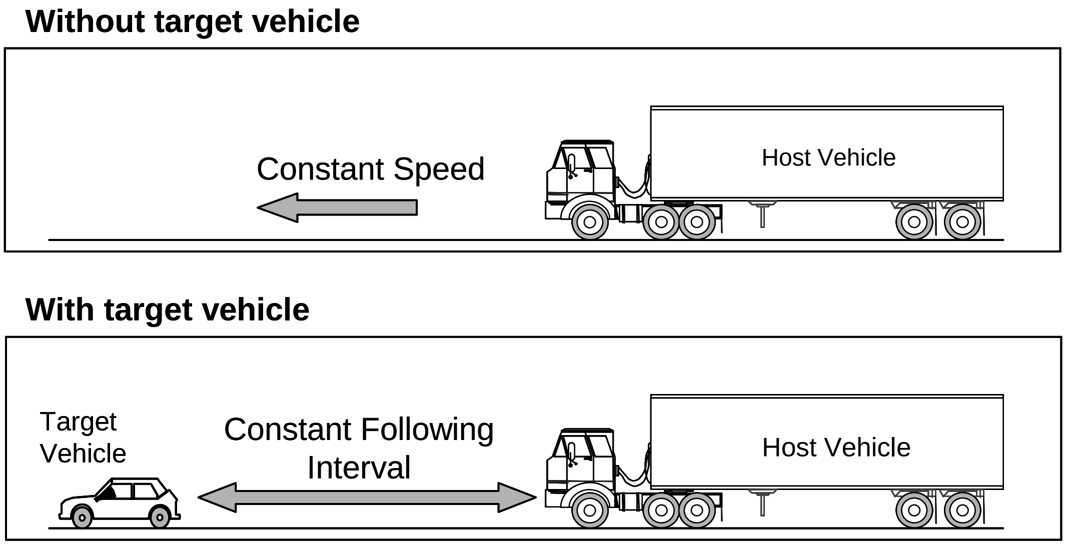

Figure 2.1-4. Principle of Operation of Adaptive Cruise Control

The system maintains the host vehicle's following interval by adjusting its speed:

- If the target vehicle speeds up (not a safety issue) increasing the following interval between the two vehicles, the system will inform the engine control module via the J1939 bus to accelerate and increase the vehicle's speed until either the set following interval or the cruise control preset speed are reached. Acceleration is limited by the vehicle capabilities, and the maximum speed is kept below a preset limit.
- If the gap between the target and the host vehicles is decreasing, the ACC informs the engine control module to reduce the vehicle's speed. The engine control module then issues a command to dethrottle the engine (e.g., reduce fuel), apply the engine brake, and, when available, downshift the automated transmission. According to material provided by Eaton® VORAD®, the deceleration rates achieved range from 0.1g to 0.2g, depending on the vehicle load, the road grade, and the vehicle's performance characteristics.[2] Section 5.1.2.1 details the acceleration and deceleration rates observed in the FOT.

The ACC system installed on the Volvo tractors for the IVI FOT did not actively control the vehicle's service brakes. As such, the ACC did not have the capability to bring the vehicle to a stop. The ACC also was not designed to react to stationary objects. As a consequence, for abrupt changes in driving state from normal following to a critical rapidly closing rate, where the deceleration needed to avoid a collision exceeds the decelerating capabilities of the ACC, the system is dependent on driver intervention and/or CWS alerts.

With ACC, a driver sets the vehicle's speed similarly to using conventional cruise control. The following interval can either be constant (preprogrammed at installation[3]) or can be adjusted by the driver between 2.25 and 3.25 seconds using the "RANGE" control knob on the CWS DDU

[2] g is the acceleration due to gravity (32.2 ft/s^2 or 9.8 m/s^2).

[3] In the Volvo IVI FOT, the range was preset by US Xpress at 3.25 seconds.

(Figure 2.1-2). As shown in Table 2.1-3, if a vehicle traveling at 60 mph is following a target vehicle with a 3.25-second following interval, its following distance is 286 ft.

Table 2.1-3. Following Intervals (Seconds) and Following Distance (Feet) at Various Speeds

Following Interval (seconds)	Following Distance, feet (meters)	
	50 mph (80 km/hr)	60 mph (97 km/hr)
2.25	165 (50.3)	198 (60.3)
3.00	220 (67)	264 (80.5)
3.25	238 (72.5)	286 (87.2)

The Adaptive Cruise Control (ACC) system is designed to avoid rear-end crashes and prevent injuries by helping drivers maintain safe following distances, and reduce the occurrence of driving situations known to lead to rear-end crashes (i.e., driving conflicts). As such, the safety benefits of the ACC technology were evaluated by comparing the frequency of occurrence of selected driving conflicts between groups of vehicles that were equipped with the ACC technology and groups of vehicles that were not equipped with the ACC technology.

2.1.3 Advanced Braking Systems (AdvBS)

The Advanced Braking System (AdvBS) includes two technologies: Volvo air disc brakes and the Eaton® Bosch electronically controlled braking system (ECBS). Both systems are designed to avoid rear-end crashes and prevent injuries by increasing the vehicle braking performance through shorter braking distances as well as improving vehicle stability under harsh braking conditions.

2.1.3.1 Air Disc Brakes and Conventional S-Cam Drum Brakes

Air disc brakes and drum brakes are different types of foundation brakes, but they operate according to the same principle. Using air from an onboard compressor and storage tank, the foundation brakes generate friction by pressing stationary non-rotating brake components against rotating brake components as they turn along with the wheels. In both drum and disc brakes, the stationary brake components are fastened to the axle/spindle flange (shoes or pads, respectively) while the rotating member is fastened to the wheel hub (drum or rotor, respectively). The friction generated at the interface of the stationary and rotating members transforms the moving vehicle's kinetic and/or potential energy into thermal energy.

On an air-braked commercial vehicle, when the driver pushes the brake pedal, a proportional air control signal is generated and air pressure is delivered to each wheel's brake chambers. This air pressure, in turn, actuates the foundation brakes. In the case of drum brakes, the air chamber under pressure applies a force proportional to the pedal position to the slack adjuster, causing a camshaft (s-cam) to rotate. The camshaft rotation forces the shoes and lining assembly to contact the rotating drum with a proportional contact pressure. In the case of air disc brakes, similar to drum brakes, air pressure is transformed to mechanical output causing brake pads to tighten inwardly on each side of a rotating rotor or disk, like a c-clamp, with contact pressure proportional to air pressure.

S-cam drum brakes can be found today on more than 95 percent of North American commercial motor vehicles. They are effective, inexpensive, simple, and easy to maintain. However, they are known to be relatively heavy and subject to fade at high temperatures as the drum expands away from the shoes. In contrast, disc brakes are known to generate a linear, stable and fade-resistant brake torque output. Indeed, in disc brakes, not only does thermal expansion bring the disc in closer contact with the pads, but also the exposed friction surfaces provide better thermal dissipation than is available with drum brakes. Disc brakes, however, require more force to generate the torque output than do drum brakes (lack of self-energization) and the exposed friction surfaces are more sensitive to contamination and moisture than drum brake surfaces.

The disc brakes installed on the Volvo tractors are shown in Figure 2.1-5.

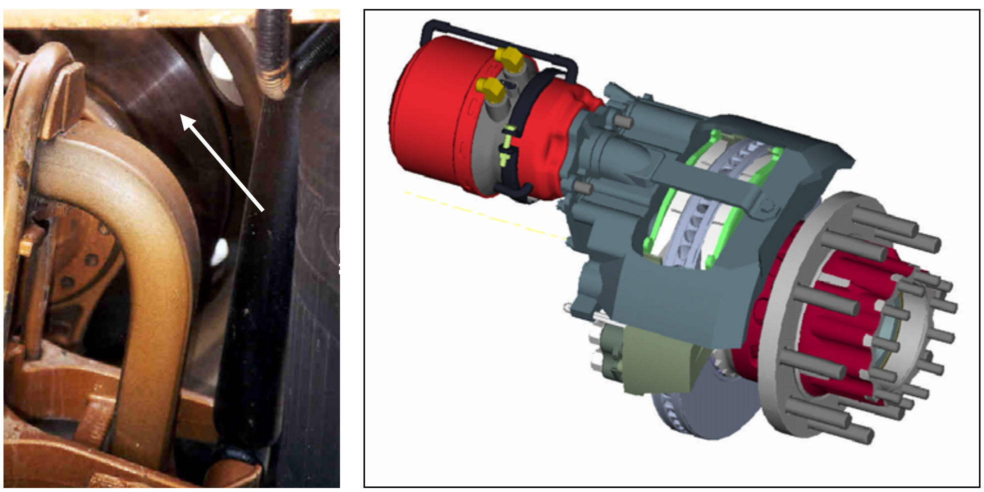

Figure 2.1-5. Air Disc Brakes

(Disc Shown at Left; Brake and Hub Assembly Shown at Right)

2.1.3.2   ECBS and Antilock Braking Systems (ABS)

Electronically Controlled Braking System (ECBS) is a new technology that builds on the existing ABS technology. In ECBS, the air signal traditionally used by ABS to control the activation of the vehicle foundation brakes is replaced by an electronic signal. In both systems, only the control modes are different; the friction force and resulting output braking torque generated at each wheel is still provided by air. To meet federal motor vehicle safety standard (FMVSS) regulations set forth by FMVSS121, ECBS is currently overlaid on top of a dual air brake system: two pneumatic control circuits and one electronic control circuit (2P/1E).

In both ABS and ECBS, the principal function of antilock braking is similar: prevent wheel lock during severe braking by monitoring wheel speed and modulating air pressure in the brake chambers using air signals (ABS) or electronic signals (ECBS). In both systems, wheel speed is continuously monitored, information is processed by an electronic control unit (ECU) (Figure 2.1-6), and appropriate signals are sent to modulator valves to control brake pressures at the wheels. Possible signals include decreasing, holding, or increasing the braking pressure to the level set by the driver. The benefits of ABS and ECBS include:

- Enhanced steerability under emergency braking
- Enhanced stable stopping on icy or wet roads, and in curves
- Reduced stopping distance with optimum deceleration rates
- Reduced potential for tractor-trailer jack-knifing
- Reduced potential for tire damage.

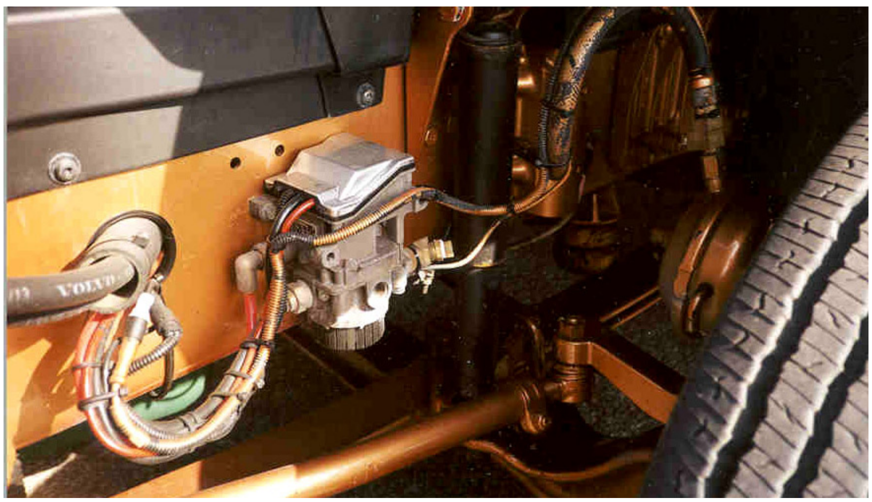

Figure 2.1-6. ECBS Control Module Installed In Front of the Steer-Axle Left Wheel

ECBS is anticipated to provide additional benefits as a result of the shorter vehicle response time, wheel-specific brake activation, and deceleration-controlled brake application.

- With electronics, the time needed to activate the brakes is greatly reduced, resulting in shorter vehicle response to driver demand, improved timing, and shorter stopping distances.
- With ECBS, during both normal and emergency braking, brakes are controlled by microprocessors, and brakes can be applied to each wheel individually. As such, ECBS is expected to show the following potential benefits:
    - Improved brake safety and vehicle stability through wheel-by-wheel adjustment of braking in response to real-time conditions
    - Improved dynamic brake force distribution with reduced pad wear

- Reduced system hysteresis, improved combination vehicle brake balance (if both the tractor and trailer are equipped[4]), brake fade warning, and self-diagnostics capabilities.

- ECBS controls braking using criteria based on vehicle deceleration, e.g., using braking torque output as well as vehicle load information. For a given brake pedal position, vehicles equipped with ECBS decelerate at a fixed rate, regardless of the load on the tractor and trailer. With a conventional braking system, the driver must apply more brake pressure to stop a heavier load than required for a lighter load. This feature of ECBS avoids the need for drivers to adjust their braking demand as a function of truck load and brake condition.

On one hand, AdvBS, combining air disc brakes with ECBS, enhances not only the vehicle braking performance but also the vehicle's stability under emergency braking. These characteristics have various anticipated effects on safety:

- In emergency situations, enhanced vehicle braking capabilities can be instrumental in avoiding rear-end crashes after a vehicle enters a driving conflict or a situation known to lead to rear-end crashes.
- Knowing that the vehicle can brake better, a driver might become more aggressive and may be more likely to enter dangerous situations leading to rear-end crashes.
- Features of AdvBS, such as the deceleration-based brake demand, may increase safety through a reduction of driver workload.

Due to the specifics of the experimental design (Section 2.2), the safety benefits of AdvBS could not be evaluated independently of those of the ACC.

2.2 Research Plan

US Xpress leased 100 Volvo VN770 tractors for their normal revenue-generating service, beginning in January 2001. Depending on the safety systems installed on the tractors, they were divided into three groups:

- 50 "Test" vehicles: equipped with the three safety technologies: CWS, ACC and AdvBS.
- 30 "Control" vehicles: equipped with CWS.
- 20 "Baseline" vehicles: equipped with a disabled CWS for the first 18 months of the FOT, and then with an enabled CWS for the remaining time of the FOT. When the CWS was disabled, data were collected, but the driver display was not active and alerts were not communicated to the drivers.

Table 2.2-1 details the specifications of the IVI technologies on each group of units.

[4] In this FOT, only the tractors were equipped with ECBS. The trailers used conventional braking systems.

Table 2.2-1. Specifications of IVI Technologies for Each Group of Vehicles

		Systems Installed on Units		
		Collision Warning System	**Cruise Control**	**Braking Systems**
BASELINE UNITS	Conventional units	Disabled / NO driver display	Conventional	Conventional (Drum brakes + ABS)
CONTROL UNITS	Conventional units + CWS	On	Conventional	Conventional (Drum brakes + ABS)
TEST UNITS	Units with all IVS Systems	On	Adaptive	Advanced (Disc brakes + ECBS)

The vehicles described in the table were compared as follows:

- A comparative analysis of the Control and Baseline vehicles provides information on the effectiveness of the CWS and its potential benefits.
- A comparative analysis of the Test and Baseline vehicles provides information on the effectiveness and potential benefits of the three safety systems over conventional vehicle configurations. As such, the Evaluation Team used the information collected to evaluate the safety benefits of the bundled systems.
- A comparative analysis of the Test and Control vehicles provides information on the safety benefits of the bundled safety package compared to those of the CWS only, hence allowing for a better understanding of the effectiveness of the ACC and AdvBS independently of the CWS.

Since all vehicles equipped with ACC were also equipped with AdvBS, the individual effectiveness of the two systems was not evaluated in this FOT.

All vehicles were instrumented for data collection by the Aberdeen Test Center (ATC). The trailers were not instrumented. Data collection is discussed in more detail in Section 4.2. Figure 2.2-1 shows the deployment schedule. The start date for the Baseline and Control vehicles was approximately January 1, 2001. The Test vehicles were entered into service beginning in March 2001, with a data collection start date of approximately July 1, 2001. Data collection was phased out vehicle by vehicle as the instrumentation was removed from the vehicles beginning in the second quarter of 2003.

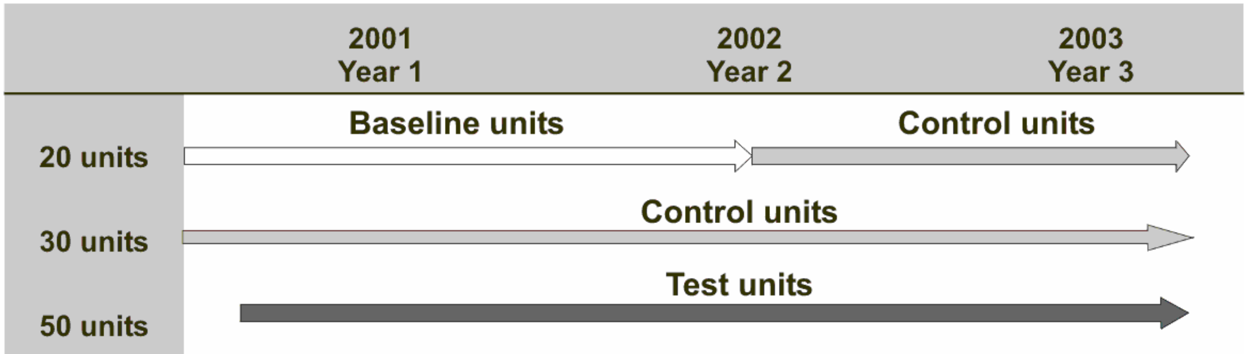

Figure 2.2-1. Vehicle Deployment Schedule

All vehicles were placed in normal revenue-generating service. All 100 vehicles were traveling over a nationwide service area, with US Xpress drivers. The average yearly mileage of the US Xpress trucks participating in the FOT was 162,000 miles. During the course of the FOT, the 100 participating trucks traveled approximately 39 million miles.

For the most part, US Xpress assigned drivers to trucks according to their normal operational needs and procedures. However, special procedures were established for assigning drivers to the Baseline vehicles. CWS had been in use for several years at US Xpress, so most drivers had experience with the system prior to the start of the FOT. Because CWS was expected to change driving behavior on a long-term basis, the data collected from Baseline units driven by existing US Xpress drivers would not have been representative of drivers with no prior experience. Therefore, to the extent possible, new hires, with no previous experience with the CWS at US Xpress, were assigned to the Baseline vehicles. Since the US Xpress driver turnover rate is greater than 100 percent per year, the total number of drivers involved in the FOT exceeded 1,000.

2.3 Operational Characteristics Affecting the FOT

Because the Test vehicles were placed in normal revenue-generating service, some operational factors affected the FOT, the experimental design, and the findings. Some of these factors are discussed below:

- **Driver assignments.** Drivers were assigned to vehicles as dictated by US Xpress's operational needs and procedures. Due to the nature of the business and driver turnover rate >100 percent, it was not practical to assign drivers to vehicles based on characteristics of the drivers. Thus it was not possible to ensure homogeneity of driver profiles amongst the different groups of vehicles. Also, some of the operational procedures used to assign drivers to new units tend to lead to some level of bias: indeed, new vehicles are typically assigned to team drivers, in particular teams of drivers who have a good driving record and show some interest in advanced technologies. A new unit is generally viewed as a benefit by drivers and operators.
- **Driver turnover rates, driver reassignments.** Several issues are noted relative to driver assignments. Operational tactics and needs as well as driver turnover led to changes in

driver assignments. A new leased unit was typically assigned to team drivers, for roughly the first 150,000 miles driven, then reassigned to an individual driver. US Xpress uses this strategy to optimize the use of the leased tractor during the warranty period. There is also the risk that some of these individual drivers may have been assigned to test units prior to receiving proper training. In addition, driver re-assignment can complicate the experimental design, data collection and resulting analyses of driver surveys. Most of these issues were mitigated by tracking vehicle assignments throughout the FOT and including questions about prior experience and training in the driver interviews.

- **Route/Trip assignments.** As with driver assignments, vehicles were routed as dictated by operational needs. However, the location of the units at a given time was tracked using GPS coordinates collected by the on-board data acquisition system. US Xpress has very limited control when trying to intercept vehicles on their delivery route. Once units were in service, it was difficult and expensive to find the units in real-time.
- **Training.** VTNA's cooperative agreement included two training tasks: "US Xpress driver training" and "US Xpress technician training." The technician training was conducted in January 2001 at the VTNA Training Center in Greensboro, NC. Traditionally, driver training takes place over several days and consists of formal in-class training, followed by in-truck training. The extent of training varied according to drivers' experience and driving records. Because the IVI FOT vehicles represented only a small percentage of all US Xpress vehicles, US Xpress conducted special training for the drivers assigned to the IVI FOT vehicles. The IVI systems training consisted of informal one-on-one discussions between the driver and a knowledgeable US Xpress staff member.
- **Maintenance and over-the-road repairs.** Routine maintenance conducted at one of the US Xpress facilities is typically very well documented and can be easily tracked by the fleet. In contrast, over-the-road repairs conducted at other facilities on an as-needed basis are not detailed.
- **Data Acquisition System (DAS) repairs and upgrade.** Because the FOT vehicles were on the road for months at a time before returning to a maintenance facility, hardware repairs and upgrades to the data acquisition system were conducted with difficulties and delays. When possible, software upgrades were done using wireless connections.

These issues did impact the ability to evaluate the safety effectiveness of the IVSS. However, recognizing the issues up front allowed the evaluation team to consider the impacts in the analysis process.

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3.0 EVALUATION GOALS

This section describes the goals and objectives that guided the evaluation of the Volvo Partnership Intelligent Vehicle Initiative (IVI) Generation 0 Field Operational Test (FOT) and how they were applied to generate specific hypotheses for evaluation and testing.

Four terms are used to describe elements of the evaluation: goals, objectives, hypotheses, and measures. ***Goals*** define broad areas of benefit that were to be evaluated in the program, such as "assess safety benefits." The goals for this evaluation were developed based upon priorities of DOT and the Volvo Partnership defined in a Workshop in December 1999. The goals were then applied by the team 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 intelligent vehicle safety systems (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.

Section 3.1 describes the broad goal areas of the FOT and how they were prioritized to achieve national IVI goals while meeting the needs of various IVI partners. Objectives are presented for each goal area in Section 3.2, and specific hypotheses that were tested are provided.

3.1 FOT Goals

Goals for the independent evaluation of the Volvo IVI FOT were based on priorities established by USDOT at an Evaluation Workshop on December 16, 1999. The workshop developed an initial framework (goals and methods) for conducting the evaluation and defined preliminary agreements on the priorities for the evaluation goals. Subsequent discussions with the Volvo Partnership and the USDOT helped to clarify and refine the evaluation objectives. Changes in the types, quantity, and availability of data as the program evolved resulted in modifications to the scope and schedule of this effort.

Three primary goals resulting from these discussions are addressed in this report:

Goal A: Achieve an in-depth understanding of the safety benefits of intelligent vehicle safety systems (IVSS).

Goal B: Assess user (driver) acceptance and human factors.

Goal C: Analyze the ratio of life-cycle benefits to costs for deploying the IVSS on a societal level.

3.2 Evaluation Goals, Objectives, and Hypotheses

This section describes the goal areas, specific objectives, and supporting hypotheses that motivated and guided the evaluation. The results of the evaluation generated by these goals, objectives, and hypotheses are presented in Section 5.

Goal A: Achieve an In-depth Understanding of the Safety Benefits of Intelligent Vehicle Safety Systems (IVSS)

IVSS are expected to provide safety benefits through a reduction in the number and severity of crashes as well as resulting injuries and fatalities by not only assisting drivers in critical situations but also by increasing their awareness. The Collision Warning System (CWS) warns drivers in situations known to lead to rear-end collisions, such as a stopped or decelerating lead vehicle in the vehicle's path. The Adaptive Cruise Control (ACC) system is designed to help drivers maintain a safe following distance. Both systems not only assist drivers in critical situations, with the potential to reduce drivers' workload, but also have the potential to improve overall driving behavior by increasing drivers' awareness of situations leading to rear-end crashes. The Advanced Braking System (AdvBS) is designed to improve the vehicle's stopping performance, and therefore has the potential to reduce the frequency of rear-end crashes by reducing the stopping distance of the vehicle but could also potentially increase drivers' aggressiveness. Three objectives were identified to evaluate the safety benefits of IVSS.

Objective A.1 Determine Reductions in Rear-End Conflicts and Crash Probabilities with IVSS

The specific groups of IVSS under evaluation are

- Collision Warning System (CWS)
- Collision Warning System + Adaptive Cruise Control (CWS + ACC)
- Collision Warning System + Adaptive Cruise Control + advanced Braking System (CWS + ACC + AdvBS), sometimes referred to as the "bundled system"

Improvements in safe driving behavior, advance warnings of potential dangers, and improved braking performance are expected to result in fewer rear-end 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 with which equipped and non-equipped drivers encounter "driving conflicts"[5] and the associated probabilities of being involved in a crash for each type of driving conflict. Specific hypotheses to test this objective were:

Hypothesis A.1-1 Drivers using IVSS will encounter fewer driving conflicts associated with rear-end crashes than drivers not using the IVSS.

Hypothesis A.1-2 Drivers using IVSS will have fewer rear-end crashes than drivers not using the IVSS.

[5] Driving conflicts are defined as measurable safety-critical events that precede crashes. For the case of CWS, driving conflict occurs when the distance between lead and following vehicles decreases below a specific threshold likely to result in a crash. The threshold depends upon the speed of the vehicles. A more detailed description of driving conflicts is provided in Section 5.1 below.

Objective A.2 Determine if Drivers Will Drive More Safely With IVSS than Without It

The safety systems under test are expected to increase drivers' awareness of critical situations, hence training them and helping them improve their driving habits. 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, following distances, reaction time). Specific hypotheses tested include

Hypothesis A.2-1 Drivers of vehicles equipped with IVSS will have fewer evasive maneuvers, hard brake applications, ABS events, and high-level VORAD® alarms (when applicable) than drivers of vehicles not equipped with IVSS.

Hypothesis A.2-2 Drivers of vehicles equipped with IVSS will approach lead vehicles more slowly, maintain longer following distances, and react more quickly to lead vehicles than drivers of vehicles not equipped with IVSS.

Objective A.3 Determine Reductions in Crashes, Injuries, and Fatalities Nationwide if All Such Fleets are Equipped

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 included national crash statistics and the effects of driver characteristics on IVSS effectiveness. Specific hypotheses tested include:

Hypothesis A.3-1 Characteristics (e.g., age, experience, driving record) of drivers in the host fleet are typical of drivers across the country.

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

Hypothesis A.3-3 The frequencies with which the host fleet vehicles encounter driving conflicts are typical for fleets across the country.

Hypothesis A.3-4 The effectiveness of the IVSS for helping the drivers from the host fleet to avoid driving conflicts and reduce the probability of crashes can be expected to be the same for drivers across the country.

Goal B: Assess User (Driver) Acceptance and Human Factors

Drivers' acceptance of the IVSS and human factors are very important factors in the overall benefits of the IVSS. For example, if drivers find the ACC technologies easy to use, they will use it more readily. The following four objectives were included in the evaluation of the IVSS. Related hypotheses and results are detailed in a separate task report (Battelle 2004).

Objective B.1 Determine Usability of the IVSS Technologies

Survey questions were developed to assess how the IVSS are used and understood by the drivers. Of particular interest was the drivers' collective 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.

Objective B.2 Determine How IVSS Affects Perceived Stress and Workload of Drivers

This objective focuses on how the IVSS affect the driving environment. Survey questions examined the effects of false alarms and the impacts on driver workload.

Objective B.3 Determine Perceived Impact on Driver Risk and Vigilance

There are two parts to this objective: (1) driver perceptions about how the use of IVSS affects the risk of an accident, and (2) whether or not use of IVSS has resulted in any change in driving behaviors. The intent of IVSS is to enhance driving safety and reduce the risks of an accident; however, the opposite effect might occur if drivers begin to rely on IVSS and reduce their driving vigilance, or if they feel they can take greater driving risks because IVSS will warn them of potentially dangerous situations with time to respond.

Objective B.4 Determine Perception of Product Quality and Maturity

Information on the perceived quality, value, and maturity of the IVSS from the perspective of the drivers was obtained. The evaluation 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 learn and use.

Goal C: Assess and Analyze the Ratio of Life-cycle Benefits to Life-cycle Costs on a Societal Level

Purchasing vehicles equipped with IVSS will increase not only the purchase price of the vehicles but also their maintenance costs. These costs can sometimes be offset by the cost savings associated with the systems' benefits. Three objectives were identified to evaluate the benefits and costs of IVSS.

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

This objective focuses on developing realistic estimates of dollar costs for deploying and using IVSS over an expected technology life cycle. Key measures include original equipment purchase and installation costs, annual maintenance costs, replacement costs at the end of the system's anticipated life, and training costs.

Objective C.2 Estimate Cost Savings Potential

This objective focuses on applying the results of the safety benefits assessment to the dollar cost values associated with truck crashes, injuries, and fatalities. Key measures include societal savings due to fewer crashes, including direct costs to the motor carrier (such as property damage and equipment repair costs), plus indirect costs to society such as delay to other travelers, medical costs, lost wages, and the costs associated with training replacement workers who are injured or killed in a crash.

Objective C.3 Conduct Comprehensive Benefit-Cost Analysis

This objective focuses on comparing, over a 20-year life cycle, the total costs to the total anticipated benefits, and determining the economic feasibility of deploying IVSS. A general framework for conducting a benefit-cost analysis of the IVSS was developed, based on input data values and life-cycle analyses.

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4.0 EVALUATION METHODS

Battelle prepared a detailed plan for conducting the evaluation (Battelle 2001). The evaluation focused on safety benefits, other benefits (i.e., mobility, efficiency, productivity, and environmental quality)—to the degree necessary to conduct a societal benefit-cost analysis, a driver acceptance evaluation, and a limited system performance analysis. The description of the technical approach for accomplishing these goals is divided into three parts: Section 4.1 presents an overview of the approach and describes which types of data and associated analyses were used to address specific goals, objectives, and hypotheses. Section 4.2 describes each type of data and discusses how the data were collected and transmitted to the Evaluation Team. Section 4.3 discusses, for each goal and objective, how the various types of data were used to address specific hypotheses.

4.1 Overview of Evaluation Approach

As described in Section 3, each evaluation goal area was divided into several evaluation objectives. For each objective, Battelle prepared specific hypotheses to be tested using data collected from a variety of sources. These sources are discussed in more detail in Section 4.2. Battelle then developed a set of analysis methods to test the hypotheses within each objective. The analysis methods were determined based on the data available and the operational conditions and constraints imposed by the FOT carrier. The carrier participating in the FOT emphasized that freight movement could not be disrupted. Some of these methods were simple and straightforward; others, such as those used to estimate safety benefits, involved mathematical models. The methods are summarized in Section 4.3 and discussed further in the context of presenting the findings in Section 5.

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

Historical and FOT Crash/Incident Data. This source included available databases on truck crashes and relevant incidents. Primary sources were public databases, such as the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES), and reports of test vehicle crashes and incidents provided by US Xpress. The public databases were used in the safety benefit analysis to estimate the frequency and characteristics of relevant crashes without the IVSS technologies at a national level. The test fleet data were used to calibrate our models.

Onboard Driving (Engineering) Data. This source includes all data collected onboard the vehicles during the FOT to characterize the kinematic motion of the lead vehicle, driver actions, or IVSS status. These data were studied extensively to identify critical conflicts or driving behaviors.

Surveys and Interviews. Opinions were solicited from personnel in the FOT (including drivers and corporate staff) and used to determine perceptions of user acceptance and system performance.

Fleet Operations Records. Data from the fleet operator's maintenance and operation records that are relevant to the FOT were requested to help, for example, estimate the costs or savings associated with the IVSS. Records from Volvo were also collected when maintenance was conducted under warranty.

Special Tests and Supplemental Data. This category includes all sources of data outside the FOT itself, such as literature findings to estimate the effect of reductions in rear-end crashes.

Table 4.1-1 illustrates 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 that were discussed in Sections 3.1 and 3.2. The next five columns identify the principal and supplemental data sources that were used in the analysis of each objective. For example, the onboard driving data was the principal data source for determining if drivers drive more safely with IVSS. Measures included vehicle speed, following interval, brake use, and longitudinal accelerations. Supplemental data sources included any crashes or incidents that might have occurred, driver interviews, and fleet operations records. A brief summary of how these data were used is presented in the last column.

4.2 Evaluation Data Sources

This section describes five types of data that were collected and analyzed during the FOT. For each type of data, the data collection process is discussed, along with a description of how the data were used to test specific hypotheses and address evaluation objectives.

4.2.1 Historical Crash Data

Historical population crash data came from the National Automotive Sampling System (NASS) General Estimates System (GES), and the corresponding fatality rates were derived from the Fatality Analysis Reporting System (FARS). Annual rates of crashes, injuries, and fatalities were based on averages for the years 1999 through 2003. The host fleet, US Xpress, also provided information on crashes and incidents that occurred during the FOT.

The number of rear-end crashes that occur each year defines the opportunities for crash reduction using any of the IVSS technologies under investigation. The historical crash data also identify which safety-critical situations (referred to as driving conflicts) lead to rear-end crashes and provide estimates for the probability, with no IVSS, that a particular safety-critical situation (driving conflict) precedes a crash given that a crash occurred. That is a crucial step in the safety analysis methodology described in Section 4.3. The fleet crash statistics and safety data were also used to assess the applicability of safety benefits estimates to fleets beyond those deployed in this FOT.

Table 4.1-1. Principal (P) and Supplemental (S) Data Sources for Addressing Evaluation Goals and Objectives

Evaluation Data Sources → Goal Area/ Objectives	Historical and FOT Crash/ Incident Data	Onboard Driving Data	Surveys and Interviews	Fleet Operations Records	Special Tests and Supple-mental Data	COMMENTS
Assess Safety Benefits						Historical data were needed to identify relevant crash types, conflicts, and driving behaviors. Crash avoidance models were based on driving data.
A.1 Determine reductions in conflicts and crash probabilities	P	P		S		
A.2 Determine if drivers drive more safely with IVSS	S	P	S			
A.3 Estimate crash reductions at full nationwide deployment	P	P	S	S		
Assess User Acceptance & Human Factors						Interviews addressed driver perceptions of all aspects of IVSS.
B.1 Determine usability of IVSS		S	P			
B.2 Determine if drivers perceive increased stress/workload		S	P			
B.3 Determine perceived impacts on driver risks and vigilance		S	P			
B.4 Determine perceptions of product quality, maturity, etc			P			
Assess Ratio of Benefits to Costs						Approach used in past IVI FOT benefit-cost analyses was adapted, with revised cost estimates based on Volvo deployment. Data from Volvo team were supplemented with values from industry and published literature.
C.1 Determine costs to deploy and maintain IVSS					P	
C.2 Estimate cost savings potential					P	
C.3 Conduct comprehensive benefit-cost analysis					P	

The GES obtains its data from a nationally representative probability sample of police-reported crashes. Police accident reports (PARs) 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. A report on the Safety Benefits Estimation Methodology (Battelle 2000) and a technical paper published during the FOT (Neighbor 2001) contain a more detailed description of the GES data, including sampling design, relevant variable information, and database acquisition.

Table 4.2-1 describes the conflict types that are common among rear-end crashes. The first five conflict types are expected to be mitigated by use of CWS, ACC, and AdvBS. It is possible the other conflict types included in the last category (6), as well as those that lead to other crash types (e.g., lane change/merge crashes) might also be mitigated by these technologies; however, it is not possible to consider those conflicts in this study without additional data collection tools, such as cameras and side object detection devices. Table 4.2-2 presents the annual average numbers of trucks in rear-end crashes and the relative frequencies with which the relevant driving conflicts precede rear-end crashes. Based on historical crash data from 1999 through 2003, conflict rates were determined for the two classes of trucks being considered for the safety benefit analysis (all large trucks over 10,000 lbs. and Class 7 or 8 tractors with trailers).

Table 4.2-1. Rear-End Conflict Types

Conflict Number	Label	Description
1*	Overtaking Slower Vehicle	Truck is traveling at a constant speed and encounters a lead vehicle traveling at a lower speed
2*	Overtaking While Slowing	Truck is decelerating and encounters a lead vehicle
3*	Changing Lanes	Truck is changing lanes or merging and encounters a lead vehicle traveling at a lower speed
4*	Stopped Lead Vehicle	Truck encounters a stopped vehicle in lane
5*	Slowing Lead Vehicle	Truck is traveling at a constant speed and encounters a lead vehicle decelerating
6	Other	Other unidentified conflicts

*Conflict types potentially mitigated by CWS, ACC, or AdvBS

Table 4.2-2. Annual Average Numbers and Relative Frequencies of Trucks in Rear-End Crashes by Conflict Type (for Two Truck Classes)

Conflict Number	Annual Number of Trucks in Crashes*		Relative Frequencies	
	Heavy Trucks	Truck-Tractors with Trailers	Heavy Trucks	Truck-Tractors with Trailers
1	6,942	3,147	13%	14%
2	2,224	859	4%	4%
3	506	386	1%	2%
4	25,444	9,268	46%	40%
5	12,709	6,075	23%	26%
6	7,213	3,566	13%	15%
Total	55,038	23,300	100%	100%

*NASS-GES (1999 to 2003)

The five stages used to identify driving conflicts within the 1999 through 2003 GES data were as follows:

1. Subset data according to target fleets, i.e., all large trucks vs. tractors pulling trailers
2. Select data for rear-end crashes only
3. Identify the predominant critical events that led to the truck's involvement in the rear-end crash
4. Identify the movements prior to those critical events
5. Use the combination of the critical events and the movements prior to define the driving conflicts.

Appendix B describes the specific coding scheme used in GES and FARS to define conflict and crash types, as well as vehicle types. FARS is further discussed in the Benefits Cost Analysis of Section 5.3.

In addition to the historical crash statistics on the national fleets, US Xpress provided crash and incident information on the 100 trucks involved in the FOT between January 2001 and June 2003. For each event, the report includes truck identification number, date of the event, assessments of whether the event was preventable and whether the safety system was potentially involved, and a brief description of the event. This US Xpress crash data were compared with the national crash rates.

4.2.1.1 Comparison of GES and FOT Data

During the analysis of the FOT data, significant differences were identified between the FOT driving conflict relative frequencies and the GES driving conflict relative frequencies. *Although the specific results of the FOT will be discussed in Chapter 5 and the methodology will be fully explained in Section 4.3, some results will be presented here to clarify decisions made with respect to Conflict Category assignments.*

According to the GES database, conflict types 1 through 5 account for 86 percent of all conflicts that precede a tractor-trailer rear-end crash. The definitions of the conflict categories were given in Table 4.2-1. The basic kinematic conditions of the lead and following vehicles, and the corresponding percentages of the historical tractor-trailer crashes that were preceded by these conflicts, are shown in Table 4.2-3. Also shown in Table 4.2-3 are the conflict percentages determined from analysis of the driving data collected in this FOT by the Volvo Partnership (Volvo 2005); these percentages are not conditional on a crash having occurred unlike the GES relative frequencies.

Table 4.2-3. Relative Frequency of the Occurrence of GES-Based Safety Benefits Driving Conflict Types for Truck Tractors with Trailers

Conflict Type	Kinematic Condition		Relative Frequency	
	Lead Vehicle	Following Vehicle	GES Data[1]	FOT Data[2]
1	Constant	Constant	14%	34%
2	Constant/ Decelerating	Decelerating	4%	30%
3	Constant	Changed Lanes	2%	22%
4	Stopped	Constant/ Decelerating	40%	7%
5	Decelerating	Constant	26%	7%

1. These relative frequencies are conditional on a crash.
2. These relative frequencies are not conditional on a crash. FOT Data is derived from Table 6.5.1-1 of the Volvo Partnership Report (Volvo 2005).

For the conflicts observed during the FOT, conflict types were defined with a similar approach using combinations of the kinematic conditions of the lead and host or following vehicles as observed in the time history data collected on board the vehicle (discussed in Section 4.3). The kinematic condition of the lead vehicle or object could be: traveling at a constant speed or accelerating[6], decelerating, or stopped, while the kinematic condition of the following IVI truck could be: traveling at a constant speed, decelerating, or just changed lanes[7]. As such, conflict types were determined based on three categorical variables:

- Lead vehicle velocity prior to critical event (stopped/constant/decelerating),
- Truck velocity prior to critical event (constant/decelerating), and
- Truck lane change prior to critical event (yes/no).

Based on the value of these three variables, each time history was assigned to a rear-end conflict type.

[6] GES does not differentiate between constant speed and acceleration

[7] DOT (Miller and Srinivasan 2005) developed an algorithm, and the Volvo Partners applied the algorithm, to determine if the host truck changed lanes (Volvo 2005).

As shown in Table 4.2-3, the relative frequency of conflict types observed in the FOT is quite different from the relative frequency of conflicts among crashes reported in GES. Small differences are not unexpected for two reasons. The first, and most basic reason, is that there is variability in any sample of a larger population. Second, FOT relative frequencies are not conditional on a crash occurring, whereas GES relative frequencies are conditional on collisions.

These differences may also be indicative of differences in the interpretation of the data and the data processing. First, the conflicts defined from GES data are based on information in police reports of actual crashes, while the FOT classification is derived from kinematic criteria applied to time histories. Police officers and truck drivers do not have the benefit of a detailed kinematic analysis of the situation leading to the rear-end collision. There will also be variability in the definition of the pre-crash movements of the truck. Some individuals can define the event by the kinematics of the vehicles immediately before impact, while some can define it by the kinematics before evasive action was taken. In general, truck drivers have better knowledge of their own vehicle's movements than of the lead vehicle's exact motion. In GES, the distinction of the condition of the lead vehicle (decelerating or not) is most likely based on the judgment of the driver or police officer. Definitions based on the truck's action in the conflict are therefore more reliable in general.

Second, of note in Table 4.2-3 is the small amount of data collected for the lead vehicle stopped conflict type (Type 4). The algorithms applied to the time history data are fully explained in Section 4.3. The single step that eliminated the most time histories from the pool of driving conflicts was the removal of "non-threat" situations. The algorithms used to accomplish this data reduction were described in Battelle (2002b) and Volvo (2005). The set of algorithms applied was different for time histories in which the lead vehicle was stopped than in those with moving lead vehicles; they were, in fact, designed to more aggressively eliminate time histories with stopped lead vehicles. The paucity of data in the stopped lead vehicle driving conflict type could be due to false positives in the non-threat algorithms and there should, in fact, be more stopped lead vehicle driving conflicts.

The algorithms were designed this way because an early analysis of the GES data, before 1999, indicated that only a small percentage of crashes (2 percent) are preceded by situations in which there is a stopped lead vehicle (Battelle 2001 and Neighbor 2001). The coding of vehicle movement information from police reports has undergone numerous changes in GES over the years. In 1999, GES eliminated a code indicating that the striking vehicle caused the crash by driving at a higher rate of speed (higher acceleration). Over 70 percent of all rear-end crashes had been assigned this code, and dividing conflicts into meaningful conflict types was difficult. After the coding change, defining conflict types that reflect the dynamic conditions of the truck and the lead vehicle was easier. Initially, in analyses based on pre-1999 GES data, it was observed in the FOT data that a very high percentage of driving conflicts were stopped lead vehicle conflicts. Because of this, a close examination of stopped lead vehicle driving conflicts was pursued. This examination resulted in the conclusion that there were many radar returns from objects other than lead vehicles that were erroneously assumed to be lead vehicles. Algorithms were developed to eliminate these time histories from consideration as driving conflicts. Because the more recent GES data have indicated that a much larger percentage of crashes (40 percent) are preceded by situations in which there is a stopped lead vehicle, it is likely that the non-threat algorithms eliminating stopped lead vehicles should not have been so aggressive. For example, stopped lead vehicles were required to be present as a radar return for more than 2 seconds; moving lead vehicles were only required to be present for more than 1 second. The stopped lead vehicle presence requirement could be changed to 1 second in future analyses, therefore allowing more stopped lead vehicles to be considered. This would be more consistent with the treatment of moving lead vehicles. There were five additional types of non-threatening stopped lead vehicle situations examined in the Volvo Partnership Report. The thresholds for each of those algorithms could be re-examined.

Finally, if there are differences in the probabilities of a crash following different conflict types, one would expect to see differences in the relative frequency of conflicts that result in crashes versus the relative frequency of all conflicts, even those that do not result in crashes. The small percentage of FOT conflicts in certain conflict categories does have implications for our ability to analyze the safety benefits (e.g., conflict category 4). In this situation, where there are relatively few conflicts in conflict type 4 and a large number of expected conflicts based on the GES data, the predicted probability of a crash given conflict type 4 would yield a probability greater than one, i.e., for the FOT data to be like the GES data, more than all of the conflict type 4 driving conflicts must result in a crash.

For these reasons, the five conflict types defined above were changed to three categories as follows. Conflict types 1 and 5 (overtaking slower vehicle and slowing lead vehicle) are merged in a conflict category labeled "constant speed," because they both represent situations in which the truck is traveling along at a constant speed and begins to overtake another vehicle moving more slowly. Similarly, conflict types 2 and 4 (overtaking while slowing and stopped lead vehicle) are merged in a conflict category labeled "slowing," because these conflict types can be generally classified as situations in which the truck is already decelerating and encounters another vehicle that is stopped or in the process of stopping. These revised conflict categories are given in Table 4.2-4.

Table 4.2-4. Classification of Conflict Types into Categories

Conflict			Kinematic Condition of the Following Vehicle	GES Relative Frequencies of Conflicts
No.	**Type**	**Category**		
1	Overtaking slower vehicle	1. Constant Speed: *Overtaking at constant speed (1+5)*	Constant	40%
5	Slowing lead vehicle			
2	Overtaking while slowing	2. Slowing: *Overtaking while slowing (2+4)*	Decelerating[1]	44%
4	Stopped lead vehicle			
3	Changing lanes	3. Lane Change: *Changing Lanes (3)*	Lane Change	2%

1. If the lead vehicle is stopped, the conflict is placed in this category regardless of the following vehicle behavior.

4.2.2 Onboard Driving (Engineering) Data

Engineering data were collected onboard the tractors to evaluate the dynamic state of the vehicle (e.g., speed), the conditions in which the vehicle was driven (e.g., following a vehicle at highway speed), the location of the vehicle in the United States, the driver's actions (e.g., braking or turning), and the functions of technologies (e.g., alarm sounded by the VORAD® CWS).

These data were important to:

- Assess drivers' general habits and driving conditions in order to evaluate fundamental trends
- Identify situations known to be dangerous, and specifically known to lead to rear-end crashes
- Determine the drivers' reactions to dangerous situations
- Characterize how the vehicles responded to the drivers' demands in these critical situations.

By comparing data elements collected on different groups of vehicles equipped or not equipped with IVSS technologies, the Evaluation Team gained the means to assess the impact of the technologies on driving habits. Data elements collected could also be used to reconstruct the driving conditions and dynamic state (e.g., traveling straight down the road or turning) of the vehicle in selected situations of interest. With such information, the Evaluation Team could, for example, characterize the resolution of selected driving conflicts and determine the avoidance maneuver taken by the driver, if any. Finally, the engineering data were collected as inputs to the safety benefits analysis, to estimate the frequency of occurrence of driving conflicts, and to estimate the severity of the conflicts.

In order to collect information onboard the vehicles, all 100 tractors were equipped with a data acquisition system (DAS), specifically designed by ATC for the purpose of collecting field data in the Volvo IVI FOT. The DAS is an onboard computer with data collection and communication capabilities, which can function without operator interaction and independently of the vehicle's operation.

Using a real-time operating system, the DAS was designed to

- Monitor several data sources onboard the vehicle, including data buses and sensors
- Handle and manage data in real-time
- Store selected data on solid-state media located onboard the truck, when prompted by an application program.

The data to be stored as well as the format in which they are stored were defined by configuration files.

The DAS was also designed to transfer data stored onboard to a remote location autonomously by wireless means using cellular communications, or manually by replacement of a PCMCIA (Personal Computer Memory Card International Association) flash memory card.

The sources of data accessible by the DAS onboard the tractor included

- J1939 vehicle data bus
- J1708 vehicle data bus
- VORAD® technology data bus
- Global positioning system (GPS) receiver
- Steering wheel position sensor
- Biaxial accelerometer installed in the DAS.

Collecting and storing data continuously at a sufficient and appropriate data collection rate for each mile driven by the vehicle could not be reasonably implemented onboard the tractors, in part because of the cost of transferring large amounts of data with wireless cellular communications. As such, to ensure that the total amount of data collected was manageable, data were stored in two different formats onboard the computer, depending on the need and end use of the data element: histogram format and time history format.

In addition, video recording equipment was also present on the tractors. Video was recorded to correlate critical events and their resolution with the vehicle data collected by the DAS. Because the amount of data collected was relatively small, video files were not analyzed in this report.

4.2.2.1 Histograms of Engineering Data

The data elements collected by the DAS to provide information on general driving habits and driving conditions were tabulated and stored in real time in histograms[8] any time the vehicle was on. Histograms represent a driving period during which certain variables are monitored continuously and during which an event could have occurred triggering additional data collection. Examples of data elements stored in a histogram format are “following interval” and “cruise control use” (Figure 4.2-1). These data elements provide generic information on driving behaviors that can be compared between groups of drivers exposed to different technologies and can be used by the Evaluation Team to address hypotheses.

[8] Histograms are generated by sorting data elements into defined groups or bins and then counting the number of elements in each bin. The bins can be defined individually, but most often, they are defined by dividing the range of the data into equal non-overlapping intervals. The graphical representation of the data counts versus the bin number illustrates the frequency distribution of the data, presenting a summary of the variation observed in a set of data.

Data stored in histograms included nondiscrete and discrete data elements.

- Nondiscrete data elements could be continuously monitored, measured, or calculated at 6 Hertz (Hz). This represents a data sample every 1/6 second. These data elements were stored in blocks of time up to 3 hours[9] (Figure 4.2-1).
- While nondiscrete data elements provided information on the dynamic and physical state of the vehicle, discrete data elements were representative of specific situations, or "events." The events were predefined by the Team according to the values of a set of specific data elements. The programmed DAS then identified the events as they occurred and, for each event, recorded the number of time increments for which the event occurred. The time increment for data collected at 6 Hz was 1/6 second.

  For example, hard braking is labeled as a "strong truck braking" event, and is defined by a condition in which the driver is braking (service brake on) and the vehicle longitudinal deceleration is greater than 0.25g. As described earlier, one of the anticipated benefits of the VORAD® CWS technology is to assist drivers in avoiding situations that would require evasive maneuvers or emergency braking. As such, the total number of hard braking events would be expected to change for a driver using the technology.

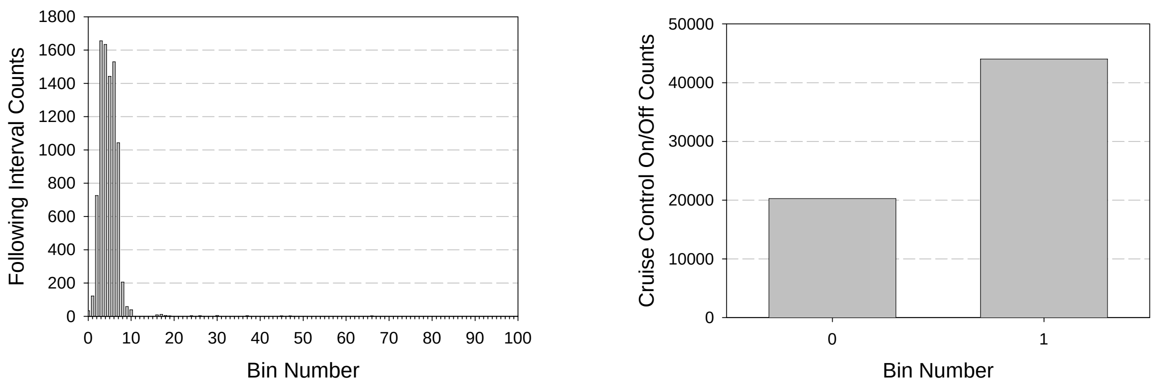

Figure 4.2-1. Examples of Histograms of Following Interval and Cruise Control Use

The non-discrete data elements and the events collected by the DAS in histogram format are summarized in Tables 4.2-5 and 4.2-6, respectively.

[9] When the vehicle ignition was turned on or off, power was removed from the DAS and a shorter block of time (less than 3 hours) was recorded.

Table 4.2-5. Histograms of Nondiscrete Data Elements, with Associated Minimum, Maximum, and Width of Bins

Data Element	Units	Minimum Bin Value	Maximum Bin Value	Bin Width
Time-to-Collision[1]	sec	-32	32	0.5
Road Speed	ft/s	0	128	1
Following Distance[2]	ft	0	384	3
Following Interval[1]	sec	0	50	0.5
F/A acceleration	g	-1	1	0.05
Service Brake Duration	sec	0	64	1
Engine Brake Duration	sec	0	64	1
Engine/Service Brake Duration	sec	0	64	1
Brake Pressure	kPa	0	768	6
Cruise Control	on/off	-0.5	1.5	1

1. When there is no lead vehicle, no data are added to these histograms.
2. Counts when there is no lead vehicle are accumulated in the first bin.

In addition to the bins of non-discrete or discrete data stored, histogram files included a header tabulating the values of selected data elements at the start and at the end of the histogram period: GPS time, vehicle odometer, GPS coordinates, and ambient temperature.

4.2.2.2 Time History Files of Engineering Data

In situations where more detailed information was needed to evaluate the technology and/or the driver's response to the technology, vehicle data were stored in a detailed, continuous "time history" data file format, rather than in the summarized histogram format. These detailed engineering data provided the Evaluation Team with means to reconstruct and characterize the specific situation and course of events.

The creation of time history data files was prompted by events that were recognized by the Evaluation Team as representative of situations leading to rear-end crashes. As such, a total of eleven unique triggers were pre-defined to capture events when a lead vehicle may be too close based on

- Conditions leading to VORAD® alarms
- Strong truck deceleration
- Rapid truck lane change.

Table 4.2-6. Histograms of Events Recorded

Event Description	Event Definition	
Truck close to lead vehicle	Kinetic Motion Equation[1] - Criteria 0 (KME0)	
	Kinetic Motion Equation[1] - Criteria 1 (KME1)	
	Time-to-Collision < 4 seconds for 4 counts[2]	
Long following interval	Following interval < 3 seconds AND road speed >16 ft/s	
Medium following interval	2 seconds < Following interval < 3 seconds	
Short following interval	1 second < Following interval < 2 seconds	
Strong truck braking	F/A Acceleration > 0.25g AND Service brake on	
Strong truck braking with ABS event	ABS Active	
Truck braking with freezing temperatures	F/A Acceleration > 0.1g AND Service brake on AND Temperature < 0ºC	
Rapid evasive lane change	Smoothed steering rate > 120 deg/s AND Road speed > 44 ft/s	
VORAD® Alarm Condition	Alarm 10	Following interval < 0.5s AND Road Speed > 16 ft/s for 3 counts[2]
	Alarm 9	Following interval < 3s AND Target speed > 51 ft/s AND Road speed > 1.25*Target speed AND Following distance < 220 ft
	Alarm 7	Following interval <1s AND Target speed < 105% of Road speed
	Alarm 6	1s < Following interval < 2s AND Target speed < 101% Road speed
	Alarm 5	Following interval < 1s AND Target speed > 105% of Road speed

1. "Kinetic Motion Equation" criteria are based on the equations of motion for two vehicles in a one-dimensional relationship with each other. A kinetic motion equation identifies situations in which the host truck will hit a lead vehicle it follows if the driver does not start to decelerate with at least 0.25g within 1.5 seconds. The equations used for KME0 and KME1 are contained in Appendix D6.
2. A count is defined as a $1/6^{th}$ second time increment.

Triggers are defined by specific values of one or more selected data elements as well as by the duration of the situation, i.e., the number of counts for which the values are met. A count is defined as a $1/6^{th}$ second time increment. The definitions of each trigger are listed in Table 4.2-7. Some triggers were implemented after the official start of the FOT, and the date of implementation is also shown in Table 4.2-7.

Table 4.2-7. Triggers for Time History Data Collection

To Capture Events When A Lead Vehicle May Be Too Close …	Trigger Condition	Trigger Duration[2]	Date of Implementation
As indicated by VORAD® conditions	Time-to-Collision[3] < 4 seconds	4 counts	FOT start
	Kinetic Motion Equation 0[1] (KME0)	4 counts	3/20/01
	Following Interval < 0.5 second AND Road speed > 16 ft/s	3 counts	4/5/01
	Kinetic Motion Equation 1[1] (KME1)	4 counts	10/1/01
As indicated by strong truck deceleration	F/A Acceleration > 0.25g	1 count	FOT start
	F/A Acceleration > 0.25g AND Service brake on	1 count	FOT start
	F/A Acceleration > 0.1g AND Service brake on AND Temperature < 0ºC	1 count	FOT start
	ABS Active	1 count	6/28/01
As indicated by rapid truck lane change	Steering angle rate > 120 deg/s	1 count	FOT start
	Smooth. steering rate > 120 deg/s AND Road speed > 44 ft/s	1 count	FOT start
	Lateral acceleration > 0.20g	1 count	FOT start

1. "Kinetic Motion Equation" criteria are based on the equations of motion for two vehicles in a one-dimensional relationship with each other. A kinetic motion equation identifies situations in which the host truck will hit a lead vehicle it follows if the driver does not start to decelerate with at least 0.25g within 1.5 seconds.
2. A count is defined as a 1/6th second time increment.
3. Time-to-Collision is defined as the range divided by the range rate between vehicles multiplied by negative one to account for closing range rates being defined as negative values.
4. Following Interval is defined as the range between the vehicles divided by the following vehicle speed.

The "time history" data files consisted of up to 17 measurement channels recorded continuously at 6 Hz (Table 4.2-8). The data ten (10) seconds prior to the time of trigger and five (5) seconds after the time of trigger were collected for a total of fifteen (15) seconds of data. Some of the data channels were used to reconstruct the situation that triggered data collection, some were used to characterize the driver reaction to the given situation, and others were instrumental in determining whether or not the VORAD® technology provided alarms appropriately. In addition to the columns of measurements for data channels, the time history files included a header tabulating the values of selected data elements at the start of the file: GPS time; vehicle odometer; GPS coordinates; ambient temperature; as well as the range, azimuth, and relative speed of all targets identified by the VORAD® sensor. These data elements were tabulated to enable the matching of time history files with histogram data (e.g., odometer and GPS time) as well as to provide high-level information that did not need to be collected at 6 Hz and for which one data point at the start of the file was sufficient (e.g., ambient temperature).

Table 4.2-8. Time History Channels

Channel	Units	Comment
Following Distance	ft	Required to identify a driving conflict
Road Speed	ft/s	
Relative Velocity	ft/s	
VORAD® Acceleration	ft/sec/sec	
VORAD® Yaw Rate	deg/sec	
VORAD® Azimuth	radians	
Steering Position	deg	Required to determine driver reaction to a driving conflict
Acceleration Pedal Percentage	%	
Service Brake	%	
ABS Active	status	
Brake Pedal Percentage[1]	%	
Brake Pressure[1]	kPa	
Cruise Control State Brake Status	status	
VORAD® Driver Display LIGHT	status	Required to assess false alarms
VORAD® Driver Display AUDIO	status	
VORAD® Driver Display Update Message	status	
Lateral Acceleration	g	Not currently used
F/A Acceleration	g	
Following Interval (Headway)	sec	Not currently used (Values were calculated)
Time-to-Collision	sec	

1. These measurements are not available on Baseline and Control trucks.

In addition to the 15-second time history files collected, abbreviated time history (ATH) files were also stored to evaluate certain performance characteristics of the CWS. For each histogram period, when the value of the "Driver Display Unit (DDU) audio" channel changed, indicating a change in the warning to the driver by the VORAD® CWS, a snapshot of the driving situation was captured by collecting, at that instant, the values of measurement channels. The measurement channels stored in these ATH files were identical to those stored in the time history files (Table 4.2-8), with the exception that "VORAD® Relative Acceleration" data were not collected and an estimate of the truck's acceleration was recorded.[10] With ATH data files, all VORAD® warnings generated during a histogram period were captured in one file.

4.2.2.3 Data Validation

The Volvo Partnership was responsible for collecting, validating, and storing the data in a database at ATC. Both during and after the FOT data collection, data were transferred to Battelle using File Transfer Protocol (FTP) sites, DVDs, or external hard drives. As data were

[10] The truck's acceleration was estimated with an 11-point regression of the local 6 Hz velocity data.

received throughout the FOT, the Battelle Evaluation Team loaded them on an SQL Server database designed to be consistent with the ATC database scheme. Battelle checked the data for completeness upon loading and submitted interim internal reports summarizing the data to USDOT and the Volvo Partnership.

The Volvo Partnership was responsible for the validation of the final FOT data. Algorithms developed jointly by Battelle and the Volvo Partnership were implemented to validate all data in order to identify data source failures. If a data source failure was identified, all of the data collected in histogram and time history files during the histogram period were flagged. The Volvo Partnership provided flags to Battelle to facilitate the identification of valid histogram and time history data.

Four algorithms were developed to screen for the failure of the data sources, namely the vehicle data bus, the VORAD® technology data bus, the analog steering angle sensor, and the biaxial accelerometer sensor. The vehicle data bus, the VORAD® CWS data bus, and the steering angle sensor algorithms were developed by Battelle, and the biaxial accelerometer algorithm was developed by the Volvo Partnership. Further information is presented in Appendix E.

4.2.2.4 Changes in Data Collection Scheme

During the course of the Volvo FOT, the USDOT, in cooperation with the Volvo Partnership, implemented changes to the onboard data acquisition system, specifically the triggering schemes, the content of the time history files collected, and the format of the time history files. Some changes in time history triggers and channels were implemented through simple configuration file changes. Histogram data collection was unchanged throughout the FOT.

The resulting onboard driving data can be categorized in three groups defined by vintages of the DAS:

1) DAS-1 data files without azimuth information
2) DAS-1 data files with azimuth information (introduced in May 2001)
3) DAS-2 data files containing yaw rate and VORAD® alarm activations data.

DAS-2 data is the basis for all results presented in Section 5 of this report.

4.2.2.5 Resulting Data Scope and Quantities

As shown in Table 4.2-9, Battelle received 1,548,831 time histories, and 197,808 histograms, representing 10,257,819 miles of driving by Baseline, Control, and Test trucks, out of approximately 39 million miles driven. A total of 36,180 abbreviated time histories were also received. Distance is expressed in vehicle miles traveled (VMT).

Table 4.2-9. Driving Data Received

DAS Vintage	Fleet	Number of Time Histories	Histogram	
			Number	VMT
Non-Azimuth Containing	Baseline	42,465	8,194	371,585
	Control	137,435	15,866	899,640
	Test	338,437	61,334	3,384,908
	Total	**518,337**	**85,394**	**4,656,133**
DAS-1	Baseline	98,538	13,239	663,738
	Control	153,820	11,616	605,503
	Test	186,608	29,852	1,634,712
	Total	**438,966**	**54,707**	**2,903,954**
DAS-2	Baseline	79,709	7,524	377,252
	Controls	263,247	24,103	1,113,972
	Test	248,572	26,080	1,206,509
	Total	**591,528**	**57,707**	**2,697,732**

Further details and supporting documentation on engineering data and other onboard data are included in Appendix E.

4.2.3 Surveys and Interviews

In an activity related to the Volvo IVI FOT, Battelle conducted a survey of drivers. The methods and results are summarized in Section 5.2 below, and are detailed in a separate report titled "Phase II Driver Survey Report: Volvo Intelligent Vehicle Initiative Field Operational Test Final Report" (Battelle 2004). That report described the second phase of a two-part interview process. The first survey (Phase I) focused on driver expectations for the new safety technologies installed on selected Volvo trucks, and the second survey (Phase II) focused on driver experiences using the technologies.

The surveys involved contacting more than 300 drivers, approximately 200 of whom responded via computer-aided telephone interviewing. A total of 25 drivers took part in both Phase I and Phase II. The Phase I survey was conducted between October 22 and 27, 2001. The Phase II survey was conducted between March 29 and April 6, 2004.

4.2.4 Fleet Operations Records

Fleet operations records are data originating with the fleet operator or the truck manufacturer. As shown in Table 4.2-10, they include drivers' information, vehicle/driver tracking, maintenance/repair, and systems status/performance/operations.

Table 4.2-10. Fleet Operations Records Expected to be Received

Driver Information
Background Age, Gender Years of driving experience (total, at USX) USX safety awards
Driving records Accidents (number, types; total, at USX, during FOT)
Vehicle/Driver Tracking
Driver tracking Driver's logs (driver ID, driver ID tracking, unit ID tracking, hours driven per day, hours driven per 5 days or per 7 days) Home Terminal
IVI Fleet Maintenance/Repair
Over-the-road repairs (IVI systems, others)
Scheduled maint. (IVI systems, others)
Warranty maint. (IVI systems: mileage, part no., date of work, labor hrs, payment, claim desc.)
System Status/Performance/Operations
Date delivered Date placed in service
System status (when placed in service, updates)
Driver's surveys
List of corresponding engine numbers and vehicle IDs

An in-service date was established for each FOT vehicle. For Baseline vehicles, this date indicates when both the CWS DDU was disabled and the vehicle was assigned a driver who did not have previous experience with the CWS. For Control and Test trucks, in-service dates were provided by US Xpress, indicating when the truck was put into revenue-generating service. Appendix A provides the pertinent in-service dates for each vehicle. Onboard driving data collected by the DAS are valid FOT data only if collected after the relevant in-service date.

4.2.4.1 Driver Background Information

Driver background information was managed by US Xpress' recruitment department. Throughout the FOT, US Xpress sent Battelle via email the driver background information in a MS Excel or ASCII file. As data were received, Battelle loaded the information into the SQL Server database with the engineering data. FOT-related information per IVSS, e.g., amount of prior experience with a given system or type of training received on a system, was collected as part of the interviews, or obtained directly from US Xpress. Battelle has received driver background information for drivers in the FOT from November 2000 to December 2003.

4.2.4.2 Vehicle/Driver Tracking

In order to merge the data collected by driver to the data collected by US Xpress unit number or vehicle identification number (VIN), US Xpress provided driver/unit tracking information. Battelle received a file for each month either in MS Excel or ASCII via email. These files contain: tractor identification (ID), driver ID, driver name, log ID number, home terminal and time period the particular driver was assigned to this particular unit. Home terminal information was used to determine the time in reference to the driver in filling up his/her log and to convert log times reported in the driver's log to Greenwich Mean Time (GMT) in order to link the log data with the onboard driving data. Battelle loaded the unit/driver information into the SQL Server database. These data were stored by unit and driver with a start and stop date. Each time a unit changed drivers, a new record was created. Battelle has unit/driver tracking information from November 2000 to December 2003.

Drivers recorded their daily activities (driving, on duty, sleeper berth, or off duty) on a paper log sent monthly to the fleet operator. At US Xpress, paper logs were scanned as tagged image file format (TIFF) pictures and systematically checked for compliance with the USDOT regulations. Significant information was also extracted and stored in a database at US Xpress. Battelle received an MS Excel or ASCII file by month (November 2001 and December 2003, with the exception of October 2001 to December 2002, when no data were received). Each file listed the driver's log data for all drivers assigned to an IVI unit at any time during a given month. Log data for the whole month were included for all drivers, regardless of the duration of the driver assignment. The log data were entered into the Battelle database and filtered using the driver/unit tracking information to store only data of relevance. If a given driver was assigned to an IVI unit for only one day, the corresponding log data for that day only were stored in the database. For each driver, the log data contained driver ID, co-driver ID, and the duration and sequence of activities. To link the driver activities to on-board data, Battelle derived the beginning and end of each activity in GMT using the home terminal information included in the driver/unit tracking reports. Driver's logs were sorted by driver ID, which was linked to the unit ID or the VIN within the database to merge the driver-specific data with the driving data.

4.2.4.3 IVI Fleet Maintenance/Repair

Maintenance/Repair data were requested from US Xpress and Volvo. Battelle received an MS Excel or ASCII file from Volvo that contained records of all relevant warranty work. A list of information collected is in Appendix F of the Evaluation Plan (Battelle 2001). Volvo warranty information was received for the period of October 2000 to March 2003. Complete maintenance/repair data were not available. Because of this it was not possible to do a full analysis on the IVI Fleet maintenance, as described in the Volvo Evaluation Plan (Battelle 2001).

4.2.4.4 System Status/Performance/Operations

System status, performance, upgrades, and other changes throughout the FOT were monitored by ATC and sent on a regular basis to Battelle in MS Excel format. System status information by truck included: DAS status (operational or not), action required, current vehicle configuration, and date of last vehicle configuration update.

4.2.5 Special Tests and Supplemental Data

4.2.5.1 Brake Test Data (Radlinski)

Data on various special tests of the following brake systems:

- Disc and drum brake durability, reliability, and maintenance costs
- ECBS and ABS durability, reliability, and maintenance costs
- Braking system stopping performance deterioration after significant time in service

are included in Sections 7.3 through 7.5 of the report from Volvo to USDOT (2005).

4.2.5.2 Brake Pad Wear Data

Data on a special test of Volvo brake system component wear are presented in Appendix I of the report from Volvo to USDOT (2005).

4.2.5.3 Data Used in Benefit-Cost Analysis

As inputs to the benefit-cost analysis, the cost values for deploying and operating/maintaining the IVSS in the Volvo IVI FOT were determined through contacts with manufacturers and component suppliers. Other cost values, such as the dollar cost per crash and all of the cost elements that feed into it (mobility, fatality, injury, lost productivity, etc.) were adapted from the Freightliner IVI FOT evaluation report (Battelle 2003b), which in turn was based primarily on a review of the transportation economics literature.

4.3 Safety Analysis Methodology

The primary focus of the safety benefits analysis is predicting the number of crashes that could be prevented by the widespread deployment of the Eaton® VORAD® CWS and ACC and the Eaton/Volvo AdvBS. The steps required to accomplish this prediction are summarized at a high level by safety objectives A.2 (fewer conflicts and crashes) and A.3 (impact of deployment). Safety objective A.1 (safer driving) will be addressed by specific analyses motivated within the methodology employed for predicting crash reductions.

4.3.1 Overview of Objectives

Figure 4.3-1 provides an overview of the data analysis tasks performed to satisfy the safety objectives. The rectangles indicate different types of data flowing into the analysis tasks, which are represented by circles. The colors of the analysis tasks indicate the purpose of the analysis as well as the subsections in which the analysis results will be discussed. Specifically, yellow (Section 5.1.1) analyses were performed to determine if the IVSS tested caused a ***reduction in rear-end driving conflicts and crash probabilities***. Blue (Section 4.2.1 and 5.1.3) analyses were performed to support estimation of the *reduction in crashes, injuries, and fatalities nationwide* under various deployment scenarios. Green (Section 5.1.2) analyses were performed to *assess IVSS system performance* and *IVSS impacts on safe driving behaviors*.

The outputs of the yellow and blue analyses are the inputs required by the Benefits Equation presented in Section 4.3 of the Volvo FOT Evaluation Plan (2001). This equation is repeated in Figure 4.3-2 for easy reference. S_i ($i = 1, 2, 3$) are the (three) rear-end driving conflict categories described in Table 4.2-4. N_{wo} is the number of rear-end crashes experienced annually by a particular fleet. $P_{wo}(S_i \mid C)$ is the relative frequency conflict category *i* precedes a rear-end crash, without the IVSS installed. (These population crash breakdowns are the outputs of the blue analyses in Figure 4.3-2 and are the percentages presented in Table 4.2-4.) ER_i and PR_i are the **exposure** and **prevention ratios**, respectively, for conflict type S_i. Exposure and prevention ratios are combined to estimate the efficacy of the IVSS at preventing rear-end crashes preceded by conflict category S_i, $Eff(S_i)$. (Efficacy estimates are the outputs of the steps shown in yellow in Figure 4.3-1.)

The exposure and prevention ratios are calculated as

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

and

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

The conditional probability $P_w(C \mid S_i)$ is the probability that a rear-end crash occurred (with an IVSS) given that driving conflict S_i occurred. $P_w(S_i)$ is the probability that driving conflict S_i occurred (with an IVSS). Quantities subscripted with "*wo*" have the same interpretation, but for unequipped vehicles (without an IVSS). Thus, **exposure ratios** are ratios of exposure to driving conflicts with and without an IVSS. Values of this ratio less than 1 indicate that an IVSS will reduce exposure to potential crash situations. **Prevention ratios** measure the efficacy of an IVSS at preventing crashes after a particular driving conflict has occurred. Again, if this ratio is less than 1, safety benefits can be inferred.

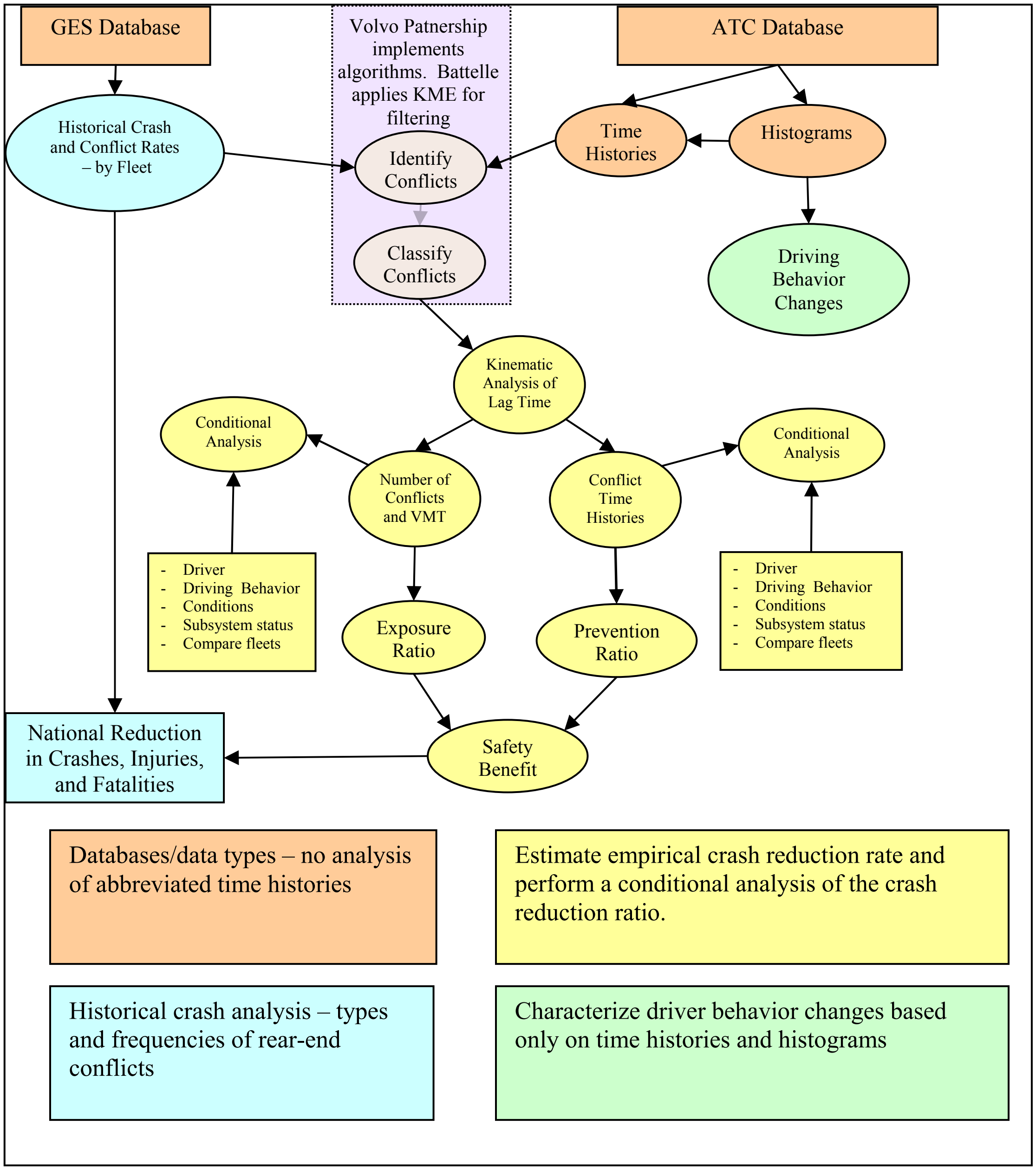

Figure 4.3-1. Safety Benefits Data Analysis Flowchart

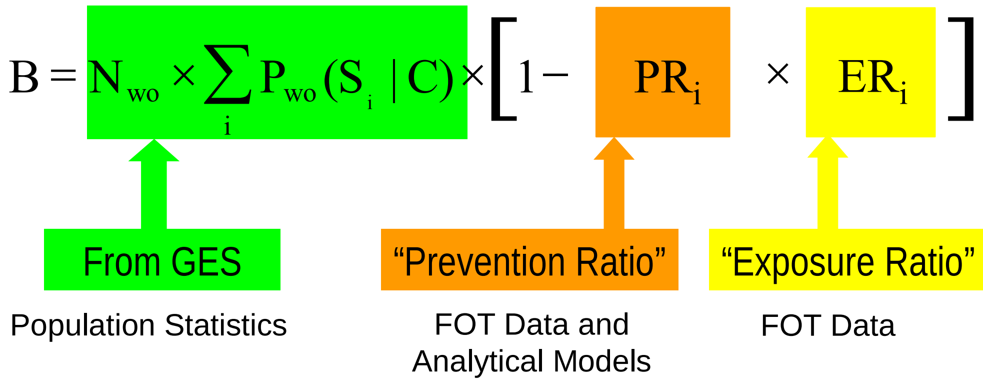

Figure 4.3-2. The Benefits Equation

The rationale behind the Benefits Equation in Figure 4.3-2 is presented in detail in Section 4.3.1 of the Volvo FOT Evaluation Plan. This approach to estimating crash reductions is consistent with the approach developed by the National Highway Transportation Safety Administration (NHTSA) and Federal Highway Administration (FHWA) of the USDOT, together with the Volpe National Transportation Systems Center (Najm 1999, Najm and daSilva 1999a, 1999b, 2000).

4.3.2 Potential Conflict Identification

The analysis coded as yellow in Figure 4.3-1 commences with all of the valid time history (TH) data collected. As detailed in Section 4.2.2, there were a number of time history data collection triggers. The goal of the large trigger set was to ensure the capture of TH data every time there was a rear-end driving conflict during FOT driving. Because a "broad net" was specified, many triggered data collections actually did not contain driving conflicts. Thus, as described below, the first step of the safety analysis was to eliminate TH data that did not contain a rear-end driving conflict.

The conditions required to identify a rear-end driving conflict were defined in Section 4.3.1 of the Volvo FOT Evaluation Plan (Battelle 2001). Specifically, these are the Lead Vehicle Stopped/Constant Speed (LVS/LVCS) and Lead Vehicle Decelerating (LVD) equations. The LVS/LVCS and LVD equations are designed to describe the kinematic situations in which a following vehicle is approaching a lead vehicle in a manner that will result in a crash if one of the vehicles does not change its behavior. In general, these are referred to as the KMEs (equations). These two kinematic equations were developed to calculate the deceleration that would be required for the following truck to avoid a rear-end crash with the lead vehicle if the following truck begins to decelerate in a specific following number of seconds. The calculation assumes that the lead vehicle continues in its current behavior.

The LVS/LVCS equation is:

$$\frac{(v_F - v_L)^2}{2(R - (v_F - v_L)t_{R,Threshold})} < a_{F,Threshold}$$

where v indicates velocity, R indicates range, $t_{R,Threshold}$ indicates reaction time threshold, $a_{F,Threshold}$ indicates following vehicle acceleration threshold, and the subscripts F and L are used to designate following or lead vehicle, respectively.

The LVD equations are:

(Terminal Location Case)

$$\frac{v_F^2}{2(v_F t_{R,Threshold} - R + \frac{v_L^2}{2a_L})} < a_{F,Threshold}$$

(Minimum Separation Case)

$$a_L - \frac{(v_L + a_L t_{R,Threshold} - v_F)^2}{2(R + (v_L - v_F)t_{R,Threshold} + \frac{a_L t_{R,Threshold}^2}{2})} < a_{F,Threshold}$$

where the terminal location case is used if $\frac{v_F}{a_F} \le t_{R,Threshold} + \frac{v_L}{a_L}$ and otherwise the minimum separation case is used.

Heuristically, these equations partition the kinematic situation space of a lead and following vehicle into two regions. The kinematic situation space consists of parameters describing the longitudinal behavior of the lead and following vehicle, including range, speed, and acceleration. The equations assume that the lead vehicle is going to continue doing what it is doing. In one region of the space, the following vehicle will collide with the lead vehicle if the following vehicle does not begin to decelerate sufficiently and soon enough. In the other region of the space, the following vehicle has more latitude (can wait longer or brake less severely) to avoid a rear-end crash. The boundary between the “crash” and “no crash” regions of kinematic space can be adjusted with two thresholds, namely reaction time $t_{R,Threshold}$ and deceleration required $a_{F,Threshold}$.

One of the data collection triggers implemented was based on the LVS/LVCS and LVD equations with thresholds set to 1.5 sec for reaction time and 8 ft/s^2 (0.25 g) for required deceleration (KME0 and KME1 in Table 4.2-7 above). Thus, anytime a truck was in a situation in which the driver had to react within 1.5 seconds with braking sufficient to produce a deceleration of 8 ft/s^2, (0.25 g) time history data were captured. Because situations requiring less severe braking or longer reaction times may not have been captured by a trigger, it is not possible to define driving conflicts with conditions less severe than these. However, it is of interest to observe the impact of changing driving conflict thresholds on the exposure ratios and predicted crash reductions. Thus, two more severe sets of rear-end driving conflict thresholds were chosen to examine the impact. These thresholds, along with our initial set of conservative thresholds, are provided in Table 4.3-1.

Table 4.3-1. Rear-end Driving Conflict Thresholds

Threshold Set	Reaction Time (sec)	Required Deceleration (ft/s^2)
Conservative	1.5	8
Medium	1.0	10
Aggressive	0.5	12

Before the time history data are analyzed, algorithms to remove data spikes and suspect data channels are run on the raw TH data. Then the LVS/LVCS and LVD equations are applied. In general, these are referred to as the KME equations. However, they are different from the KME1 and KME0 triggers used in data collection. The KME trigger calculations considered only the terminal location case because it was conservative and simpler to implement. The KME equations as discussed further (the LVS/LVCS and LVD equations) were applied to all time histories, regardless of their actual trigger. Only time histories that met the conditions of the KME equations were considered in the safety benefits calculations. Figure 4.3-3 illustrates the partition of kinematic situation space based on the conservative, medium, and aggressive sets of thresholds when both the lead vehicle and the following truck are moving at constant (or lead vehicle stopped) speeds (LVS/LVCS). The figure illustrates the concept that the faster the truck is closing on the lead vehicle (range rate) the greater the distance (range) between the two vehicles at which the situation becomes a conflict. Note that the x-axis indicates that the two vehicles are closing faster with more negative values of range rate.

Similarly, Figure 4.3-4 illustrates the partition of kinematic situation space based on the conservative, medium, and aggressive sets of thresholds when both the lead vehicle and the truck are moving and the lead vehicle is decelerating (LVD). Kinematic situation space is higher dimensional when the lead vehicle is decelerating, and thus, the partitioning cannot be captured in the Range/Range Rate space. Specifically the deceleration of the lead vehicle must be considered and the speed of the vehicles must be considered individually rather than only relative to each other (range rate). Figure 4.3-4 considers the specific case where the truck is moving at a constant speed of 68 mph (100 ft/s) and the lead vehicle is decelerating at 16 ft/s^2 (0.5 g). As with the case in which the lead vehicle is moving at a constant speed, faster closing rates cause driving situations to be classified as conflicts at larger distances (range). However, in the “lead vehicle decelerating” scenario, a situation can be a conflict even if the lead vehicles are not initially closing. Reducing the deceleration of the lead vehicle from 16 ft/s^2 will shift the conflict boundaries to the right. Reducing the truck’s speed will make the boundaries bend down from their current positions for higher range rate values.

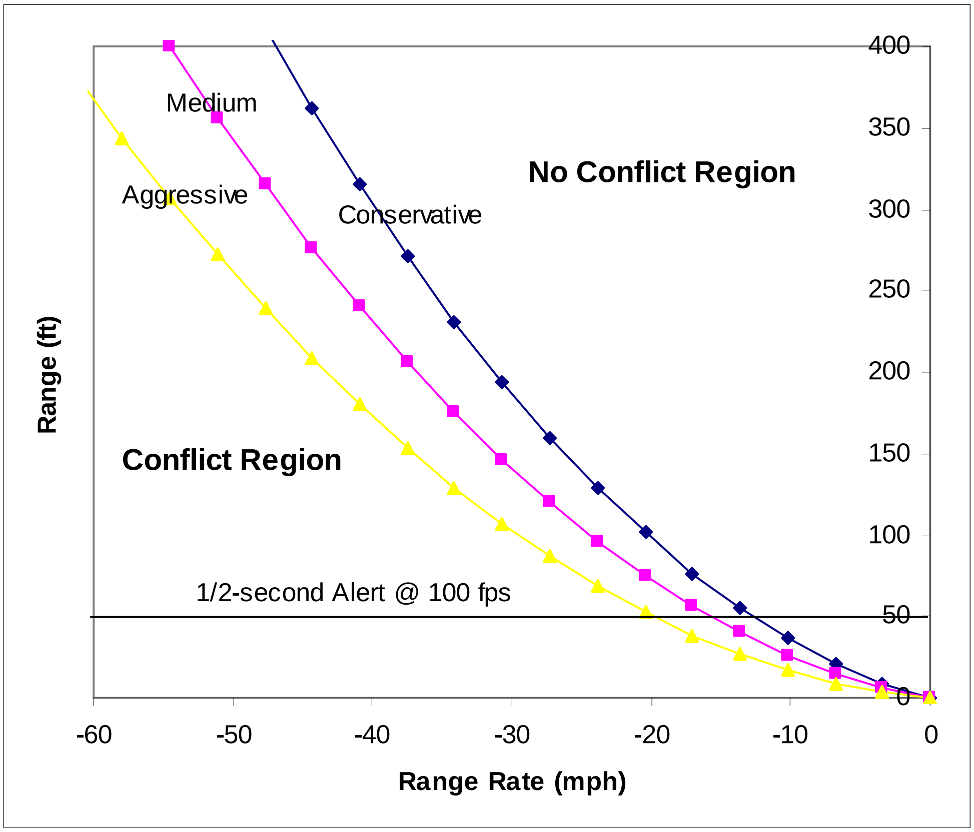

Figure 4.3-3. Partitioning of Kinematic Situation Space When Lead Vehicle is Stopped or Moving at Constant Speed (LVS/LVCS)

Partitioning the kinematic space according to the LVS/LVCS and LVD equations does not necessarily exclude situations with short following intervals and times to collision. Situations in which two vehicles are moving with the same speed and small following intervals are examples of excluded events. These events would be characterized by the space where range rate equals 0 ft/s in Figure 4.3-3. However, this situation can rapidly become a conflict if the lead vehicle decelerates to generate a negative range rate as shown in Figure 4.3-4. Also, in the LVS/LVCS situation in Figure 4.3-3, most of the kinematic space is both below the 0.5 second short following interval limit and below the conservative KME threshold when range rate is closing.

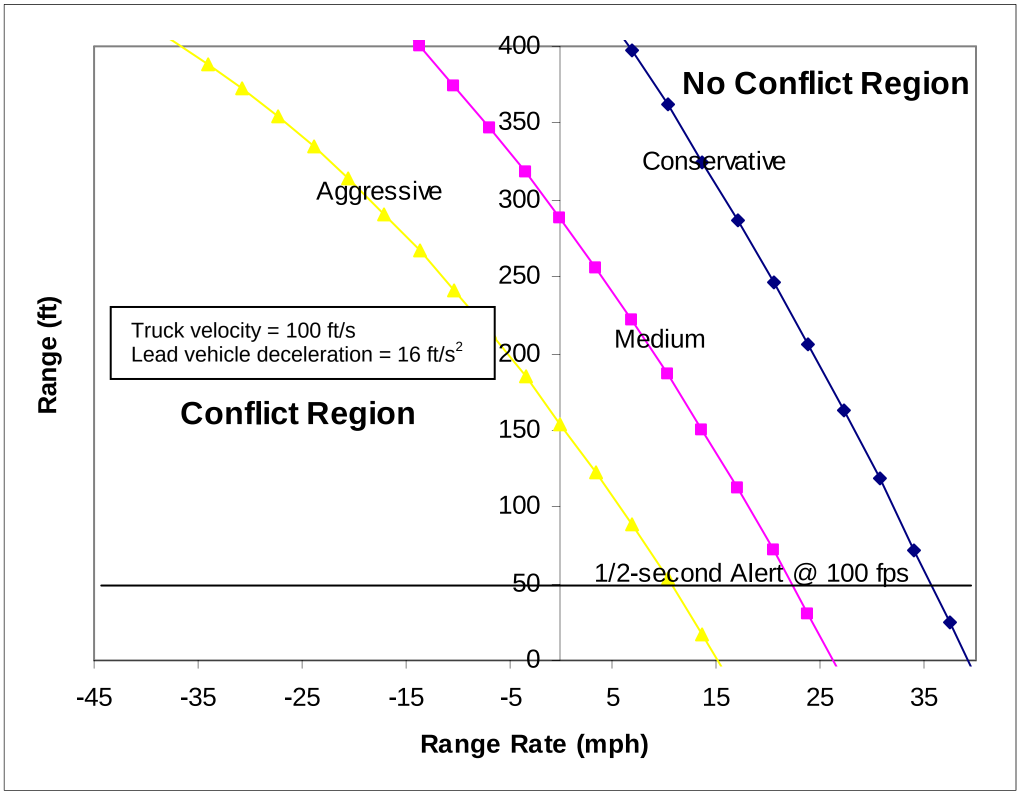

Figure 4.3-4. Partitioning of Kinematic Situation Space When Lead Vehicle is Decelerating (LVD)

As illustrated by Figures 4.3-3 and 4.3-4, many time histories that were recorded due to other triggers (Following Interval and Time-To-Collision) would also satisfy the LVS/LVCS or LVD equations and be included in the safety benefits calculations. As discussed previously, the initial triggering condition (FI, TTC, KME0, KME1) did not factor into further analysis of the time histories. All time histories, regardless of their triggering condition were analyzed using the KME equations to determine if they were conflicts.

4.3.3 Safety Benefits Methodology Procedure

The methodology for calculating the parameters of the safety benefits equation followed a ten step process. The outline of those steps will be given in this section. Results of the procedure will be reported in Section 5.

The ten steps in the procedure to calculate the parameters of the safety benefits equation are as follows:

1. Select conflict events from the set of all time history data.
2. Assign conflicts to three levels of severity according to the thresholds in Table 4.3-1.
3. Assign conflicts to three groups based on their truck configuration.
4. Allocate each conflict to one of the three conflict categories from Table 4.2-4.

5. Apply an analytical model to each conflict to determine the conflict severity by calculating the time the driver could have waited to take action (lag time).
6. Compute summary statistics of conflict severity for each combination of kinematic threshold and truck configuration.
7. Transform conflict severity to the probability of crash given the conflict category for each group and then calculate the prevention ratio.
8. Assign each conflict to the histogram during which it occurred and calculate exposure ratios for each combination of kinematic threshold and truck configuration.
9. Compute the crash reduction ratio.
10. Compute the percent reduction in crashes.

Step 1. Select Conflict Events from the Set of All Time History Data

This section describes in detail the process that was applied to the data received from the Volvo Partnership from collection through to the statistical analysis. Many steps in the process deal with validating and classifying the data to identify the relatively rare events defined that constitute a driving conflict.

Section 4.2.2 described the driving data that were collected with on-board DAS during the FOT. Data collection began in January 2001 and continued through December 2003. In March of 2002, the USDOT and the Volvo Partnership developed and began installing a new version of the DAS (DAS-2) in order to add yaw rate to the suite of time history (TH) channels as well as to incorporate a new type of triggered data collection called abbreviated time histories. This initiation of DAS-2 data collection involved a rolling start as each vehicle to be upgraded had to be captured from normal revenue-generating service. The upgrades generally occurred before September 2002. Because the yaw rate became the primary measure used to assess lateral movement of the vehicle in place of the existing lateral acceleration measure, only data collected with DAS-2 were validated and analyzed by the Volvo partnership and, thus, are the only data included in this report (Appendix D12).

Table 4.3-2 presents a summary of the data available for safety analysis including the VMT accumulated for each of the three fleets, the number of trucks that have supplied data that can be used in this analysis, the total number of triggered events (see trigger criteria in Section 4.2.2), and the rate of triggered events per 10,000 miles. The VMT and triggers summarized in this table are the data that the Volvo Partnership has indicated are valid data for analysis. The Volvo Partnership was responsible for performing the validation checks, removing non-threatening targets, and assigning triggered events to driving conflict types using methods that were first described in Battelle's Summary Data Report No. 3 (Battelle 2002). These methods are further described in the Volvo Partnership Final Report (Volvo 2005).

Table 4.3-2. Summary of Valid DAS-2 Data for Analysis by Truck Group

Fleet	Number of Histograms	VMT	Number of Trucks	Number of Triggers	
				Count	Rate*
Baseline	7,524	375,935	11	**39,032**	1,038
Control	24,103	1,108,674	31	**95,308**	860
Test	26,080	1,202,059	23	**104,259**	867
Total	57,707	2,686,668	59	**238,599**	880

* Rate is the number per 10,000 miles.

The table shows that 2.6 million miles, traveled by 59 trucks, were used for this analysis. These miles and trucks were divided among the baseline, control, and test fleets. The total number of histograms reported in Table 4.3-2 (57,707) is consistent with the number of valid DAS-2 histograms indicated in Figure 6.2-1 of the Volvo Partnership Final Report (2005). The total number of triggered events reported in Table 4.3-2 (238,599) is more than the total number of time histories reported in Figure 6.2-1 of the Volvo Partnership Final Report (237,811). However, the additional 788 time histories do not impact the reported benefits analyses, because none of them were identified as threats. A full discussion of the comparison between the conflicts contained in the Volvo Partnership Report and this report is contained in Appendix D12.

Figure 4.3-5 shows how the total numbers of DAS-2 triggered events are filtered into conflicts. A formal definition of a conflict is given in the following paragraphs. **Step A** consisted of removing a large number of triggered events that were determined to have been collected under non-threat situations. Non-threat situations were defined by the following Non-Threat Criteria.

Non-Threat Criteria

- Situations in which the lead vehicle was present for less than 1 second for stopped lead vehicles or less than 2 seconds for moving lead vehicles.
- Situations in which the truck was going around a curve (yaw rate greater than 2 degrees per second for 3 seconds) and the lead vehicle was stopped or on-coming.
- Situations in which the lead vehicle was out of the truck's lane (lateral distance to target greater than 2 feet).
- Situations in which the lead vehicle crossed in front of the truck, e.g., at an intersection.
- Situations in which the lead vehicle was so close to the truck that an unreasonable (0.4 g) lateral acceleration would be required to avoid a crash.
- Situations in which there was no reaction (braking, decelerating, reduce accelerator pedal, or lane change) by the driver of the truck.

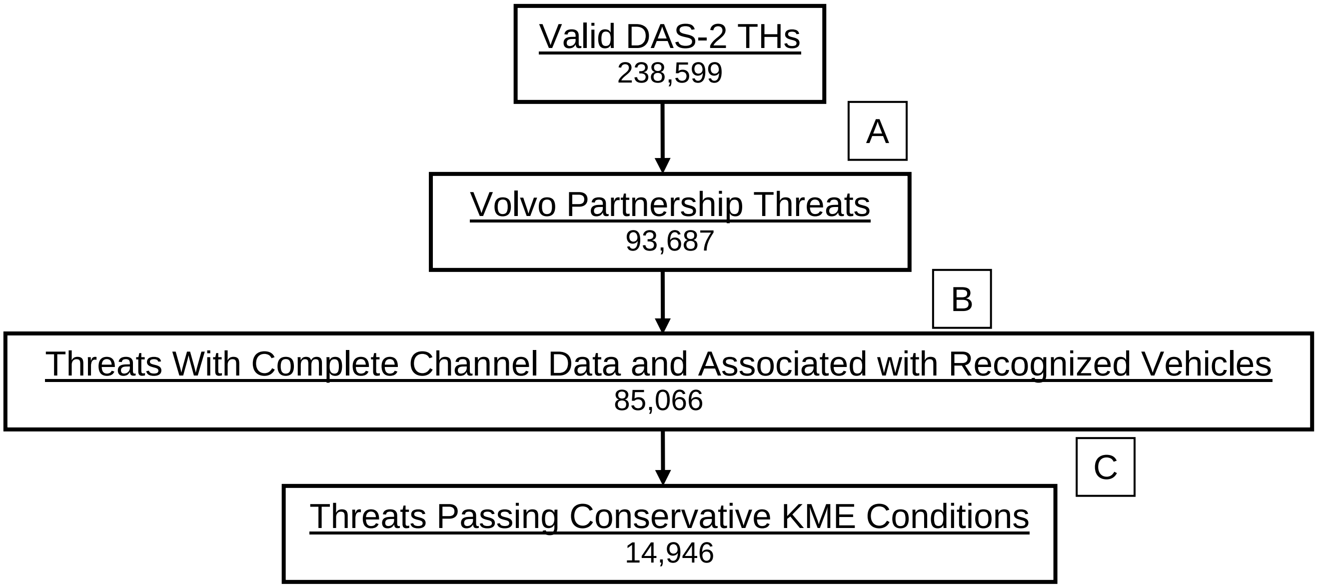

Figure 4.3-5. Process of Filtering Triggered Events into Conflicts

The algorithms used to identify non-threat situations were first described in Summary Report No. 3 (Battelle 2002). These algorithms were extended and described again in the Volvo Partnership Final Report (2005). The Volvo Partnership implemented the algorithms, resulting in 93,687 triggered events (or time histories) called "threats."

Step B indicates the reduction in data available due to missing channel data. The missing channel data did not affect counts of triggered events; however, the missing channel data did affect the analysis of triggered events.

The criterion for a rear-end driving conflict was an event in the FOT data that would require a "quick reaction" or "hard braking" by the driver in order to avoid a rear-end crash. Most conservatively, a "quick reaction" was defined as a scenario in which the driver has to react in less than 1.5 seconds, and "hard braking" was defined as a scenario in which the driver has to brake harder than 8 ft/s^2 (0.25 g) to avoid a crash. If these thresholds were exceeded for three consecutive time steps (0.5 second total) in a threat, the threat was identified as a conflict. **Step C** identifies the threats that satisfied the criteria for a conflict. Details of the KME conditions indicating a driving conflict were described in Section 4.3.2. At **Step C,** the KME conditions were applied at the most conservative thresholds. Figure 4.3-5 indicates that 14,946 threats were identified as driving conflicts. As discussed previously, the KME equations were applied to all driving conflicts regardless of their original triggering condition. These 14,946 threats are contained in the 57,550 time histories reported in Figure 6.2-1 of the Volvo Partnership Final Report (2005).

Threats that met the conservative KME conditions were used at the exclusion of other criteria that could have potentially been used. Following Interval and Time-To-Collision triggers were also used as triggers for data collection. They were not used to classify threats as conflicts for the following reasons. First, the KME criteria identify situations which are consistently in close proximity to a rear-end collision in all three conflict categories. Following Interval measures can be misleading in that two vehicles can be moving down the road together at the same speed, but have a small following distance, and therefore a small following interval. This situation is not indicative of an event that is in close proximity to a rear-end collision. It is, however, indicative of unsafe driving and therefore is treated separately in this report. Time-To-Collision is a better measure than Following Interval, but it does not indicate the level to which action must be taken as the KME criteria do. Time-To-Collision takes into account the range and range-rate, but not the deceleration of the lead vehicle or the necessary deceleration of the following vehicle. Changes in Time-To-Collision across the fleets are also detailed in Chapter 5. As discussed earlier in this section, situations with small Following Interval can immediately become conflicts if the lead vehicle brakes. Additionally, Time-To-Collision and KME are similar measures when the lead vehicle is not braking. The KME equations will be more conservative when the lead vehicle is decelerating. Examples of eight selected threats triggered by following interval and time-to-collision are included in Appendix D9. These threats illustrate that a threat not triggered by KME can still meet the KME conditions. (The KME triggers are different from the KME conditions.) These threats also illustrate the nature of the threats defined by following interval.

These 14,946 driving conflicts identified by Step C also included time histories with up to seven follow-on time histories. If a trigger condition remained at the end of a time history, the data collection for that event was continued into another 15-second time history called a follow-on. The specific procedure for appending follow-on time histories is given in Appendix D1.

Step 2. Assign Conflicts to Three Levels of Severity According to the Thresholds in Table 4.3-1

In order to observe the impact of changing driving conflict thresholds on the exposure ratios and predicted crash reductions, three different thresholds were chosen for reaction time and required develeration (Table 4.3-1). These thresholds, as part of the KME equations, were applied to each of the 14,946 driving conflicts. By definition, the conflicts in the aggressive threshold were a subset of the medium thresholds, and the medium were a subset of the conservative thresholds. The number of conflicts associated with each threshold is given in Table 4.3-3.

Table 4.3-3. Assignment of Conflicts to KME Thresholds

KME Threshold	Total Number of Conflicts	Percentage of Conflicts
Conservative	14,946	100%
Medium	7,530	50.4%
Aggressive	4,733	31.7%

Step 3. Assign Conflicts to Three Groups Based on the Truck Configuration

All conflicts were assigned to one of three truck configurations based on the systems available on that truck. As described in Section 2.2, three different IVSS configurations were evaluated with the three test fleets taking part in the Volvo IVI FOT: the Baseline trucks had no IVSS, the Control trucks had CWS alone, and the Test trucks had the bundled system (CWS + ACC + AdvBS). A small number of trucks collected data as both Baseline and Control trucks; data from these trucks was split appropriately for the analysis.

To determine the benefit of CWS, safety measures for Control trucks are compared to Baseline trucks. The effect of the ACC and AdvBS can be found by comparing Test trucks to Control Trucks. Finally, a comparison of the Test trucks to the Baseline trucks yields the effect of the bundled system. Table 4.3-4 gives the number of conflicts allocated by fleet.

Table 4.3-4. Assignment of Conflicts to Fleets

Fleet	Total Number of Conflicts	Percentage of Conflicts
Baseline[1]	2,126	14.2%
Control[2]	6,100	40.8%
Test[2]	6,720	45.0%

[1] Once the Baseline data collection was complete (after approximately 18 months), the Baseline tractors were converted to Control tractors, resulting in 50 total Control tractors for the remainder of the FOT.

[2] Control and Test tractors were driven for longer periods of time and for more miles than the Baseline tractors (Table 4.3-2).

Step 4. Allocate Each Conflict to One of the Three Conflict Categories

Next, the 14,946 conflicts were assigned to the three conflict categories according to their original assignment into five conflict types by the Volvo Partnership. Some conflicts did not match the criteria for the five conflict categories and were placed in the *other* category. Those conflicts did, however, meet the conservative KME criteria. Table 4.3-5 gives the number of conflicts in each category.

Table 4.3-5. Assignment of Conflicts to Conflict Categories

Driving Conflict Category	Total Number of Conflicts	Percentage of Conflicts
Constant Speed	4,671	31.3%
Slowing	8,879	59.4%
Lane Change	1,030	6.9%
Other	366	2.4%
Total	14,946	

Step 5. Apply an Analytical Model to Each Conflict to Determine the Conflict Severity by Calculating the Time the Driver could have Waited to Take Action (Lag Time)

Estimation of prevention ratios requires a realistic measure of the severity of the conflict, i.e., a measure of how close each individual conflict was to resulting in a crash. This measure of severity is determined by a kinematic analysis of each FOT driving conflict. The measure of severity resulting from the kinematic analysis is the additional time that a following vehicle driver could have waited to take action and still avoid a crash. This analysis assumes that the driver would react in the same manner as he or she did in the event. It also assumes that the truck maintains its kinematic profile throughout the additional time. Finally, the analysis assumes that the lead vehicle also reacts in the same way. This measure of driver lag time indicates how close a driver was to a rear-end collision. Events where a driver had two seconds to react and still avoid a collision are less severe than those where, if the driver had taken action one half second later, a collision would have occurred.

In order to calculate the prevention ratio for the safety benefits equation, crash probabilities had to be assigned to the conflicts. These crash probabilities are based on the severity measures resulting from the kinematic analysis. The crash probabilities were calibrated using historical rear-end conflict and crash rates for tractor-trailers using data from GES. The kinematic analysis is performed as follows:

Kinematic Analysis for Determining Lag Time

1. Calculate the (x,y) location of the truck and lead vehicle (relative to an arbitrary zero location at the beginning of the conflict) at each time step of the conflict using vehicle speed, yaw rate, range, range rate, and azimuth.
2. Identify the point at which the driver "reacts," i.e., brakes or steers, or, if the driver does not react, the point at which the critical target appears.
3. Insert an extra time point ($1/6^{th}$ of a second) in the driving conflict immediately after the driver reaction time (or critical target start) to produce a delayed reaction time, with vehicle dynamic data duplicated from the previous time step.
4. Re-calculate the (x,y) location of the truck only.
5. Determine if the truck and target vehicle crash (as indicated by an overlap in locations) with the delayed reaction time of the driver introduced by Step 3.
6. Repeat steps 3 through 5 until either the truck and target vehicle crash or the lag has been increased to 15 seconds.

The result of the above procedure is the minimal additional reaction time ($t_{i,k}$) that results in a crash for the k^{th} conflict of type i ($S_{i,k}$).

The algorithms used to calculate (x,y) location take into account (1) steering maneuvers of the truck through the use of yaw rate and (2) steering maneuvers of the lead vehicle through the use of azimuth. Conflicts in which the driver steered away are not specifically differentiated from conflicts in which the driver braked, but are analyzed in a unified model that addresses both braking and steering.

Kinematic Analysis Location Determination Equations

Calculation of the set of (x,y) positions of the following vehicle with initial conditions:

$$\phi_t = \phi_{t-1} + \dot{\phi}\Delta t \qquad t > 0 \quad \phi_0 = 0$$

$$(x_{f,0}, y_{f,0}) = (0,0)$$

$$x_{f,t} = x_{f,t-1} + v_{f,t-1}\sin(\phi_{t-1}\frac{\pi}{180})\Delta t + \frac{1}{2}a_{f,t-1}\sin(\phi_{t-1}\frac{\pi}{180})\Delta t^2$$

$$y_{f,t} = y_{f,t-1} + v_{f,t-1}\cos(\phi_{t-1}\frac{\pi}{180})\Delta t + \frac{1}{2}a_{f,t-1}\cos(\phi_{t-1}\frac{\pi}{180})\Delta t^2$$

Calculation of the set of (x,y) positions of the lead vehicle:

$$x_{l,t} = x_{f,t} + R_t \sin(\theta + \phi\frac{\pi}{180})$$

$$y_{l,t} = y_{f,t} + R_t \cos(\theta + \phi\frac{\pi}{180})$$

where

θ = Azimuth (rad)

R = Range (ft)

v_f = Following Vehicle Speed (ft/s)

a_f = Following Vehicle Acceleration (ft/s^2)

ϕ = Following Vehicle Heading (deg)

$\dot{\phi}$ = Following Vehicle Yaw Rate (deg/s)

v_l = Lead Vehicle Speed (ft/s)

a_l = Lead Vehicle Acceleration (ft/s^2)

Δt = 1/6 sec

To more specifically define the algorithm used to determine excess reaction time, let t_1 be the seconds of driving data available after the point at which the truck's reaction was assumed to be delayed. Let t_2 be the delay length in seconds. The length of time history data available for the truck after the insertion of the delay is $t_1 + t_2$. The length of time history data available for the lead vehicle after the point at which the delay is inserted is t_1. The position of the lead vehicle for duration t_2 after the end of the lead vehicle data is inferred, assuming that the lead vehicle continues the behavior it exhibited during the last time step of data for t_2 seconds. The entire period of length $t_1 + t_2$ after the insertion of delay into the truck data is examined to determine if a crash occurred.

Special consideration was also given to the end of a time history. If there was no follow-on time history then certain parameters were extended beyond the end of the time history during the lag time calculation. If the lead vehicle was present at the end of the time history then the yaw rate and acceleration for the following vehicle was held constant using the heading and road speed at the end of the time history as the initial conditions. The heading and acceleration of the lead vehicle were also held constant using the velocity at the end of the time history as an initial condition. For time histories with follow-on time histories appended to them, no special consideration needed to be made; the 15 second lag time was always contained with in the follow-on time history.

The driver reaction point of each conflict (step 3 of the kinematic analysis) was identified using algorithms developed by Martin and Burgett (2001) provided by the Volvo Partnership in a separate database containing variables indicating lane changes and braking events. If either a lane change or a braking event was identified for a driving conflict, its onset was defined to be the reaction point. If both were indicated, the first one was chosen. If no reaction was identified, the “reaction point” was set to the time that the critical target appeared.[11] To test the performance of the algorithms, the methodology was replicated using the point where the KME condition was satisfied and the appearance of the critical target for all conflicts as alternatives to the “reaction point.” Results were qualitatively the same based on each of these methods. A graphical representation of the kinematic analysis is presented in Appendix D8.

The kinematic analysis is one approach to objectively evaluating how close individual conflicts are to crashes; it is the approach taken in this safety benefits analysis. No model-based approach to assigning a single severity metric to each conflict is going to be perfect, especially when the collection of conflicts requiring assessment is quite disparate. However, upon completion of this analysis, it was assessed that the kinematic analysis did not optimally address estimating the severity of conflicts in which the following vehicle executes a lane change. The potential effect of this on the overall safety benefits analysis is examined in Appendix D13.

Two observations were immediately apparent from kinematic analysis. First, the percentage of conflicts that would have resulted in a crash had the driver delayed his or her reaction by less than $1/6^{th}$ of a second was 3 percent (these conflicts accounted for 14 percent of lag times that were less than 15 seconds). Review of these driving conflicts indicated that they were not threats, and should have been eliminated from consideration as driving conflicts when the “High Lateral Acceleration” non-threat removal algorithm was applied to triggered events. Thus, these driving conflicts were removed from the analysis. Similar review of histograms in the 1/3 and 1/2 second bin revealed that these driving conflicts were likely real threats.

For example, Figure 4.3-6 shows a conflict where the kinematic algorithm predicted a collision with a 1/6th second lag. This figure illustrates a non-threat scenario with a stationary target and is not considered a conflict. Figure 4.3-7 gives a conflict with a 1/3 second lag. This figure

[11] The time of appearance of the critical target was identified using algorithms developed jointly by Battelle and the Volvo Partnership. The algorithms are detailed in Appendix D7.

shows a following vehicle that had to decelerate quickly behind a decelerating lead vehicle. This time history was considered to be a valid conflict. Figure 4.3-8 shows an example of a conflict in the ½ second bin. This time history is also considered to be a valid conflict where the following vehicle nearly has to stop behind a lead vehicle to avoid a collision. If the following vehicle had continued its kinematic profile for ½ second more before braking with the same deceleration, a collision would have occurred.

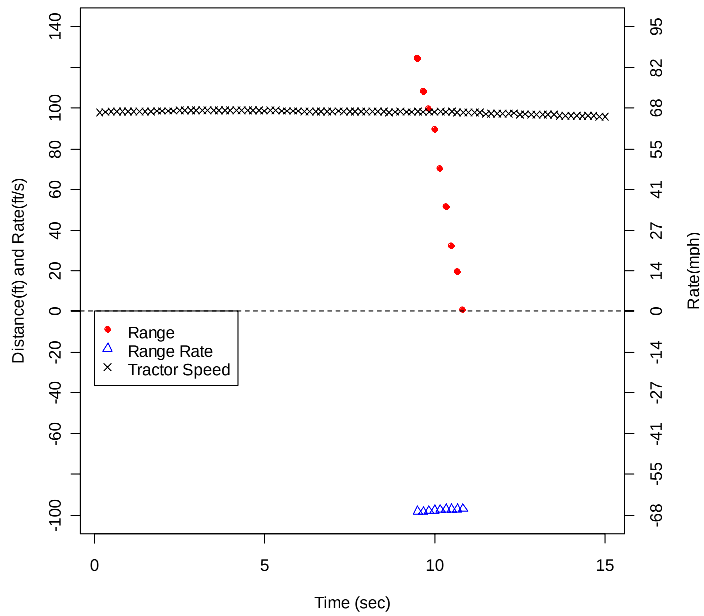

Figure 4.3-6. Example Time History Where the Kinematic Analysis Resulted in a 1/6th Second Lag Time

(UUID = BF13051704162003544D00D0810001E7)

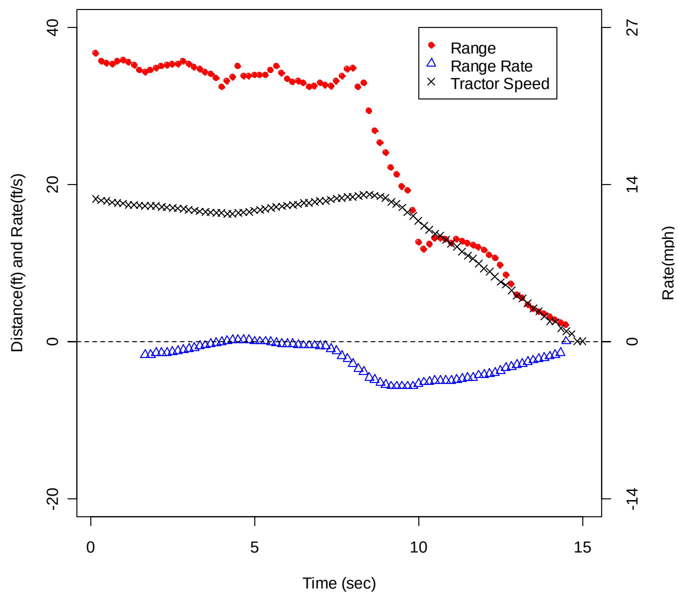

Figure 4.3-7. Example Time History Where the Kinematic Analysis Resulted in a 1/3rd Second Lag Time

(UUID = 711504301119200254 4D00D081000104)

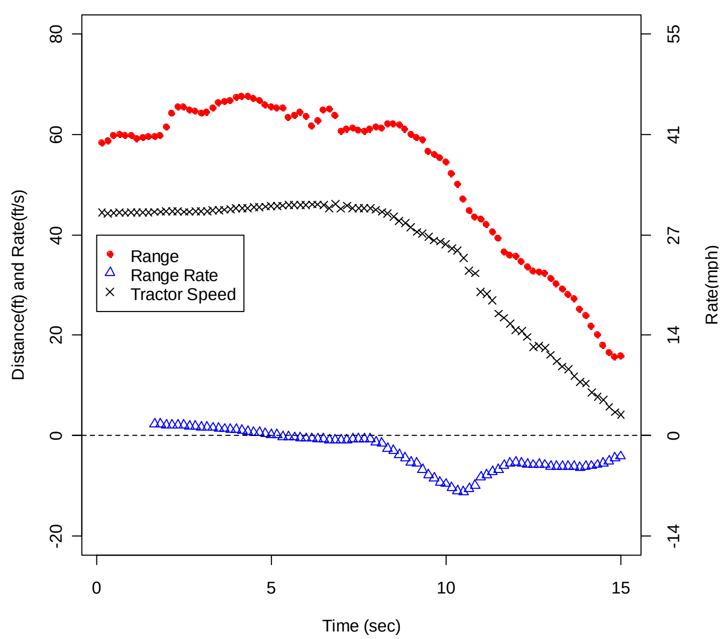

Figure 4.3-8. Example Time History Where the Kinematic Analysis Resulted in a 1/2 Second Lag Time

(UUID = 13021750102820025 44D00D0810001EF)

The second result immediately apparent from the analysis was that many of the driving conflicts did not result in a crash even after lagging the driver's reaction for 15 seconds. Review of these conflicts revealed that either targets were not real threats or the lead vehicle's actions resolved the situation. Figure 4.3-9 is an example of a time history with a 15-second lag time. In this case, the following vehicle was overtaking a slower moving vehicle. This time history was resolved by a lane change at the 6 second time point. Because of the lateral positions of the vehicles, even if the lane change would not have happened for 15 seconds, there would not have been a collision.

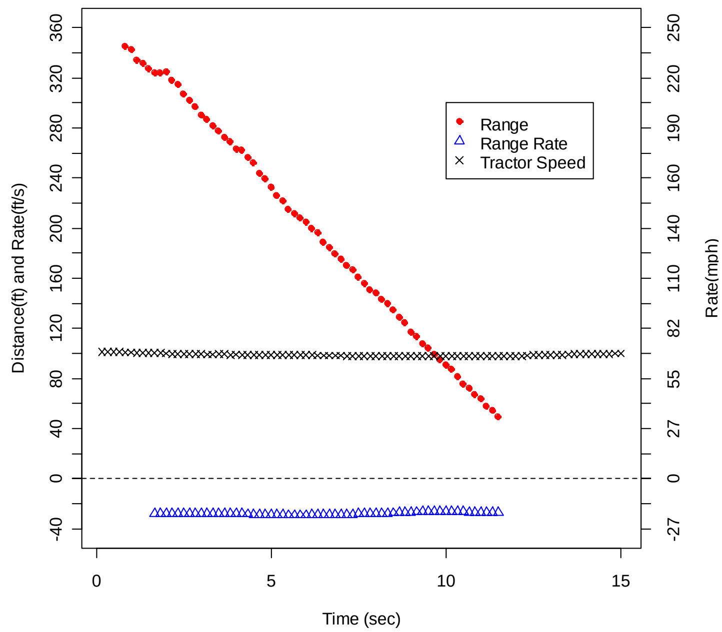

Figure 4.3-9. Example Time History Where the Kinematic Analysis Resulted in a 15 Second Lag Time

(UUID = 0100532408182002544D00D0810000F4)

Table 4.3-6 extends Table 4.3-5 with these additional data subsets. The results in column 3 follow the removal of conflicts with lag times less than or equal to 1/6th seconds. These results are conflicts according to the KME Conflict Definition because they are largely defined by the fact that they are KME conflicts. Column 4 follows the removal of the conflicts with longer than 15 second lag times. The results are conflicts according to the Restricted KME Conflict Definition because the KME criteria are further restricted by the kinematic analysis above. The conflicts removed from the Restricted KME conflict are called "Non-crashes" because the vehicles would not have collided even if the following driver had waited 15 seconds to take action.

Safety benefits calculations will be performed using the KME Conflict Definition and the Restricted KME Conflict Definition conflicts separately. The KME Conflict Definition results will be used as a sensitivity study for comparison with the results from the Restricted KME Conflict Definition. The sensitivity study assesses the decision to remove the non-crash conflicts.

There are two reasons for selecting the smaller subset of conflicts for use in the main analysis. First, the kinematics of those 2,556 driving situations show that they are definitely situations where substantial action had to be taken to avoid a collision; the larger subset included many situations where no collision would have occurred even if no action was taken. Second, limiting the set of conflicts improves the benefits estimate by creating a homogenous population of conflicts. These are all the conflicts that have some degree of severity.

Table 4.3-6. Numbers of Driving Conflicts Available for Analysis

Driving Conflict Type	Total Number of Conflicts	KME Conflict Definition Number of Conflicts with Additional Non-Threats Removed	Restricted KME Conflict Definition Number of Conflicts with Non-Crashes Removed
Constant Speed	4,671	4,437	220
Slowing	8,879	8,711	1,872
Lane Change	1,030	1,026	293
Other	366	365	171
Total	14,946	14,539	2,556

In some time histories where the calculated lag time is 15 seconds, the target may have disappeared before the end of the time history. Target disappearance could be caused by a lead vehicle lane change or by a phantom radar return. Of the 11,983 time histories (14,539 - 2,556) where the lag time was equal to 90 seconds, 85 percent had a target disappear before the end of the time history. Two scenarios are possible when the target disappears before the end of the time history. First, the following vehicle can take action (braking or lane change) after the situation meets the KME criteria, but before the target disappears (52 percent). It is not always obvious that the reaction is directly related to the target in this scenario when the conflict resolution is not dependent on the time of the driver's reaction. Second, the following vehicle can take no action to resolve the conflict that meets the KME criteria before the target disappears (33 percent). It is open to interpretation whether conflicts that were resolved by the lead vehicle should be considered in the safety benefits methodology. The KME Conflict Definition includes these time histories, while the Restricted KME Conflict Definition does not.

The following two steps from the Safety Benefits Methodology Procedure will be broken into a KME Conflict Definition analysis and Restricted Conflict Definition analysis section.

Step 6. Compute Summary Statistics of Conflict Severity for Each Combination of Kinematic Threshold and Truck Configuration

Restricted KME Conflict Definition

The geometric mean lag time was calculated for each conflict category and fleet for the Restricted KME Conflict Definition (2,556 conflicts) case. Then the geometric mean lag time was converted to a probability. Because the distribution of smallest time lags resulting in a crash are roughly lognormal, a geometric mean was calculated rather than an arithmetic mean in order to better capture the central behavior across the set of conflicts.

Briefly, the probability of a crash given a driving conflict is assumed to be inversely proportional to the average minimal additional reaction time for each driving conflict category and fleet. Inverse proportionality is chosen as the relationship between the severity measure and crash probability because it is the simplest relationship capturing the heuristic behavior that as minimal additional reaction time increases, the probability of a crash should decrease and vice versa. Simple inverse proportionality is only required to be appropriate over the very narrow range of minimal additional reaction time averages observed in the FOT.

The method employed for this crash probability estimation was slightly different from the method employed on the Freightliner FOT safety analysis (Battelle 2003) in that, for the Freightliner calculations, averaging was performed after the transformation from severity to probability. This change in procedure was implemented because it was expected to make the crash probability—given a driving conflict estimated for each driving conflict category and fleet—more representative of the entire set of applicable conflicts and less sensitive to the small set of most severe conflicts.

The probabilities for each conflict category and fleet were found by:

$$\overline{P}_k(C \mid S_i) = \frac{a_i}{\overline{\tau}_{i,k}} \qquad \overline{\tau}_{i,k} = \sqrt[n_{i,k}]{\prod_{j=1}^{n_{i,k}} \tau_{i,k,j}}$$

where,

$\overline{P}_k(C \mid S_i) =$ Average probability of a collision given fleet k and conflict category S_i

$a_i =$ proportionality constant discussed later

$\tau_{i,k,j} =$ Conflict severity (lag time) for the j^{th} conflict in fleet k and conflict category S_i

$\overline{\tau}_{i,k} =$ Geometric mean severity for fleet k and conflict category S_i

$n_{i,k} =$ The number of conflicts in fleet k and conflict category S_i

KME Conflict Definition

In the case of the 14,539 conflicts, lag times were first converted to probabilities of a crash using the inverse proportionality relationship, and then the arithmetic mean probability was used further. The summary statistic for the KME Conflict Definition had to be different from the Restricted KME Conflict Definition because the 15-second lag time was not an actual time. In reality it was a code for time histories in which no collision would have occurred no matter how long the driver waited to react. Therefore, the geometric mean lag time could not be calculated with infinite lag times. Instead, these time histories with long lag times were given zero probability of a crash and summary statistics of the probabilities were calculated instead. The probabilities were calculated as:

$$P_{kj}(C \mid S_i) = \frac{a_i J_{i,k,j}}{\tau_{i,k,j}}$$

$$J_{i,k,j} = \begin{cases} 1 & \text{if } \tau_{i,k,j} < 15 \text{ sec and } \tau_{i,k,j} > 1/6 \text{ sec bin} \\ 0 & \text{if } \tau_{i,k,j} = 15 \text{ sec} \end{cases}$$

a_i = proportionality constant discussed later

$\tau_{i,k,j}$ = Conflict severity (lag time) for the j^{th} conflict in fleet k and conflict category S_i

The arithmetic mean was then calculated as:

$$\overline{P}_k(C \mid S_i) = \frac{1}{n_{i,k}} \sum_{j=1}^{n_{,ki}} P_{kj}(C \mid S_i)$$

where,

$P_k(C \mid S_i)$ = Probability of a collision given fleet k and conflict category S_i

$\overline{P}_k(C \mid S_i)$ = Average probability of a collision given fleet k and conflict category S_i

$n_{i,k}$ = The number of conflicts in fleet k and conflict category S_i

Step 7. Transform Conflict Severity to the Probability of Crash given the Conflict Category for Each Group and then Calculate the Prevention Ratio

According to GES, the average rear-end crash rate for tractor-trailers is approximately one crash per 4 million miles traveled. This is based on the annual average number of tractor-trailer rear-end crashes that occurred during the period from 1999 to 2003 and the average miles driven annually by tractor-trailers. If we assume that the national tractor-trailer fleet is similar to US Xpress baseline trucks, the GES overall rear-end crash rate and the relative frequencies of various conflict categories given a rear-end crash can be used to estimate the rate of rear-end crashes preceded by each conflict category:

$$P(C, S_i) = P(S_i \mid C) \times P(C)$$

where $P(C,S_i)$ is the probability of a collision and conflict category *i*, $P(S_i|C)$ is the probability of being in conflict category *i*, given that a collision has occurred, and *P(C)* is the probability of a collision.

The rate of each category of driving conflict was determined based on the Baseline FOT driving data. The rules of conditional probability determine that

$$P_{B,GES}(C \mid S_i) = \frac{P(C, S_i)}{P_B(S_i)}$$

where *B* indicates the Baseline trucks, $P_{B,GES}(C|S_i)$ is the probability that a baseline truck will have a collision given the situation is in conflict category *i*, and $P_B(S_i)$ is the probability that a Baseline truck is in conflict category *i*. These values are calculated for all three kinematic thresholds.

This equation assumes that the joint probabilities in GES [$P(C, S_i)$] are equal to the same probabilities in this FOT Baseline driving. This was assumed because there is no other obvious basis for determining the FOT joint probability of a crash and a driving conflict. One issue associated with this assumption was that the national tractor-trailer fleet consisted of flatbed, tank, and other vehicle configurations as well as the dry freight van trailers operated by US Xpress.

The approach taken to estimate crash probabilities given a specific driving conflict (**$P(C|S_i)$**) was the same for all three rear-end driving conflict categories. It was, however, performed separately for each driving conflict category because the GES data provided individual calibration numbers for each driving conflict category.

Then, a_i, the constant by which calibration is performed, is calculated by:

Restricted KME Conflict Definition:

$$\overline{P}_B(C \mid S_i) = P_{B,GES}(C \mid S_i) \qquad a_i = \frac{P_{B,GES}(C \mid S_i)}{1/\overline{\tau}_{i,B}}$$

KME Conflict Definition:

$$\overline{P}_B(C \mid S_i) = P_{B,GES}(C \mid S_i) \qquad a_i = \frac{P_{B,GES}(C \mid S_i)}{\frac{1}{n_{i,B}} \sum_{j=1}^{n_{i,B}} \frac{J_{i,B,j}}{\tau_{i,B,j}}}$$

Calculation of the prevention ratio was insensitive to the value calculated for a_i because when the ratio of probabilities is used, the a_i parameter cancels from the numerator and denominator. The constant a_i was necessary only if conditional crash probabilities were to be examined individually.

This methodology for inferring crash probabilities from average smallest time lag resulting in a crash has not been validated using real crash data. To validate this methodology, onboard driving data for a set of driving conflicts, including some which resulted in a crash, would be needed. These data would be needed from both Control and Test vehicles. If these data were available, the methodology could be tested to determine if it produces accurate estimates of the probability of a crash given a conflict category for the Control and Test fleets. However, if such data were available, these data could be used directly to estimate the prevention ratio and an analytical model would not be needed.

The prevention ratio is a measure of the ability of a safety system, namely CWS, ACC + AdvBS, or the bundled systems (CWS + ACC + AdvBS), to prevent crashes given that a driving conflict has already occurred. It is calculated as the ratio of two conditional crash probabilities: the conditional probability that a driving conflict ***with*** a safety system in place will result in a crash (in the numerator of the equation) divided by the conditional probability that a driving conflict ***without*** that system in place will result in a crash (in the denominator). The equation is given in Section 4.3.1 with the safety benefits equation.

Values of the prevention ratio less than 1 indicate that a safety system is effective at preventing crashes given that a driving conflict has occurred. A prevention ratio greater than 1 does not necessarily indicate that the safety system is ineffective at preventing crashes. It is possible that the safety system helps to reduce the number of conflicts; but the conflicts that remain tend to be more severe than those that occur without the system. Thus, combining the exposure ratio with the prevention ratio is necessary to estimate the percentage of rear-end crashes that can be prevented by these safety systems. Together, the exposure and prevention ratios characterize the ability of the safety systems to prevent crashes.

Variability in the prevention ratio was calculated using two methods. For the Restricted KME Conflict Definition, the variance of the log transformed severity measurements was calculated for the numerator and denominator and then combined using a Taylor Series approximation. For the KME Conflict Definition, the variance in the probability of a crash given a conflict category was calculated for the numerator and denominator, and then combined using a Taylor Series approximation to calculate the variance of the ratio (Hogg and Craig 1995). Complete details of the variance estimation can be found in Appendix D11.

Step 8. Assign Each Conflict to the Histogram during which it Occurred and Calculate Exposure Ratios for Each Combination of Kinematic Threshold and Truck Configuration

Each driving conflict is assigned to the histogram during which it occurred. This matching is required to calculate rates of each driving conflict type across the FOT by truck, fleet, or other driving condition; information on how much driving (in vehicle miles traveled, or VMT) was performed to generate the driving conflicts must be provided by the histogram data. Direct calculation of driving conflict rates by fleet allowed estimation of Exposure Ratios used in the Benefits Equation in Figure 4.3-2. These estimates, which do not consider any of the information garnered from the histogram data other than VMT, are referred to as empirical estimates.

Triggered events that did not occur during a histogram period for which data were collected could not be used to estimate exposure to driving conflicts. These triggered events that were not associated with histograms were labeled "orphans." They were not used for the driving conflict exposure analysis, but were used for the driving conflict severity analysis. (A small number of time histories were removed during this step because they matched to histograms associated with no VMT.) This reduced the 14,539 conflicts down to 12,360 for the KME Conflict Definition, and the 2,556 conflicts down to 2,203 for the Restricted KME Conflict Definition analysis.

Time-To-Collision and Following Interval triggers are also represented in the Exposure Ratio. Thirty-five percent of the time histories in the KME Conflict Definition included a Time-To-Collision trigger and two percent included an Following Interval trigger. In the Restricted KME Conflict Definition, six percent were Time-To-Collision triggers and two percent were Following Interval triggers.

Variance in the exposure ratio was calculated using the Poisson distribution variance for the numerator and denominator (Appendix D4). The variances were then combined using a Taylor Series approximation (Appendix D11).

Steps 9 and 10. Compute the Crash Reduction Ratios and Compute the Percent Reduction in Crashes

The final stage of the safety benefit analysis is to calculate the overall efficacy of each combination of IVSS technologies for reducing crashes. This is accomplished by calculating a Crash Reduction Ratio (*CRR*) for each conflict type or category. The *CRR* is the product of the Exposure Ratio (*ER*) and the Prevention Ratio (*PR*). That is,

$$CRR_i = ER_i * PR_i.$$

Alternatively, the percent reduction in crashes (Efficacy) for each conflict category is calculated as

$$Eff(S_i) = (1-CRR_i)*100\%.$$

The overall percent reduction in crashes was then calculated as the weighted average of the percent reduction in crashes from the three conflict categories (Figure 4.3-2). GES relative frequencies (Table 4.2-4) for each of the three conflict categories were used in this calculation.

There are situations in which the following vehicle is already braking when we apply the 1.5-second reaction time to delay their braking. However, the analysis as it was performed still accurately estimates the safety benefits of the tested systems. While the definition of driving conflicts may not have been optimal, the correct handling of the dynamic state of the truck in the prevention ratio analysis accounts for the definition employed. The data show that the following truck is slowing in the majority of driving conflicts. This indicates that redefining the driving conflict definition to differentially treat driving conflicts in which the truck is braking at the time of the conflict has the potential to impact the exposure ratio considerably. However, it would also impact the prevention ratio in an offsetting manner. The first step in the prevention ratio calculation is to determine the minimal additional reaction time leading to a crash for each driving conflict. Conflicts in which additional reaction time does not lead to a crash are thrown out of the pool of driving conflicts. Thus, time histories in which the truck is already decelerating sufficiently do not hit the lead vehicle at the time the LVCS or LVD criteria are met are not considered driving conflicts; the truck may be braking, but it needs to brake more to avoid a crash. Additionally, for the driving conflicts in which the truck is already braking at the time of conflict onset, the deceleration at that time is considered in determining the minimal additional reaction time leading to a crash. In other words, in these driving conflicts, which are slightly less severe than other driving conflicts, the truck is given "credit" for its deceleration at conflict onset and a longer minimal additional reaction time is estimated. Thus, the prevention ratio accounts for the slight mismatch in driving conflict severities.

4.3.4 Conditional Safety Benefits Analysis

The purpose of the conditional analysis of driving conflict rates is to assess the effectiveness of the IVSS conditional on different driving conditions that were encountered by the three FOT fleets (i.e., Test, Baseline, Control). Controlling for these conditions may reduce variability in the estimates of the effectiveness of the IVSS by separating situations where the effectiveness of the IVSS is different. To this end, statistical models for the occurrence of driving conflicts and the severity of driving conflicts were developed.

The occurrence of driving conflicts is most naturally modeled using Poisson regression. The Poisson regression model (McCullagh and Nelder, 1989) states that the expected number of driving conflicts during any interval of driving is proportional to the distance driven during that driving interval, with a constant of proportionality that is a function of conditions describing the driving interval. Poisson regression assumes that observed numbers of driving conflicts experienced during each interval are independent and follow a Poisson distribution with the designated mean value. Specifically, the expected value of the number of driving conflicts, $E(Y_i)$, is defined by:

$$E(Y_i) = e^{x_i \beta} D_i$$

where i is the driving interval, Y_i is the number of conflicts during interval i, X_i is a vector of covariates and categorical variables describing driving conditions during interval i, β is a vector of regression parameters, and D_i is the distance driven during interval i.

The smallest intervals of driving in which driving conflicts occur—and for which information is available on the distance traveled and the conditions of travel—are the histograms. Thus, the basis of the conditional analysis is counts of driving conflicts in each histogram reporting period. Possible conditioning variables are quantities that can be calculated from the histogram data. Table 4.3-7 lists the driving conditions to be considered in Poisson regression models of driving conflict rates. Included in the list of conditioning variables are the Cruise Control group and the

Collision Warning System group. These variables separated the Baseline, Control, and Test fleets according to their common features. The Baseline and Control fleets were included in the conventional Cruise Control group while the Test fleet had the ACC. The CWS group consisted of the Control and Test fleets separated from the Baseline fleet.

By incorporating interactions between driving condition variables and fleet into the Poisson regression model, differential effects of the driving conditions on the effectiveness of the IVSS were considered. A random effect was used to account for the variability in the drivers. Backwards variable selection was used to identify a Poisson regression model with statistically significant predictor variables. By requiring the fleet effect to remain in the model, the Poisson regression models provide model-based estimates of exposure ratios.

Table 4.3-7. Driving Condition Variables Considered in Driving Conflict Poisson Regression

Driving Condition	Description
Cruise Control Type	Group 1 included the Baseline and Control Fleets, Group 2 was the Test Fleet
Cruise Control On	0 for cruise control off driving and 1 for cruise control on driving
CWS Available	Group 1 included the Baseline, Group 2 included the Control and Test Fleets
Fleet	Indicator of Baseline, Control, or Test truck was considered
Hours of Service	A linear service hour effect was considered
Driver Gender	Class effect for male/female
Driver Age	Linear age effect was considered
Driver Years with US Xpress	A linear driver US Xpress experience effect was considered
Driver Years with CDL	A linear driver experience effect was considered
Cruise Control	An indicator variable to indicate cruise control usage
Average Road Speed	A linear effect of the average road speed during the histogram was considered.
Percent Road Speed > 55 mph	Percent of the time that road speed is greater than 55 mph
Sine Hour of the Day	Sinusoidal (circular) effects in the hour of the day
Cosine Hour of the Day	
Sine Day of the Year	Sinusoidal (circular) effects in the Julian date
Cosine Day of the Year	

To account for different drivers and driving conditions that may increase the severity of a driving conflict when assessing the differences between fleets, a conditional analysis of the severity measure was performed. A generalized linear model was used to assess the dependence of the severity measure on driver and driving condition variables. The model assumed a gamma distribution for the error term. Other distributions were considered, but the gamma distribution yielded the best fit. A random effect was used to account for the variability in the drivers. Covariates considered in this model are contained in Table 4.3-8. As in the conditional exposure rate analysis, the fleets were divided up into a Cruise Control Group and a Collision Warning System group in order to better differentiate between the effects of those respective systems. The methods in Section 4.3.3 were used to calculate the severity (lag time) measures for each conflict. Only the Restricted KME Conflict Definition was used (2,556 conflicts).

Table 4.3-8. Variables Considered in the Generalized Linear Model for Conditional Conflict Severity

Variable	Description
Cruise Control Group	Group 1 included the Baseline and Control Fleets, Group 2 was the Test Fleet
Collision Warning System Group	Group 1 included the Baseline, Group 2 included the Control and Test Fleets
Cruise Control Status	The status of the cruise control at target appearance (On/Off)
Reaction Speed	Road Speed at the time of braking, lane change time, or secondarily, the time of target appearance
Average Speed	Average road speed over the 15 second time history
Driver Identification Number	Modeled as a random effect blocking variable to account for behavior differences between drivers
Age	The age of each driver
Sex	Driver Gender
Years with a CDL	The number of years since the driver first gained his CDL
Years with US Xpress	The number of years since the driver was hired by US Xpress

The results of the conditional analysis of crash probabilities are presented in Section 5.1.1. The conditional analysis models are used as a compliment to the empirical models discussed earlier. The conditional models should yield consistent results and aid in the interpretation of those results.

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5.0 FINDINGS

Results from the Volvo IVI FOT are presented for each of the three evaluation goals, described in Section 3:

- Goal A: Achieve an in-depth understanding of the safety benefits of intelligent vehicle safety systems (IVSS).
- Goal B: Assess user (driver) acceptance and human factors.
- Goal C: Analyze the ratio of life-cycle benefits to costs for deploying the IVSS on a societal level.

Within each goal area, results are organized according to the objectives, hypotheses, and measures defined in Section 4.3 (Analysis Approach).

5.1 Goal A: Achieve an In-Depth Understanding of Safety Benefits

This section presents findings related to the safety benefits of selected combinations of in-vehicle safety systems tested in this FOT. In particular, the benefits of (1) using a CWS, (2) using the bundled systems (CWS, ACC, and AdvBS) compared to using no IVSS in a tractor-trailer unit, as well as (3) using the bundled systems compared to using CWS only were evaluated. Hence, the incremental benefits of ACC and AdvBS could be determined. Highlights of the results, organized by the three safety objectives, are presented below:

The first objective (Section 5.1.1) seeks to **determine if vehicles equipped with the various combinations of systems encounter fewer rear-end 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. For rear-end crashes, the conflicts of interest are defined in terms of the reaction time and deceleration rate that are needed to avoid the crash.

- Under the conditions observed in the FOT, it was estimated that a CWS can help eliminate approximately 52 percent of the conflicts in which the truck is traveling at a constant speed and begins to overtake another vehicle moving more slowly.
- Furthermore, it was estimated that the addition of ACC and AdvBS can help eliminate an additional 9 percent (total of 61 percent) of the same types of conflicts.
- Across all conflict types, it is estimated that the bundled systems help reduce the total number of truck-initiated rear-end crashes by 28 percent.
- The CWS is most effective at reducing rear-end conflicts when the truck is traveling at higher speeds (> 55 mph).

Drivers were also surveyed to determine their perception of the systems. Results of those surveys are contained in this report; specific survey questions can be found in Battelle (2004). The vast majority of the drivers participating in the drivers' survey believe that the CWS and

AdvBS technologies are beneficial and prefer to drive trucks equipped with these systems. Approximately 80 percent of the drivers prefer to drive trucks with CWS because they believe it increases their ability to avoid rear-end conflicts. Over 90 percent of the drivers said they prefer to drive trucks with AdvBS because they believe it can help stop the truck sooner. Driver reactions to the ACC were mixed: 53 percent prefer to use ACC and 44 percent prefer not to use it.

The second objective (Section 5.1.2) asks **whether these IVSS help drivers drive more safely.** Because the severity of brake application, road speed, following distance and following time are parameters known to affect the likelihood of rear-end crashes, these parameters were compared among the three groups of vehicles equipped with the different combinations of systems: no technologies, CWS, CWS + ACC + AdvBS.

- There were no significant differences in brake application measures or average road speed;
- Drivers with the CWS tended to maintain greater following distances than drivers without the CWS.
- Drivers with ACC and the AdvBS were less likely to operate the truck in a manner that would result in very short times to collision (0.5 to 1.0 seconds) than drivers without these systems—regardless of whether they were equipped with CWS.

Drivers were also surveyed to evaluate their opinions on whether or not they drive more safely with these systems. Almost 80 percent of the drivers reported that CWS helps reduce the risk of accidents because it makes them more vigilant, helps them maintain a safer following distance, and increases their reaction time and awareness. Approximately 60 percent reported that they changed their driving habits. A smaller percentage of drivers (50 percent) reported that the ACC reduces accident risk by helping to maintain safer distances, but 18 percent thought it increased risk due to reduced attentiveness and driver control. Although three-quarters of the drivers believed that AdvBS improved driving safety due to improved braking ability, 55 percent felt that the system did not change their driving behaviors, while the rest felt that it changed driving behaviors somewhat or a lot.

Section 5.1.3 presents findings for Objective A.3, i.e. involving the extrapolation of 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 nationwide fleets were equipped with these systems.** Two nationwide fleets were targeted: (1) all class 7 and 8 tractors pulling at least one trailer, and (2) all large trucks (> 10,000 lbs. GVW).

- Assuming that the US Xpress drivers participating in this FOT are representative of drivers in similar fleets, it is estimated that deployment of CWS on all 1.75 million tractor-trailers in U.S. can help avoid 4,700 tractor-trailer rear-end crashes each year, along with 2,500 associated injuries and 96 fatalities.
- Deployment of the bundled system (CWS + ACC + AdvBS) can help avoid 6,500 crashes, 3,400 injuries, and 122 fatalities.

Tractor-trailers are responsible for nearly half of all rear-end crashes involving large trucks (> 10,000 lbs. gross vehicle weight, or GVW), yet they represent less than 25 percent of the large truck population. Thus, even if these systems were equally effective at reducing crashes on all large trucks, the benefit per unit deployed would be substantially less under the broader deployment.

The following sections discuss findings for the three objectives of the independent evaluation in more detail.

5.1.1 Objective A.1 Determine Reductions in Rear-End Conflicts and Crash Probabilities with IVSS

This section addresses the first and critical safety objective of the study, specifically to estimate the reduction in the rates of driving conflicts and crashes that are attributable to the use of the advanced safety systems in applications similar to those of US Xpress.

The analysis was conducted according to the procedure in Section 4.3.3. These steps are repeated here.

1. Select conflict events from the set of all time history data.
2. Assign conflicts to three levels of severity according to the thresholds in Table 4.3-1.
3. Assign conflicts to three groups based on their truck configuration.
4. Allocate each conflict to one of the three conflict categories from Table 4.2-4.
5. Apply an analytical model to each conflict to determine the conflict severity by calculating the time the driver could have waited to take action (lag time).
6. Compute summary statistics of conflict severity for each combination of kinematic threshold and truck configuration.
7. Transform conflict severity to the probability of crash given the conflict category for each group and then calculate the prevention ratio.
8. Assign each conflict to the histogram during which it occurred and calculate exposure ratios for each combination of kinematic threshold and truck configuration.
9. Compute the crash reduction ratios.
10. Compute the percent reduction in crashes.

The results described in this section begin mainly with Step 5 above. Steps 1 through 4 have been discussed in detail in Section 4. We begin with a brief summary of the analytical methods.

Three major quantities were estimated through the 10 steps.

- First, a "prevention ratio" was calculated to determine if the systems are effective at helping drivers avoid a crash after they enter a driving conflict situation. For each conflict category, the prevention ratio compared the conditional probabilities of a rear-end crash (with IVSS versus without IVSS), given that the driver is in a specific category of driving conflict. A prevention ratio less than 1 suggests that the IVSS helps the driver avoid crashes in that type of driving conflict. The prevention ratio is calculated in steps 5 through 7.

- Second, an estimated "exposure ratio" was calculated to determine the efficacy of the systems in helping drivers avoid the various driving conflict types that may lead to rear-end crashes (step 8). For each conflict type, the exposure ratio compares the estimated probability that a driver will encounter the given conflict type when using the IVSS (with IVSS) to the estimated probability that he or she will encounter the same conflict type when not using the IVSS (without IVSS). An exposure ratio less than 1 suggests that the IVSS helps the driver avoid that driving conflict type.
- Third, the exposure ratio and the prevention ratio were combined to estimate a "crash reduction ratio," which is used to calculate the percent reduction in crashes that can be realized using IVSS technologies (steps 9 and 10).

The exposure ratio analysis addresses hypothesis A.1-1: Drivers using IVSS will have fewer conflicts. The prevention and crash reduction ratios both address hypothesis A.1-2: Drivers using IVSS will have fewer rear-end crashes. At each stage of the overall safety benefits analysis, additional conditional analyses were performed as a function of driving conditions to characterize the conditions under which the systems might be more or less effective at producing safety benefits. These conditional analyses are included at the end of Section 5.1.1. The data used for the conditional analyses also followed the 10-step process.

Depending on the severity of a driving conflict as defined by its threshold values, the safety benefit of a particular system may be represented as an exposure benefit or a prevention benefit. CWS and ACC are both anticipated to help reduce exposures to severe conflicts, i.e., reduce the exposure ratio, because the CWS warns the driver of possible conflicts and the ACC helps the driver maintain safer following distances. On the other hand, the AdvBS is expected to produce a prevention benefit, i.e., reduce the prevention ratio, because the system improves braking capabilities during conflict situations.

Following a brief description of the data used to perform the analysis, the results are presented according to the 10-step process.

5.1.1.1 Onboard Driving Data and Conflict Identification Summary

Section 4 of the report gives the complete details of the data collection and conflict identification process. Highlights of that process include data collection and conflict identification.

As detailed in Section 4.2.2, data were collected in two formats to address Objective A.1, which was to evaluate the frequency of driving conflicts and the probability of crashes given a conflict category:

- Driving summaries were collected in histogram format to summarize selected driving parameters during 3-hour time periods over which the vehicle was operated. Histogram files included information on vehicle miles traveled (VMT), vehicle speed, following distance, and time intervals.
- Important vehicle movement and safety system parameters during potential safety critical events were recorded in 15-second time histories. Data collection was triggered whenever the vehicle was involved in a situation potentially indicative of a rear-end

driving conflict. Because of the wide range of criteria used in the triggering schemes, not all time histories collected were necessarily driving conflicts.

Data were validated, and each time history file was matched with its corresponding histogram file to estimate conflict rates and to perform conditional analyses of system effectiveness as a function of driving conditions.

Driving conflicts are situations known to lead to a particular type of crash if the driver takes no action or insufficient action. For a given type of crash, several driving conflicts can be identified. They are defined by specific criteria, i.e., by selected parameters exceeding threshold values. Criteria for defining driving conflicts known to lead to rear-end crashes are based on the driver reaction time and deceleration rate needed to avoid a rear-end crash. In general, a conflict is defined as a situation where there is a lead vehicle in the lane of the following vehicle and where to avoid a rear-end crash according to the vehicles' kinetic motion equations, the truck must begin to decelerate at a given rate (e.g., 0.25g) within a given amount of time (e.g., 1.5 seconds). That behavior is defined by the LVS/LVCS and LVD equations (KME equations) described in Section 4.

The threshold values defining conflicts (driver reaction time and deceleration rate) can be adjusted to generate a number of conflicts sufficient for making statistical comparisons, while attempting to ensure that the conflicts represent meaningful safety events. Figure 5.1-1 summarizes the approach taken to determine the number of conflicts used in the safety benefits analysis.

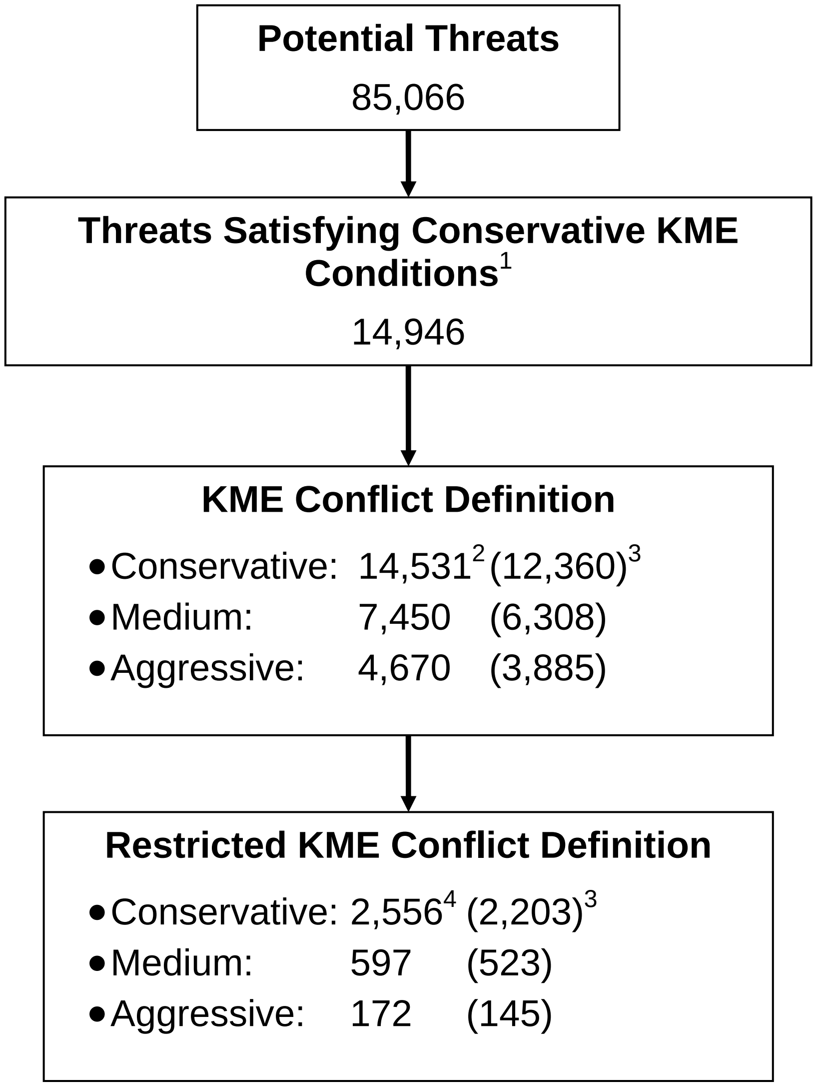
In the first step, a minimum requirement for a conflict was established by applying kinetic motion equations (KMEs) with "conservative" threshold values (deceleration rate of 8 ft/s^2 (0.25 g) and reaction time of 1.5 seconds). As shown in Figure 5.1-1, 14,946 potential threats meeting this criterion were identified.

These potential threats were then analyzed using a kinematic analysis described in Section 4.3 to further characterize the severity of the threats. A few of these 14,946 potential threats were further screened out as driving conflicts because kinematic analysis revealed the target to not be a threat. After additional non-threats were removed, 14,531 conflicts remained. The KME Conflict Definition refers to this set of conflicts.

In order to test the sensitivity of the analysis results to the choices of threshold metrics used in this evaluation, two additional threshold criteria were considered. The "medium" criterion assumes that the driver will have to react within 1.0 second at a deceleration rate of 10 ft/s^2 to avoid a crash, and the "aggressive" criterion assumes a reaction time of 0.5 second with a deceleration rate of 12 ft/s^2. The number of potential threats meeting each of these criteria are shown as well. Threats meeting the medium and aggressive criteria are subsets of the conservative threats by definition.

The threats must also be matched to valid histogram data to be used to estimate the exposure ratio because the histograms contain information on vehicle miles traveled. As shown in

Figure 5.1-1, the total number of threats meeting the conservative criteria that could be matched to valid histogram data were 12,360.



1. Threats that satisfy the kinetic motion equation (KME) condition that the driver must decelerate at 8 ft/s^2 within 1.5 sec. in order to avoid the crash using the LVS/LVCS and LVD equations.
2. Threats that satisfy the conservative KME condition after application of the kinematic severity algorithm and removal of additional non-threat time histories. Medium and aggressive KME conditions are defined using 10 ft/s^2 (0.31 g) deceleration within 1.0 sec and 12 ft/s^2 (0.37 g) deceleration within 0.5 sec, respectively.
3. Numbers in parentheses represent the numbers of conflicts that were matched to histograms – thus, could be used in the estimation of conflict rates.
4. Threats that satisfy the conservative KME condition after application of the kinematic severity algorithm with the additional restriction that the severity algorithm predict a lag time less than 15 seconds.

Figure 5.1-1. Determination of Conflicts from the Set of Potential Threats

Finally, the Restricted KME Conflict Definition further subsets the conflicts according to the results of the kinematic severity algorithm. The algorithm attempts to find the time that the driver could have waited to react (lag time) and still have avoided a collision. Only conflicts with lag times of less than 15 seconds are included here. The total number of threats meeting the conservative criteria under the restricted KME conflict definition and with associated histogram data is 2,203.

Results of the analysis are presented in the order of the 10 step process from Section 4, beginning with step 5.

Step 5. Apply an Analytical Model to Each Conflict to Determine the Conflict Severity by Calculating the Time the Driver could have Waited to take Action (Lag Time)

Figure 5.1-2 shows the histogram of lag times calculated by the kinematic analysis of Section 4.3 for all 14,946 threats that satisfied the conservative KME equations. First, the additional non-threat situations must be removed from this set. Those non-threats are located in the 1/6 second bin. The resulting 14,531 time histories meet the KME Conflict Definition. These time histories are then further subset into the appropriate fleets. Figure 5.1-3 shows the histograms for the KME Conflict Definition for the Baseline, Control, and Test fleets respectively. All conflict categories are represented in all histograms shown in this step. Also, since the medium and aggressive thresholds are subsets of the conservative threshold, conflicts from each of those thresholds are represented as well.

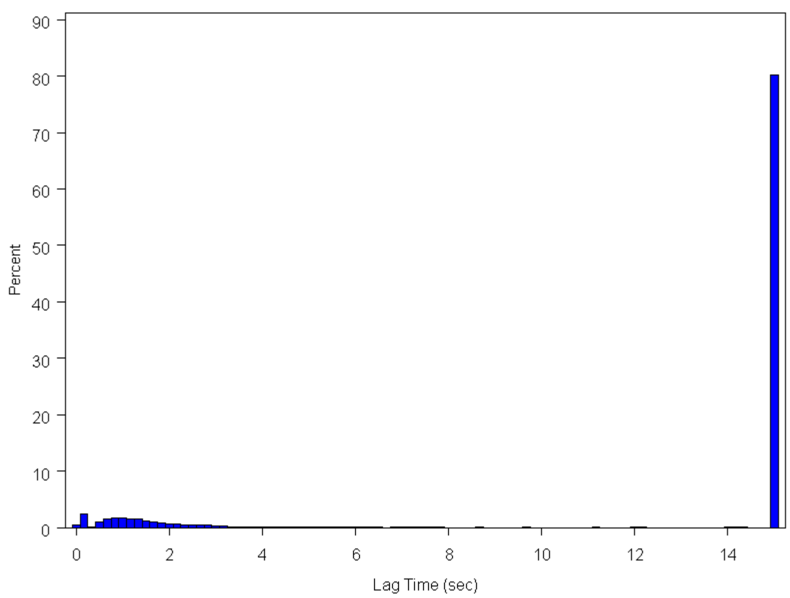


Figure 5.1-2. Histogram of Smallest Lag Times Resulting in a Crash for all Driving Conflicts Satisfying the KME Equations

(14,946 Time Histories are Represented)

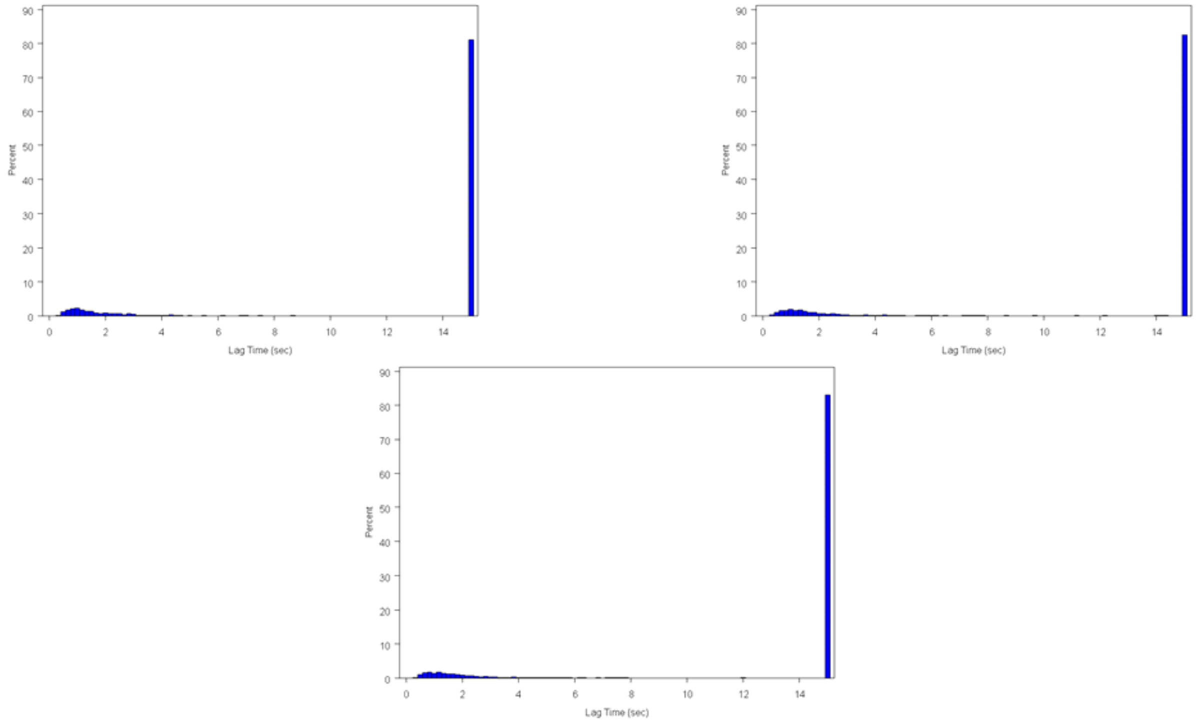


Figure 5.1-3. Histogram of Smallest Lag Times Resulting in a Crash Satisfying the KME Conflict Definition

For the Baseline Trucks 2,088 Time Histories are Represented (top left); the Control Fleet Includes 5,908 Time Histories (top right) and the Test Fleet Includes 6,535 (bottom)

For the Restricted KME Conflict Definition, the time histories in the 15-second bin are also removed for the reasons discussed in Section 4.3. For the conservative threshold, 2,556 time histories were left once the 15-second bin was removed. These time histories were also subset according to fleet, and they are shown in Figures 5.1-4a through 5.1-4c for the Baseline, Control, and Test fleets respectively.

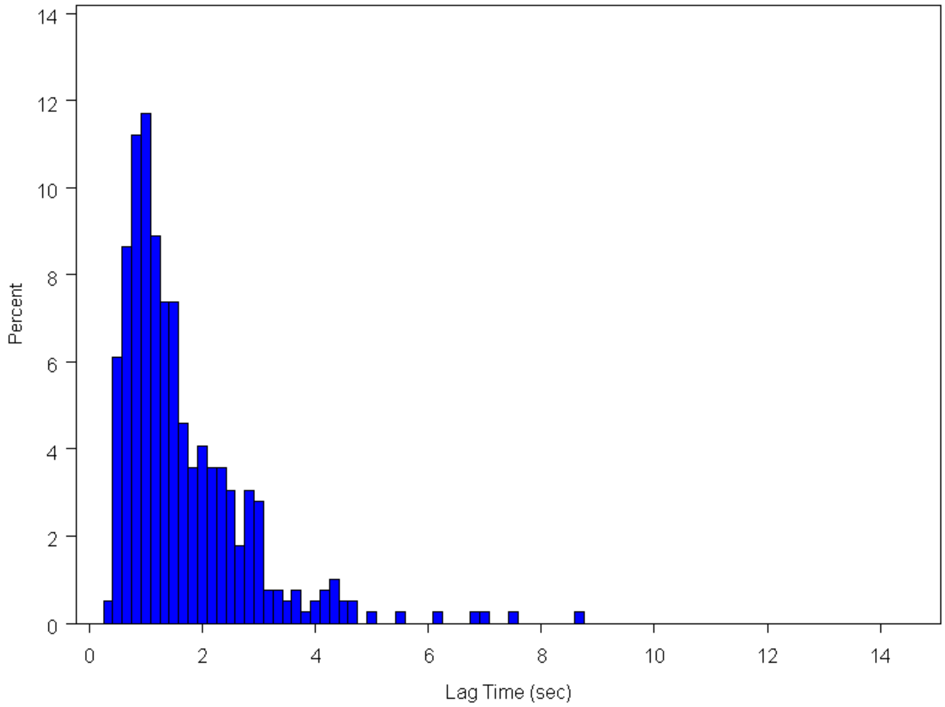


Figure 5.1-4a. Histogram of Smallest Lag Times Resulting in a Crash for Baseline Trucks Satisfying the Restricted KME Conflict Definition

(393 Time Histories are Represented)

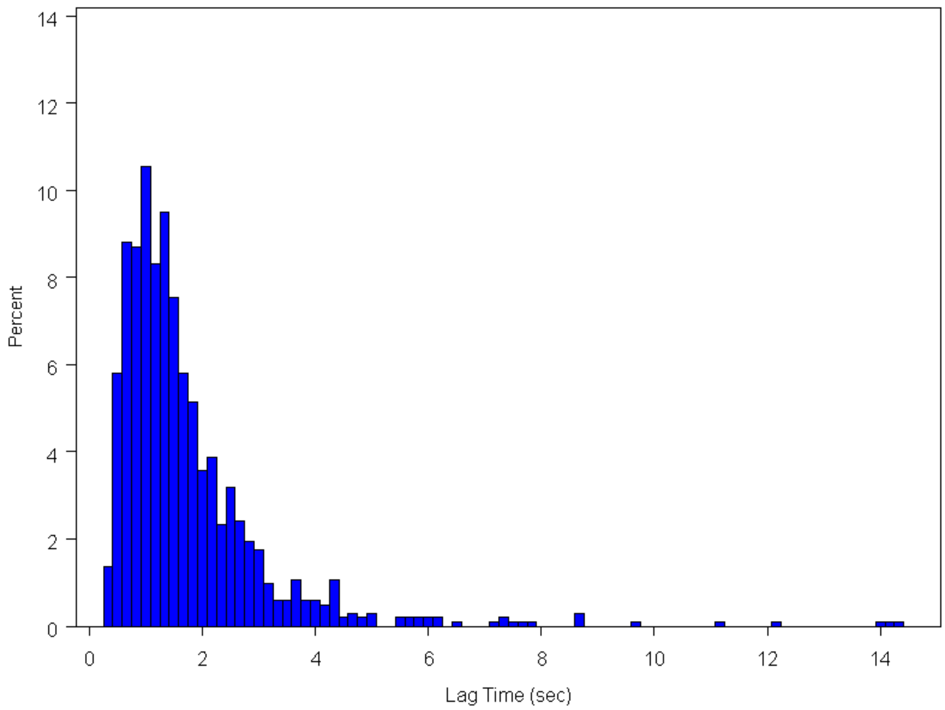


Figure 5.1-4b. Histogram of Smallest Lag Times Resulting in a Crash for Control Trucks Satisfying the Restricted KME Conflict Definition

(1033 Time Histories are Represented)

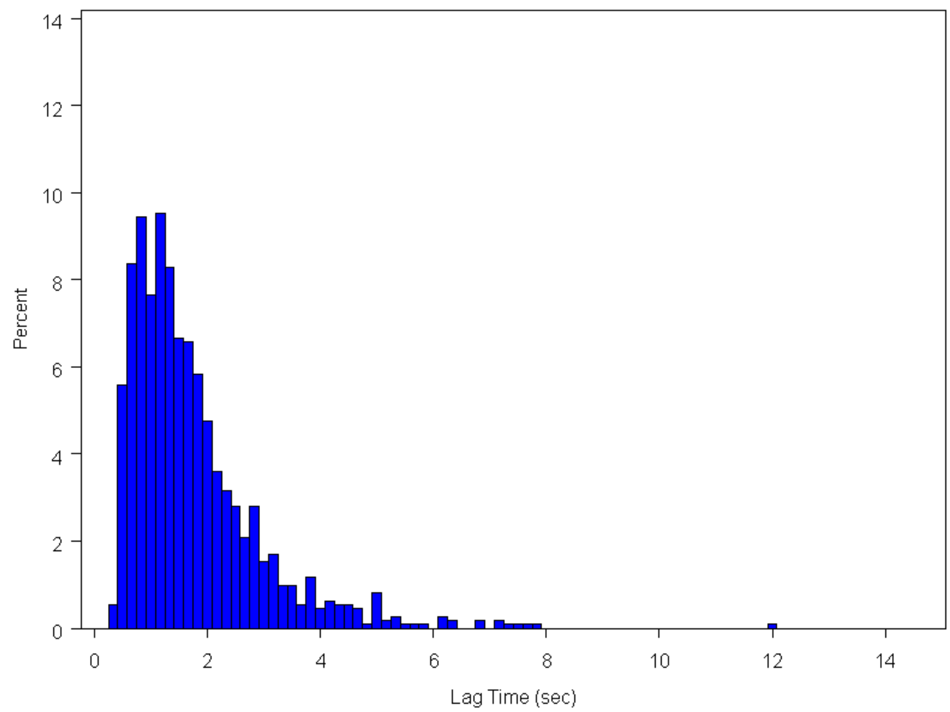


Figure 5.1-4c. Histogram of Smallest Lag Times Resulting in a Crash for Test Trucks Satisfying the Restricted KME Conflict Definition

(1112 Time Histories are Represented)

Step 6. Compute Summary Statistics of Conflict Severity for Each Combination of Kinematic Threshold and Truck Configuration

The results in this step follow the equations in Section 4.3.

Restricted KME Conflict Definition

First, the geometric mean lag times were calculated for each conflict category, fleet, and threshold for the Restricted KME Conflict Definition. Table 5.1-1 gives the results of the geometric mean calculation for the conservative, medium, and aggressive thresholds respectively. Table 5.1-1 contains the three fleets subset by the three conflict categories. The number of conflicts is shown for each subset in addition to the geometric mean lag time. The geometric mean severity corresponds to the median of the histograms in Figures 5.1-4a through 5.1-4c once they are subset appropriately.

Table 5.1-1. Conflict Severity Measures by Fleet, Threshold, and Conflict Category

(Restricted KME Conflict Definition)

Fleet	Conflict Category	Thresholds					
		Conservative		Medium		Aggressive	
		No. of Conflicts	Geometric Mean Severity (sec)	No. of Conflicts	Geometric Mean Severity (sec)	No. of Conflicts	Geometric Mean Severity (sec)
Baseline	Constant Speed	41	1.220	12	1.551	3	1.326
	Slowing	276	1.420	61	1.489	19	1.463
	Lane Change	45	1.468	13	1.223	7	1.100
Control	Constant Speed	90	1.117	20	1.472	6	1.340
	Slowing	770	1.413	175	1.659	46	1.692
	Lane Change	119	1.626	29	1.485	6	1.103
Test	Constant Speed	89	1.264	16	1.534	4	1.421
	Slowing	826	1.480	188	1.712	54	1.707
	Lane Change	129	1.570	25	1.995	5	1.581

Note: The total number of conflicts shown here do not match the histograms in Figures 5.1-4a through 5.1-4c because the conflicts in the "other" category have been removed.

KME Conflict Definition

In the KME Conflict Definition, a summary statistic of the probability of a crash given a conflict category is calculated instead of a summary statistic about the lag time itself. This calculation follows the equation in Section 4.3 with a_i set equal to one. The a_i parameter is calculated separately based on this data. Table 5.1-2 gives the number of time histories included in each calculation and the results of the calculation of the mean probability of a crash given a conflict category.

Step 7. Transform Conflict Severity to the Probability of a Crash given the Conflict Category for Each Group and then Calculate the Prevention Ratio

In order to estimate crash probabilities given conflict categories, the a_i parameter must first be calculated. Table 5.1-3 shows the values computed for the joint probability of a crash and a conflict category ($P_{GES}(S_i,C)$). For example, in the constant speed category, the joint probability of a crash and conflict category is equal to the rate of crashes per 10,000 miles from GES ($P_{GES}(C)$) times the probability (from GES) that a conflict is in a conflict category given that a crash occurred ($P_{GES}(S_i|C)$): $0.002041 * 0.40 \approx 0.000808$. Not all significant figures are shown in the table. The rate of crashes per 10,000 miles from GES includes conflicts from the three conflict categories shown, as well as others in GES.

Table 5.1-2. Mean Probability of a Crash by Fleet, Threshold, and Conflict Category with a_i Set Equal to One

(KME Conflict Definition)

Fleet	Conflict Category	Conservative		Medium		Aggressive	
		No. of Conflicts	Mean Probability (a_i=1)	No. of Conflicts	Mean Probability (a_i=1)	No. of Conflicts	Mean Probability (a_i=1)
Baseline	Constant Speed	734	0.009	600	0.003	534	0.001
	Slowing	1155	0.033	441	0.017	171	0.014
	Lane Change	130	0.046	44	0.043	17	0.066
Control	Constant Speed	1819	0.009	1418	0.002	1255	0.001
	Slowing	3548	0.030	1439	0.014	592	0.009
	Lane Change	412	0.039	120	0.034	41	0.028
Test	Constant Speed	1884	0.007	1437	0.002	1262	0.001
	Slowing	4008	0.027	1687	0.013	689	0.010
	Lane Change	484	0.034	148	0.018	65	0.009

Note: The total number of conflicts shown here do not match the histograms in Figure 5.1-3 because the conflicts in the "other" category have been removed.

Table 5.1-3. Calculation of the Rate of Rear-end Crashes Preceded by Each Conflict Category in GES

Conflict Category	$P_{GES}(C)$	$P_{GES}(S_i\|C)$	$P_{GES}(S_i,C)$
Constant Speed	0.002041	0.40	0.000808
Slowing		0.43	0.000887
Lane Change		0.02	0.000034

Next, the empirical conflict rates for the Baseline fleet must be computed in order to determine the appropriate normalizing constant a_i and transform severity into probability. Tables 5.1-4a and 5.1-4b give the empirical conflict rates for the Restricted KME Conflict Definition and the KME Conflict Definition respectively. The counts in each cell of the tables are found after matching the appropriate conflicts to each driving data histogram period and calculating the VMT associated with those driving histogram periods.

Table 5.1-4a. Calculation of the Empirical Conflict Rate per 10,000 Miles for the Baseline Fleet (Restricted KME Conflict Definition)

Conflict Category	Measure	Baseline Fleet		
		Conservative	Medium	Aggressive
Constant Speed	Count	31	12	3
	Rate[1]	*0.82*	*0.32*	*0.08*
Slowing	Count	208	49	14
	Rate[1]	*5.53*	*1.30*	*0.37*
Lane Change	Count	38	10	4
	Rate[1]	*1.01*	*0.27*	*0.11*
VMT		375,935		

1. Rate is in conflicts per 10,000 miles.

Table 5.1-4b. Calculation of the Empirical Conflict Rate per 10,000 Miles for the Baseline Fleet (KME Conflict Definition)

Conflict Category	Measure	Baseline Fleet		
		Conservative	Medium	Aggressive
Constant Speed	Count	637	531	474
	Rate[1]	*16.94*	*14.12*	*12.61*
Slowing	Count	891	351	135
	Rate[1]	*23.70*	*9.34*	*3.59*
Lane Change	Count	106	33	10
	Rate[1]	*2.82*	*0.88*	*0.27*
VMT		375,935		

1. Rate is in conflicts per 10,000 miles.

Now, the probability of a crash given a conflict category for the Baseline fleet ($P_B(C|S_i)$) can be calculated from the empirical conflict rate ($P_B(S_i)$) and the GES joint probability of a crash and a conflict category. The assumption in this calculation is that the Baseline fleet is like the national GES statistics. This calculation is shown in Tables 5.1-5a and 5.1-5b for the Restricted KME Conflict Definition and the KME Conflict Definition respectively. For example, in the constant speed category, the probability of a crash for a baseline vehicle given the constant speed category is equal to the joint probability from GES of a crash and a conflict category divided by the rate of conservative driving conflicts per 10,000 miles for the baseline fleet: $0.000808/0.82 \approx 0.000980$.

Table 5.1-5a. Calculation of $P_B(C|S_i)$ for each KME Threshold (Restricted KME Conflict Definition)

Conflict Category	$P_{GES}(S_i,C)$	Conservative		Medium		Aggressive	
		$P_B(S_i)$	$P_B(C\|S_i)$	$P_B(S_i)$	$P_B(C\|S_i)$	$P_B(S_i)$	$P_B(C\|S_i)$
Constant Speed	0.000808	0.82	0.000980	0.32	0.002531	0.08	0.010123
Slowing	0.000887	5.55	0.000160	1.30	0.000681	0.37	0.002382
Lane Change	0.000034	1.01	0.000033	0.27	0.000127	0.11	0.000317

Table 5.1-5b. Calculation of $P_B(C|S_i)$ for each KME Threshold (KME Conflict Definition)

Conflict Category	$P_{GES}(S_i,C)$	Conservative		Medium		Aggressive	
		$P_B(S_i)$	$P_B(C\|S_i)$	$P_B(S_i)$	$P_B(C\|S_i)$	$P_B(S_i)$	$P_B(C\|S_i)$
Constant Speed	0.000808	16.94	4.8E-05	14.12	5.7E-05	12.61	6.4E-05
Slowing	0.000887	23.70	3.7E-05	9.34	9.5E-05	3.59	2.5E-04
Lane Change	0.000034	2.82	1.2E-05	0.88	3.8E-05	0.27	1.3E-04

Finally, each a_i can be calculated along with the probabilities of a crash given a conflict category. Tables 5.1-6a through 5.1-6c show this calculation for the Restricted KME Conflict Definition and the three KME thresholds. First, a_i is computed in this example for the Baseline Constant Speed values in Table 5.1-6a; a_i is equal to the probability of a crash given a conflict category for the baseline fleet, conservative threshold from Table 5.1-5a times the geometric mean severity for the baseline fleet, constant speed category from Table 5.1-1: $0.000980 * 1.220 \approx 0.001195$.

Then each probability of a crash given a conflict category is calculated for the control and test fleets. The probability of a crash given a conflict category is equal to a_i divided by the geometric mean severity. For example, using the Control fleet Slowing values in Table 5.1-6a: $0.000227/1.413 \approx 0.000161$.

Table 5.1-6a. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (Restricted KME Conflict Definition with the Conservative Threshold)

Fleet	Conflict Category	Number of Conflicts	Geometric Mean Severity (sec)[1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	41	1.220	0.001195	0.000980[2]
	Slowing	276	1.420	0.000227	0.000160[2]
	Lane Change	45	1.468	0.000049	0.000033[2]
Control	Constant Speed	90	1.117		0.001071
	Slowing	770	1.413		0.000161
	Lane Change	119	1.626		0.000030
Test	Constant Speed	89	1.264		0.000946
	Slowing	826	1.480		0.000153
	Lane Change	129	1.570		0.000031

1. From Table 5.1-1
2. From Table 5.1-5a

Table 5.1-6b. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (Restricted KME Conflict Definition with the Medium Threshold)

Fleet	Conflict Category	Number of Conflicts	Geometric Mean Severity (sec) [1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	12	1.551	0.003924	0.002531[2]
	Slowing	61	1.489	0.001014	0.000681[2]
	Lane Change	13	1.223	0.000155	0.000127[2]
Control	Constant Speed	20	1.472		0.002666
	Slowing	175	1.659		0.000611
	Lane Change	29	1.485		0.000105
Test	Constant Speed	16	1.534		0.002559
	Slowing	188	1.712		0.000592
	Lane Change	25	1.995		0.000078

1. From Table 5.1-1
2. From Table 5.1-5a

Table 5.1-6c. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (Restricted KME Conflict Definition with the Aggressive Threshold)

Fleet	Conflict Category	Number of Conflicts	Geometric Mean Severity (sec) [1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	3	1.326	0.013427	0.010123[2]
	Slowing	19	1.463	0.003486	0.002382[2]
	Lane Change	7	1.100	0.000349	0.000317[2]
Control	Constant Speed	6	1.340		0.010024
	Slowing	46	1.692		0.002060
	Lane Change	6	1.103		0.000316
Test	Constant Speed	4	1.421		0.009451
	Slowing	54	1.707		0.002043
	Lane Change	5	1.581		0.000221

1. From Table 5.1-1
2. From Table 5.1-5a

Tables 5.1-7a through 5.1-7c similarly show the calculations for the KME Conflict definition. First, a_i is computed in this example for the Baseline Constant Speed values in Table 5.1-7a; a_i is equal to the probability of a crash given a conflict category for the baseline fleet, conservative threshold from Table 5.1-5b divided by the mean probability with a_i =1 for the baseline fleet, constant speed category: $0.000048 / 0.009 \approx 0.0.005074$.

Table 5.1-7a. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (KME Conflict Definition with the Conservative Threshold)

Fleet	Conflict Category	Number of Conflicts	Mean Probability (a_i=1) [1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	734	0.009	0.005074	0.000048[2]
	Slowing	1155	0.033	0.001147	0.000037[2]
	Lane Change	130	0.046	0.000260	0.000012[2]
Control	Constant Speed	1819	0.009		0.000044
	Slowing	3548	0.030		0.000035
	Lane Change	412	0.039		0.000010
Test	Constant Speed	1884	0.007		0.000038
	Slowing	4008	0.027		0.000032
	Lane Change	484	0.034		0.000009

1. From Table 5.1-2
2. From Table 5.1-5b

Table 5.1-7b. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (KME Conflict Definition with the Medium Threshold)

Fleet	Conflict Category	Number of Conflicts	Mean Probability (a_i=1) [1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	600	0.003	0.021226	0.000057 [2]
	Slowing	441	0.017	0.005471	0.000095 [2]
	Lane Change	44	0.043	0.000898	0.000039 [2]
Control	Constant Speed	1418	0.002		0.000043
	Slowing	1439	0.014		0.000077
	Lane Change	120	0.034		0.000031
Test	Constant Speed	1437	0.002		0.000032
	Slowing	1687	0.013		0.000071
	Lane Change	148	0.018		0.000016

1. From Table 5.1-2
2. From Table 5.1-5b

Table 5.1-7c. Conflict Severity Measures and $P(C|S_i)$ by Fleet and Conflict Category (KME Conflict Definition with the Aggressive Threshold)

Fleet	Conflict Category	Number of Conflicts	Mean Probability (a_i=1) [1]	Constant (a_i)	$P(C\|S_i)$
Baseline	Constant Speed	534	0.001	0.084543	0.000064 [2]
	Slowing	171	0.014	0.017441	0.000247 [2]
	Lane Change	17	0.066	0.001939	0.000128 [2]
Control	Constant Speed	1,255	0.001		0.000059
	Slowing	592	0.009		0.000152
	Lane Change	41	0.028		0.000055
Test	Constant Speed	1,262	0.001		0.000049
	Slowing	689	0.010		0.000171
	Lane Change	65	0.009		0.000018

1. From Table 5.1-2
2. From Table 5.1-5b

Then each probability of a crash given a conflict category is calculated for the control and test fleets. The probability of a crash given a conflict category is equal to a_i times the mean probability for that category with a_i =1. For example, using the Control fleet Slowing Values in Table 5.1-7a: $0.030 * 0.001147 \approx 0.000035$.

5.1.1.2 Determination of the Prevention Ratios

Restricted KME Conflict Definition

Table 5.1-8 contains the estimated prevention ratios for each conflict category and threshold. These ratios represent the relative amount by which the probability of a crash is reduced due to the IVSS compared to the probability without the system. Both probabilities are conditional on the event that a conflict has occurred. A ratio less than 1 represents a reduced probability of a crash and thus a safety benefit. For example, with the conservative threshold, constant speed category, for the effect of the CWS, the prevention ratio is equal to the probability of a conflict given the constant speed category for the conservative threshold control fleet divided by the same quantity for the baseline fleet (values in Table 5.1-6a): $0.001071/0.000980 \approx 1.09$.

Using the conservative threshold, there are no prevention ratios significantly different from one. Most of the conservative prevention ratios are less than one, suggesting that the systems offer a positive prevention benefit. However, none of the estimates are statistically different from 1.0 at the 95-percent confidence level.

As the severity of the conflict threshold is increased to the medium level, the bundled system has a statistically significant effect on preventing crashes during lane change conflicts. Ratios that are significantly different from one at the 0.05 level are marked with an asterisk (*) in Table 5.1-8. The estimated reduction in conditional crash rates involving lane change maneuvers using CWS is 18 percent = (1-0.82)*100 percent; although this estimate is not statistically significant. **When the ACC and AdvBS are added to the CWS, there is a statistically significant reduction in crash rates of 39 percent.**

Table 5.1-8. Estimated Prevention Ratios with Standard Errors by Conflict Type and Threshold (Restricted KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	1.09	0.14	0.88	0.08	0.97	0.12
Slowing	1.00	0.04	0.95	0.03	0.96	0.04
Lane Change	0.90	0.10	1.04	0.09	0.94	0.10
Medium						
Constant Speed	1.05	0.28	0.96	0.23	1.01	0.28
Slowing	0.90	0.07	0.97	0.06	0.87	0.07
Lane Change	0.82	0.14	0.74	0.14	0.61*	0.11
Aggressive						
Constant Speed	0.99	0.37	0.94	0.53	0.93	0.54
Slowing	0.86	0.12	0.99	0.12	0.86	0.13
Lane Change	1.00	0.34	0.70	0.29	0.70	0.22

* Statistically significant with 95-percent confidence.

Each of the three IVSS technologies may be contributing to this benefit. For example, when the truck driver changes lanes and encounters another vehicle moving more slowly, the crash might be avoided because the CWS alerted the truck driver that there was a conflict. Alternatively, if the truck driver was using ACC at the time, the system might have activated and begun to slow the truck. Finally, the driver could have been able to avoid the crash because the AdvBS provided improved braking ability. These possibilities are explored further using the conditional analysis and the evaluation of the impact of IVSS on safe driving behaviors.

Finally, Table 5.1-8 also includes the prevention ratio estimates based on conflicts defined by the aggressive threshold. In general, the results are similar to those obtained using the medium threshold; however, the smaller sample size did not yield statistically significant estimates.

Figure 5.1-5 contains a graphical representation of the prevention ratios with error bars representing an approximate 95-percent confidence interval. The confidence interval assumes a lognormal distribution of the ratio. A lognormal distribution was chosen because it is a strictly positive distribution, appropriate for a ratio of the geometric mean of quantities observed to be roughly lognormally distributed themselves. A confidence interval constructed by using plus or minus 2 standard deviations can sometimes incorrectly yield bounds less than zero. Error bars that do not contain one are statistically significant. The center black line of the error bar is the empirical estimate.

KME Conflict Definition

Table 5.1-9 and Figure 5.1-6 present the same set of results for the KME Conflict Definition. There are more statistically significant prevention ratios in the KME Conflict Definition.

Table 5.1-9 shows that there are statistically significant results for the Lane Change category in both the medium and aggressive thresholds, for both the effect of the ACC and AdvBS and the Bundled System. The reasoning for this follows from above, with the additional significance in the aggressive threshold for very severe conflicts. Also the Bundled System has a statistically significant ability to prevent Slowing conflicts in the conservative category. In slowing situations, the AdvBS and CWS technologies may have the most impact. Here, the ability to brake quickly can keep the following vehicle farther from a conflict situation, and the CWS can warn of a vehicle that stopped more quickly ahead than anticipated.

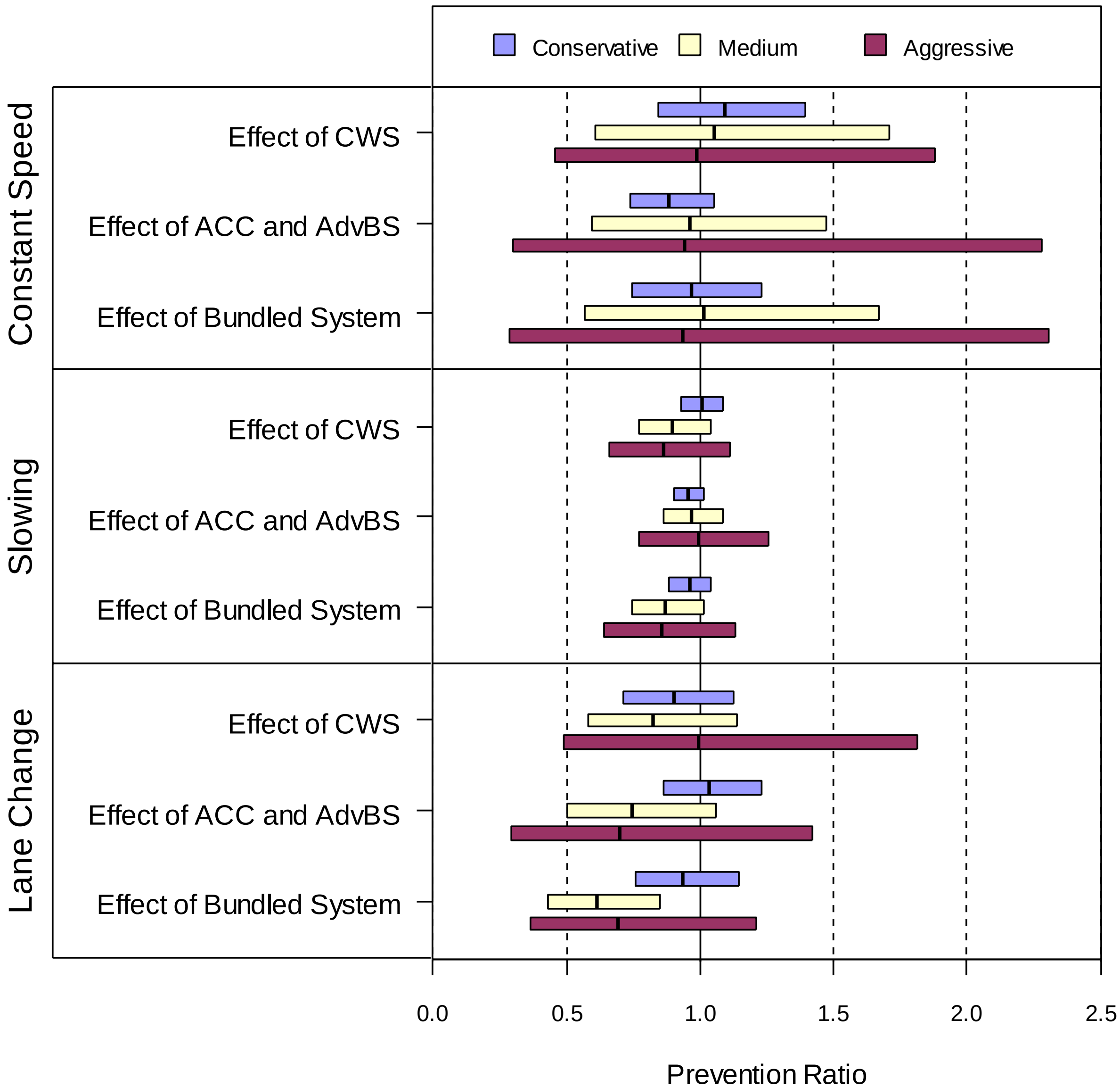


Figure 5.1-5. Graphical Representation of Prevention Ratios with 95-Percent Confidence Intervals (Restricted KME Conflict Definition)

The area to the left of the vertical 1.0 line represents Benefits, and the area to the right represents Disbenefits

Table 5.1-9. Estimated Prevention Ratios with Standard Errors by Conflict Type

(KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	0.92	0.20	0.86	0.15	0.79	0.17
Slowing	0.93	0.07	0.91	0.05	0.84*	0.06
Lane Change	0.83	0.15	0.87	0.12	0.73	0.13
Medium						
Constant Speed	0.75	0.33	0.76	0.32	0.57	0.26
Slowing	0.81	0.13	0.92	0.11	0.75	0.12
Lane Change	0.80	0.26	0.51*	0.16	0.41*	0.14
Aggressive						
Constant Speed	0.92	0.71	0.82	0.71	0.76	0.71
Slowing	0.62	0.18	1.13	0.26	0.69	0.21
Lane Change	0.43	0.25	0.33*	0.23	0.14*	0.09

* Statistically significant with 95-percent confidence.

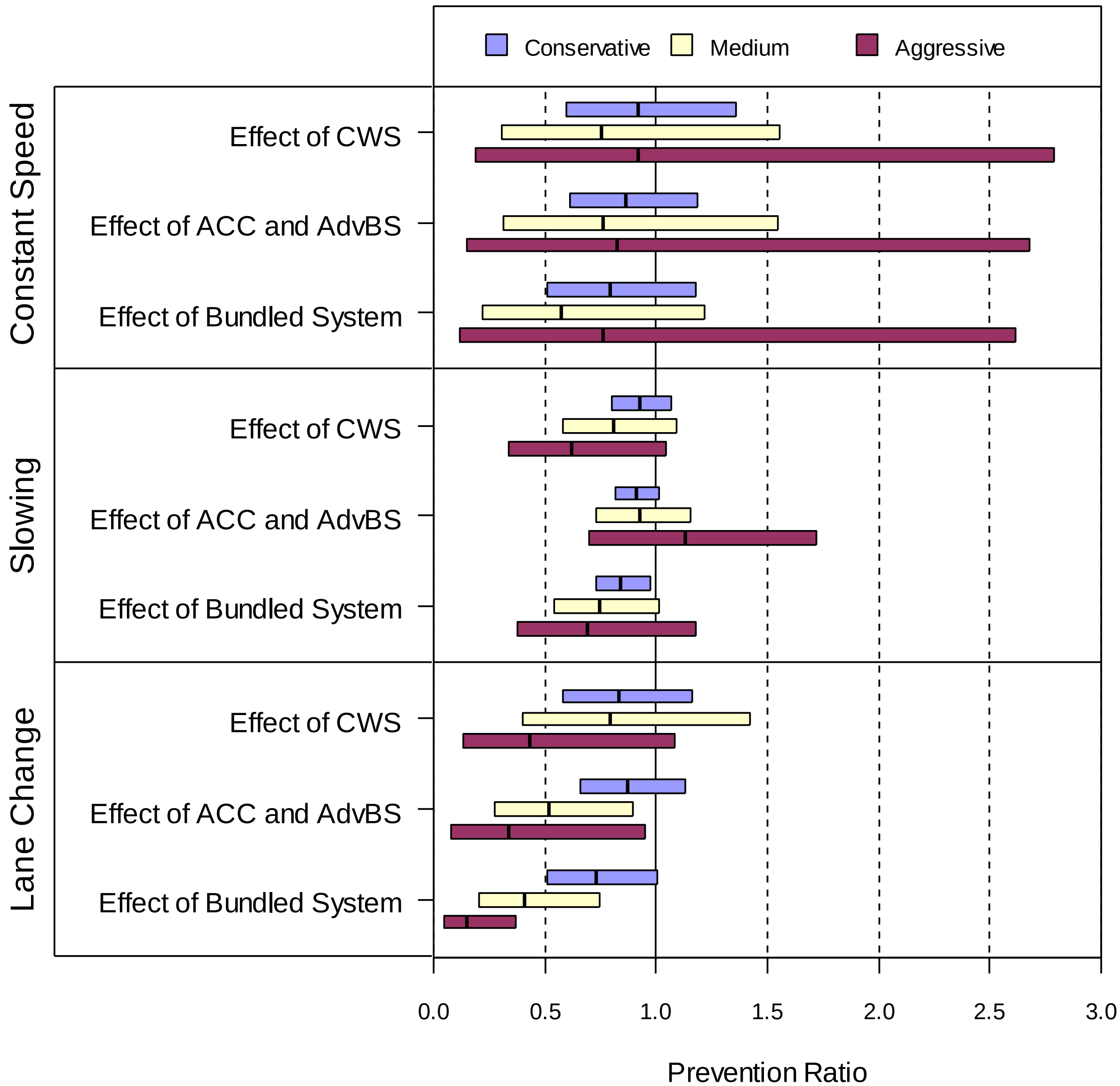


Figure 5.1-6. Graphical Representation of Prevention Ratios with 95-Percent Confidence Intervals (KME Conflict Definition)

The area to the left of the vertical 1.0 line represents Benefits, and the area to the right represents Disbenefits

Step 8. Assign Each Conflict to the Histogram during which it Occurred and Calculate Exposure Ratios for each Combination of Kinematic Threshold and Truck Configuration

The numbers of conflicts (counts) and conflict rates for each conflict type as a function of fleet are shown in Tables 5.1-10a through 5.1-10c for the conservative, medium, and aggressive thresholds and the Restricted KME Conflict Definition. Tables 5.1-11a through 5.1-11c similarly show the conflict rates for the KME Conflict Definition. Counts in each category do not sum to the total number of conflicts because some conflicts could not be associated with the three conflict categories and were therefore placed in an "other" category. These conflicts are not considered in safety benefits calculations because they cannot be matched to GES rates.

Table 5.1-10a. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (Restricted KME Conflict Definition for the Conservative Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	31	81	76	**188**
	Rate	*0.82*	*0.73*	*0.63*	***0.70***
Slowing	Count	208	661	750	**1619**
	Rate	*5.53*	*5.96*	*6.24*	***6.03***
Lane Change	Count	38	102	111	**251**
	Rate	*1.01*	*0.92*	*0.92*	***0.93***
All Conflicts[1]	Count	299	898	1,006	**2,203**
	Rate	*7.95*	*8.10*	*8.37*	***8.20***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Table 5.1-10b. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (Restricted KME Conflict Definition for the Medium Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	12	17	15	**44**
	Rate	*0.32*	*0.15*	*0.12*	***0.16***
Slowing	Count	49	159	167	**375**
	Rate	*1.30*	*1.43*	*1.39*	***1.40***
Lane Change	Count	10	25	23	**58**
	Rate	*0.27*	*0.23*	*0.19*	***0.22***
All Conflicts[1]	Count	82	216	225	**523**
	Rate	*2.18*	*1.95*	*1.87*	***1.95***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Table 5.1-10c. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (Restricted KME Conflict Definition for the Aggressive Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	3	5	4	**12**
	Rate	*0.08*	*0.05*	*0.03*	***0.04***
Slowing	Count	14	40	47	**101**
	Rate	*0.37*	*0.36*	*0.39*	***0.38***
Lane Change	Count	4	6	4	**14**
	Rate	*0.11*	*0.05*	*0.03*	***0.05***
All Conflicts[1]	Count	26	57	62	**145**
	Rate	*0.69*	*0.51*	*0.52*	***0.54***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Table 5.1-11a. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (KME Conflict Definition for the Conservative Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	637	1380	1658	**3675**
	Rate	*16.94*	*12.45*	*13.79*	***13.68***
Slowing	Count	891	3027	3582	**7500**
	Rate	*23.70*	*27.30*	*29.80*	***27.92***
Lane Change	Count	106	354	420	**880**
	Rate	*2.82*	*3.19*	*3.49*	***3.28***
All Conflicts[1]	Count	1682	4871	5,807	**12,360**
	Rate	*44.74*	*43.94*	*48.31*	***46.00***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Table 5.1-11b. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (KME Conflict Definition for the Medium Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	531	1043	1269	**2843**
	Rate	*14.12*	*9.41*	*10.56*	***10.58***
Slowing	Count	351	1235	1513	**3099**
	Rate	*9.34*	*11.14*	*12.59*	***11.53***
Lane Change	Count	33	104	132	**269**
	Rate	*0.88*	*0.94*	*1.10*	***1.00***
All Conflicts[1]	Count	934	2414	2,960	**6,308**
	Rate	*24.84*	*21.77*	*24.62*	***23.48***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Table 5.1-11c. Driving Conflict Counts and Rates (Counts per 10,000 Miles) by Fleet and Conflict Type (KME Conflict Definition for the Aggressive Threshold)

Conflict Category	Measure	Fleet			Total
		Baseline	Control	Test	
Constant Speed	Count	474	911	1110	**2495**
	Rate	*12.61*	*8.22*	*9.23*	***9.29***
Slowing	Count	135	500	613	**1248**
	Rate	*3.59*	*4.51*	*5.10*	***4.65***
Lane Change	Count	10	35	57	**102**
	Rate	*0.27*	*0.32*	*0.47*	***0.38***
All Conflicts[1]	Count	628	1456	1,799	**3,883**
	Rate	*16.71*	*13.13*	*14.97*	***14.45***
	VMT	375,935	1,108,674	1,202,059	**2,686,668**

[1]Includes "other" conflicts not associated with GES events.

Figures 5.1-7a and 5.1-7b are graphical representations of the combined empirical conflict rates (displayed in Tables 5.1-10a through 5.1-11c) for each fleet of vehicles, for the three thresholds, and for the Restricted KME and the KME Conflict Definitions respectively. The statistical confidence that the true conflict rate lies within two standard errors of the mean is approximately 95 percent. As expected, there are significant differences between the conflict rates of the various thresholds, since more conflicts are excluded as the threshold values increase. Also, the conflict rates for the KME Conflict Definition are much larger than the Restricted KME Conflict

Definition because more conflicts are retained in the analysis. Another difference between the Conflict Definitions is in the Constant Speed category as a proportion of the total rate. In the Restricted KME Conflict Definition, the Constant Speed and Lane Change categories are small compared to the Slowing Category, whereas in the KME Conflict Definition, the Constant Speed category is relatively larger. This suggests that a relatively larger proportion of the Constant Speed category was excluded when the kinematic analysis predicted a lag time of 15 or more seconds.

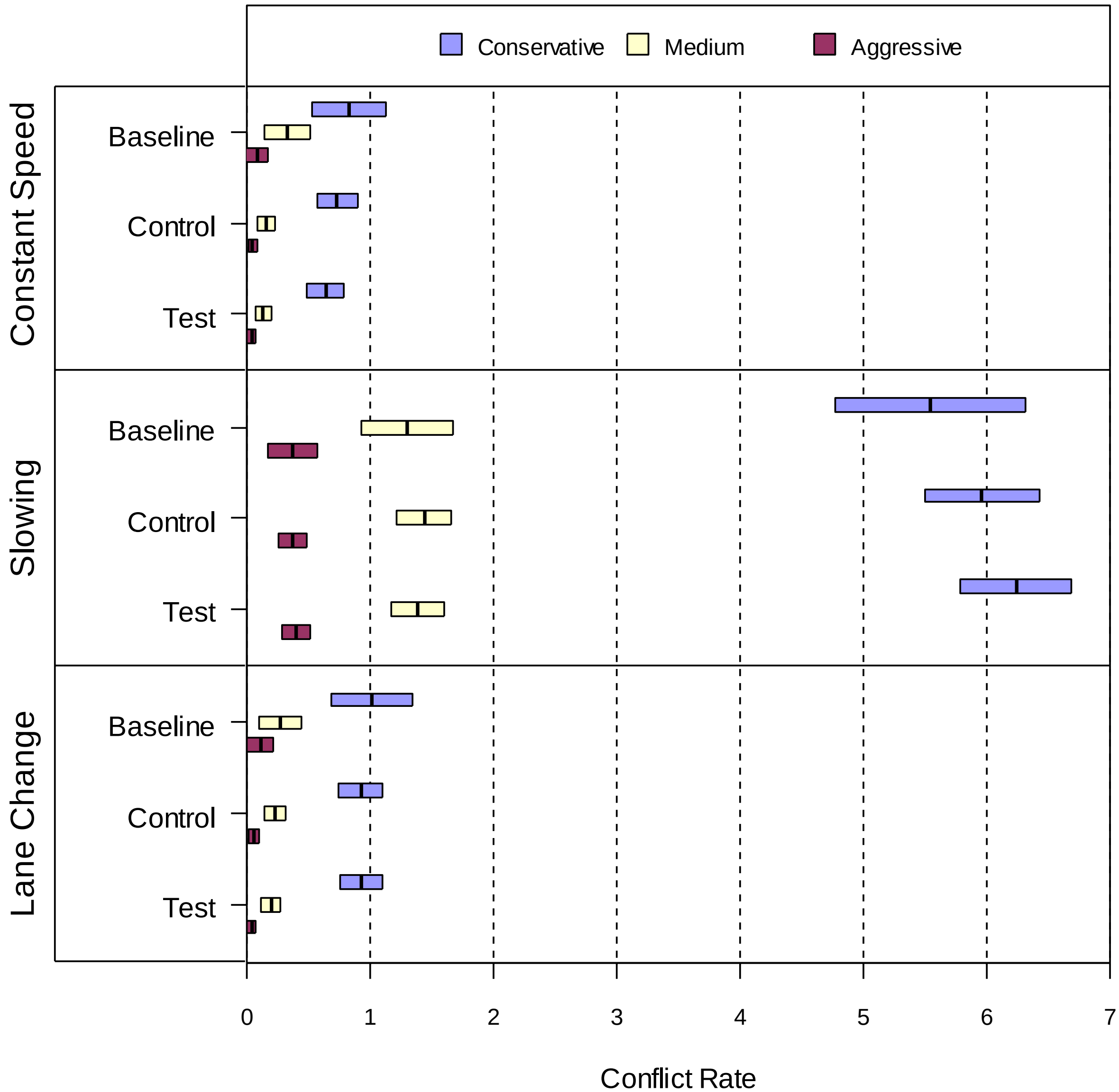


Figure 5.1-7a. Average Conflict Rate by Conflict Category, Fleet, and Threshold with 95-Percent Confidence Intervals (Restricted KME Conflict Definition)

Error bars denote +/- two standard errors

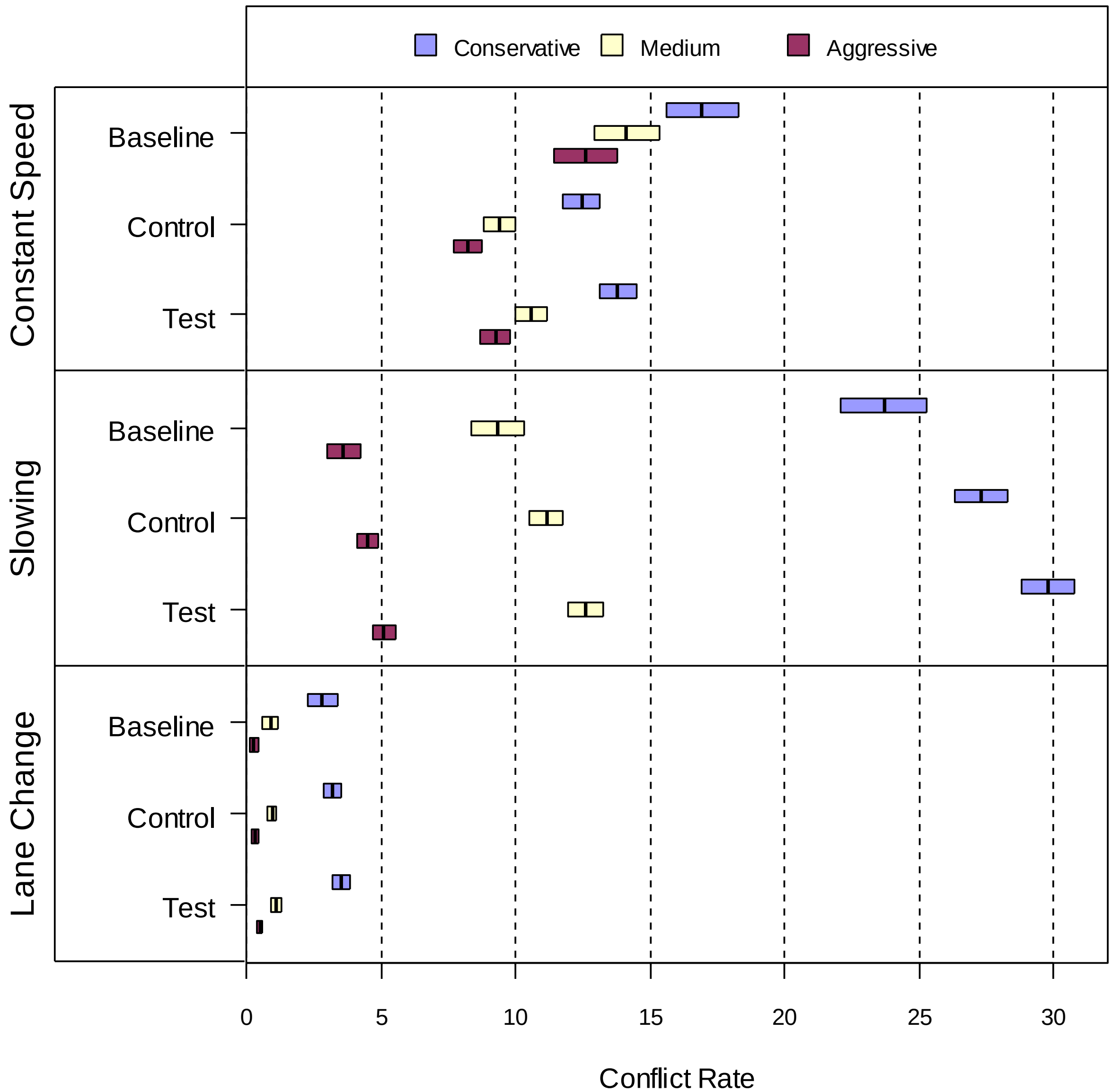


Figure 5.1-7b. Average Conflict Rate by Conflict Category, Fleet, and Threshold with 95-Percent Confidence Intervals (KME Conflict Definition)

Error bars denote +/- two standard errors

The remainder of this section presents statistical comparisons of conflict rates through the calculation and analysis of exposure ratios.

Restricted KME Conflict Definition

Table 5.1-12 lists, for the three thresholds, the estimated exposure ratios with corresponding standard errors for each conflict category and for each combination of IVSS under evaluation. As indicated earlier, an exposure ratio less than 1.0 suggests that the combination of IVSS helps the driver avoid driving conflicts. The exposure ratios estimated are reported as being statistically significant if their values differ from 1.0 with 95-percent confidence, shown with an asterisk (*) in Table 5.1-12. Under this level of confidence, no statistically significant exposure ratios were identified in the conservative threshold. Using values from Table 5.1-10a, the conflict rates per 10,000 miles for the constant speed category, conservative threshold, Restricted KME definition were 0.73 and 0.82 for Control and Baseline, respectively. The Exposure Ratio for the corresponding case was found by: $0.73/0.82 \approx 0.89$.

Table 5.1-12. Estimated Exposure Ratios with Standard Errors by Conflict Type

(Restricted KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	0.89	0.19	0.87	0.14	0.77	0.16
Slowing	1.07	0.09	1.05	0.06	1.12	0.09
Lane Change	0.91	0.17	1.00	0.14	0.91	0.17
Medium						
Constant Speed	0.48*	0.18	0.81	0.29	0.39*	0.15
Slowing	1.10	0.18	0.97	0.11	1.07	0.17
Lane Change	0.85	0.32	0.85	0.25	0.72	0.27
Aggressive						
Constant Speed	0.57	0.41	0.74	0.49	0.42	0.32
Slowing	0.97	0.30	1.08	0.23	1.05	0.32
Lane Change	0.51	0.33	0.61	0.40	0.31*	0.22

* Statistically significant with 95-percent confidence.

Although findings using the conservative conflict criterion were not statistically significant at the 95-percent confidence level, the graphical representations of the exposure ratios in Figure 5.1-8 suggest that the use of CWS as well as the bundled systems might help reduce exposures to the "constant speed" conflicts. For example, although not statistically significant at the 95-percent confidence level, the estimated exposure ratio for the bundled system in the "constant speed" category is 0.77, thus implying that the bundled system would help reduce the number of rear-end conflicts that occur while the truck is operating at constant speed by 23 percent.

As the KME threshold increases to the medium and aggressive cases, the conflicts are more closely associated with safety critical events, and the resulting safety benefit of the different systems should be easier to identify. However, the total number of conflicts in the data set is reduced, impacting the ability to yield statistically significant results.

The results for the medium conflict criterion:

- Show trends similar to those observed with the conservative criterion; and
- Demonstrate that exposure ratios for the CWS and the bundled systems involving constant speed conflicts are statistically significant.

These findings indicate that the CWS and the bundled systems can reduce the number of rear-end conflicts that occur while the truck is operating at constant speed by 52 percent and 61 percent, respectively. Since the AdvBS is not designed to affect the exposure to driving conflicts, the incremental benefit of ACC over CWS in reducing rear-end conflicts in which the truck is traveling at constant speed is 9 percent.

The results of increasing the severity of the conflict criterion to the aggressive level show:

- The exposure ratios associated with the constant speed conflicts are no longer statistically significant (as a result of the reduced number of conflicts), and
- The exposure ratio for the bundled systems involving lane change conflicts is statistically significant.

This latter finding could be attributed to the ACC, because the system will slow down a truck that attempts to merge into a lane immediately behind another vehicle, or because the drivers using the system will tend to avoid lane change maneuvers.

The estimated effects of all three IVSS systems on conflict rates are not statistically significant using the conservative threshold; however, as the severity of the conflict definition is increased, the effect of the CWS and the bundled system on the rate of constant-speed conflicts becomes statistically identifiable. Increasing the severity threshold further reveals the effect of the bundled systems on the rate of lane change conflicts; however, because increasing the severity of the conflict definition reduces the number of available conflicts, the difference in the estimated rates of constant-speed conflicts is no longer statistically significant. This demonstrates the value of considering different conflict severity definitions to trade off the problem of events that are too benign (conservative threshold) with the problem of only very severe events being included in the analysis (aggressive threshold). Events that are too benign do not indicate a safety benefit due to many situations that are not addressed by the system being included in the analysis. If the conflict thresholds are too severe, then there are an insufficient number of conflicts to produce statistically significant results.

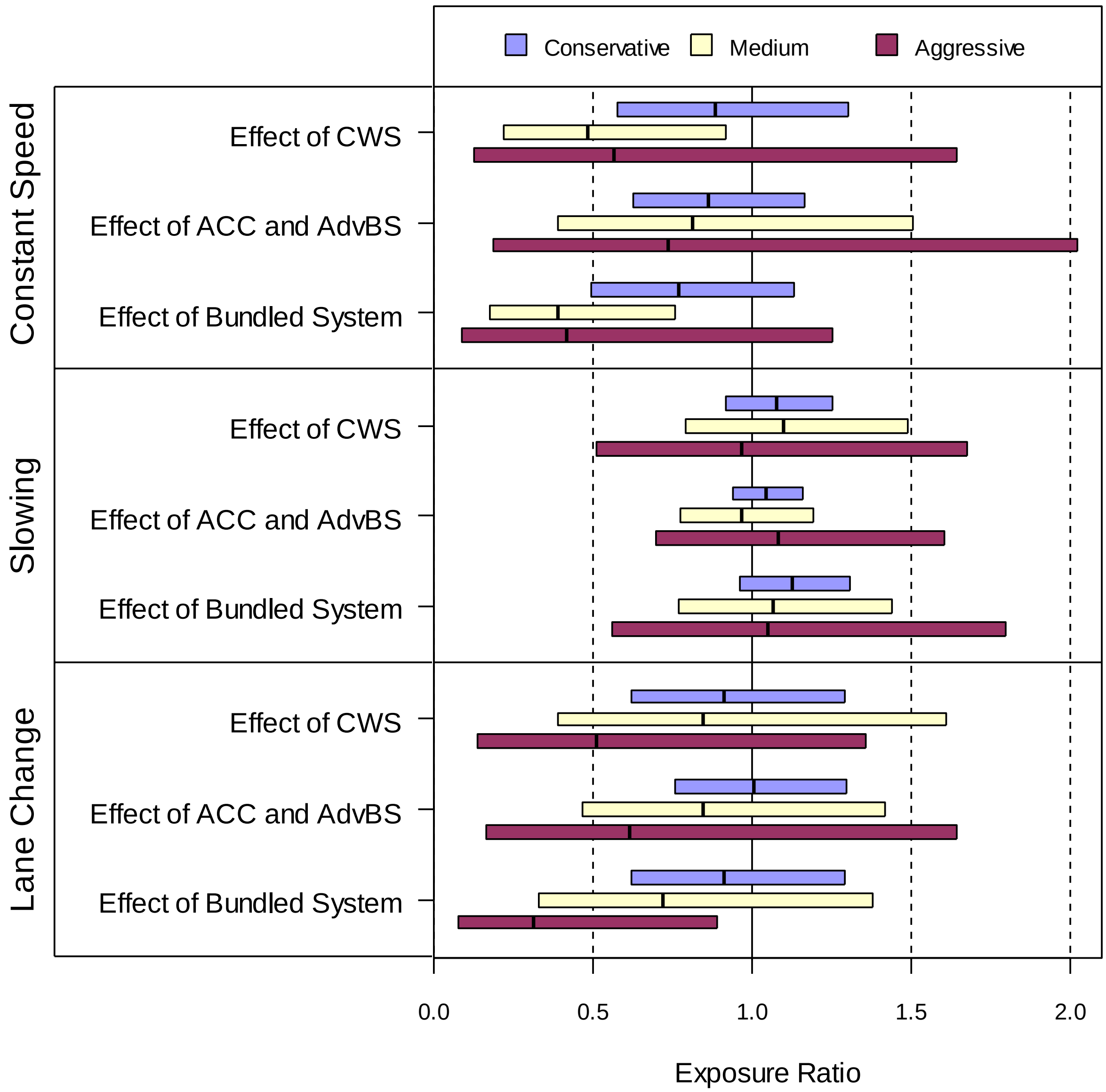


Figure 5.1-8. Exposure Ratios by Conflict Category, Fleet, and Threshold with 95-Percent Confidence Intervals (Restricted KME Conflict Definition)

Error bars denote +/- two standard errors; benefits are to the left of 1.00; disbenefits are to the right

KME Conflict Definition

In the KME Conflict Definition case, there are more observed conflicts and higher rates of conflicts per 10,000 miles. This increases the power of the statistical test to detect differences between fleets. Table 5.1-13 and Figure 5.1-9 show that there are more statistically significant results in the KME Conflict Definition. The CWS and the bundled system provide a significant benefit in reducing conflict exposure in the constant speed category for all thresholds, while the

ACC and AdvBS provide a significant disbenefit in that category. Also, all technologies show a disbenefit to exposure for the slowing and lane change categories for all thresholds, although no lane change exposure ratios are statistically significant, while most slowing exposure ratios are statistically significant.

Table 5.1-13. Estimated Exposure Ratios with Standard Errors by Conflict Type

(KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	0.73*	0.04	1.11*	0.04	0.81*	0.04
Slowing	1.15*	0.04	1.09*	0.03	1.26*	0.05
Lane Change	1.13	0.13	1.09	0.08	1.24	0.13
Medium						
Constant Speed	0.67*	0.04	1.12*	0.05	0.75*	0.04
Slowing	1.19*	0.07	1.13*	0.04	1.35*	0.08
Lane Change	1.07	0.21	1.17	0.15	1.25	0.24
Aggressive						
Constant Speed	0.65*	0.04	1.12*	0.05	0.73*	0.04
Slowing	1.26*	0.12	1.13	0.07	1.42*	0.14
Lane Change	1.19	0.43	1.50	0.32	1.78	0.61

* Statistically significant with 95-percent confidence.

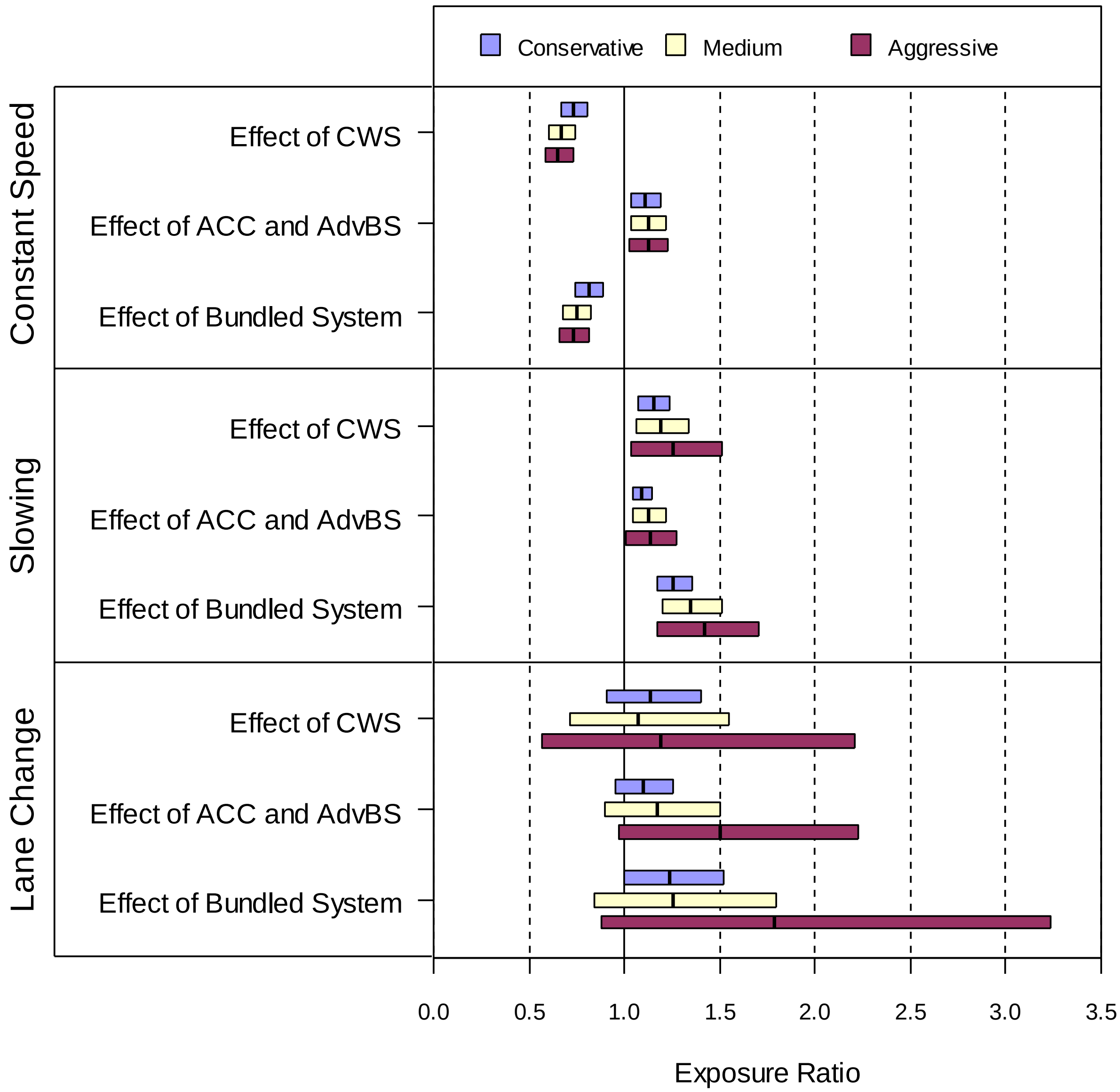


Figure 5.1-9. Exposure Ratios by Conflict Category, Fleet, and Threshold with 95-Percent Confidence Intervals (KME Conflict Definition)

Error bars denote +/- two standard errors; benefits are to the left of 1.00; disbenefits are to the right

From a technology design perspective, CWS is expected to affect both the exposure and prevention ratios. By contrast, ACC is expected to affect only exposure ratios, and AdvBS is expected to affect only the prevention ratios.

The ACC is expected to reduce exposure to conflict situations by maintaining sufficient following intervals, hence reducing the likelihood that a vehicle enters a conflict. At the medium conflict criterion, the effect of ACC and AdvBS was significant under the constant speed conflict category. Since AdvBS is not expected to affect the exposure ratio, this effect is most likely due to the ACC maintaining safe following intervals between the following vehicle and the lead vehicle.

The alerts generated by the CWS are designed such that, depending on the severity level of the alerts generated, they can affect either the exposure or the prevention ratios. On one hand, low-level alerts, such as alert #1, which is triggered when a target is detected in the lane of the vehicle with a 2- to 3-second following interval (Table 2.1-1, presented previously) have a potential to reduce the probability that the drivers enter conflicts, for example the constant speed conflict. On the other hand, the high-level alerts, such as alert #10, which is triggered when a target is detected in the lane of the vehicle with a ½-second following interval (Table 2.1-1) have the potential to reduce the probability of a crash because, when this alert is communicated to the drivers, the drivers may have already entered the conflict situation.

The likelihood of detecting a significant effect of the CWS on the exposure ratio is also affected by the severity of the conflict criterion. As the severity of the conflict criterion increases, the driving conflicts identified exclude less critical situations in which only low-level alerts would be triggered. As such, the potential for situations involving only low-level alerts to affect the exposure ratio is expected to be greater using the conservative criteria. These alerts (e.g., illuminated yellow and amber indicators on the DDU) may not be noticed by the drivers, and therefore may have a limited effect. In conclusion, the lack of significant effect of CWS on the exposure ratio in the conservative conflict criterion is consistent with the design of the technology and the details of the analysis conducted.

As the severity of the conflict criterion increases to medium, additional alerts of a higher level are expected to be generated before the conflict occurs. Such alerts are more likely to be noticed by the drivers, and, as a result, are more likely to affect the exposure ratio. As such, significant results were found for constant speed conflict categories. If the driver is applying the brakes (hence the vehicle is slowing), alerts generated do not include audible alerts and are less likely to grab the attention of the driver.

In the case of the aggressive conflict criterion, the system would be expected to have a greater effect on the exposure ratio. However, statistically significant results were not obtained most likely as a result of the small number of conflicts identified.

Step 9. Compute the Crash Reduction Ratios

The third estimated quantity in the safety benefit analysis is the overall efficacy of each combination of IVSS technologies for reducing crashes, i.e. the crash reduction ratio (*CRR*).

Restricted KME Conflict Definition

Table 5.1-14 presents the crash reduction ratios for each conflict category based on the three thresholds. Each row lists the estimated *CRR* along with the standard error for each combination of technologies being evaluated. The *CRR* values were obtained by multiplying the exposure ratios in Table 5.1-12 by the prevention ratios in Table 5.1-8. For example, in the conservative, constant speed category, for the effect of the CWS, $1.09 * 0.89 \approx 0.97$. Figure 5.1-10 is a graphical representation of the results. Because no statistically significant exposure ratios or prevention ratios were found using the conservative conflict criterion, it is not surprising that the *CRRs* are not statistically different from 1.0.

Also presented are the crash reduction ratios based on the medium conflict criterion. In this case, a 60 percent = (1-0.40)*100 percent reduction in rear-end crashes involving driving at constant speed when using the bundled system was observed. This estimate is statistically significant at the 95-percent confidence level. The benefits are primarily due to reduced exposures to conflicts that occur at constant speeds. (See the Exposure Ratio estimates in Table 5.1-12.) A statistically significant reduction of 56 percent = (1-0.44)*100 percent in rear-end crashes that involve lane change conflicts when using the bundled system was found. However, this benefit may be due to a combination of reduced exposures (*ER*=0.72) and reduced severity (*PR*=0.61). The estimated exposure ratio was not statistically significant (See Table 5.1-12); but, the prevention ratio was significant at the 95-percent confidence level (See Table 5.1-8).

Table 5.1-14. Estimated Crash Reduction Ratios with Standard Errors by Conflict Category

(Restricted KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	0.97	0.24	0.76	0.14	0.74	0.18
Slowing	1.08	0.10	1.00	0.06	1.08	0.10
Lane Change	0.82	0.18	1.04	0.17	0.85	0.18
Medium						
Constant Speed	0.51	0.23	0.78	0.33	0.40*	0.19
Slowing	0.99	0.18	0.94	0.12	0.93	0.17
Lane Change	0.70	0.29	0.63	0.22	0.44*	0.18
Aggressive						
Constant Speed	0.56	0.46	0.70	0.61	0.39	0.37
Slowing	0.84	0.28	1.07	0.27	0.90	0.30
Lane Change	0.51	0.37	0.43	0.33	0.22*	0.17

*Statistically significant with 95-percent confidence.

For completeness, the results based on the aggressive conflict criterion are presented. The results are similar to those obtained with the medium conflict criteria, except that there is more variability due to the smaller number of conflicts that satisfied the aggressive KME conditions.

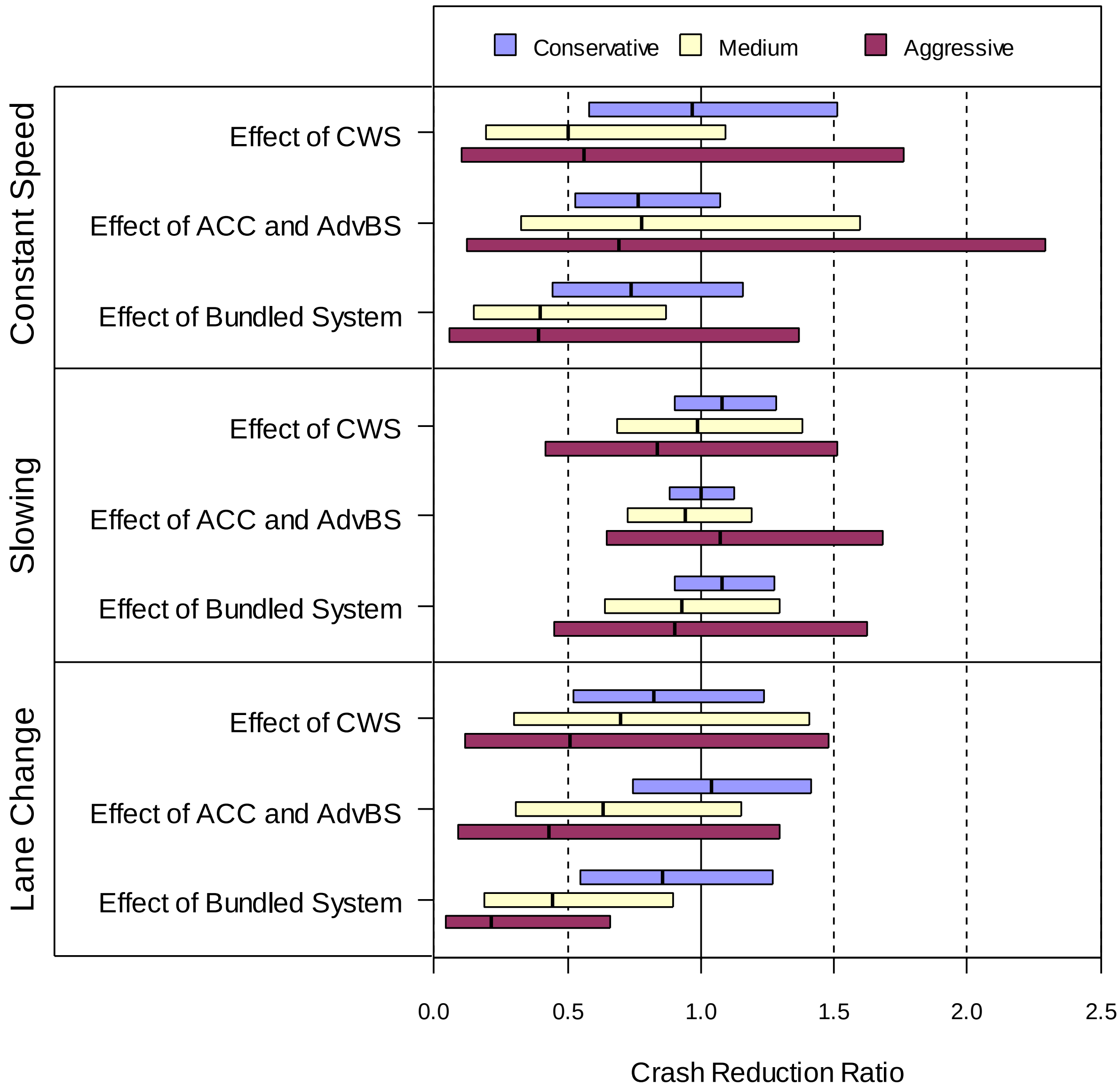


Figure 5.1-10. Graphical Representation of Crash Reduction Ratios with 95-Percent Confidence Intervals (Restricted KME Conflict Definition)

KME Conflict Definition

Table 5.1-15 and Figure 5.1-11 give the estimated crash reduction ratios for the KME conflict definition. In the KME Conflict Definition case, the Bundled System is able to significantly reduce constant speed collisions in the conservative and medium thresholds. However, the medium threshold lane change is not significant, unlike the Restricted KME Conflict Definition. In both definitions, the Bundled system is effective at reducing crashes for the lane change category and aggressive threshold.

Table 5.1-15. Estimated Crash Reduction Ratios with Standard Errors by Conflict Category

(KME Conflict Definition)

Conflict Category	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative						
Constant Speed	0.67	0.15	0.95	0.17	0.64*	0.14
Slowing	1.07	0.09	0.99	0.06	1.06	0.09
Lane Change	0.94	0.20	0.95	0.15	0.90	0.19
Medium						
Constant Speed	0.50	0.22	0.85	0.36	0.42*	0.20
Slowing	0.96	0.17	1.04	0.13	1.01	0.17
Lane Change	0.85	0.33	0.60	0.20	0.51	0.20
Aggressive						
Constant Speed	0.60	0.47	0.92	0.80	0.55	0.52
Slowing	0.77	0.24	1.27	0.31	0.99	0.31
Lane Change	0.51	0.35	0.50	0.37	0.26*	0.18

*Statistically significant with 95-percent confidence.

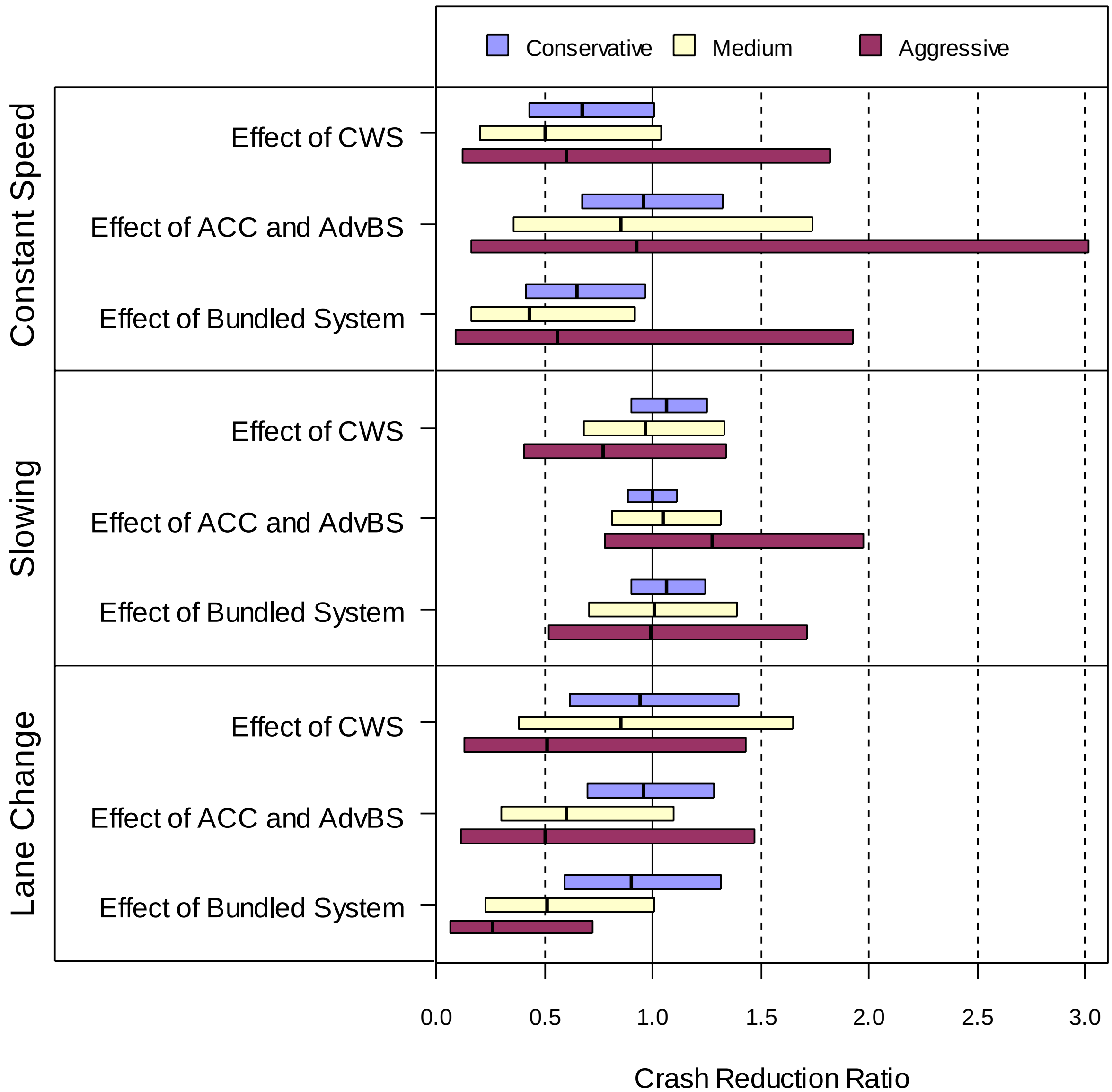


Figure 5.1-11. Graphical Representation of Crash Reduction Ratios with 95-Percent Confidence Interval (KME Conflict Definition)

Step 10. Compute the Percent Reduction in Crashes

Estimated Percent Reduction in Crashes

The preceding discussions presented exposure ratios, prevention ratios, and crash reduction ratios using two different methods of classifying conflicts (Restricted KME Conflict Definition and KME Conflict Definition) and three levels of severity (conservative, medium, and aggressive) for defining a conflict. This provided insight into how the different combinations of systems impact safety under various operating conditions. It also provides a means of evaluating the sensitivity of the findings to different modeling assumptions.

The overall crash reduction ratio was calculated using the weighted average of the CRRs from the three conflict categories. The overall percent reduction in crashes is then calculated using the Safety Benefits Equation in Section 4.

Restricted KME Conflict Definition

Table 5.1-16 shows the estimated percent reduction in crashes and the associated standard error for each combination of IVSS technologies and conflict threshold level for the Restricted KME Conflict Definition. Using values from Table 5.1-14 and GES percentages in each conflict category from Table 4.2-4, the values in Table 5.1-16 can be calculated. For example, for the effect of the CWS in the conservative threshold,

$$(1-0.97)*40\% + (1-1.08)*44\% + (1-0.82)*2\% \approx -1.9\% .$$

Table 5.1-16. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(Restricted KME Conflict Definition)

Conflict Threshold	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative	-1.9%	10.4%	9.4%	6.2%	7.2%	8.4%
Medium*	20.7%	12.1%	12.0%	14.2%	28.1%**	10.5%
Aggressive	25.3%	22.0%	9.8%	26.8%	29.9%	19.8%

* The medium conflict threshold is the best estimate of safety benefits.

** Statistically significant with 95-percent confidence.

Table 5.1-17 gives the percent confidence that the calculated results in Table 5.1-16 are different from zero. These p-values are based on a normal distribution assumption. Appendix D10 investigates this assumption using a simulation approach. The distribution of the aggressive threshold estimates are not normally distributed. P-values are not provided for the aggressive threshold as a different calculation methodology would have been needed as compared to the conservative and medium thresholds for which the normal assumption was appropriate.

The benefit of the CWS was consistently positive for the medium and aggressive threshold levels, with slight negative benefits observed based on the conservative thresholds. None of these estimates were statistically significant. For the ACC and AdvBS systems, the crash reduction benefit was consistently positive. Again, none of the benefits were statistically significant; however, the positive estimates across different conflict thresholds lend credence to the potential benefit of the ACC and AdvBS.

Table 5.1-17. Significance of the Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(Restricted KME Conflict Definition)

Conflict Threshold	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System
Conservative	14.6%[1]	86.9%	60.6%
Medium	91.2%	60.0%	99.3%
Aggressive[2]	NA	NA	NA

[1] Estimated effect of the technology indicates a disbenefit at the level of significance indicated

[2] The percent reduction in rear-end crashes for the aggressive threshold is not normally distributed. P-values based on normality are not available.

The crash reduction benefit of the bundled system was consistently positive under all threshold levels. Furthermore, under the medium threshold condition, the estimated benefit of the bundled system was statistically significant. Similar sized benefits are observed when the aggressive threshold levels are employed, but the small number of conflicts available at the aggressive threshold level results in larger uncertainty in the estimates, and thus, the crash reduction estimates are not statistically significant.

Figure 5.1-12 presents the results graphically. The center horizontal black line of each bar indicates the crash reduction benefit. Any positive benefit indicates increased safety. The error bars represent two standard errors of the estimate. The statistically significant result is indicated with cross hatching.

KME Conflict Definition

The KME Conflict Definition yields results that are generally consistent with the Restricted KME Conflict Definition. The results are given in Table 5.1-18 and Figure 5.1-13. Again, the medium threshold shows a statistically significant benefit for the effect of the Bundled System. Table 5.1-19 gives the percent confidence that the calculated results in Table 5.1-18 are different from zero. These p-values are based on a normal distribution assumption.

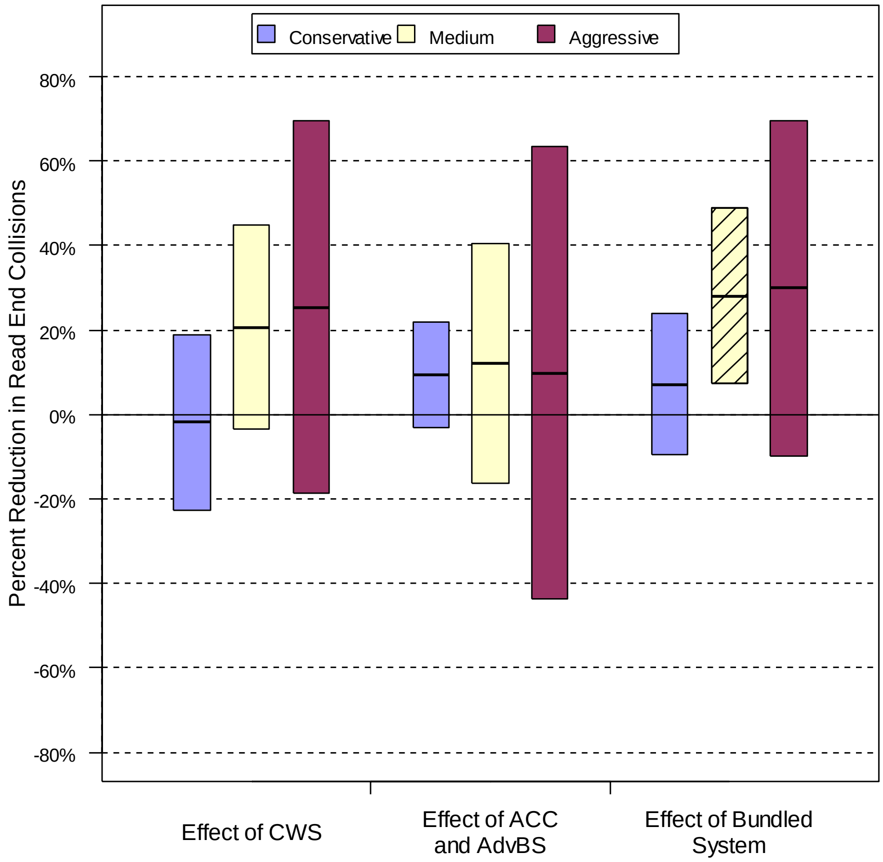


Figure 5.1-12. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(Restricted KME Conflict Definition)

Error Bars Represent Approximate 95-Percent Confidence Intervals

Table 5.1-18. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(KME Conflict Definition)

Conflict Threshold	Effect of CWS		Effect of ACC and AdvBS		Effect of Bundled System	
	Estimate	Standard Error	Estimate	Standard Error	Estimate	Standard Error
Conservative	10.1%	7.0%	2.2%	7.1%	11.7%	6.8%
Medium*	21.6%	11.3%	4.7%	15.3%	23.4%**	10.9%
Aggressive	26.5%	21.2%	-8.1%	34.2%	19.5%	24.6%

* The medium conflict threshold is the best estimate of safety benefits.

** Statistically significant with 95-percent confidence.

Table 5.1-19. Significance of the Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(KME Conflict Definition)

Threshold	Effect of CWS	Effect of ACC and AdvBS	Effect of Bundled System
Conservative	85.1%	23.8%	91.5%
Medium	94.5%	24.1%	96.9%
Aggressive[1]	NA	NA	NA

[1] The percent reduction in rear-end crashes for the aggressive threshold is not normally distributed. P-values based on normality are not available.

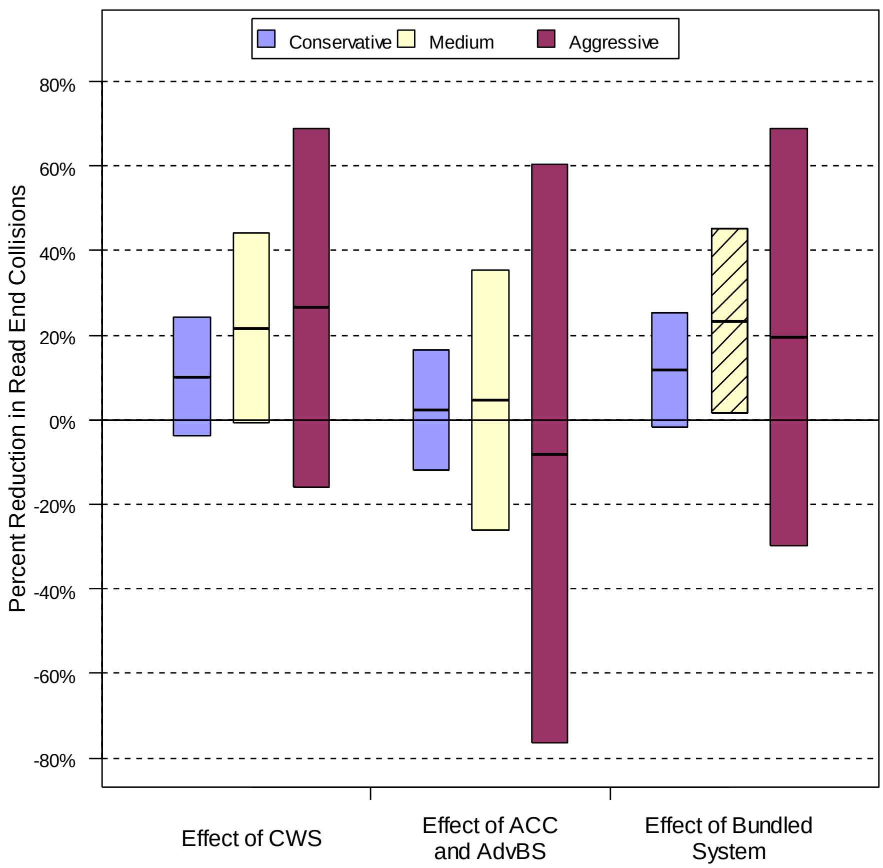


Figure 5.1-13. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies

(KME Conflict Definition)

Error Bars Represent Approximate 95-Percent Confidence Intervals

5.1.1.3 Empirical Benefits Summary

In summary, the results suggest that the CWS has a positive exposure benefit under more severe driving conflicts. This implies that driving behaviors related to less severe conflicts are not changed by the CWS, but that exposure to the more severe situations defined by the medium and aggressive thresholds is reduced by the CWS.

The ACC/AdvBS system produces smaller positive benefits, which were not found to be statistically significant. Furthermore, similar benefits were observed across the range of driving conflict thresholds considered. This indicates that, in spite of the fact that ACC should be maintaining a 3.5-second following interval behind a lead vehicle, exposure to driving conflicts is not improved. This could be because of lead vehicle cut-ins, or because the driver without ACC maintains a sufficient following distance on his/her own.

Like the CWS, the bundled system shows increasing benefit as the severity of the driving conflict definition is increased. This is primarily due to the benefits of the CWS. Previously the bundled system was shown to produce both exposure and prevention benefits that are statistically significant. Also, as with the CWS, the benefit increases as the severity of the driving conflict definition is increased.

Tables 5.1-16 and 5.1-18 also show that the Restricted KME Conflict Definition has advantages over the KME Conflict Definition. In the majority of estimates, the Restricted KME Conflict definition yields smaller standard errors. Most importantly, in the medium threshold, the Restricted KME Conflict definition yields less variance in the effect of the ACC and AdvBS and the effect of the Bundled System. There are two competing effects in the comparison of the definitions. The KME Conflict definition has more conflicts and therefore has less variance in the Exposure Ratio, but the Restricted KME Conflict definition yields conflicts which are more homogeneous in their proximity to collision causing less variability and more consistency in the Prevention Ratio. Overall, the advantage of reducing the Prevention Ratio variability outweighed the advantage of reducing the Exposure Ratio variability to make the Restricted KME Conflict Definition superior.

For the above reasons, further analysis will focus only on the Restricted KME conflict definition including the conditional safety benefits analysis and the benefit cost analysis.

5.1.1.4 Conditional Safety Benefits Analysis

The conditional safety benefits analysis is based on the Restricted KME Conflict definition in Section 4.3. The purpose of the conditional analysis is to determine if variations in driver characteristics or driving conditions between the fleets affected the safety benefits results. Conditional analyses are able to account for these external variations and therefore provide better estimates. They are also able to give insight into important driver factors which affect safety.

5.1.1.5 Conditional Analysis of Conflict Severity

A conditional analysis of conflict severity was performed to determine if variations in driver characteristics or driving conditions can affect the severity of a driving conflict and to evaluate the impact that various IVSS technologies have on conflict severity. Using a backwards selection regression approach (McCullagh and Nelder 1989) with a Gamma distribution of errors (e.g., Bain and Engelhardt 1987), the reaction lag times that caused conflicts to become crashes were fit to different variables related to IVSS technology used (CWS, ACC + AdvBS), cruise control status, driving conditions, and driver characteristics. The specific variables and interactions used are shown in Table 5.1-20. As in the conditional analysis of exposure rates, the fleets were divided into groups according to Cruise Control Type (conventional and adaptive) and CWS availability (with and without), in order to evaluate the effects of those systems. The Cruise Control On variable in Table 5.1-20 was given a value of 1 if the cruise control system was actively maintaining vehicle speed in hold, resume, set, or decelerate mode. The reaction speed variable represents the speed of the IVI truck at the time of braking or at the lane change time, whichever is first. If neither value is available for a time history, then the speed at the time of target appearance is used. Average road speed is given as an average over the 15-second time history.

Table 5.1-20. Variables included in the Generalized Linear Model for Conditional Conflict Severity

Variable	Remarks	Interactions
Cruise Control Group* (p=0.0335)	Conventional (Baseline and Control Fleets), ACC[1] (Test Fleet)	Reaction Speed, Average Speed, Cruise Control Group
CWS Group	Group 1 included the Baseline, Group 2 included the Control and Test Fleets	Average Speed* (p<0.0001) and Reaction Speed
Cruise Control Status	0 for "cruise control off" driving and 1 for "cruise control on" driving	Cruise Control Group, Reaction Speed, Average Speed
Reaction Speed* (p<0.0001)	Road Speed at the time of braking, lane change time, or secondarily, the time of target appearance	Cruise Control Group, CWS Group, Cruise Control Status
Average Speed	Average road speed over the 15 second time history	CWS Group* (p<0.0001), Cruise Control Status, Cruise Control Group
Driver Identification Number	Modeled as a random effect blocking variable to account for behavior differences between drivers	
Age	The age of each driver	
Sex	Driver Gender	
Years with a CDL* (p=0.0001)	The number of years since the driver first gained his CDL	
Years with US Xpress* (p=0.0215)	The number of years since the driver was hired by US Xpress	

* Variables which were statistically significant in the Generalized Linear Model. P-values are included for statistically significant variables only. All other variables had a p-value of >0.05 in the backward selection procedure.

1. The ACC effect includes any effect of AdvBS

The results of the stepwise regression analysis are summarized in Table 5.1-20. The variables marked with an asterisk (*) were found to be statistically significant. The only significant interaction identified was that between the average speed during the conflict and the use of CWS. Figure 5.1-14 illustrates how the various combinations of CWS, ACC, and AdvBS interact with the reaction lag time and average road speed at the time of the incident. A reaction lag time ratio greater than 1.0 implies that the particular combination of technologies results in less severe conflicts. That is, the reaction time required to avoid a crash with the IVSS technology is greater than the reaction time required without the technology.

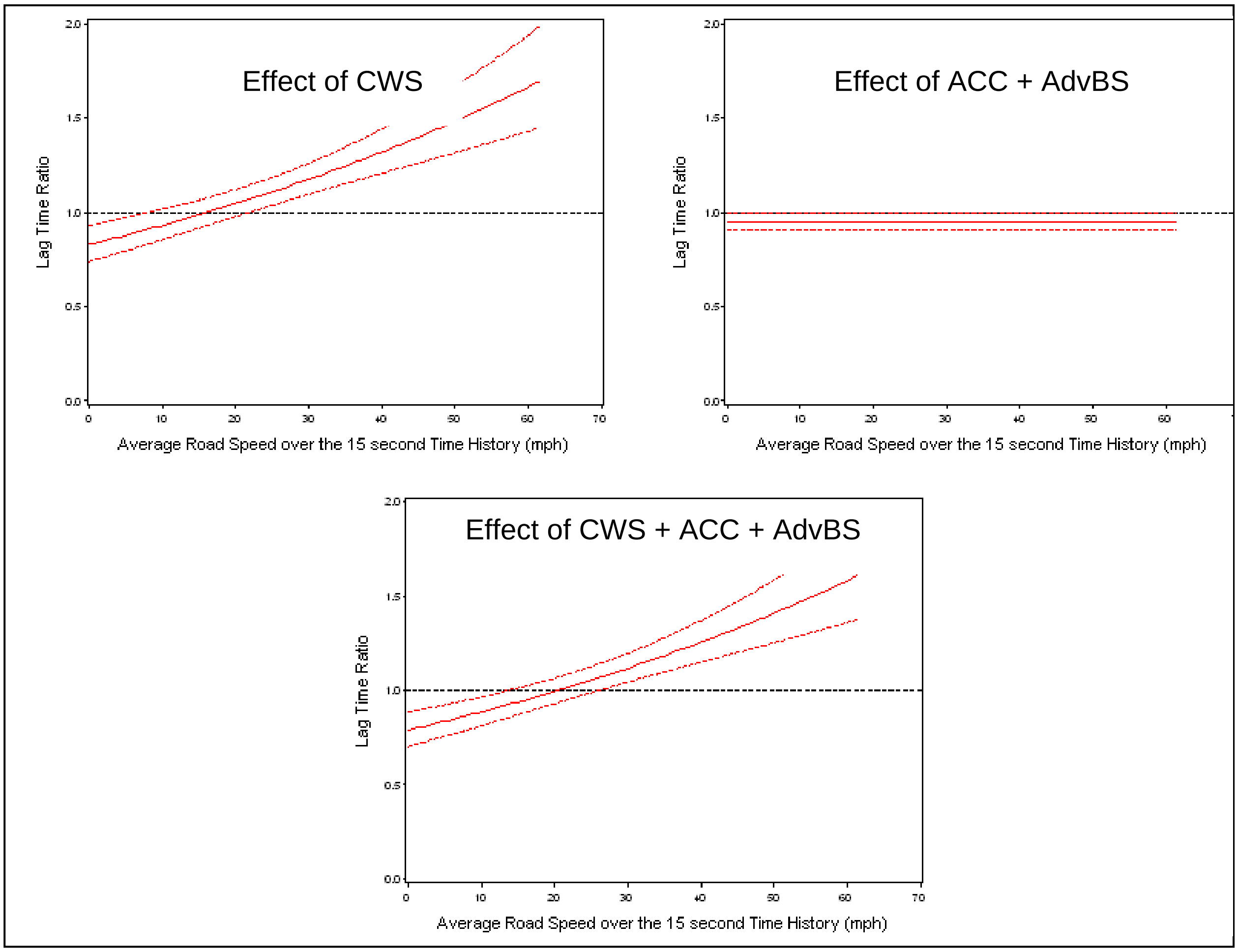


Figure 5.1-14. Reaction Lag Time Ratios Associated with the Deployment of Various IVSS Technologies versus the Average Road Speed During a 15-Second Time History

Dashed Lines Indicate 95-Percent Confidence Intervals

Lag Time Ratios <1 Indicate More Severe Conflicts with the indicated technology

The upper left panel of the figure shows that the ratio of average lag times ("with CWS" divided by "without CWS") increases with the average road speed during the conflict. The 95-percent confidence bounds are used to determine the speeds at which the ratios are less than or greater than 1.0. In this case, the ratio is less than 1.0 (indicating more severe conflicts with CWS) at low speeds (less than 10 mph), while the ratio is greater than 1.0 (less severe conflicts with CWS) at higher speeds (greater than 25 mph). One possible explanation is that drivers tend to use the CWS warnings to navigate in heavy traffic at slow speeds, but they also use it to maintain greater following distances in heavy traffic. The upper right panel shows that there is a small but statistically significant negative impact of adding the ACC and AdvBS technologies; and this impact is independent of travel speed. This may be due to the drivers having increased confidence in their ability to stop more quickly using the AdvBS.

Finally, the lower panel gives the effect of the bundled system, which also has a dependence on the speed of the vehicle during the time history. This reflects the dominant impact of the CWS, which also showed an increase in the reaction lag time with increasing average road speed. This may be a reflection of the longer following intervals that would be expected at higher road speeds. Also, if an IVI truck maintains an average of 55 mph over an entire time history, then there was little braking involved in the conflict resolution, and so it is expected that the conflict is not as severe.

The effects of other variables that were found to have a statistically significant relationship with reaction lag time are shown in Figures 5.1-15 through 5.1-17. The range over which each covariate is shown reflects the range of values included in the data. The reaction lag time decreases with both the years a driver has been with US Xpress (Figure 5.1-15) and the years that a driver has maintained his CDL (Figure 5.1-16), indicating that more experienced drivers tend to be involved in conflicts that require faster reaction times. This may be reflecting the fact that experienced drivers are more familiar with the trucks' braking capabilities; so, they tend to operate in a mode that requires quicker reaction times. Finally, Figure 5.1-17 displays the relationship between reaction lag time and reaction speed. This makes physical sense as it is expected that the faster the truck is traveling just before the conflict begins, the less time the driver has to react.

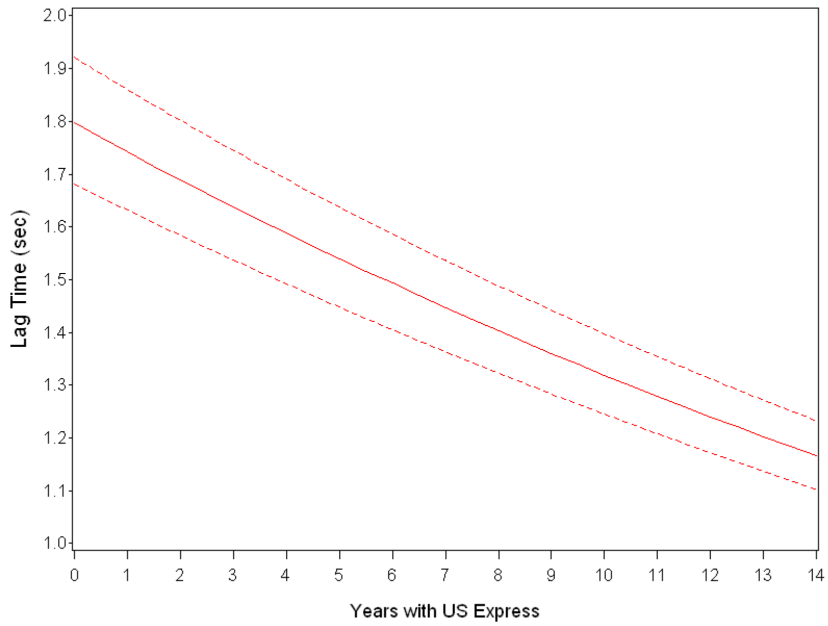


Figure 5.1-15. Conflict Lag Time versus a Driver's Years with US Xpress

Dashed lines indicate a 95-percent confidence interval

Shorter lag times are indicative of more severe conflicts

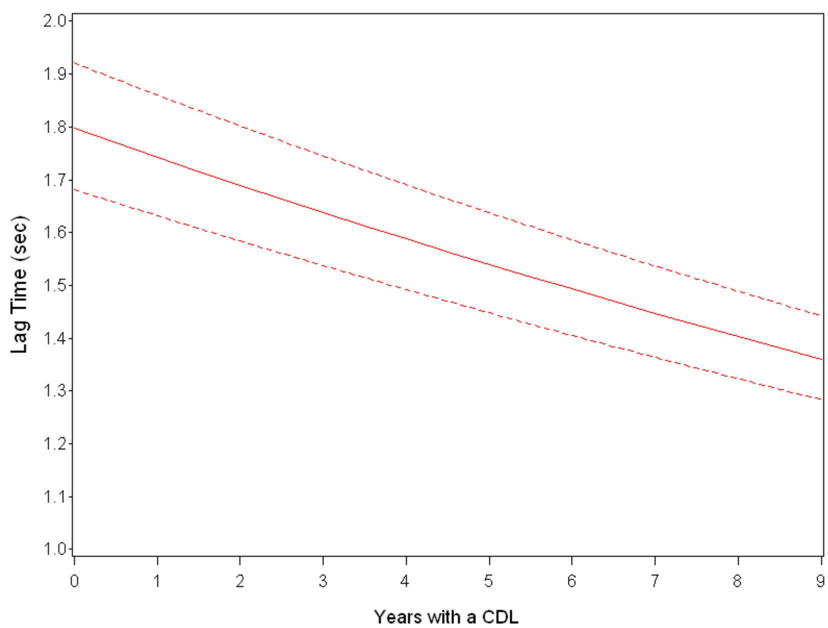


Figure 5.1-16. Conflict Lag Time versus the Years a Driver has Maintained a CDL

Dashed lines indicate a 95-percent confidence interval

Shorter lag times are indicative of more severe conflicts

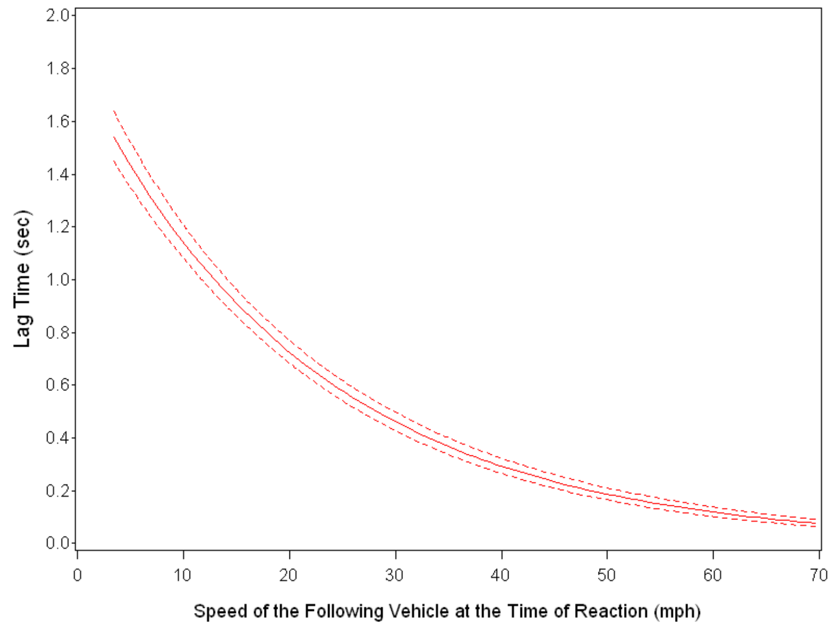


Figure 5.1-17. Conflict Lag Time versus the Speed of the Following Vehicle at the Time of Reaction

Dashed lines indicate a 95-percent confidence Interval

Shorter lag times are indicative of more severe conflicts

5.1.1.6 Conditional Analysis of Conflict Rates

To understand how different driving conditions and driver characteristics may have affected conflict rates, statistical analyses were performed with the Poisson regression methodology using conflicts defined by the conservative severity threshold. Although the medium threshold produced more statistically significant findings when comparing conflict rates across drivers and driving conditions, the smaller number of conflicts available jeopardized the statistical significance of the findings.

The data set used for the conditional analysis was created by merging the conservative conflict data with the histogram data, unit tracking data, driver log data, and driver characteristics data. Summaries of data available for the conditional analysis are included in Appendix D3. The relevant data from the histogram files included the average road speed, percent of time that the truck was traveling at greater than 55 mph, amount of time that the cruise control was on (in use), and vehicle miles traveled (VMT).

A linear regression was applied to the cruise control data collected in histogram files prior to use in the Poisson regression methodology. First, the cruise control data, i.e., the amount of time that the cruise control was on during a histogram period, were converted into the number of miles (VMT) during which cruise control was on (in use)[12]. Second, further processing of the cruise control data was necessary because the data collected included two types of cruise control "on"

[12] The method of calculating the VMT with cruise control on during a histogram reporting period is described in Appendix D5.

conditions: "on" during driving conditions, and "on" as a mean to control engine speed during a high-idle state. The former type only was of interest to the conditional analysis since the later cruise control type occurred when the parking brake was set or when the vehicle's speed was below a threshold (typically 5 mph).

Figure 5.1-18 illustrates the VMT assigned to cruise control "off" and "on" states, as a function of average road speed. As expected, the majority of the miles driven occurred at highway speeds, with an average road speed of greater than 50 mph. Of note, however, is the fact that the Test fleet drove nearly twice as far with cruise control "off" as they did with cruise control "on" at these highway speeds.

The conflicts identified with the conservative criterion and assigned to each histogram were assigned either to the "on" state VMT or the "off" state VMT depending on the value of the cruise control variable contained in the conflict data. If the variable indicated that cruise control was actively controlling speed in some way at the beginning of a conflict, then the conflict was assigned to the VMT with cruise control "on." Otherwise, the conflict was assigned to the "off" state VMT.

The driver characteristic and driver log data variables are listed in Table 5.1-21. Appendix D2 provides useful summaries of driver characteristics and details the process used to merge the histogram and driver data.

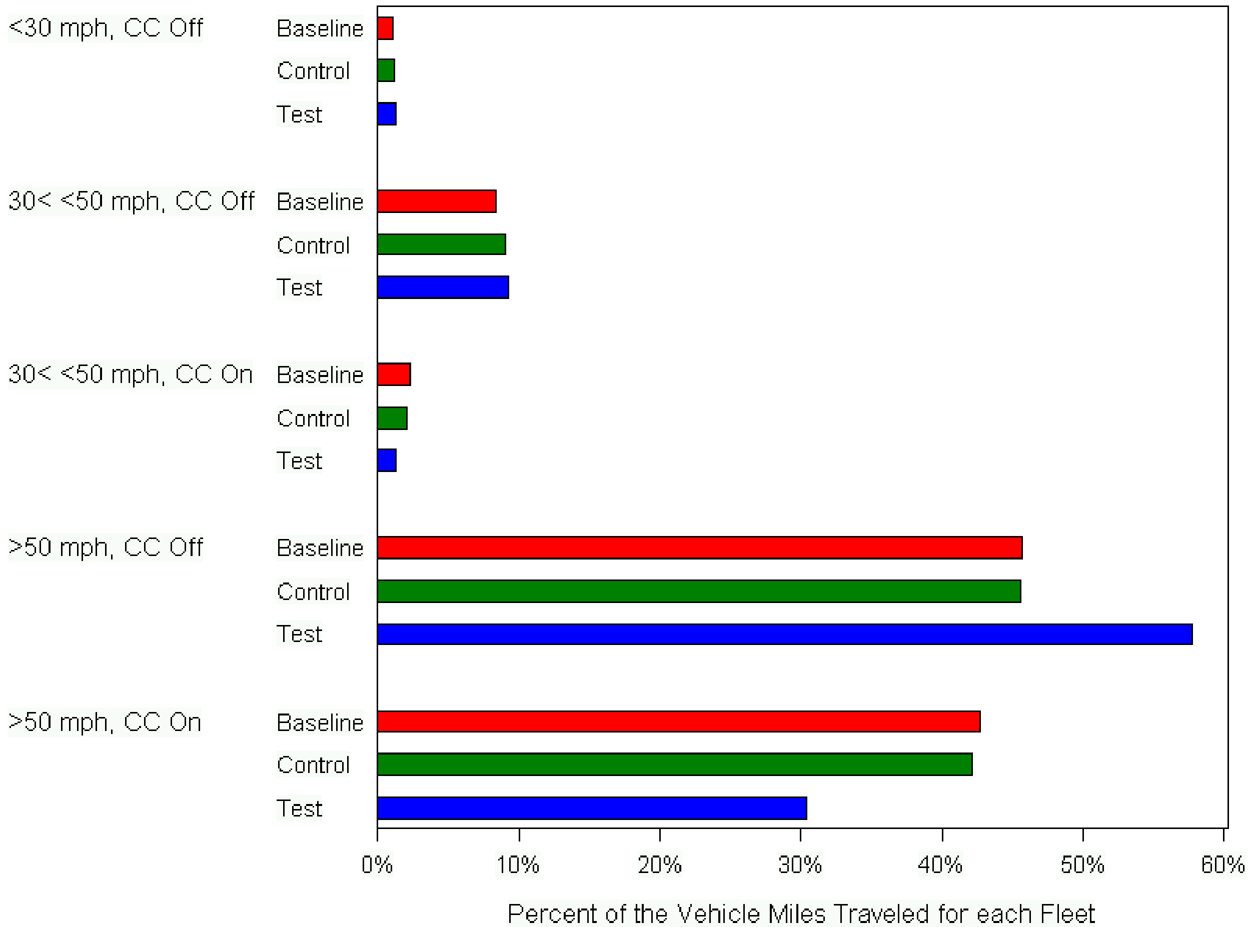


Figure 5.1-18. Percent of the Vehicle Miles Traveled for each Fleet Divided into Portions with Cruise Control "On" and "Off" as well as into Groups of Average Road Speeds

Table 5.1-21. Driver Characteristic and Log Variables

Data Type	Variable	Description
Driver Characteristic	Age	The age of each driver
	Years with a Commercial Drivers License (CDL)	The number of years since the driver first gained his/her CDL
	Years with US Xpress	The number of years since the driver was hired by US Xpress
	Sex	The gender of the driver
Driving Log	Log hours	The number of hours each driver was actively driving during the histogram period
	Service hours	The number of hours that each driver has been actively driving during the preceding 10 hours

The goal of the conditional exposure rate analysis was to identify the set of conditions (as represented by the individual variables or combinations thereof) that explained the variability in the driving conflict rates using differences in the driving behavior of the fleets.

When the variables related to the driving log were included in the analysis model, the amount of data available was reduced significantly, because a significant portion of DAS-2 data were collected during the time when log data were not available (Appendix D2). As such, the Poisson regression model was fitted without incorporating the driving log data. The variables included in this model are listed in Table 5.1-22. Variables that were statistically significant at the 0.05 level, i.e., having a multiplicative effect on the rate of driving conflicts, are noted with asterisks in Table 5.1-22.

Table 5.1-22. Variables Included in the Poisson Regression Model without Driver Log Data

Variable	Remarks	Interactions
Cruise Control Group* (p<0.0001)	Conventional (Baseline & Control Fleets), ACC[1] (Test Fleet)	Average Road Speed, and Percent Road Speed > 55mph
Cruise Control Status* (p<0.0001)	0 for cruise control off driving 1 for cruise control on driving	Cruise Control Group
CWS Group	No (Baseline Fleet) Yes (Control & Test Fleets)	Percent Road Speed > 55mph* (p<0.0001) and Average Road Speed
Vehicle Fleet	Baseline, Control, Test	None
Percent Road Speed > 55 mph	Percent of the time that Road Speed is greater than 55 mph	CWS Group* (p<0.0001) and Cruise Control Group
Average Road Speed	Average Road Speed	Cruise Control Group and CWS Group
Sine Hour of the Day* (p<0.0001)	Sinusoidal (circular) effects in the hour of the day	None
Cosine Hour of the Day		
Sine Day of the Year	Sinusoidal (circular) effects in the Julian date	None
Cosine Day of the Year* (p<0.0001)		
Age* (p<0.0001)	The age of each driver	None
Years with a CDL* (p<0.0001)	The number of years since the driver first obtained his CDL	None
Years with US Xpress* (p<0.0001)	The number of years since the driver was hired by US Xpress	None

1. The ACC effect includes any effect of AdvBS

* Variables which were statistically significant in the Poisson regression model of driving conflict rates. P-values are included for statistically significant variables only. All other variables had a p-value of >0.05 in the backward selection procedure.

In order to better differentiate between the various fleets and to isolate the effects of CWS and ACC + AdvBS on driving conflict rates, the fleets were divided into two groups as a function of the technologies installed. The CWS was available on the Control and Test vehicles, while the ACC + AdvBS was available on only the Test vehicles. These differentiations are captured by the "Cruise Control Group" and "CWS Group" variables.

Individual variables as well as interactions of variables were included in the model. A significant interaction indicates that the estimates of the effect of one variable depend on the value of the other variables it is interacted with. The interactions of variables are listed in Table 5.1-22, and significant interactions are also marked by an asterisk (*). For example, Table 5.1-22 shows that the interaction between CWS Group and the percent road speed greater than 55 mph is significant, indicating that the effect of the collision warning system varies with the percent of the time that the truck spends above 55 mph.

The findings discussed below were found to be statistically significant, namely the effect of the time spent at highway speeds, the effect of cruise control usage, the effect of driver age and experience, the effect of the time of day, and the effect of service hours.

Effects of Time Spent at Highway Speeds

Figure 5.1-19 illustrates how the effects of various combinations of CWS, ACC, and AdvBS interact with road speed. The exposure ratio is plotted against the percent of the time road speed is greater than 55 mph. Exposure ratios greater than 1 indicate that trucks with CWS are exposed to more conflicts than trucks without CWS.

- Statistically, the results indicate that a truck with CWS that spends less than 35 percent of its time at highway speeds is exposed to more conflicts than a truck without CWS.
- The figure also shows that if the truck spends between 35 percent and 75 percent of the time at highway speeds, there is no statistically significant difference between a fleet equipped and a fleet not equipped with CWS (Control fleet, and Baseline fleet, respectively).
- Above 75 percent of the time spent at highways speeds, there is a statistically significant reduction in the exposure to conflicts for trucks equipped with the CWS, hence demonstrating that the CWS is more effective at preventing conflicts when used at highway speeds than at lower speeds.

The same conditional analysis was performed to evaluate the effects of adding ACC + AdvBS to a truck already equipped with CWS. The upper right panel of Figure 5.1-19 shows the exposure ratio for Test trucks compared to Control trucks. There is a statistically significant effect (benefit) of adding ACC + AdvBS on the exposure ratio, independently of road speed. Findings of the previous analysis (Table 5.1-12) showed that the addition of ACC + AdvBS did not have a statistically significant effect on the exposure ratio. Test trucks are exposed to significantly fewer conflicts than Baseline and Control trucks regardless of amount of time spent at highway speeds. Unlike the Poisson regression approach used here in the conditional analysis, this previous analysis did not account for the effects of other factors[13].

Finally, results of the Poisson regression for the bundled systems (Test trucks versus Baseline) are presented in the lower panel of Figure 5.1-19. There is a significant reduction in the exposure to conflicts for Test trucks with the bundled systems as compared to Baseline trucks when more than 50 percent of the time is spent at highway speed, independently of cruise control usage.

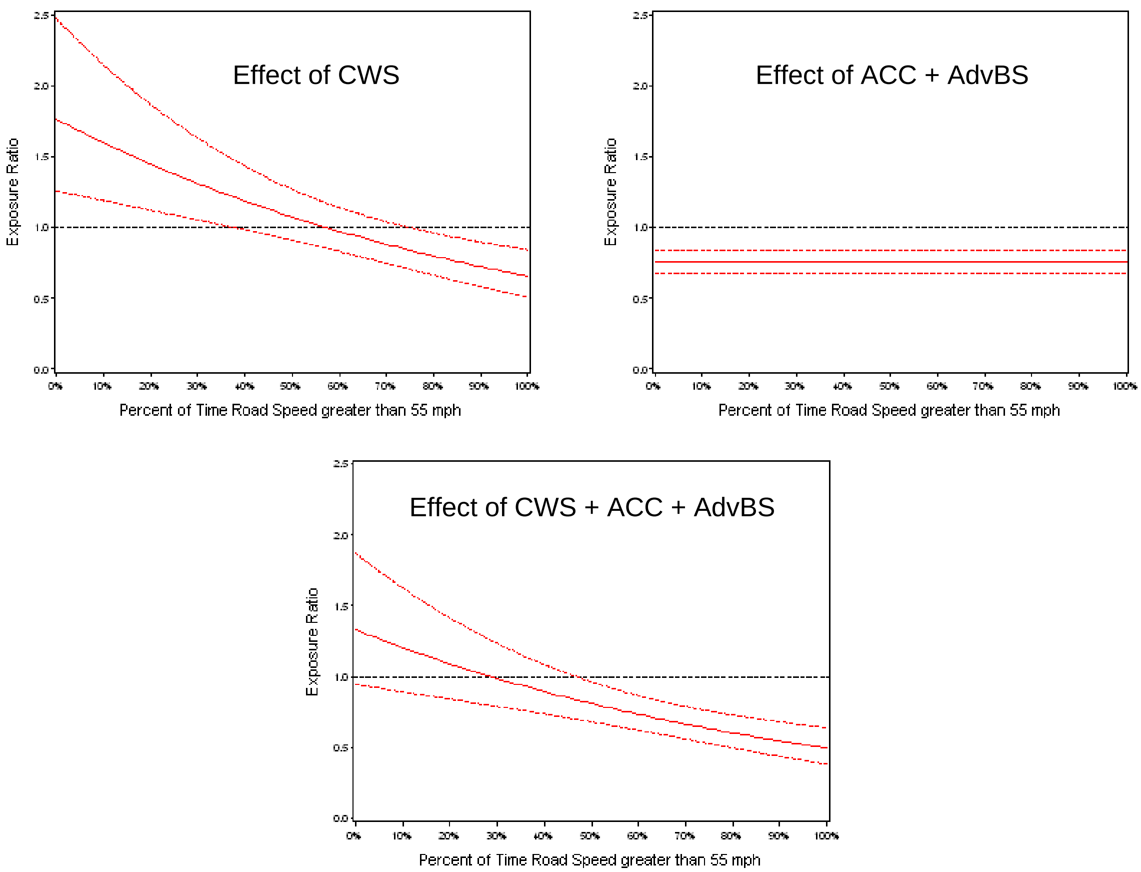


Figure 5.1-19. Exposure Ratios Associated with the Effects of Three Combinations of IVSS Technologies versus Percent of Time at Road Speeds Greater than 55 mph

(Dashed lines indicate 95-percent confidence intervals; disbenefits are above the horizontal ER=1.0 line; benefits are below)

[13] When these other factors are not controlled, the ability to detect smaller differences is limited, especially when the number of conflicts is reduced.

Effect of Cruise Control Usage

The previous analysis demonstrated that the addition of ACC (or ACC + AdvBS) reduces exposures to conflicts when other factors are controlled. As indicated in Table 5.1-22 above, there is a statistically significant difference between the rate of conflicts with cruise control "on" and the rate with cruise control "off." Figure 5.1-20 shows the estimated rate of driving conflicts for each type of driving, cruise control on and cruise control off, along with 95-percent confidence intervals. Approximately half of the miles traveled were with cruise control "on," while 1 percent of the driving conflicts were attributed to cruise control "on" driving.

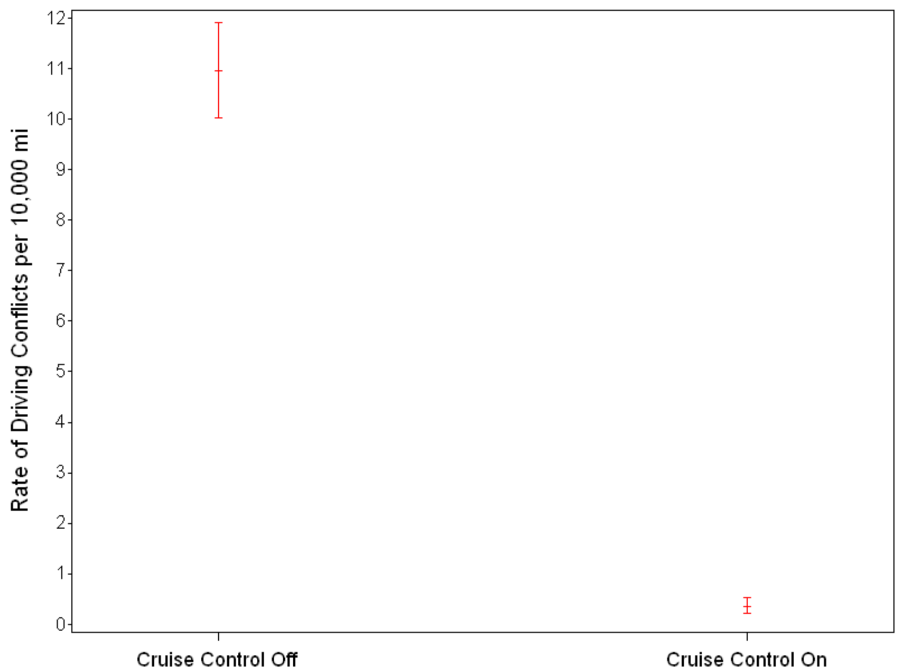


Figure 5.1-20. The Rate of Driving Conflicts per 10,000 Miles versus the Cruise Control Category in which that Driving Conflict Occurred

Error bars indicate 95-percent confidence intervals using the Tukey-Kramer adjustment

In evaluating the safety impacts of ACC, it is important to recognize that access to ACC versus conventional cruise control (CCC) can affect both the frequency of cruise control usage and the effectiveness of cruise control usage on conflict rates. The conditional analysis demonstrated that ACC reduces conflict rates when the analysis controls for other factors. However, one of those factors is the amount of time that cruise control is used. Because drivers with access to ACC tend to use cruise control less often than drivers with CCC (Figure 5.1-18), the apparent benefits of ACC are offset by the reduced usage. The lower usage may be related to changes in the distribution of driving conditions under which a driver will use cruise control. It could also relate to driver attitudes toward ACC. The driver survey indicated that 44 percent of the drivers prefer not to use ACC.

Effect of Driver Age and Experience

Figure 5.1-21 shows that the rate of conflicts with cruise control on decreases with driver age. Figures 5.1-22 and 5.1-23 show that the rate of conflicts increases significantly with CDL experience and years of employment with US Xpress.

The findings that exposure to conflicts decreases with driver age and increases with years with a CDL are seemingly contradictory, since one would expect that driver age and years with a CDL would be correlated. However, in the FOT data set, the correlation between these variables is small, because some of the drivers involved in the FOT were older drivers with minimal experience.

Older drivers are naturally less likely to enter situations where they are exposed to conflicts, while more experienced drivers can be more aggressive and more comfortable being in conflict situations.

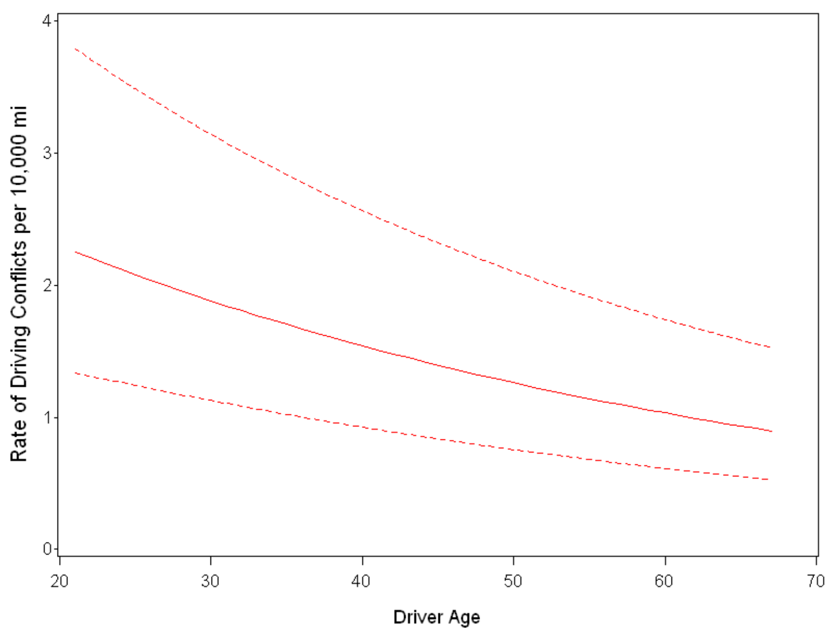


Figure 5.1-21. Rate of Driving Conflicts per 10,000 Miles versus Driver Age (with Cruise Control On)

The dashed lines indicate 95-percent confidence intervals

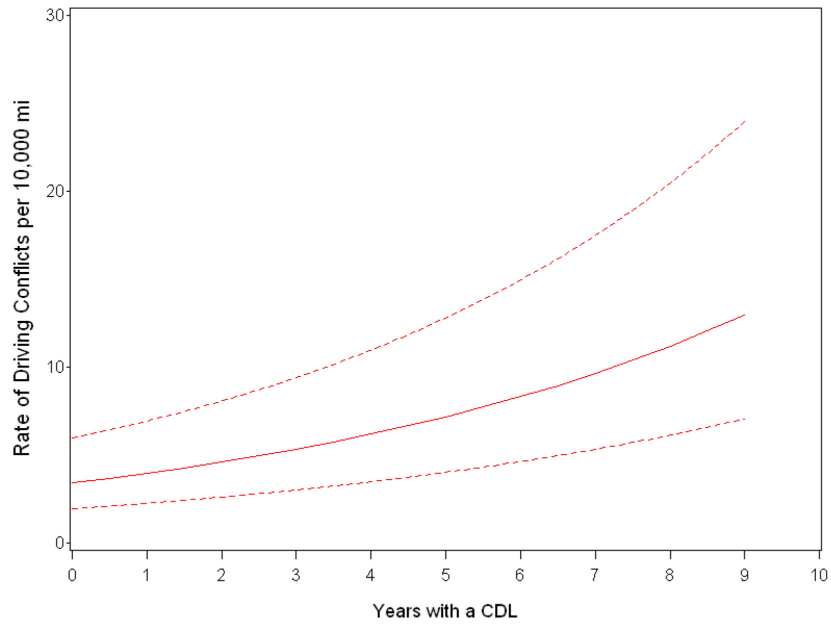


Figure 5.1-22. Rate of Driving Conflicts per 10,000 Miles versus the Years a Driver has Held his or her Commercial Drivers License (CDL)

The dashed lines indicate 95-percent confidence intervals

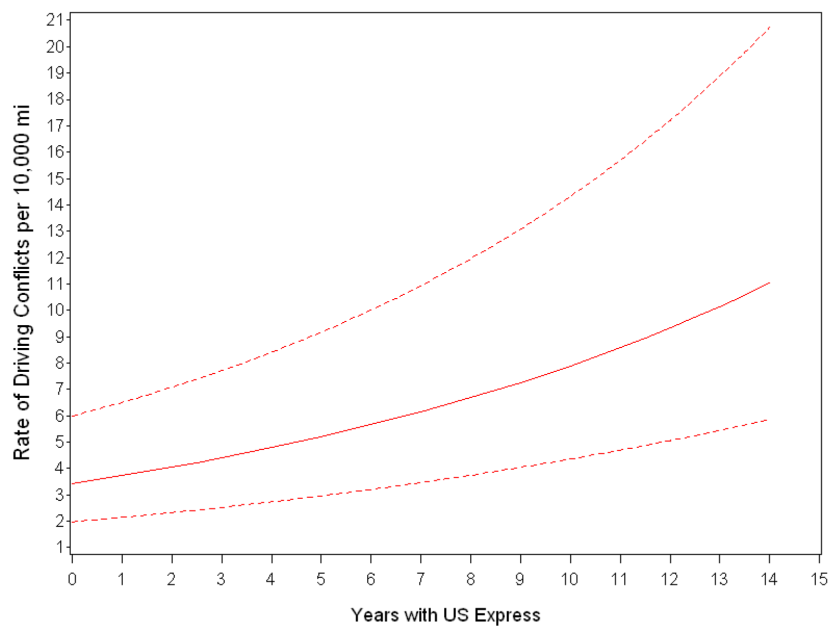


Figure 5.1-23. Rate of Driving Conflicts per 10,000 Miles versus the Years a Driver has been Employed with US Xpress

The dashed lines indicate 95-percent confidence intervals

Effect of Time of Day

Figure 5.1-24 shows the rate of conflicts as a function of the time of day. The hours between 5 and 8 GMT correspond to midnight locally, depending on the time zone in which the truck is located across the United States. The highest conflict rates were found to occur during the day, with a maximum at 18 GMT, i.e. at times corresponding to 10AM (PST) through 1PM (EST) in the United States.

Figure 5.1-25 gives the rate of conflicts as a function of Julian date. Most conflicts occur during the summer months.

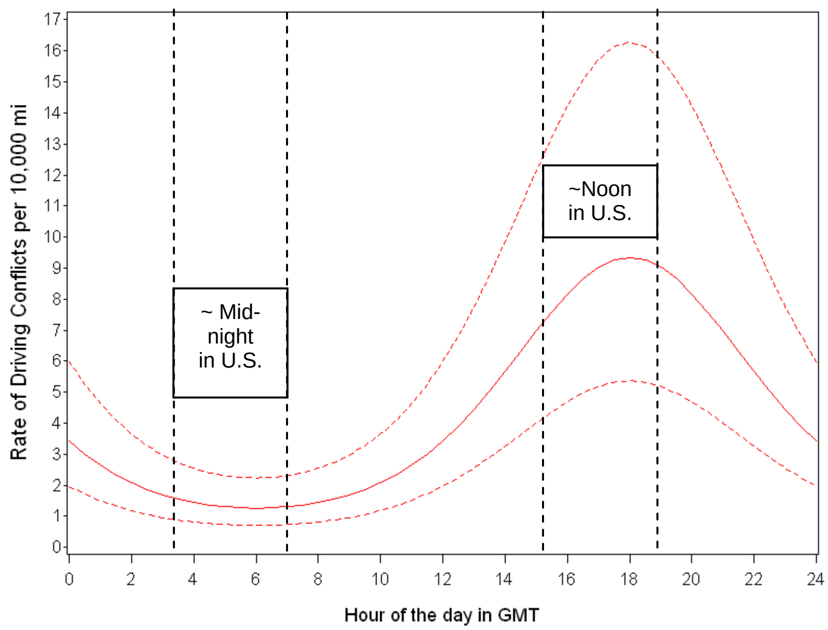


Figure 5.1-24. Rate of Driving Conflicts per 10,000 Miles versus the Hour of the Day in GMT

The dashed lines indicate 95-percent confidence intervals

Time ranges in U.S. are approximate

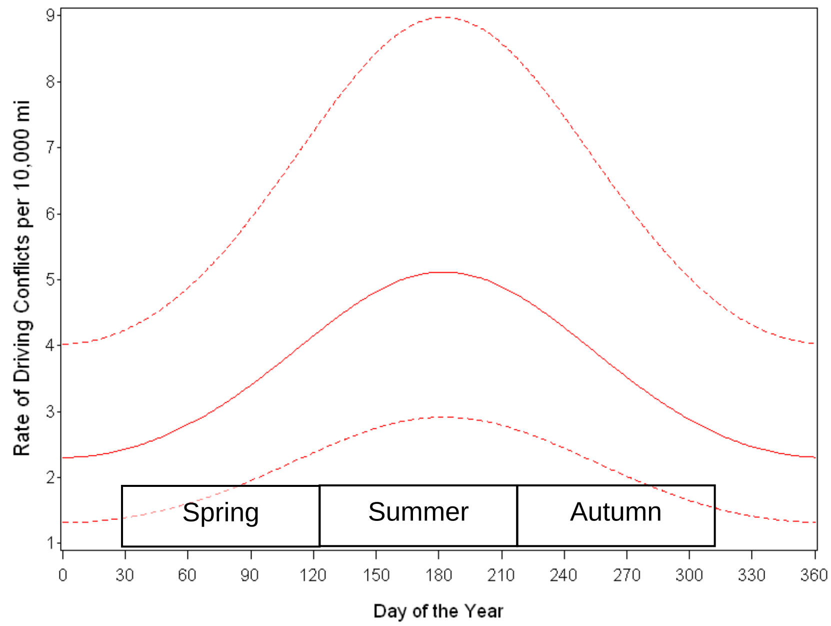


Figure 5.1-25. The Rate of Driving Conflicts per 10,000 Miles versus the Julian Date

The dashed lines indicate 95-percent confidence intervals

Seasons of year in U.S. are approximate

Effect of Service Hours

A Poisson regression model was used to evaluate the effect of service hours (amount of time driving during the last 10 hours) on conflict rates and the interaction of this effect with CWS and ACC usage. No statistically significant relationships could be identified among these factors.

As discussed previously, the second and third stages of the safety benefits analysis address the second hypothesis set forth under the first Objective A.1, specifically Hypothesis A.1-2: Fewer rear-end crashes will be encountered using CWS, ACC, and AdvBS. The second stage of the safety benefits analysis is to estimate the effectiveness of the IVSS in helping avoid a crash once the vehicle is involved in a conflict. This is accomplished by estimating the "prevention ratio," which compares the conditional (given that a conflict has occurred) crash probability with the IVSS with the conditional crash probability without IVSS. The third stage is to combine the exposure ratio and the prevention ratio to determine the overall benefit—namely, the total percent reduction in crashes that can be attributed to the use of the IVSS.

5.1.1.7 Conditional Analysis of Benefit Ratio

The conditional analyses of conflict rates and conflict severity presented in the previous sections were combined to develop a conditional analysis of the overall crash reduction ratio. Previously it was demonstrated that the exposure ratio associated with the CWS decreased as the truck spent more time operating at speeds greater than 55 mph. This implies that the CWS is more effective at helping to avoid conflicts at highway speeds than at slow speeds. Similarly, the conditional analysis of conflict severity showed that the CWS and bundled system is more effective at reducing the severity of conflicts when the conflict occurs at speeds greater than 35 mph. This analysis evaluates how the overall crash reduction ratio is affected by these two factors:

- Percent of time at speeds greater than 55 mph
- Average speed during the 15-second conflict.

Although the primary benefits estimates in this evaluation are based on the analysis performed with the medium conflict threshold, this analysis was performed using the conservative threshold in order to have sufficient data to estimate and evaluate the conditional factors.

As an example, assume that the truck spends 90 percent of its time at greater than 55 mph and that it has an average speed of 60 ft/s (40 mph) over the 15-sec time history. Table 5.1-23 compares the overall average crash reduction ratios with the ratios predicted from the model that accounts for the various conditions. The model used in this analysis included other driver and driving condition variables that were found to be statistically significant. As discussed in the previous sections, none of the estimated overall crash reduction ratios for CWS, ACC + AdvBS, and the bundled system were significantly less than 1.0 using the conservative threshold. The CRRs are between 0.9 and 1.0. However, the model predicts that the CRR will be between 0.4 and 0.8 when operating a truck at 40 mph on the highway (90 percent of time spent above 55 mph). Furthermore, the effect of the bundled system is statistically significant at the 95-percent confidence level. (Note that the confidence interval for the CRR estimate of 0.43 does not contain the value 1.0.)

Table 5.1-23. Comparison of Overall Average Crash Reduction Ratios with Estimated Ratios at Highway Speeds

	Overall Average		At 40 mph on Highway*	
	Crash Reduction Ratio	95% Confidence Interval	Crash Reduction Ratio	95% Confidence Interval
Effect of the CWS	1.019	(0.811, 1.227)	0.542	(0.263, 1.118)
Effect of the ACC and AdvBS	0.906	(0.782, 1.300)	0.793	(0.392, 1.603)
Effect of the Bundled System	0.928	(0.760, 1.096)	0.430	(0.208, 0.888)

* Road Speed > 55 mph for 90 percent of 3-hour period

Figures 5.1-26 to 5.1-28 show the relationships between the estimated crash reduction ratio and these two continuous variables for the CWS, ACC + AdvBS, and bundled systems, respectively. When the surface dips below one, there is a benefit. The dotted lines in the X-Y planes of the figures show where the benefits surface is equal to one. The solid lines in the X-Y planes show where the benefits ratio becomes significantly less than one. The benefits ratio is significantly less than one in the rear corner of Figures 5.1-26 and 5.1-28, demonstrating that the benefits occur at highway speeds.

Also shown on the vertical surfaces of the figures are frequency distributions of VMT versus % Time Road Speed is > 55 mph and percent of the total conflicts versus the Average Speed over the 15-sec time history. These histograms indicate that the majority of the VMT is spent in an area where the benefit ratio is less than 1; but many of the conflicts occur at slower speeds, where the systems are not as effective at reducing the risk of crashes.

The CWS is most effective at reducing rear-end conflicts when the truck is traveling at higher speeds (>55 mph). It is likely that drivers are alert when driving at slower speeds, possibly in traffic, and therefore the CWS does not show a benefit. These results indicate that there is a real safety benefit for the CWS, in spite of the fact that the empirical analyses were not statistically significant. Similar conclusions can be drawn for the bundled system.

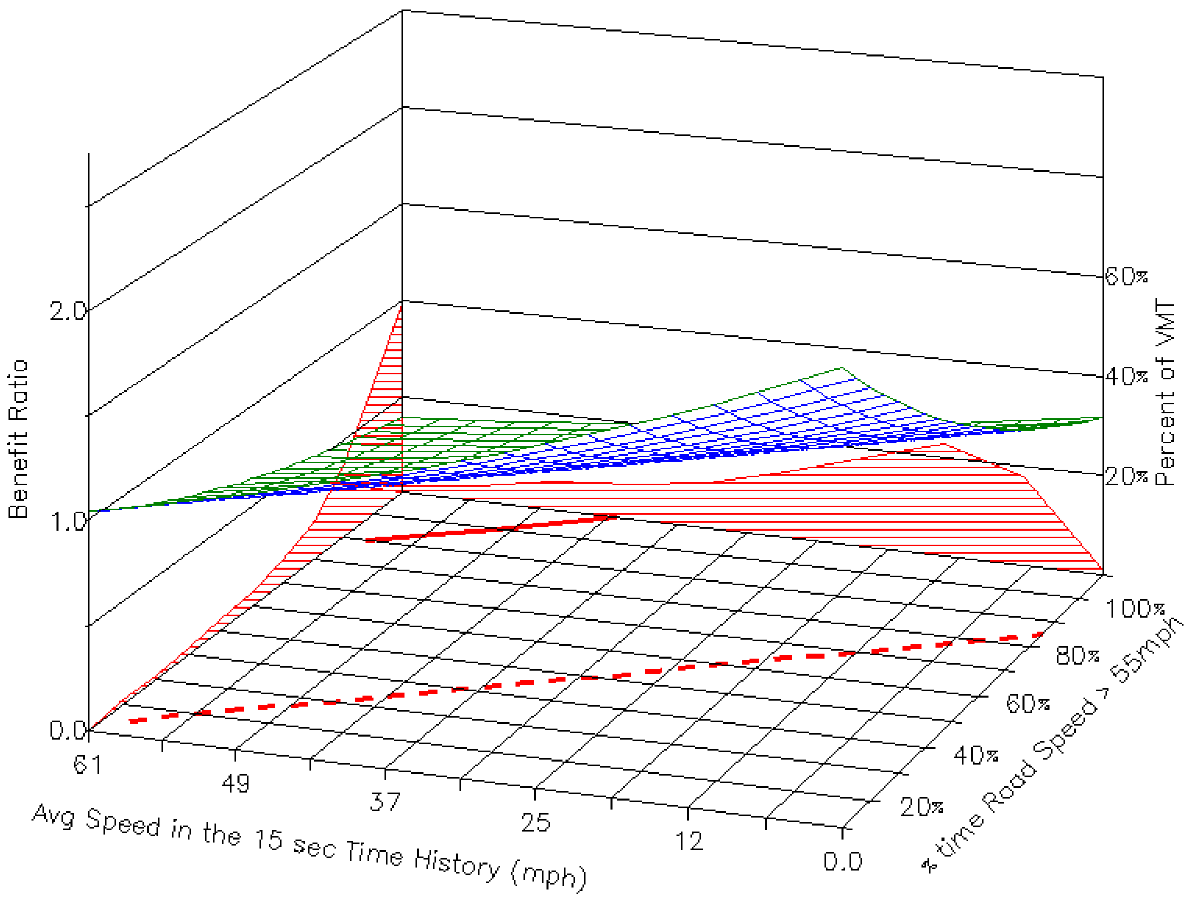


Figure 5.1-26. Benefits Surface for the Effect of the Collision Warning System

The dotted line indicates where the benefits surface is equal to one. The solid line indicates the area where the benefits ratio becomes significantly different from one. The histogram on the left vertical surface gives the percent of the vehicle miles traveled for different % Time Road Speed is > 55mph. The histogram on the rear vertical surface gives the percent of conflicts at the various average speeds in the 15 sec Time History.

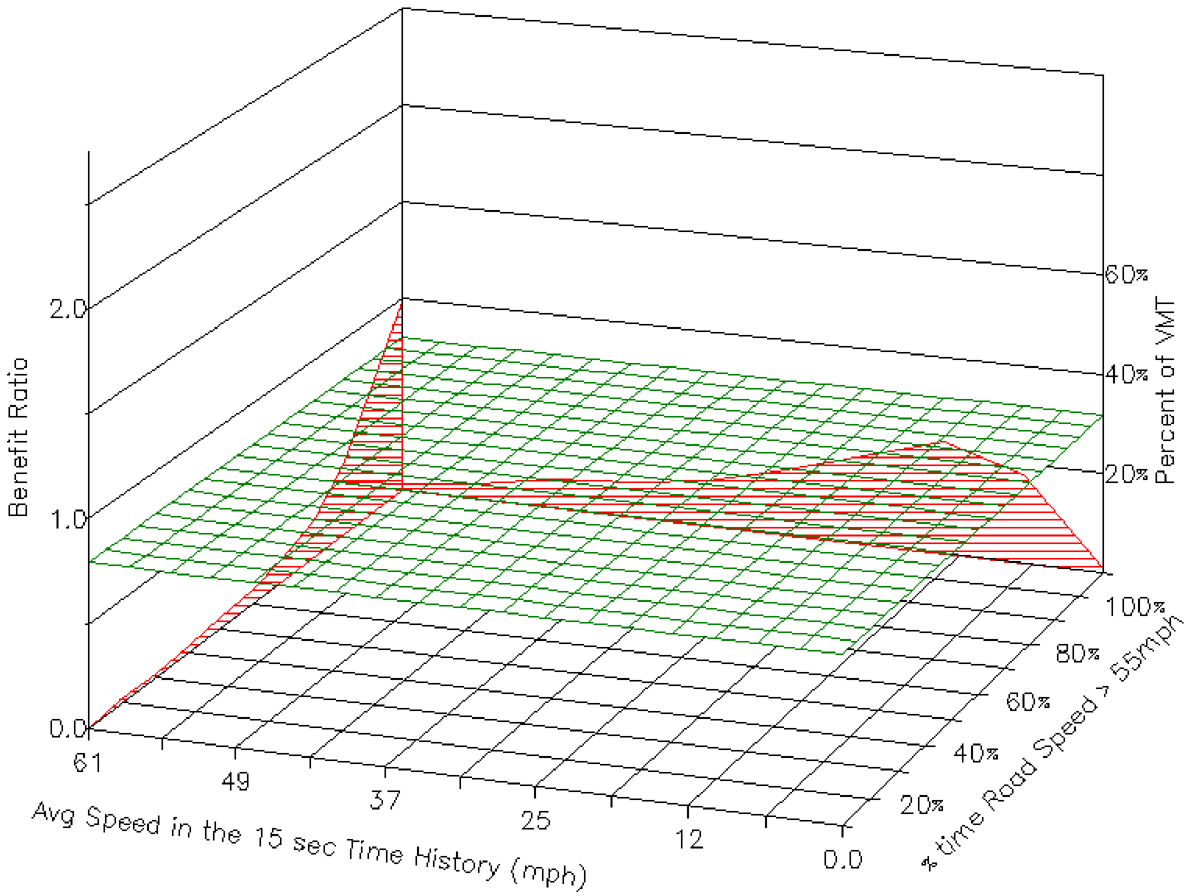


Figure 5.1-27. Benefits Surface for the Effect of the ACC and AdvBS

This surface does not depend on the indicated covariates. The histogram on the left vertical surface gives the percent of the vehicle miles traveled for different % Time Road Speed is > 55mph. The histogram on the rear vertical surface gives the percent of conflicts at the various average speeds in the 15 sec Time History. The benefit surface is not significantly different from one.

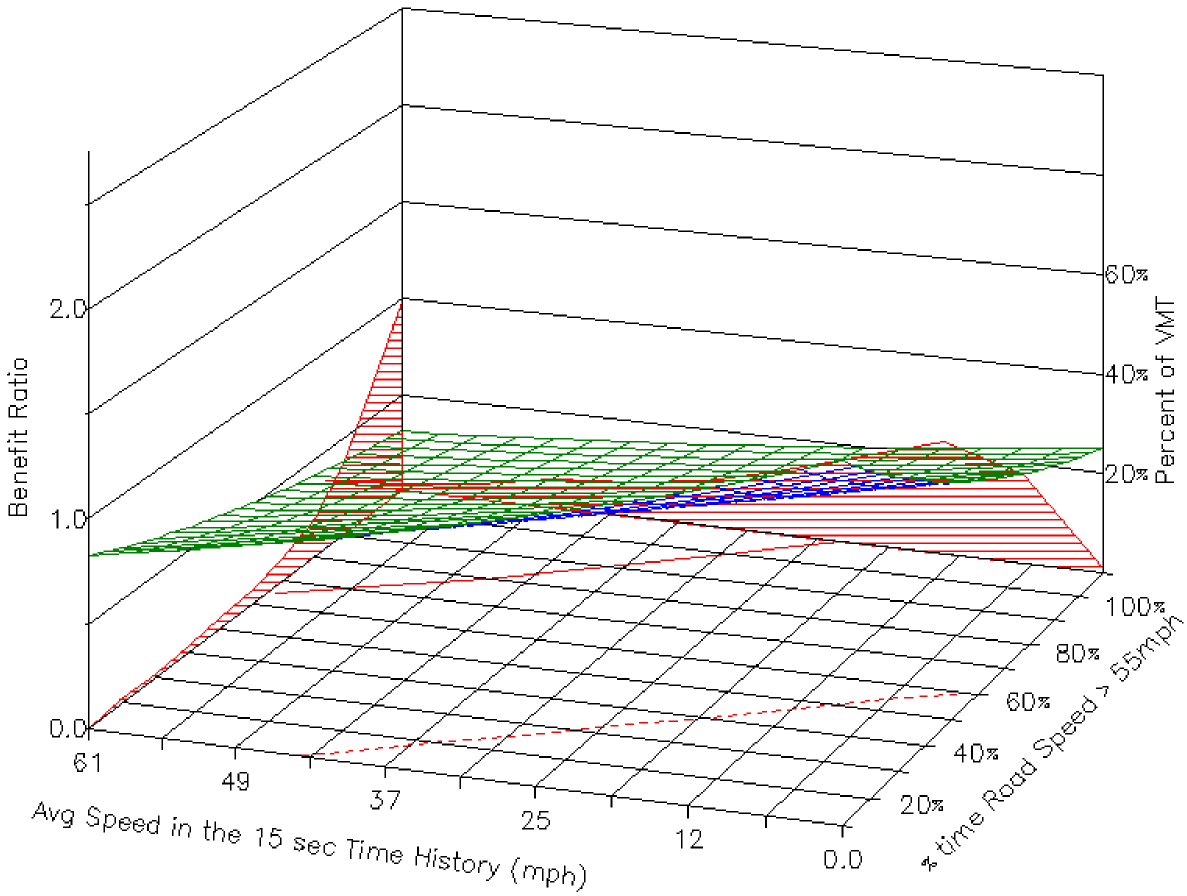


Figure 5.1-28. Benefits Surface for the Effect of the Bundled System

The dotted line indicates where the benefits surface is equal to one. The solid line indicates the area where the benefits ratio becomes significantly different from one. The histogram on the left vertical surface gives the percent of the vehicle miles traveled for different % Time Road Speed is > 55mph. The histogram on the rear vertical surface gives the percent of conflicts at the various average speeds in the 15 sec Time History.

5.1.2 Objective A.2: Determine if Drivers Will Drive More Safely with IVSS than Without It

This section contains descriptive summaries and analyses of FOT driving data pertaining to Safety Objective A.2. The safety systems under test are expected to increase drivers' awareness of critical situations, hence training them and helping them improve their driving habits. Thus, in this analysis, driving behaviors of drivers in the different fleets of vehicles (Baseline, Control and Test) are empirically observed to determine if the various combinations of IVSS deployed result in drivers driving more safely.

Driving behaviors are characterized by the frequencies of specific events generally associated with safety (e.g., frequency with which drivers encounter dangerous situations) as well as by various measures generally associated with safe driving (e.g., vehicle speed, following distances, reaction time).

5.1.2.1 Hypothesis A2.1: Drivers of vehicles equipped with IVSS will have fewer evasive maneuvers, hard brake applications, ABS events, and high-level VORAD® alarms (when applicable) than drivers of vehicles not equipped with IVSS

Under this objective, the first hypothesis was designed to compare the frequency of specific events generally defined as surrogate safety measures, specifically evasive maneuvers, hard brake applications, ABS events, and high-level VORAD® alarms. These measures were initially defined and programmed into the DAS units to trigger data collection during potential conflicts. However, these triggered events were not necessarily representative of dangerous situations, hence of driving conflicts. Section 5.1.1 described the methods used to identify and determine the resolution of conflicts and presented a comparative analysis of conflict rates among the three truck fleets. As such, in this section, the surrogate safety measures analyzed are measures of braking behaviors that can be quantified using DAS recorded histogram driving data rather than triggered events:

- Longitudinal acceleration,
- Brake pressure (Test trucks only)
- Duration of engine brake events
- Duration of engine plus service brake events.

Comparison of the surrogate measures or their derivatives across the three groups provides insights as to the safety benefits of the IVSS. For example, safer driving of one fleet versus another could be indicated by

- Reduced percentages of time that the vehicle’s longitudinal deceleration exceeds 0.15 g, or
- Braking events with lower brake pressure and shorter duration, i.e., less severe braking events.

Histogram data are illustrated in this section in frequency distribution charts or scatter plots. In all such plots, the product of bin width and bin height summed over the graph yields 100 percent. As such, the vertical axis of a graph having coarser (fewer) bins tends to show relatively larger percentage values, whereas the vertical axis of a graph having finer (more) bins tends to show relatively smaller percentage values.

Longitudinal Acceleration

Figure 5.1-29 shows frequency distribution of the longitudinal acceleration for the three fleets of trucks. The data do not suggest disparate behavior among the three fleets.

Bins in the raw data collected range from -1g to +1g, but the graphs in Figure 5.1-29 display only the limited portion of the range that is of interest in assessing differences in behavior among the three groups pictorially. Unfortunately, the large number of counts in the middle five bins and the relative coarseness of the bins make it impossible to draw firm distinctions between the fleets at this level.

Negative longitudinal acceleration values are assumed to indicate deceleration. It is not clear why the observed values are not centered about zero, but the shift is consistent across the three truck groups.

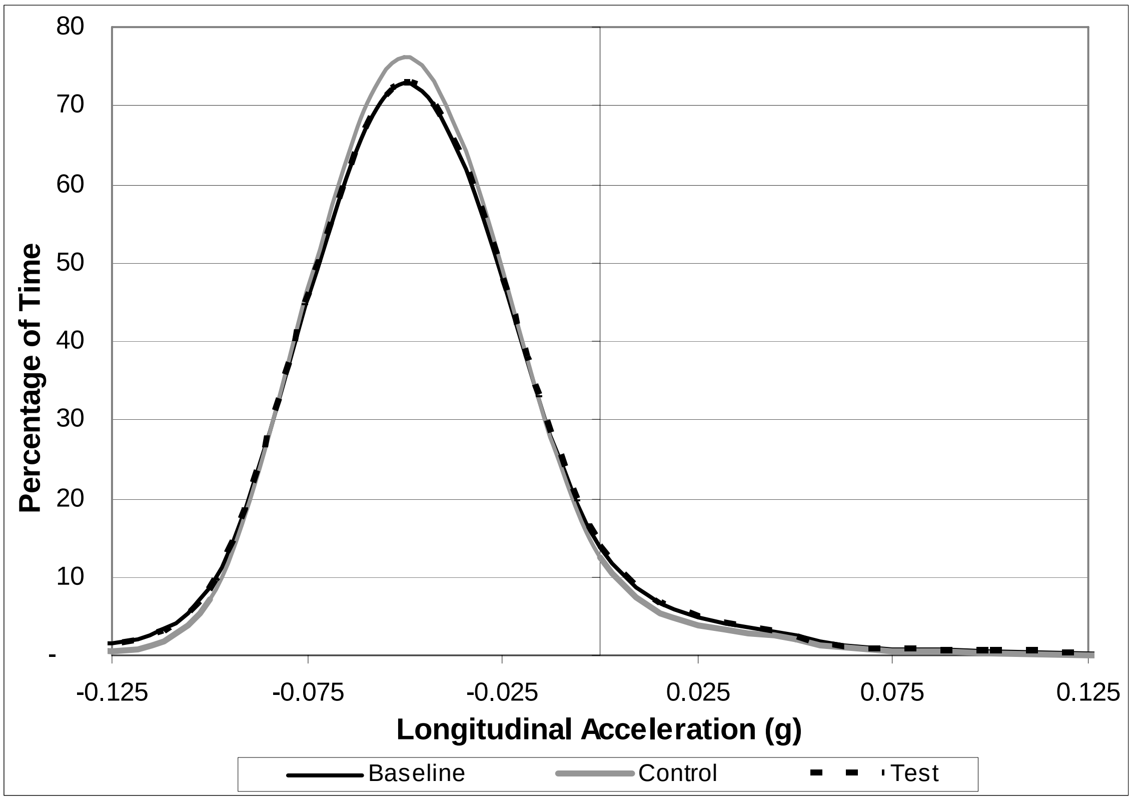


Figure 5.1-29. Distribution Chart of the Longitudinal Acceleration for the Three Fleets

Brake Pressure

Comparisons of brake pressure behaviors across the three fleets cannot be made because brake pressure measurements were only available for Test trucks.

- The observed brake pressure behavior of the Test trucks indicates that the brakes are not in use 97.2 percent of the time.
- When brakes are in use, Figure 5.1-30 shows that most brake applications are in the range of 3 to 20 psi (20 to 150 kPa), indicative of routine braking.

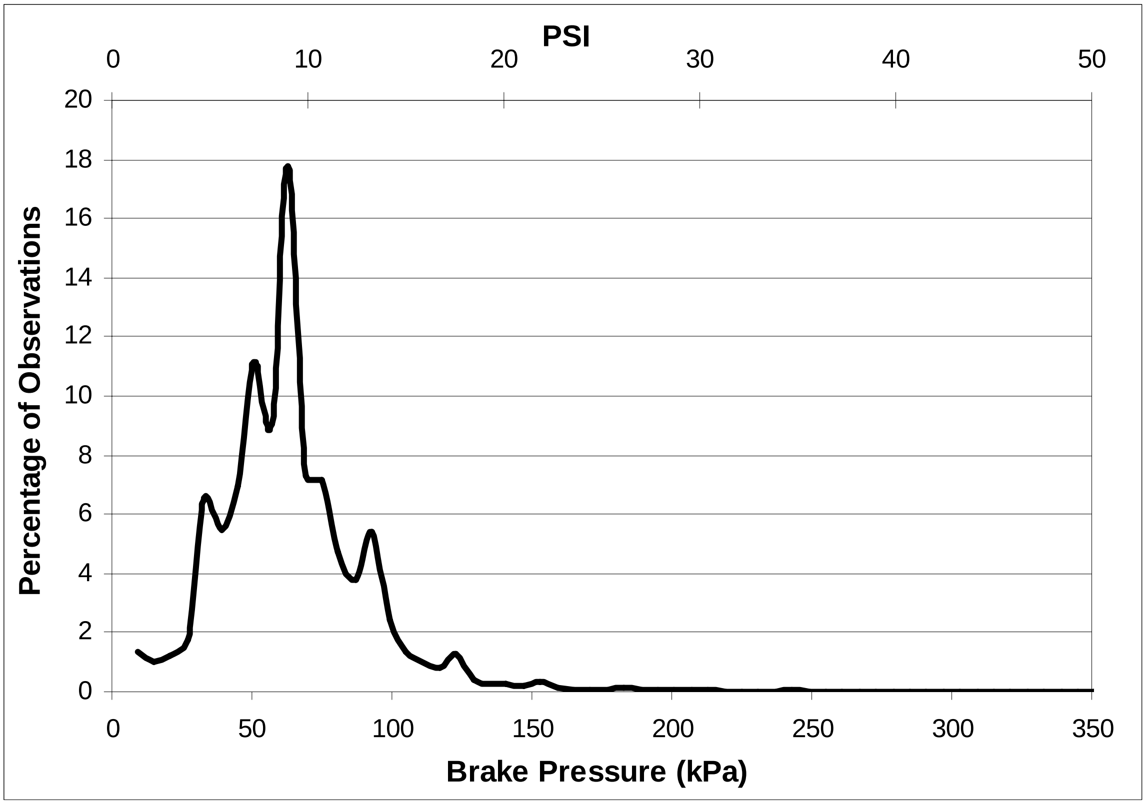


Figure 5.1-30. Distribution Chart of the Brake Pressure Behavior of Test Trucks

Duration of Service Brake Events

Figure 5.1-31 shows a comparison of the durations of service brake events, i.e. the period of time service brakes are applied, for each of the three fleets:

- Test vehicles have a larger percentage of short braking events (less than 2 seconds).

This observation could be indicative of enhanced braking capability, as the driver can decelerate his/her vehicle more efficiently, or of safer driving as the driver may not be in situations requiring longer braking. Durations of service braking events alone cannot be used to infer safer (or less safe) driving behavior. Short-duration events can be indicative of both normal and emergency braking. Long durations of service braking, e.g., greater than 10 seconds, are likely to be reflective of routine slowing down or downhill retardation. Additional knowledge related to the braking severity (for example through brake pressure), the vehicle parameters (use of engine brake), or driving circumstances (urban or highway driving conditions) is needed to relate service brake durations trends to safety trends.

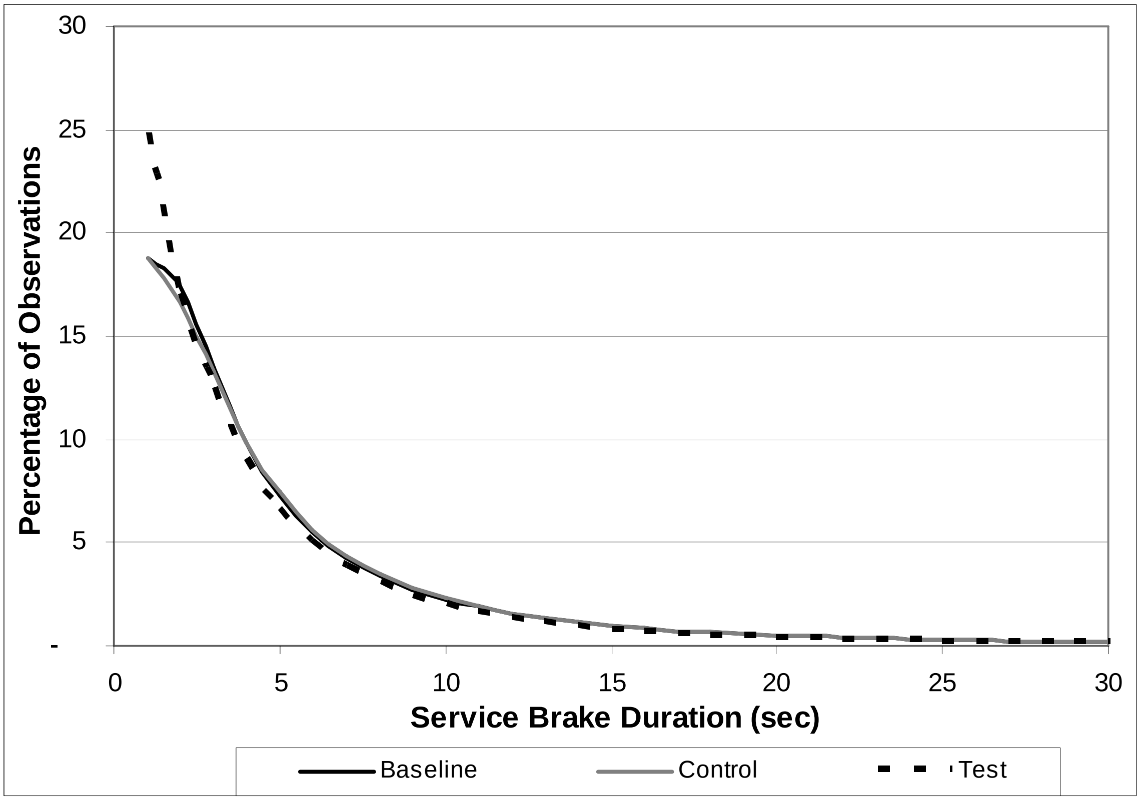


Figure 5.1-31. Distribution Chart of the Duration of Service Brake Events for the Three Fleets

Duration of Engine Brake Events

Figure 5.1-32 shows the percentage of observations that trucks in each fleet are in an engine-braking event of a given duration. The DAS records engine braking events from 0 sec to 63 sec in duration. Few braking events last longer than 30 sec., so that portion of the data is not graphed in Figure 5.1-32:

- Engine brakes are used by Baseline, Control, and Test trucks less than 1 percent of the driving time.
- Most engine brake events are less than 10 seconds long for all three fleets.
- Figure 5.1-32 does not indicate any differences in long-duration engine brake use between the fleets. In contrast to service braking events, long-duration engine braking events might be related to safer driving through reduction in service brake demand and resulting heat generation. Hence, the risk of fade (more applicable to s-cam drum brakes than to disk brakes) in subsequent high-demand braking events would be reduced.
- The percentage of short engine brake events (less than 3 seconds) increases from Baseline trucks to Control trucks to Test trucks. This finding could explain in part the increased percentage of short service brake events for Test trucks in Figure 5.1-31. The increased use of the engine brake could reduce the need for service braking.

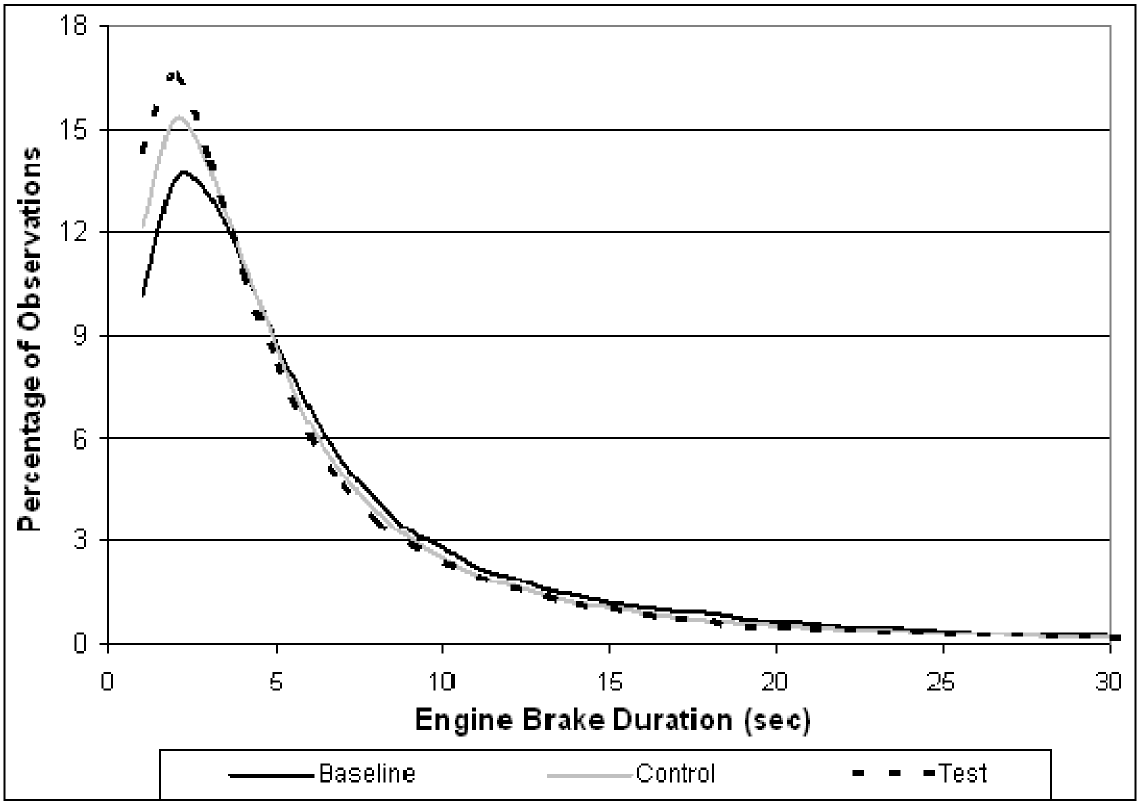


Figure 5.1-32. Distribution Chart of the Duration of Engine Brake Events for the Three Fleets

In summary, safety benefits of IVSS as defined by Hypothesis A2.1 could not be verified, because no significant differences in braking-related driving behaviors (longitudinal acceleration, service brake event duration, and engine brake event duration) were observed among the Baseline, Control, and Test fleets.

5.1.2.2 Hypothesis A2.2: Drivers of vehicles equipped with IVSS will approach lead vehicles more slowly, maintain longer following distances, and react more quickly to lead vehicles than drivers of vehicles not equipped with IVSS

Similarly to Hypothesis A2.1, this second hypothesis is addressed using histogram data for four variables related to the vehicle's driving condition: average road speed, following distance, following interval, and time-to-collision. Empirical comparisons of the average values of these surrogate measures of safety can determine if the various combinations of IVSS deployed result in drivers driving more safely.

Road Speed

Figure 5.1-33 shows the percent of the time that trucks in each fleet spend moving, at speeds up to 120 feet per second (ft/s) or 80 mph:

- The Baseline, Control, and Test trucks are stationary between 50 and 60 percent of their time (54.6 percent, 59.9 percent, and 55.4 percent, respectively).
- The majority of driving by all three fleets is at speeds between ~ 55 and 72 mph (80 and 105 ft/s), which is consistent with the US Xpress long-haul type of operations.
- Peaks in percentage of observations are seen in speeds typical of highway speed limits, i.e., between 55 and 60 mph (80 to 88 ft/s), as well as between 65 and 70 mph (95 to 103 ft/s). At the lowest range (between 80 and 90 ft/s), a more defined peak is observed for control trucks at 88 ft/s (60 mph), which could be indicative of increased cruise control use of Control vehicles compared to Baseline vehicles. Since Test trucks are equipped with ACC, such steady vehicle speed is less likely, because the following interval, not the speed, would be controlled at times when a target vehicle is present.

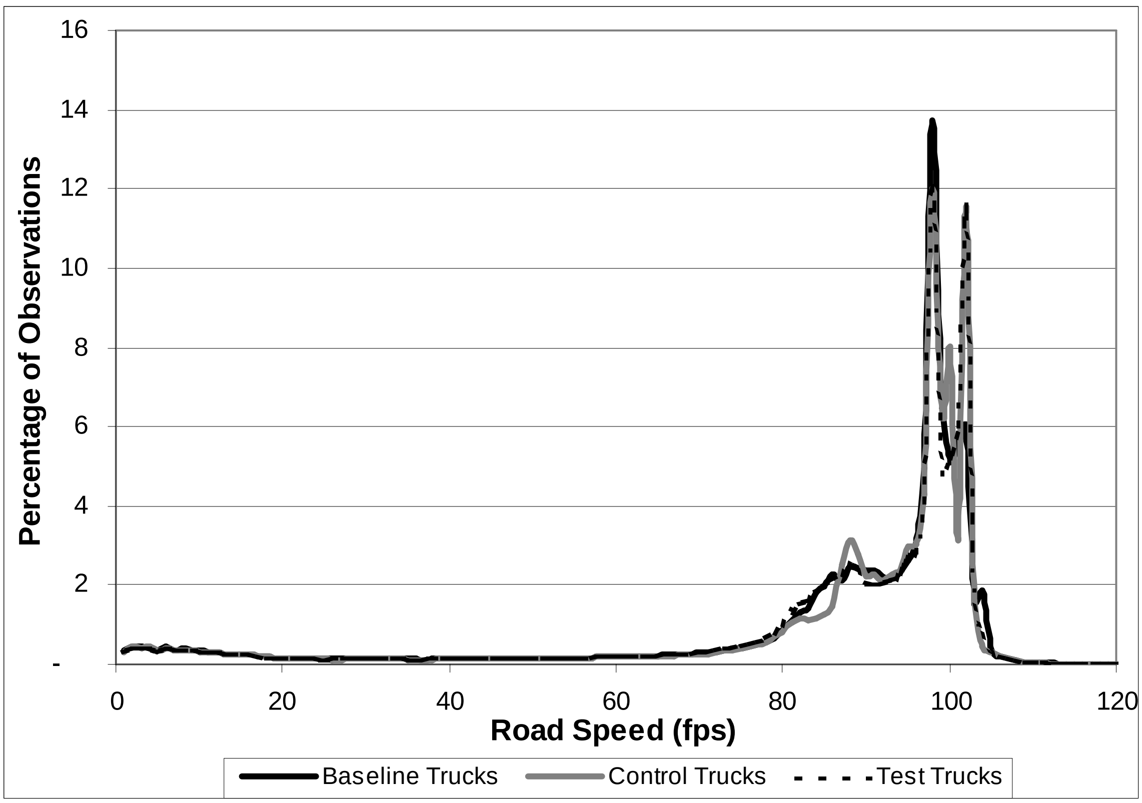


Figure 5.1-33. Distribution Chart of the Average Road Speed for the Three Fleets

Following Distance

Longer following distances are assumed to be associated with safer driving. Figure 5.1-34 displays the following distances for each of the three fleets. These graphs include behavior only when the lead vehicle is less than 381 ft in front of the truck – the maximum range of the CWS.

- There is no lead vehicle within 381 ft of the Baseline, Control, and Test trucks for ~ 85 percent of the time (87.2 percent, 86.8 percent, and 84.9 percent, respectively).

Figure 5.1-34 presents a compelling indication that the IVSS deployed in this FOT may make driving safer:

- Control and Test trucks spend a larger percentage of the time a target is present following at longer distances (greater than 180 ft).
- At shorter distances, there are mixed indications about the driving behavior. The mode of the distribution occurs near 120 ft. This distance appears to have the greatest significance for the Baseline drivers.

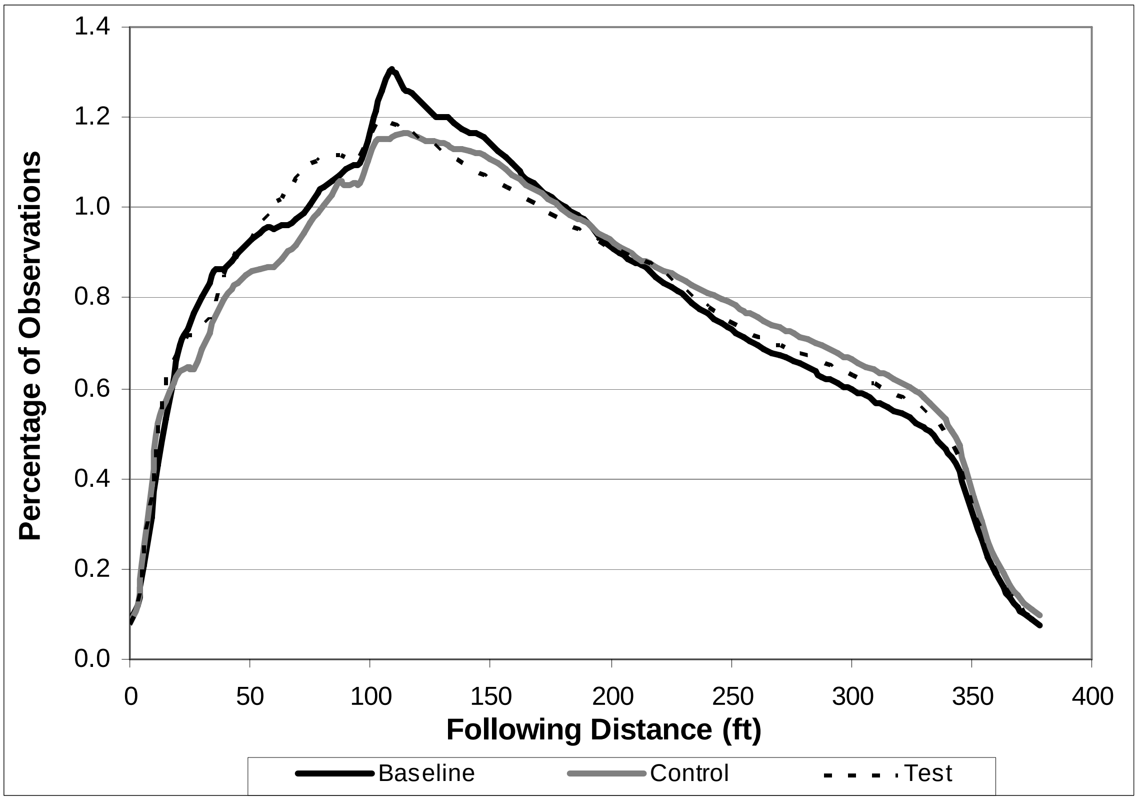


Figure 5.1-34. Distribution Chart of the Following Distance for the Three Fleets

Figure 5.1-35 illustrates the average following distance for the Baseline, Control and Test trucks, with 95-percent confidence intervals.

- There are significant differences in the average following distance of the various trucks.
- The Baseline trucks have the shortest following distances, followed by Test trucks, with Control Trucks having the largest average following distances. Thus, drivers of CWS-equipped Control trucks maintain the largest average following distance of all FOT vehicles. This observation could indicate that CWS is effective in assisting drivers to be safer by helping drivers maintain longer following distances than drivers of vehicles not equipped with the CWS. The observation that the average following distance of Test trucks is significantly lower than that of the Control trucks, yet still greater than the

Baseline trucks, could be explained by the use of ACC. ACC controls the following interval behind the target vehicle, not the following distance.

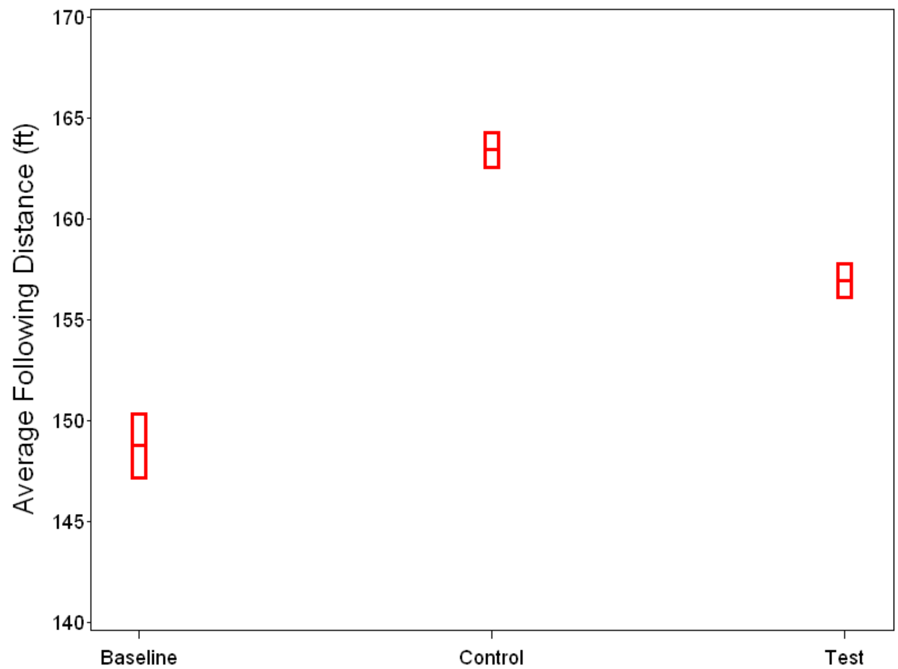


Figure 5.1-35. Average Following Distance for Each Fleet

Error boxes indicate a 95-percent confidence interval

Figure 5.1-36 illustrates the percent of the time spent by each fleet at following distances below 100 and 200 ft, with 95-percent confidence intervals.

- Significant differences between fleets are observed, and a benefit is shown for both the Control and Test trucks over the Baseline trucks.
- The trend illustrated in Figure 5.1-35 is observed: the percent of time spent by the Control fleet at following distances below 100 or 200 ft is significantly lower than that spent by either the Baseline or Test fleets. The percent of time spent by the Baseline fleet at following distances below 100 or 200 ft is also significantly greater than that spent by the Test fleet.
    - The percentage of the time that a target is present spent at following distances less than 200 ft is 70.5 percent for Baseline trucks, 67 percent for Test trucks, and 64.5 percent for Control trucks.
    - The percentage of the time that a target is present spent at following distances less than 100 ft is 36.5 percent for Baseline trucks, 34 percent for Test trucks, and 31 percent for Control trucks.

- Hence, the difference in the percentage of time spent at following distances below either 100 or 200 ft is approximately 6 percent between Baseline and Control vehicles.

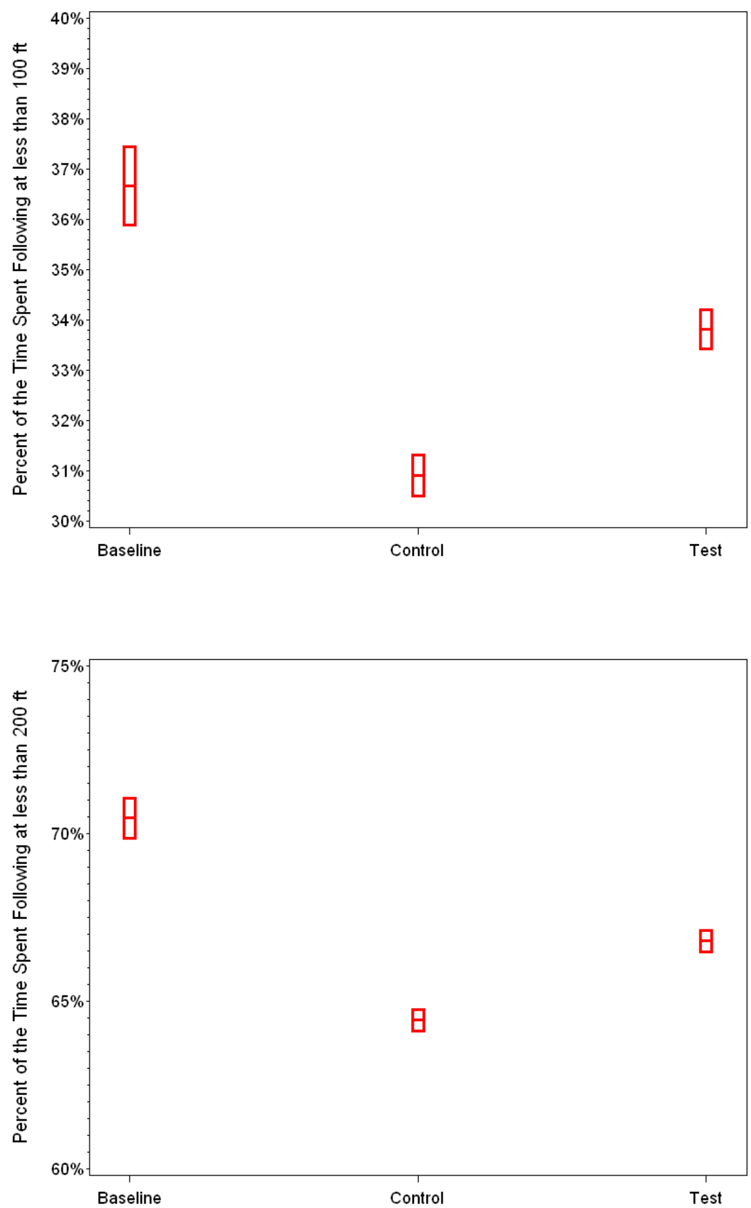


Figure 5.1-36. Percent of the Time spent at Following Distances Less than 100 ft (Top) and 200 ft (Bottom) for the Three Fleet of Trucks

Error boxes indicate a 95-percent confidence interval

A given following distance that is safe at given speeds may become unsafe at greater speeds. Thus, measures of following interval and time-to-collision, presented below, are better measures of safety. Figure 5.1-37 illustrates the relationship among following intervals, following distances, and vehicle speeds.

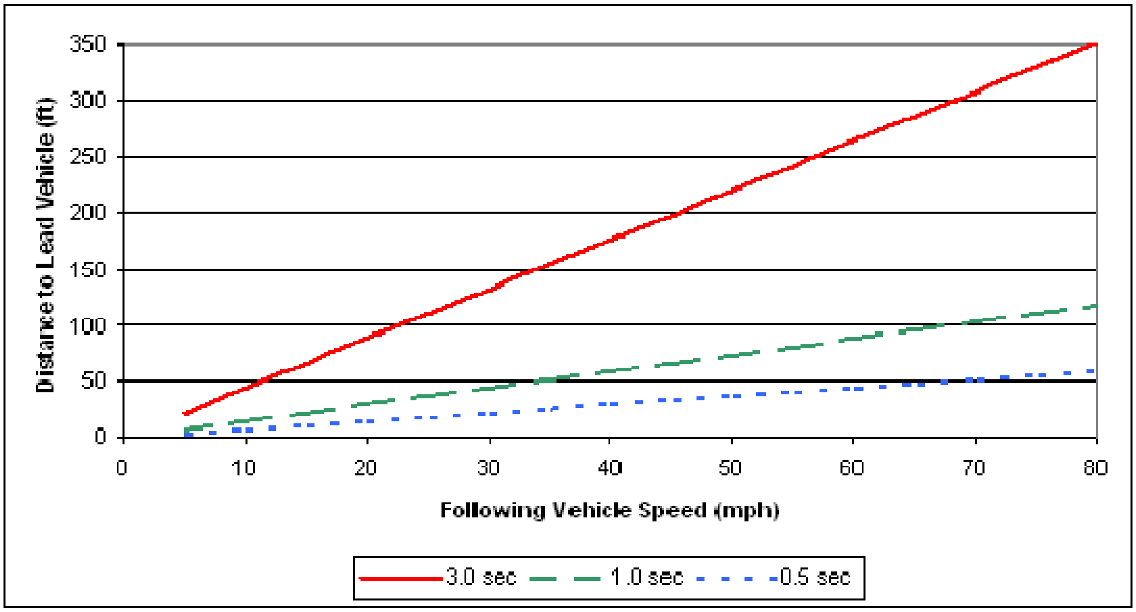


Figure 5.1-37. Range to the Lead Vehicle (Following Distance) as a Function of Vehicle Speed for three Following Intervals

Following Interval

Figure 5.1-38 presents the following intervals for each of the three fleets. As with the following distance data plotted in Figure 5.1-34, data were not recorded when there was no lead vehicle within 381 ft of the truck, implying that, since most data were collected at road speeds ranging from 80 to 105 ft/s, following interval values above 3.6 seconds were not indicative of safety. Indeed, if a truck is traveling at 80 or 105 ft/s, a 381-ft following distance would yield following intervals equal to 4.8 and 3.6 seconds, respectively. Since Figure 5.1-38 gives data for following intervals only when a target is present, differences in the percentage of time a target is present between the fleets are not reflected.

- Figure 5.1-38 echoes Figure 5.1-34 in terms of indicating a safety benefit associated with the IVSS.
- Figure 5.1-38 shows that Control trucks maintain greater following intervals than Test trucks, which in turn maintain greater following intervals than Baseline trucks.

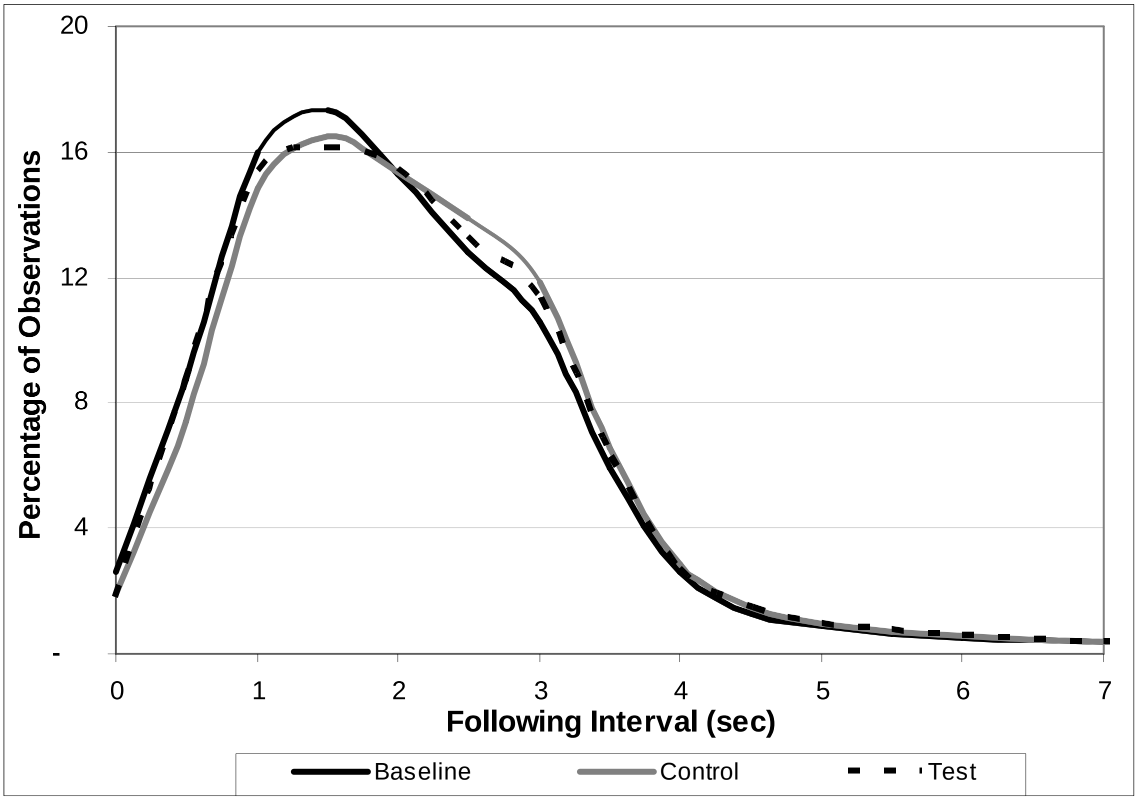


Figure 5.1-38. Distribution Chart of the Following Interval for the Three Fleets

Figures 5.1-39 and 5.1-40 also support these conclusions. Figure 5.1-39 illustrates the average following interval for the Baseline, Control and Test trucks, while Figure 5.1-40 illustrates the percent of the time spent by each fleet at following intervals below 0.5, 1 and 3 seconds.

- Test trucks have significantly longer average following intervals than Control trucks, and Control trucks significantly longer than Baseline trucks, with averages all exceeding 3.6 seconds.
- The percentage of time that a target is present spent by Baseline trucks at following intervals of 0.5, 1 and 3 seconds is greater than that of Control trucks, by 2 to 4 percent.
- The percentage of time that a target is present spent by Test trucks at following intervals of 0.5, and 1 second is similar to that of Control trucks, while the percentage of time spent by Test trucks at following intervals of 3 seconds is lower than that of Control trucks, by 1 percent.

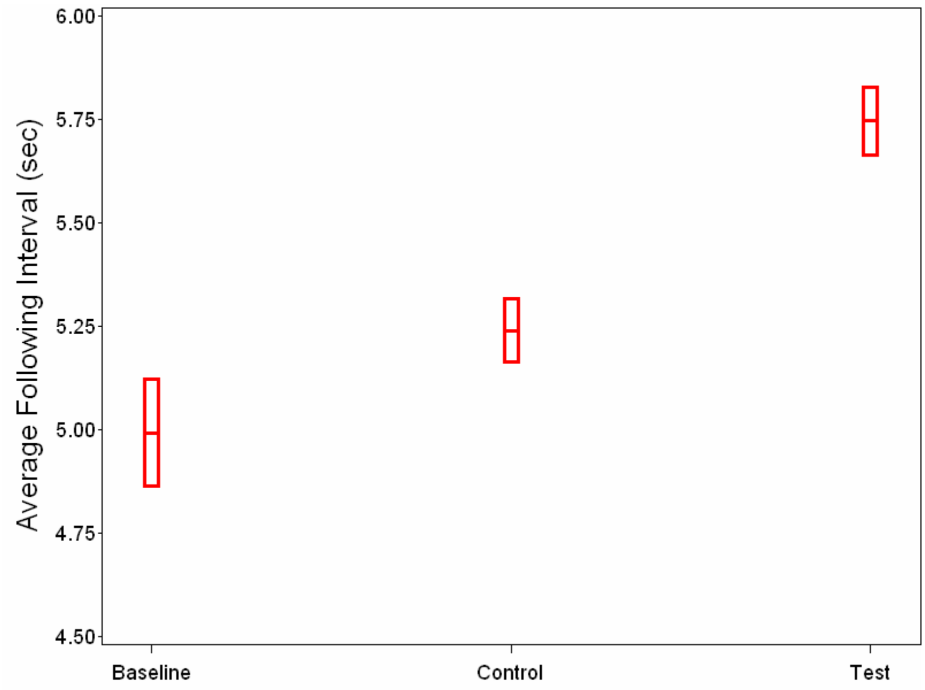


Figure 5.1-39. Average Following Interval for Each Fleet

Error boxes indicate a 95-percent confidence interval

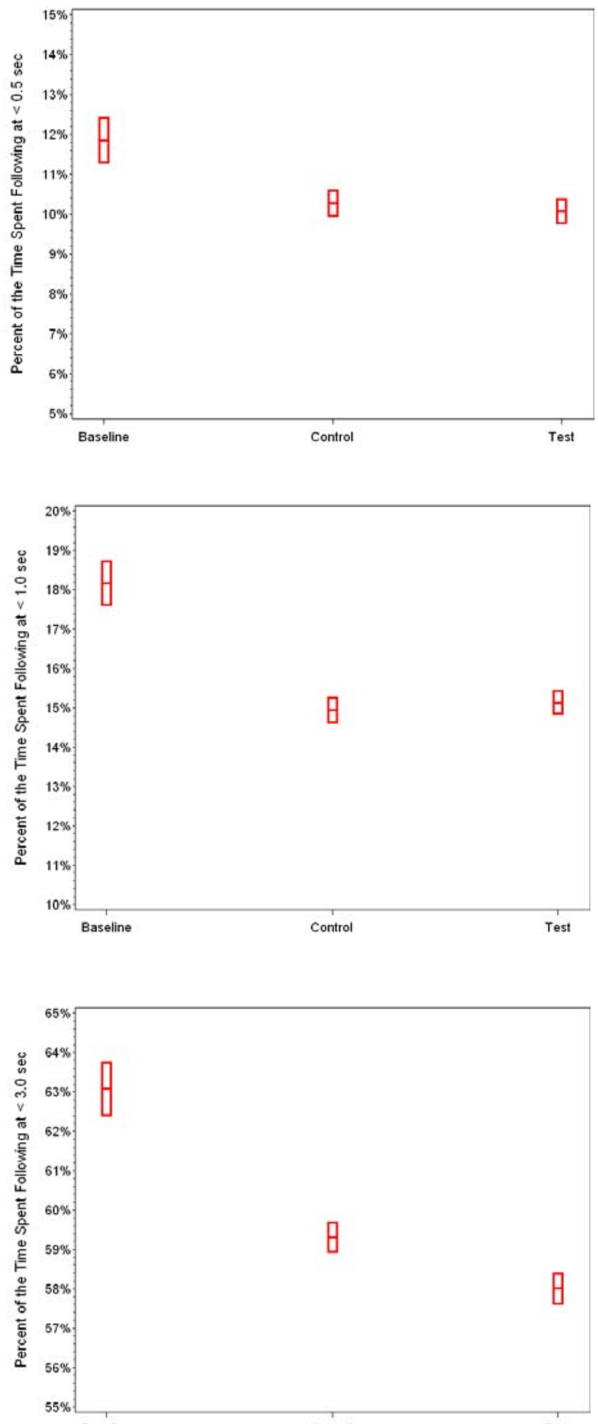


Figure 5.1-40. Percent of the Time Spent at Less than 0.5, 1 and 3 Seconds for the Three Fleets of Trucks

Error boxes indicate a 95-percent confidence interval

Time-to-Collision

The final surrogate safety measure presented is time-to-collision. Similar to the following interval measure, no time-to-collision data were recorded when there was no lead vehicle within 381 ft.

If there is a lead vehicle within 381 ft of the truck and the lead vehicle is pulling away from the truck, the vehicles will not collide, so there is no time-to-collision. The vehicles are not expected to collide. There are cases where the lead vehicle could be pulling away from the truck but decelerating, which would result in a rear-end collision, but the simple time-to-collision measure used and defined as the range divided by range rate does not capture this situation.

- There is a vehicle within 381 ft and no time-to-collision (i.e., there are separating vehicles) for about 20 percent of the time for Baseline, Control, and Test trucks (20.1 percent, 20.0 percent, and 20.6 percent, respectively).

As with following interval, this affects the interpretation of the time-to-collision data. An extreme case of failure to capture all relevant time-to-collision data as a result of the limitation introduced by the 381 ft maximum following distance collected is illustrated by the following scenario: if the truck is traveling at 105 ft/s and approaching a stopped lead vehicle, the value of the time-to-collision will not be collected in the histogram until it is equal to 3.6 seconds. A less extreme case of failure to capture all relevant time-to-collision data is as follows: If a truck is traveling at 105 ft/s (71 mph) and approaches a very slow-moving vehicle traveling at 30 ft/s (20 mph), time-to-collision data are collected in the histogram at about 5 seconds. Thus, the time-to-collision data between 0 and 5 seconds is assumed to be fairly accurate and is presented in Figure 5.1-41 for the three fleets.

- The times to collision between Baseline, Control, and Test trucks and a closing lead vehicle are greater than 5 seconds over 95 percent of the time (95.1 percent, 95.0 percent, and 95.4 percent, respectively).

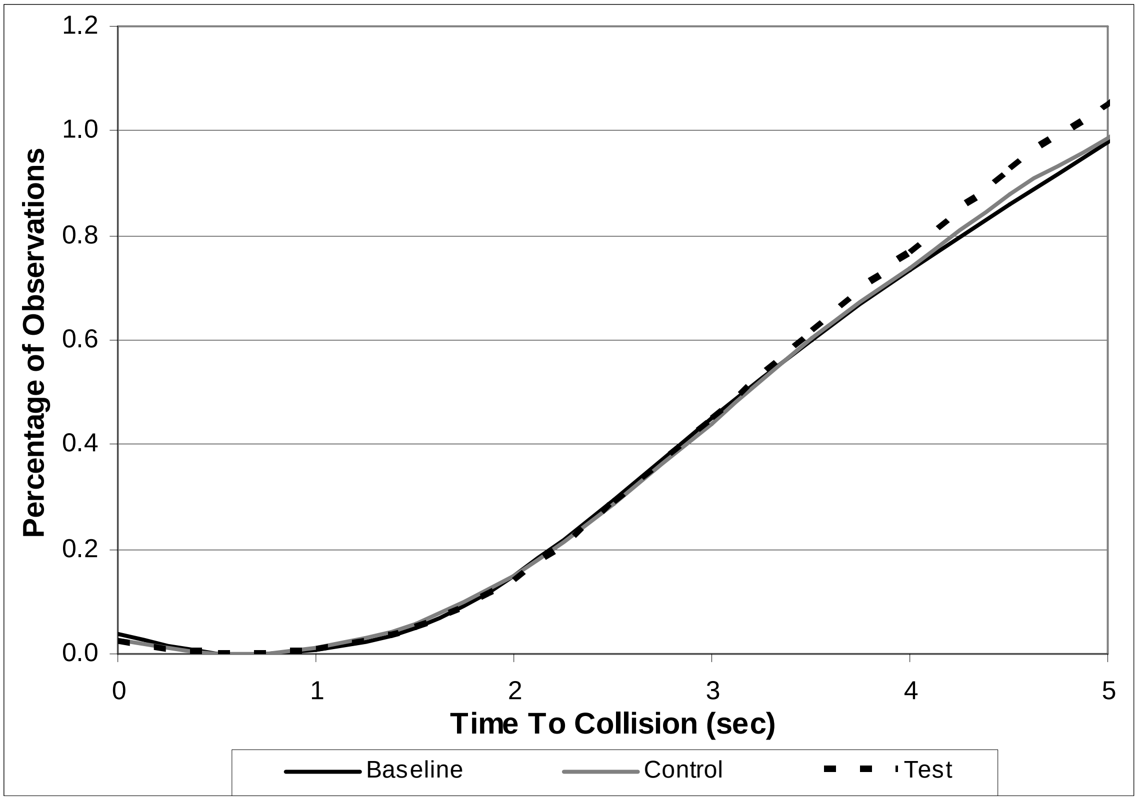


Figure 5.1-41. Distribution Chart of the Time-to-Collision for the Three Fleets

Figures 5.1-42 and 5.1-43 give additional information about the comparison between fleet times to collision. Figure 5.1-42 illustrates the average time-to-collision for the Baseline, Control and Test trucks, while Figure 5.1-43 illustrates the percent of the time spent by each fleet at time-to-collision below 0.5, 1, 3 and 5 seconds.

- Significant differences are observed between the three fleets. Control trucks have the longest average time-to-collision (~17.9 seconds), greater than that of Test trucks (17.7 seconds) and Baseline trucks (17.5 seconds).
- Baseline trucks tend to spend the highest percentage of time (although very small) at the selected times to collision. For example, Baseline trucks spend nearly 1.8 percent of the time a target is present at time-to-collision less than 5 seconds, compared to less than 1.65 percent for Control and Test trucks.
- Test trucks spend the least percentage of the time that a target is present with a time-to-collision less than 1 second and less than 0.5 seconds. This indicates a near-collision benefit for the Test trucks.

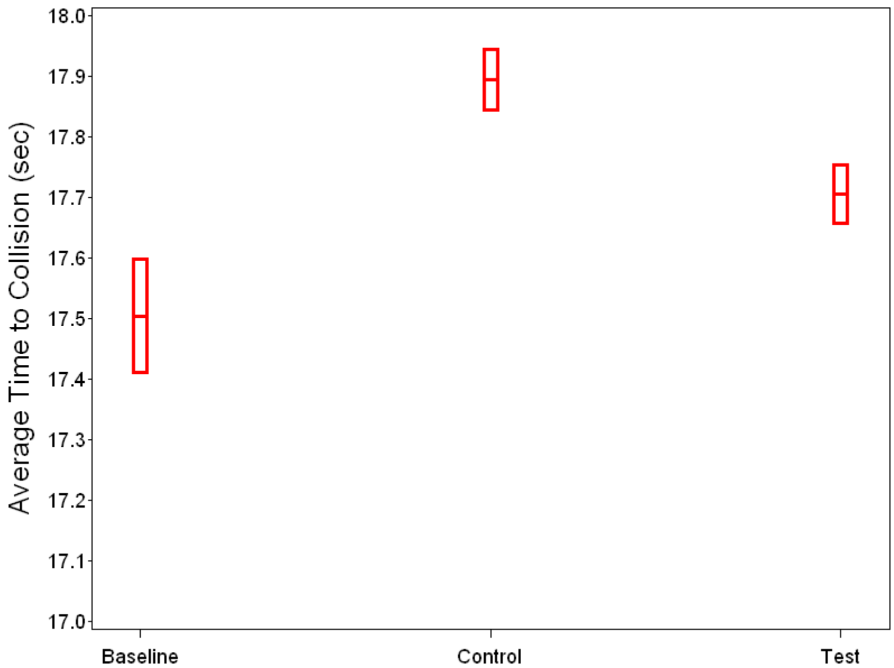


Figure 5.1-42. Average Time-to-Collision for Each Fleet

Error boxes indicate a 95-percent confidence interval

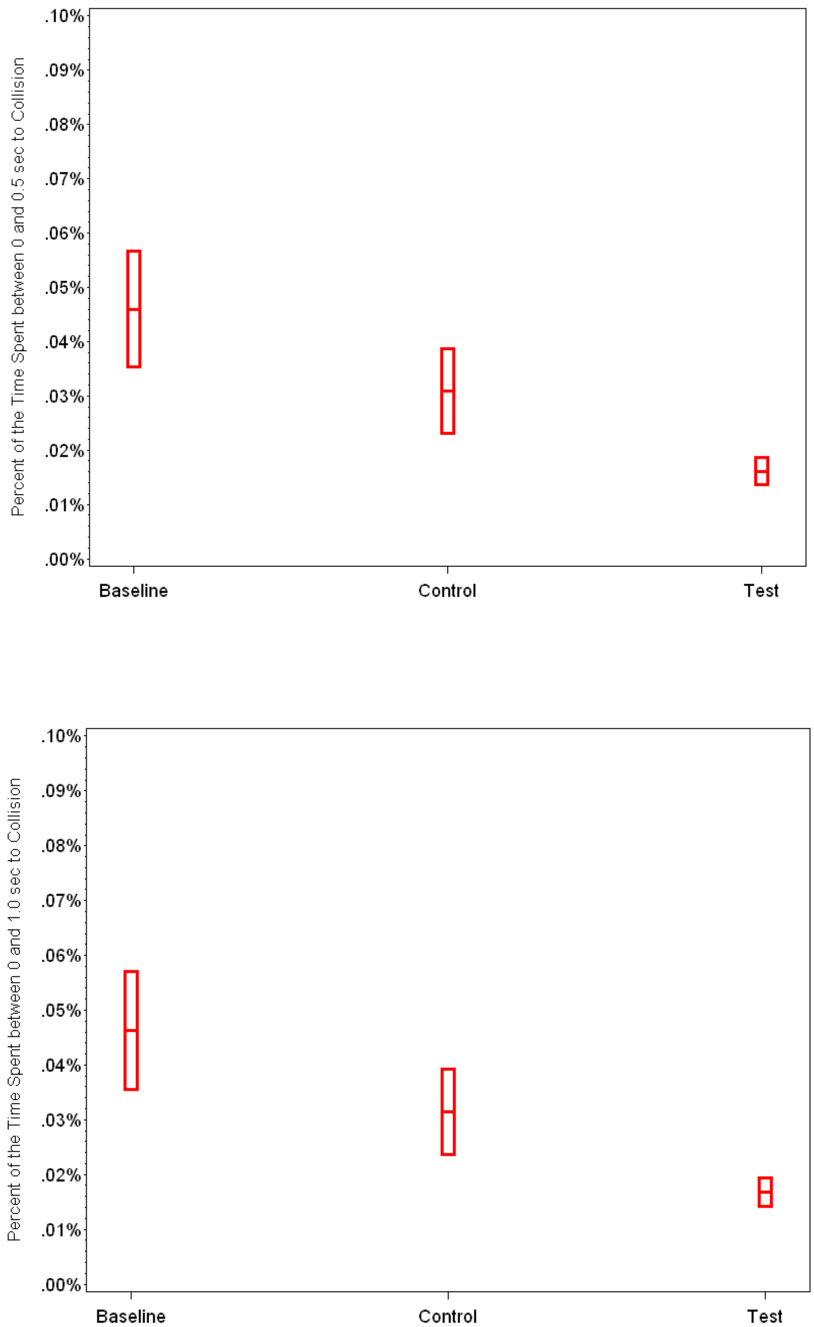
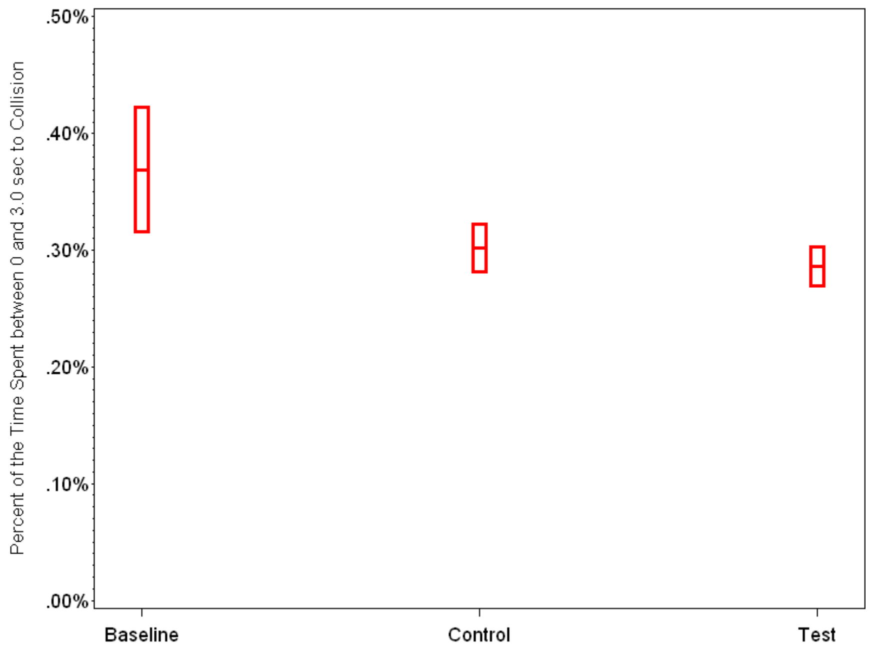


Figure 5.1-43. Percent of the Time Spent at Less than Each Time-to-Collision (Indicated on the Vertical Axis)

Error boxes indicate a 95-percent confidence interval. **(Continued on next page)**



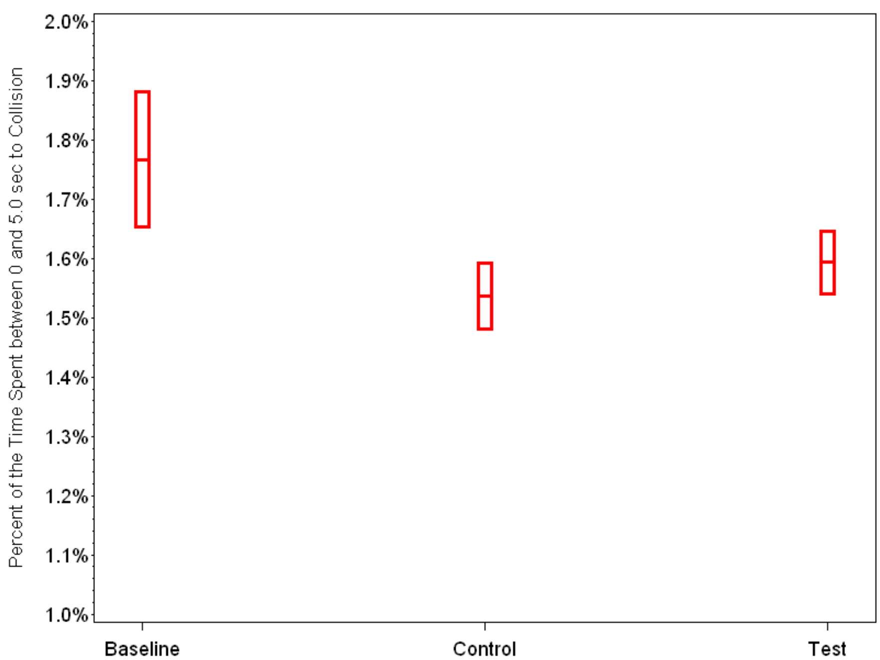


Figure 5.1-43 (continued). Percent of the Time Spent at Less than Each Time-to-Collision (Indicated on the Vertical Axis)

Error boxes indicate a 95-percent confidence interval

5.1.3 Objective A.3: Reductions in Crashes, Injuries, and Fatalities Nationwide if All Such Fleets are Equipped

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 various IVSS technologies. The approach follows from the safety benefits estimation methodology for Objective A.3, which was summarized in Section 4.3.

5.1.3.1 Overview

The goal of this analysis is to extrapolate the estimated safety benefits of the different combinations of CWS, ACC, and AdvBS that were tested in this FOT, to different populations of trucks for which the systems might be deployed. Volvo believes that these technologies can be beneficial for all large trucks (i.e., trucks with gross vehicle weight over 10,000 lbs.) by helping to avoid rear-end crashes. Each year approximately 55,000 large trucks are involved in rear-end crashes. This represents approximately 12 percent of all large truck crashes.

Because the findings are being extrapolated from a single field test to a larger fleet, it is important to consider the degree to which the findings are applicable to the target population. Although it is informative to perform the calculations to estimate the potential safety benefits of deploying these technologies in various target populations, one should be aware that 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 might influence the use, performance, or benefits of the IVSS.

The population of almost 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 another target population. The population of class 7 and 8 tractors pulling trailers, which is represented by the US Xpress fleet that hosted this FOT, is of particular interest . This section describes the calculation of the potential safety benefits under various deployment scenarios and discuss how some of these factors might impact the benefits. However, it is beyond the scope of this study to evaluate how these different factors might alter the effectiveness of these technologies.

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

$$B_s = N_{wo} \times P(S|C) \times (1 - CRR),$$

where N_{wo} is the average annual number of rear-end crashes for trucks without the IVSS, P(S|C) is the conditional probability that driving conflict S was the first harmful event given that a rear-end crash has occurred, and CRR is the estimated crash reduction ratio for the particular conflict type. The conditional probabilities [P(S|C)] are estimated in GES by the relative frequency of driving conflicts determined from actual crash investigations (see Table 4.2-4 above). After summing the benefits across all conflict types, the overall benefit of the IVSS is estimated by

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

where Eff is the estimated overall efficacy or "percent reduction of rear-end crashes" that is attributable to deployment of the technology. The estimated reduction in the number of fatalities or injuries is calculated in the same manner using the number of fatalities or injuries for the term N_{wo}.

The primary focus of the safety benefits for various combinations of CWS, ACC, and AdvBS is on driving conflicts where the subject vehicle is approaching another (target or lead) vehicle in the same lane and that target vehicle is moving more slowly or stopped. As shown in Table 4.2-2 above, these types of conflicts (conflict numbers 1 through 5) lead to 86 percent of all rear-end crashes involving truck tractors pulling trailers and 87 percent of rear-end crashes among all large trucks.

In the remainder of this section the benefits equation is applied to three fleets of trucks, beginning with the US Xpress national fleet, extrapolating these findings to the approximately 1.8 million tractor-trailer combinations, and then to the approximately 8 million large commercial trucks in the U.S.

5.1.3.2 Characteristics of the US Xpress Fleet

US Xpress, Inc., headquartered in Oklahoma City, Oklahoma, is a nationwide general freight carrier with a truck fleet of nearly 6,000 power units (SafeStat 2005, ref: http://ai.fmcsa.dot.gov/SafeStat/SafeStatMain.asp) that average approximately 110,000 miles per year. In this FOT, the average truck mileage was approximately 162,000 miles per year.

Examination of carrier information from the SafeStat system shows that US Xpress has a satisfactory safety rating. Over the past 24 months, nearly 8,000 roadside inspections were performed on US Xpress vehicles with less than 13 percent placed out-of-service (OOS). The national average OOS rate for vehicle inspections is 23 percent. During this same period, 6 percent of the 13,000 US Xpress drivers inspected received OOS orders, compared to the national averages of 6.8 percent. US Xpress has an Inspection Selection System (ISS) rating of 72. ISS recommends that trucks from carriers with ISS ratings of 1-49 be allowed to bypass an inspection station and trucks from carriers with rating of 75 to 100 be inspected. Thus US Xpress falls in the Optional category.

US Xpress' SafeStat Safety Evaluation Area (SEA) scores for vehicle and driver inspections and violations are 30.49 and 65.67, respectively. The SEA score represents a percentile of the distribution of safety measures among motor carriers. For example, the vehicle SAE score of 30.49 means that this carrier's vehicle OOS rate is lower than almost 70 percent of the carriers in the country.

Unfortunately it is currently not possible evaluate US Xpress' accident SEA score because FMCSA has temporarily restricted public access to the SafeStat accident SEA and overall SafeStat scores because "these scores rely on state-provided crash report, which are sometimes not of the highest data quality based on timeliness, completeness, and accuracy" (http://ai.fmcsa.dot.gov/SafeStat/Removal_SafeStat_Explain.asp).

5.1.3.3 Safety Benefits for the US Xpress Fleet

Section 5.1.1 described estimates of the efficacy of various combinations of CWS, ACC, and AdvBS for preventing rear-end crashes. The best estimate of the efficacy of the CWS is 21 percent, and the best estimate of the efficacy of the bundled system is 28 percent. That is, 21 percent or 28 percent of rear-end crashes can be avoided through the deployment of CWS or the bundled system, respectively.

Precise statistics on the number of rear-end crashes involving all US Xpress trucks are not available; however, according to the crash data provided by US Xpress for the 100 trucks involved in this FOT, there were four rear-end crashes during a 30-month period starting in 2001. Extrapolating this to the entire fleet of 5,948 power units, there are approximately 95 rear-end crashes involving US Xpress trucks each year. Clearly, this estimate is subject to considerable statistical error; but assuming it is accurate, deployment of CWS is estimated to help US Xpress avoid approximately 20 rear-end crashes (21 percent of 95) per year. Similarly, the bundled system can help the company avoid about 27 crashes (28 percent of 95) per year.

5.1.3.4 Extrapolation of Safety Benefits to Other Fleets

Before estimating the potential safety benefits of the various IVSS technologies for other populations of trucks, the effect of characteristic differences between the US Xpress fleet and other target populations on the efficacy estimates obtained in this FOT should be considered. Had the FOT been conducted in such a way 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 establish if there are 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-trailers). 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 can be obtained. Thus, the estimated safety benefits properly take these different rates into account.

Table 5.1-24 shows the estimated average annual number of trucks involved in rear-end crashes and the associated injuries and fatalities for two target fleets of trucks: all large trucks (>10,000 lbs GVW) and all tractor-trailer combinations. The numbers of trucks involved in crashes and the numbers of injuries within each combination of truck fleet and conflict category, as well as the distribution of fatalities among conflict categories for each fleet, were estimated from GES crash statistics for the five-year period from 1999 through 2003. The total numbers of fatalities for the two fleets (304 for tractor-trailers and 395 for all large trucks) 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. Some minor adjustments to the distribution of fatalities were necessary to make sure that the number of tractor-trailer fatalities do not exceed the number of fatalities from all large trucks.

Table 5.1-24. Average Annual Number of Trucks Involved in Rear-End Crashes[1] and Associated Injuries[1] and Fatalities[2] – by Rear-End Conflict Category (1999-2003)

Rear-End Conflict Type	Trucks in Crashes		Injuries		Fatalities	
	All Large Trucks	Tractor-Trailers	All Large Trucks	Tractor-Trailers	All Large Trucks	Tractor-Trailers
Constant Speed	19,651	9,222	10,726	4,916	191	192
Slowing	27,668	10,127	13,196	4,852	158	85
Changing Lanes	506	386	182	112	2	2
Other	7,213	3,566	3,517	2,041	45	25
Total	**55,038**	**23,300**	**27,621**	**11,921**	**395**	**304**

Not all columns add up exactly, because of normal rounding differences.

1. Estimates from the General Estimates System 1999-2003.
2. Source: Fatality Analysis Reporting System.

Analysis of the FOT driving data included various conditional analyses of conflict rates and crash probabilities. In addition to investigating the effects of driving conditions—such as cruise control status, wiper status (indication of rain or snow), and length of time into the trip—conditional analyses were performed to determine if the efficacies of the various combinations of IVSS technologies are related to driver age, or equivalently, years of experience. Although the analysis demonstrated that there are statistically significant relationships between the frequency of driving conflicts and the age and years of experience of the driver (see conditional analyses in Section 5.1.1.), no statistically significant relationship was found between driver age and experience and the efficacy of any IVSS technology. Thus, while younger and more experienced drivers tend to have more driving conflicts and more severe conflicts, there is no evidence to suggest that the efficacy of the IVSS technologies (i.e., the percent reduction in conflicts or crashes) is related to these driver characteristics. The ages of drivers participating in this FOT were nearly uniformly distributed between 20 and 60 years; however, the most had fewer than 10 years' experience. The implication of these findings is that there is no reason to make adjustments to the efficacy estimate obtained in this FOT as the benefits are extrapolated to other populations of drivers.

The most natural extension of safety benefits from this FOT to a national fleet is to consider the impact of deploying these technologies to the fleet of all truck-tractors pulling trailing units. Nationwide, there are approximately 1.8 million such tractor units. To illustrate the potential safety benefits of wider deployment, the safety benefits estimated in this FOT were also extrapolated to the larger population of approximately 8 million large trucks. Although there is no evidence—nor can it be claimed—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.

Table 5.1-25 illustrates how the crash reduction ratios (CRRs) estimated for each conflict category and IVSS technology combination are applied to the average annual numbers of rear-end crashes involving tractor-trailers. For this illustration the medium conflict threshold criterion was used to obtain "best estimates" of the CRRs. The total numbers of crashes predicted with the IVSS within each conflict category are summed and compared to the total number of crashes without the IVSS to determine the total number of crashes avoided and the percent reduction in crashes.

Table 5.1-25. Estimated Annual Numbers of Tractor-Trailer Crashes Avoided Due to the Deployment of IVSS Technologies – Using Medium Conflict Threshold Criterion

Rear-End Conflict Type	Total Tractor-Trailer Crashes	Percent of Total	CWS		ACC + AdvBS[1]		Bundled System	
			CRR	Crashes With IVSS	CRR	Crashes With IVSS	CRR	Crashes With IVSS
Constant Speed	9,222	39.6%	0.51	4,704	0.78	7,194	0.40	3,689
Slowing	10,127	43.5%	0.99	10,025	0.94	9,519	0.93	9,418
Changing Lanes	386	1.7%	0.70	270	0.63	243	0.44	170
Other	3,566	15.3%	1.00	3,566	1.00	3,566	1.00	3,566
Total	**23,300**	100%		18,564		20,521		16,842
Crashes Avoided				4,736		2,779		6,458
Percent of Total Crashes				20.3%		11.9%		27.7%

[1] Effect of adding ACC + AdvBS to trucks with CWS

Not all columns add up exactly, because of normal rounding differences.

The same approach was used in Table 5.1-26 to calculate the numbers injuries and fatalities avoided with the deployment of the technologies to all tractor-trailers, as well as the numbers of crashes, injuries, and fatalities avoided with their deployment in the fleet of all large trucks. Although the best estimates of the systems' efficacies are based on the CRRs derived using the medium conflict threshold, the calculations were performed using the conservative and aggressive criteria as well in order to assess the sensitivity of the various assumptions on the findings. These results are carried over to the benefit-cost analysis in Section 5.3

Table 5.1-26. Estimated Annual Numbers of Trucks in Crashes, Injuries, and Fatalities Avoided Due to the Deployment of IVSS Technologies – by Truck Fleet and Conflict Threshold Criterion

IVSS	Conflict Threshold Criterion	Trucks in Crashes		Injuries		Fatalities	
		All Large Trucks	Tractor-Trailers	All Large Trucks	Tractor-Trailers	All Large Trucks	Tractor-Trailers
CWS	Conservative	-1,533	-464	-701	-221	-7	-1
		-2.8%	-2.0%	-2.5%	-1.8%	-1.7%	-0.2%
	Medium[1]	10,058	4,736	5,442	2,491	96	96
		18.3%	20.3%	19.7%	20.9%	24.4%	31.5%
	Aggressive	13,321	5,867	6,920	2,994	111	99
		24.2%	25.2%	25.1%	25.1%	28.0%	32.6%
ACC + AdvBS[2]	Conservative	4,696	2,198	2,567	1,175	46	46
		8.5%	9.4%	9.3%	9.9%	11.7%	15.2%
	Medium[1]	6,170	2,779	3,219	1,414	52	48
		11.2%	11.9%	11.7%	11.9%	13.3%	15.9%
	Aggressive	4,247	2,278	2,398	1,199	53[3]	53
		7.7%	9.8%	8.7%	10.1%	13.4%	17.4%
Bundled System	Conservative	2,972	1,646	1,760	907	44[3]	44
		5.4%	7.1%	6.4%	7.6%	11.1%	14.3%
	Medium[1]	14,011	6,458	7,461	3,352	127	122
		25.5%	27.7%	27.0%	28.1%	32.3%	40.3%
	Aggressive	15,149	6,939	8,005	3,571	134	127
		27.5%	29.8%	29.0%	30.0%	34.1%	41.9%

[1] Best estimate is based on medium threshold criterion

[2] Effect of adding ACC and AdvBS to trucks equipped with CWS

[3] The statistical estimate of the number of fatalities avoided in all large trucks was adjusted to be at least as large as the number of fatalities avoided in tractor-trailers.

5.2 Goal B: Assess User (Driver) Acceptance and Human Factors

[Editor's note: The following results were adapted from a separate, related USDOT-sponsored report (Battelle 2004).]

This section presents findings from an analysis of the data collected through driver surveys conducted at both the beginning and the end of the Volvo IVI FOT evaluation period. The first survey (Phase I) focused on driver expectations for the new safety technologies installed on selected Volvo trucks and the second survey (Phase II) focused on driver experiences using the technologies.

The surveys involved contacting more than 300 drivers, approximately 200 of whom responded via computer-aided telephone interviewing. A total of 25 drivers took part in both Phase I and Phase II. As mentioned previously, the turnover rate at US Xpress during the FOT was over 100 percent per year. This did not have an explicit impact on the survey responses, but it did make it less likely that a driver would take part in all survey questions. The Phase I survey was conducted between October 22 and 27, 2001. The Phase II survey was conducted between March 29 and April 6, 2004.

5.2.1 Objectives

Objective B.1: Determine usability of the IVSS technologies
Objective B.2: Determine how IVSS affects perceived stress and workload of drivers
Objective B.3: Determine perceived impact on driver risk and vigilance
Objective B.4: Determine perception of product quality and maturity

This goal area focuses on understanding if and how human factors may play a role in the eventual acceptance and deployment of the systems. This report presents an overview of what was learned from the drivers who responded to each of these surveys.

5.2.2 Methods

The method for collecting data was to conduct telephone interviews with drivers using a survey questionnaire to guide the interviews. Drivers were notified to call in to an 800 number, and trained interviewers were available to conduct the interviews. The answers to the survey questions were entered into a computer using a Computer-Aided Telephone Interview (CATI) system. This allowed automated checks for the validity of responses and transfer into a database for further analysis.

5.2.3 Findings

5.2.3.1 Driver Expectations from Phase I

Findings on drivers' expectations for the IVSS from Phase I are summarized below:

- Most of the drivers in the Baseline, Control, and Test groups expressed positive attitudes toward each of the IVSS technologies (CWS, ACC, and AdvBS). Those drivers who had not yet tried these technologies were positive about their likely benefits, and those who already had driving experience with any of them reported that the benefits outweighed any drawbacks.
- Many drivers reported that they had limited or no training in the use of the CWS. Those drivers who did have training and who thought the training was useful tended to be more positive about the value of the technology. Therefore, emphasis on training could lead to greater benefits to be derived from these technologies, coupled with greater support from the drivers.

- Drivers in the initial Phase I survey said they believed that these technologies would help avoid front-end collisions, that they would be better off with these systems in their trucks than without them, and that the benefits are likely to vary depending on driving conditions.
- The research expectation at the end of Phase I was that driver attitudes toward each of these technologies would improve with experience using them, based on comparing responses between Baseline drivers (with no experience with any of the three systems), Control drivers (experienced only with the CWS) and Test drivers (experienced with all the systems). Drivers in the first survey believed that these technologies would help avoid front-end collisions, that drivers are better off with these systems on their trucks, and that the benefits are likely to be greater in some driving condition (such as poor visibility) than in others (such as heavy traffic).

5.2.3.2 Driver Experiences from Phase II

Findings on drivers' experiences with the IVSS from Phase II are organized according to the hypotheses that were described in the Evaluation Plan for Objective B.2. The drivers interviewed in Phase II reported a substantial amount of experience both with truck driving and driving with each of the IVSS technologies. This level of experience, shown in Table 5.2-1, is more than sufficient for providing informed judgments about each of the three safety technologies.

Table 5.2-1. Average Driving Experience Driving Trucks and Driving with IVSS (Years)

Average Driving Experience (Years)	Truck Driving Overall	Driving with VORAD®	Driving with SmartCruise	Driving with AdvBS
Mean*	11.9	3.1	1.1	1.5
Median**	8.5	3.0	1.0	1.0

*The arithmetic average.

**The mid-point such that half the drivers have more years and half have less years.

Objective B.1. Determine the Usability of the IVSS Technologies

This objective focuses on how IVSS are used and understood by the drivers. In particular 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.

The evaluation asked drivers to indicate their perceptions of the ease of learning the IVSS and the adequacy of training they may have received. The results are summarized in Table 5.2-2.

Table 5.2-2. Objective B.1: Training and Learning

Evaluation Hypotheses	Test Outcome*	Findings
Drivers find the IVSS and components easy to learn.	👍👍	About half of the drivers reported receiving CWS training (54%), and only 24% and 19% received training in ACC and AdvBS respectively. Almost all the drivers said the training they received was "very" or "somewhat" helpful. The majority (between two-thirds and three-quarters) of the drivers said they learned these systems by trial and error. Trial and error was rated more helpful than learning with a manual or from informal discussions with other drivers. However, drivers did recommend more training as one possible improvement.
Drivers believe that they are adequately trained to use these systems.	👍	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

The evaluation asked drivers to indicate their perceptions of the understandability of the IVSS visual and audible alerts. The results are summarized in Table 5.2-3.

Table 5.2-3. Objective B.1: Understandability

Evaluation Hypotheses	Test Outcome*	Findings
Drivers understand the IVSS capabilities.	👍👍	When asked to express in their own words the meaning of the visual and audible alerts from the CWS, drivers showed that they had a general understanding of these different warnings, but most did not understand the meanings in specific terms (distance to object or time left to react). They had a more accurate understanding of the visual warnings than the audible warnings. Most drivers knew that a double beep represented a more dangerous situation than a single beep, but they were not aware of the exact level of urgency or nature of the situation.
Drivers understand the signals and controls.	👍	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

The evaluation asked drivers to indicate their perceptions of the ease of use of the IVSS, including how easy the alerts are to see and hear, and distinguish from other warnings in their truck. The results are summarized in Table 5.2-4.

Table 5.2-4. Objective B.1: Usability

Evaluation Hypotheses	Test Outcome*	Findings
Drivers find the IVSS and components easy to use and control.	👍👍	Most of the drivers reported that the visual and audible signals from the CWS are “always” easy to see (87%) and hear (93%). Drivers were asked how easily they could distinguish the different warnings in their truck (forward, side, visual, auditory, and other non-IVSS warning systems). Most of the drivers (64%) said they could “always” distinguish IVSS alerts from one another, but sometimes they could be confused (for example, when the driver is tired, or is focusing on a particular driving situation). Drivers rarely reported problems distinguishing IVSS warnings from those provided by other systems in the truck, but 38% of the drivers said they have other, potentially competing, systems in their truck anyway. Drivers said that the CWS is more useful in low visibility conditions such as fog (78%), heavy rain/snow (61%), or night (52%) and more likely to be distracting in heavy traffic. Driver comments on related questions indicate that they think the ACC is generally useful in all conditions other than climbing hills or in heavy traffic, and AdvBS is useful in all conditions.
Drivers perceive that the IVSS signals are recognizable and easy to see or hear.	👍👍	
Drivers understand how to use information from the IVSS.	👍	
Drivers believe that the IVSS messages are unambiguous and clearly understood.	👍	
Drivers have reasons for using the IVSS under specific, if not all, driving conditions (e.g., drivers might not use ACC under congested traffic conditions).	👍👍	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

Objective B.2. Determine How IVSS Technologies Affect the Perceived Stress or Workload of Drivers

This objective focuses on how the IVSS affect the driving environment. Of particular interest are the effects of false alarms and the impacts on driver workload. Specific hypotheses tested are shown in the following tables.

Drivers were asked to indicate their perceptions of distractions due to the use of the IVSS, including the nuisance effects of false alarms. The results are summarized in Table 5.2-5.

Table 5.2-5. Objective B.2: Distraction and False Alerts

Evaluation Hypotheses	Test Outcome*	Findings
Drivers perceive that IVSS do not distract them or interfere with their other tasks.	👍	Most drivers said the CWS visual (78%) and auditory (84%) warnings "rarely" or "never" drew their attention away from their driving tasks. Some drivers said they should not have to look away from the road to see what the alert means. On average drivers reported that they received CWS alerts when there was no apparent cause 4.7 times out of every 10 alerts (about half the time). Only 8% of the drivers reported no false positive alerts and 7% reported every alert was a false positive. False negative alerts are reported much less frequently, averaging less than 1 out of every 10 times drivers thought that an alert should have been provided, and 72% of the drivers said they never receive a false negative alert. 59% of the drivers said false alerts were a nuisance.
Drivers perceive that IVSS false positive[14] alarms are a nuisance.	👍👍	
Drivers perceive that IVSS false negative[15] alarms degrade their confidence in the systems.	👎👎	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

Drivers were asked to indicate whether they thought the IVSS had the effect of reducing or increasing their levels of driving stress and fatigue compared with driving without these systems. The results are summarized in Table 5.2-6.

Table 5.2-6. Objective B.2: Stress and Fatigue

Evaluation Hypotheses	Test Outcome*	Findings
Drivers perceive that IVSS reduce their levels of stress or fatigue.	👍	Drivers report driving is "somewhat" or "a lot" less stressful and tiring with the CWS (49%), ACC (38%) and AdvBS (56%). Some said these IVSS can increase stress and fatigue "somewhat" or "a lot" (23.6%, 17%, and 7% respectively). About one-third of the drivers (33.7%, 38.2% and 37.0% respectively) said that the CWS, ACC and AdvBS did not affect their stress and fatigue.

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

Drivers were asked to rate the amount of mental workload they experienced on a scale from 1 (lowest) to 10 (highest). Mental workload refers to the amount of mental effort (level of concentration or degree of mental focus) it takes to drive their truck under various conditions. The results are summarized in Table 5.2-7.

[14] A "false positive" alert occurs when VORAD® issues an alert when in reality there was no cause for the alert.

[15] A "false negative" occurs when VORAD® should have given a warning but failed to do so.

Table 5.2-7. Objective B.2: Driver Workload

Evaluation Hypotheses	Test Outcome*	Findings
Drivers perceive that IVSS reduce their driving workload.	👍👍	Without IVSS, perceived driving workload increases from driving a truck under good conditions, to heavy traffic, to low visibility, from an average score of 5.7 to 8.7 (up 53%). With IVSS, workload increased less, from 4.8 to 6.9, from good conditions up to the most demanding conditions (low visibility). The important point is that **the IVSS serve to lower perceived workload** under each of these conditions, between 14% and 21%.

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

If truck drivers do not find new safety technologies acceptable and useful, then they will either not use them or they will use them reluctantly, thereby not gaining full benefit. As a measure of acceptance, drivers were asked whether they preferred to drive a truck equipped with each of these technologies or one not equipped. They also were asked to indicate what they liked most and least about these systems. The results are summarized in Table 5.2-8.

Table 5.2-8. Objective B.2: Driver Satisfaction

Evaluation Hypotheses	Test Outcome*	Findings
IVSS increase job satisfaction of drivers.	👍	About 81% of the drivers said they would rather drive a truck equipped with CWS than without it. Benefits included safety, helpfulness and awareness. About 53% of drivers prefer to drive with ACC and 44% prefer to drive without it. Benefits included safety and stress reduction. Almost all drivers (93%) preferred driving with AdvBS. Drivers dislike the CWS's false alarm tendency as well as excessive alarm noise.
Drivers trust the IVSS and perceive that they are useful.**	👍👍	
Drivers perceive that the IVSS are effective under specific (if not all) driving conditions (to be determined).	👍👍	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

** This hypothesis was included under Objective B.1 in the Evaluation Plan.

Objective B.3. Determine the Perceived Impacts on Driver Risk and Vigilance

Driver perceptions about how the use of IVSS affects the risk of an accident, and whether or not use of IVSS has resulted in any change in driving behaviors are summarized under this objective. The intent of IVSS is to enhance driving safety and reduce the risks of an accident; however, the opposite effect might occur if drivers begin to rely on IVSS and reduce their driving vigilance, or if they feel they can take greater driving risks because IVSS will warn them of potentially dangerous situations with time to respond. Driving behavior effects are summarized in Table 5.2-9.

Table 5.2-9. Objective B.3: Driver Behaviors

Evaluation Hypotheses	Test Outcome*	Findings
Drivers are aware that they modify their driving behavior (speed, following distance, braking, turn signal usage) for particular reasons (to be determined) in response to the IVSS.	👍👍	Drivers were more likely to say their driving had changed “somewhat” or “a lot” with CWS (62%) than with ACC (41%) or AdvBS (44%). Drivers who said their driving had changed talked about increasing following distances and being more aware.

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

Drivers were asked whether they thought the likelihood of an accident or a near-accident situation had been affected (reduced, increased, or no change) by the use of any of the three safety technologies. The drivers were asked to briefly explain in their own words how each of the IVSS affects the likelihood of accidents or near-accident situations. Risk taking effects are summarized in Table 5.2-10.

Table 5.2-10. Objective B.3: Risk Taking

Evaluation Hypotheses	Test Outcome*	Findings
Drivers with the CWS and ACC systems 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.	👍👍	Most drivers (77%) said they thought the CWS reduced the risk of an accident because it helps them maintain a safe following distance, increases reaction time, helps in low visibility, and increases awareness if they are distracted. 52% said ACC reduces accident risks by keeping safe following distances and increasing reaction time. 18% thought it increased risk due to reduced attentiveness and driver control. 78% said AdvBS reduced the risk of an accident by reducing stopping distances.

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

Objective B.4. Determine Perceptions of Product Quality, Maturity, etc.

Information on the perceived quality, value, and maturity of the IVSS from the perspective of the drivers were obtained. The evaluation 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 and learn how to use. The results are summarized in Table 5.2-11.

Table 5.2-11. Objective B.4: Recommended Changes

Evaluation Hypotheses	Test Outcome*	Findings
Drivers have recommendations for changes that might make it easier to use or learn how to use the IVSS.	👍👍	Most drivers did not have recommendations for improvements, but of those who did (38%) some wanted more detailed information on CWS indicators (e.g. actual distances), volume controls for alerts, and better training or simpler manuals. A few drivers suggested improved ACC training. Few drivers reported performance problems--CWS 39%; ACC (21%); AdvBS (19%), and those who did said they experienced more downtime with VORAD® than the other two systems, but reports of frequent downtime were rare.
Drivers have recommendations for changes that might improve the performance or functionality of the IVSS.	👍	

* 👍👍 = Supported; 👍 = Partially supported; 👎👎 = Not supported.

5.2.4 Conclusions

The two surveys of drivers regarding their expectations and experiences associated with three truck safety technologies—CWS, ACC and AdvBS—suggest that drivers understand and appreciate the benefits that these technologies can provide. These are highly experienced drivers who take great pride in their driving skills, and they can be expected to want to be convinced of the merits of technology before accepting the need for it in their trucks. The surveys reflected a range of positive and negative reactions to various aspects of these technologies, but the drivers believe these technologies help avoid or reduce accidents, and most prefer to have them installed on their trucks. The evaluation hypotheses that could be tested with the survey data were generally supported. The perceived benefits of each technology outweigh the drawbacks and depend mainly on driving conditions (particularly visibility and traffic density) and system performance (false alerts and distraction or annoyance factors). The results from these surveys lend support to the further refinement and deployment of these technologies throughout truck fleets to enhance driver safety, performance and satisfaction.

5.3 Goal C: Assess and Analyze the Ratio of Life-cycle Benefits to Life-cycle Costs on a Societal Level

An important objective of this evaluation of the Volvo IVI FOT was to conduct a benefit-cost analysis (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 IVI FOT Evaluation (Battelle 2003a), and in the earlier CVISN Model Deployment Initiative evaluation (Battelle 2002). In the Volvo IVI FOT evaluation, the cost assumptions were updated and modified appropriately to fit the specifics of the field operational test.

5.3.1 Benefit-Cost Analysis Approach

Several approaches can be taken to performing benefit-cost analysis, such as return on investment analysis for a particular company or industry segment, or for an entire industry. Regulators use societal benefit-cost analyses to assess the net effect of changes in proposed laws and government regulations. The approach taken in the Volvo IVI FOT evaluation was to provide a more 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 Volvo 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. The question to be answered in a BCA is: Do these benefits exceed the costs? If the answer is yes, the benefit-cost ratio (BCR) is greater than 1, and the project is said 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 C.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 operating 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, national deployment, all drivers at the time of deployment would be trained to use the IVSS. Also, as drivers leave and new drivers enter the occupation through normal turnover, the new drivers would also need to be trained in future years.

The best available quantitative information on costs estimated to be incurred during real-world deployment and operation of the IVSS were 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 Evaluation Team attempted to obtain and itemize the estimated costs so that future analysts can compare the costs reported in each FOT with cost elements for related IVSS deployments in the future, as better data become available.

Objective C.2 Estimate Cost Savings Potential

The deployment of IVSS is expected to result in cost savings through the avoided costs of crashes prevented. Each large-truck crash that can be prevented is estimated to save between approximately $59,000 and $88,000 in lifetime medical, emergency services, property damage, productivity, and death or injury costs among others, expressed in year 2000 dollars (Zaloshnja & Miller 2004). 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, however, are difficult to quantify and document in an FOT, and were not evaluated in the Volvo IVI FOT.

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

Objective C.3 Conduct Comprehensive Benefit-Cost Analysis

The purpose of the benefit-cost analysis (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 systems 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 costs of truck crashes, the value of mobility and environmental benefits, and analyses of national fleet populations and characteristics. Therefore, the BCA was coordinated among the three FOTs. The specific hypothesis that was tested in a BCA is 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 the benefits and costs input to 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,
- 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. Not duplicative means that benefits and costs cannot be double counted.

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 Tables 5.3-1 and 5.3-2 below. The process of identifying the appropriate set of benefits is further complicated by the way values are customarily placed on such benefits as crashes 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.

Table 5.3-1. Benefits, Values, and Information Sources Related to IVSS Deployment

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

Table 5.3-2. Costs, Values, and Information Sources Related to IVSS Deployment

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

Finally, to test the hypothesis that the IVI systems have 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 the 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 one replacement cycle for the IVSS equipment at a 10-year interval, as described below.

Each of the benefits and costs occurring each year between 2005 and 2024 was 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. For example, the U.S. Environmental Protection Agency (2000) recommends a real rate of 2 to 3 percent for some public projects. 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; 2000). Results shown in this chapter are based on the 4-percent discount rate; results for undiscounted, 4 percent, and 7 percent rates are included in Appendix C.

Tables 5.3-1 and 5.3-2 show the benefits and costs that were to be measured in the IVI FOTs, respectively. For each benefit or cost, these tables present the measurable values to be sought, along with the sources of information.

The Freightliner, Mack, and Volvo FOTs mainly involve on-board, self-contained safety systems providing warning, braking, and stability improvements, etc. Therefore, the main benefit is increased safety in the form of reduced numbers of crashes involving trucks. The main evaluation task then is to estimate the accident rate reduction and the monetary values of the truck crashes. Values of truck crashes have been estimated in a number of studies reported in the literature (see, for example, Section 5.9 and Appendix F of Battelle 2003b), and summarized in related DOT-sponsored projects (e.g., Pacific Institute 2000, 2002). The best available relevant estimates of the costs of a truck crash were used in the analysis.

5.3.2 Benefit-Cost Assumptions

5.3.2.1 Scenarios Modeled

Not counting a series of sensitivity analyses that were performed, a total of 24 scenarios were modeled in the Volvo IVI FOT evaluation, determined as follows:

(2 national fleets) × (2 IVSS equipment configurations) ×
(3 conflict thresholds) × (2 cost range assumptions) = 24 BCA scenarios.

In the Volvo IVI FOT, the two fleets of interest were (1) all trucks greater than 10,000 pounds and (2) all truck tractors pulling trailers. National fleet populations for the Volvo FOT evaluation were assumed to be 8,389,877 (all large trucks) and 1,863,422 (tractor pulling trailer) in the first or Baseline year (2005). Population estimates for these national fleets were derived from the FHWA *Highway Statistics* Tables VM-9 and VM-1 data for 2003, escalated to year 2005 values based on an annual growth rate of 2.98 percent (according to ATA U.S. Freight Transportation Forecast to 2008).

Two IVSS equipment deployment options were modeled, namely (1) the CWS alone and (2) the CWS bundled with the ACC and the AdvBS, labeled the “bundled system” in this section.

Three separate driving conflict thresholds were modeled, labeled “conservative, medium, and aggressive.” These terms, as discussed further in Section 5.1.1, relate to modeling assumptions as to what constitutes a countable driving conflict, and how quickly the driver of the host or following vehicle (the truck) must react to a given situation involving a leading or target vehicle.

The three conflict thresholds represent varying levels of conflict severity based on the maximum reaction time required for the truck driver to react to the conflict situation, and the rate of truck deceleration (braking) required to avoid a crash:

- Conservative—Driver must react in 1.5 seconds and decelerate at 8 feet per second
- Medium—Driver must react in 1 second and decelerate at 10 feet per second
- Aggressive—Driver must react in 0.5 second and decelerate at 12 feet per second.

The “medium” conflict threshold is the main or best guess scenario, because it is statistically the most valid. The “conservative” and “aggressive” thresholds were used for sensitivity analyses.

Low and high equipment cost assumptions were modeled separately, as described below, to provide a gauge to the effect of first costs on the BCRs.

5.3.2.2 Cost-Side Assumptions

As noted above, component developers, suppliers, original equipment manufacturers (OEMs), and dealers tend to be reluctant to disclose actual costs for individual components in a highly competitive market. Conventional wisdom is that the cost figures 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. To perform a benefit-cost analysis, however, reasonable cost estimates are required.

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 5.3-3 lists the component cost estimates used as sources for the cost values used in this report.

Because some of the technologies evaluated are just now entering the marketplace, 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 first costs to decline over time. Also, the apparent likelihood of published cost estimates to err on the high side led us in general to choose, as inputs to the benefit-cost model, installed cost values that were slightly lower than those observed in the informal survey.

For the CWS-only 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 was **$2,000** and the high cost assumption was **$3,000** per tractor. Because there are only two purchase events in the 20-year life-cycle model (occurring in model years 1 and 10), and because future cost estimates are not available, the 10-year replacement cost was assumed to be the same as the year-1 purchase cost.

Table 5.3-3. Preliminary Installed Cost Estimates per Tractor, from Various Sources

Component	Estimated Cost, $	Source
Collision Warning System	3,200 to 5,600	Major truck manufacturer (OEM)
	1,200	Battelle engineering estimate, based on industry contacts
	2,000 to 3,000	IEEE Spectrum web site article, "Big Rigs Need Protection, Too."
	<2,500	Intelligent Transportation Society of America web site Information Clearinghouse Fact Sheet #3, citing Eaton® VORAD® materials.
	2,000	IVsource.net web site article, "CON-Way Makes Commitment," March 2002.
	2,500 to 3,000	Component Installer
	2,500	USDOT, FHWA ITS Benefits and Costs Report (2005, Table 3.1.1, pg. 126). Includes side sensor.
Adaptive Cruise Control	300 to 400	Component Installer
	127 to 254	USDOT, FHWA ITS Benefits and Costs Report (2005, Appendix A.2, pg. 179). Adjusted from 1995 data to $2003 by USDOT, then inflated to $2005 by Battelle.
	350 to 400	USDOT, FHWA ITS Benefits and Costs Report (2005, Table 3.1.1, pg. 126). As an add-on to CWS.
CWS + ACC	4,600 to 7,100	Major truck manufacturer (Standard discounted price and higher "list price" are shown at left.)
Advanced Braking System (ECBS + Disc Brakes)	5,000 to 8,000	Battelle engineering estimate, based on industry contacts
Disc Brakes Only	2,100	Component Supplier: $800 for steer axle plus $1,300 for tractor drive axles (incremental upcharges to upgrade from drum brakes)

For the bundled system scenarios, a slightly different method was used. The low cost point for the bundled system (CWS + ACC + AdvBS) was based on disregarding the first cost of the AdvBS. The rationale for this alternate approach was as follows: It was recognized that the crash avoidance benefits accruing from the combination of ACC and AdvBS in the bundled system cannot easily be separated. However, the safety benefits analysis indicated that the majority of benefits appeared to accrue from the avoidance of conflicts in the first place (an improvement in the exposure ratio), which was assumed to be an effect of the CWS and ACC. By contrast, the AdvBS was expected to improve the prevention of crashes once the truck is in a conflict. In the safety benefits analysis, relatively less improvement was observed in the prevention ratio.

Because a greater exposure benefit was observed, when compared with the prevention benefit, the low cost assumption for the bundled system scenarios was determined as if the benefits were due to the combination of CWS ($2,000) and ACC ($300) alone per tractor. In the low cost BCA scenarios for the bundled system, the cost of installing the AdvBS ($4,000 per truck) was disregarded. Therefore, for the bundled system, the estimated low cost was **$2,300.**

The high cost range for the bundled system was based on summing the costs for CWS ($2,000), ACC ($300), and AdvBS ($4,000), adapted from the informal survey described above, to produce an estimated installed cost of **$6,300.**

First cost (installed cost) values were the only cost elements varied to model different cost ranges for deployment of the IVSS in the Volvo IVI FOT. That is, 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

Data on annual maintenance costs were estimated by Battelle, based on information in the FOT report prepared for USDOT by Volvo Trucks North America (2005). Specifically, the average cost for repair of the CWS was reported at approximately $475 per tractor per 1 million miles driven, yielding an average annual cost of $47.50 (page 92 of Volvo's report). This assumes that each tractor is driven approximately 100,000 miles per year.

Similarly, the repair costs for brake components themselves were reported at $703 per tractor per million miles for disc brakes, versus $230 for conventional drum brakes. So the incremental maintenance cost would be $47.30 per tractor per year for disc brakes. The repair costs for the ECBS were $741 per tractor per million miles, compared with $253 for an antilock brake system, resulting in an incremental maintenance cost of $48.80 per tractor per year for the advanced system (page 95 of Volvo's report).

As indicated in the Volvo report and in subsequent communication with the Volvo team, the relatively high maintenance costs reported for the AdvBS (ECBS plus disc brakes) can be attributed to the high cost of low-volume, pre-production materials and systems, and the relative unfamiliarity of repair and maintenance technicians with the systems and procedures, so these costs may be anticipated to decline over time. Thus, Battelle adjusted the reported maintenance costs slightly downward from those given in the Volvo report, to **$40** per tractor per year for all of the CWS-only scenarios, both low and high cost.

For the bundled system low cost scenario, following the logic described above, the annual O&M cost of deploying the AdvBS was disregarded. In these scenarios, only the CWS O&M cost of

$40 per tractor per year was used. The high cost scenarios for the bundled system used a value of **$110** per tractor per year (i.e., $40 for CWS + $70 for AdvBS), applied annually throughout the 20-year life of the deployment.

Because the Volvo team indicated that the equipment costs and the annual O&M costs as reported in 2005 were likely to be higher than those expected for more mature, high-production equipment in the future, a side sensitivity analysis was performed to gauge the effects of sharply reducing both first cost and annual O&M costs. This sensitivity analysis is described in the results section below.

According to the Volvo team, the electronic components are expected to last the life of the tractor, so the benefit-cost modeling assumed nationwide purchases of the respective IVSS for all trucks in each fleet at the beginning of the life cycle in 2005 and again ten years later in 2014. No purchase in the final year of the 20-year life-cycle analysis (2024) was modeled.

According to the Volvo team, the ECBS does not require any driver training, because it operates the same as conventional brake systems from the driver's perspective. A modest assumption of **0.5 hour** per driver for paid training on the CWS was assumed. The training was assumed to be paid at the prevailing driver hourly rate (national average including fringe benefits). This was assumed to be a one-time training per driver for all drivers in the first year. In subsequent years, it was assumed to include training for every driver every time he or she is hired, 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 U.S. was provided by American Transportation Research Institute. U.S. Xpress reports a higher annual turnover rate, of approximately 100 percent. In the course of analysis, it was noted that the annual training cost, which affects a relatively small number of drivers after year 1, has a minimal effect on the final BCRs, when compared with the annual O&M costs, which are applied to all trucks in all years modeled.

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, taken to be 0.42:1, 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 (3,135,170), 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.

5.3.2.3 Benefit-Side (Crash Avoidance) Assumptions

The numbers of crashes, injuries, and fatalities were derived from the statistical modeling described earlier in Chapter 5. 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 IVI FOT report.

The per-crash costs were largely derived from a study performed by Pacific Institute (2002) on behalf of FMCSA on the costs of large truck and bus-involved crashes. Legal costs were included in the Volvo BCA model through the injury and fatality cost values. Specifically, Pacific Institute had broken out costs for the following categories per victim injured or killed: Medical, Emergency Services, Property Damage, Lost Productivity, and Monetized "Quality of Life Years." Legal costs are imbedded in the "Lost Productivity" cost element, and described as follows on page 10 of the Pacific Institute report:

> *Legal and insurance administration costs per crash victim were derived from the medical and work loss costs, using models developed by Miller (1997). Legal costs include the legal fees and court costs associated with civil litigation resulting from motor vehicle crashes. In estimating these costs, the probability of losing work, the percentage of victims who claimed, the percentage of claimers who hired an attorney, estimated plaintiff's attorney fees, and the ratio of legal costs over plaintiff's attorney fees were taken into consideration (Pacific Institute 2002).*

Where updated crash cost values were readily available, they were applied to the Volvo BCA. A detailed, updated literature review, however, was not performed. Instead, where updated values were not available, the values documented in the earlier report (typically expressed in constant 2000 U.S. dollars) 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 5.3-4 compares the values used in the earlier IVI FOT report with those that were modified for use in the Volvo IVI FOT report, and describes the modifications that were applied.

It is noteworthy that the per-crash costs for personal injury, property damage, delays to other traffic went down sharply from the earlier report to the current Volvo 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 the Volvo IVI 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 expresses injury reductions in terms of the numbers of victims injured, not in terms of number of injury crashes. As the table below shows, this change resulted in each injury being counted as approximately $100,000 less expensive in the Volvo analysis 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 (ATA), for the costs of rollover and single-vehicle road departure crashes. No similar current cost data were available for the rear-end crashes being modeled in the Volvo IVI FOT crash cost evaluation, so the latest available Pacific Institute per-crash property damage values (2002), which were markedly lower than the values provided by the ATA for the Freightliner report, were used in this Volvo BCA.

Table 5.3-4. Comparison of Relevant Cost Values ($) from Freightliner (2003) and Volvo (2005) IVI FOT Evaluation Reports

Description	Freightliner Report	Volvo Report	Comments
$/Injury (Truck-tractor, 1 trailer)	162,095	61,779	Freightliner had used Pacific Inst. $/crash (Table 10). Volvo uses revised Pacific Inst. $/victim, Table 9, inflated from $(2000) to $(2005).
$/Injury (All trucks)	156,558	51,861	Freightliner had used Pacific Inst. $/crash (Table 10). Volvo uses revised Pacific Inst. $/victim, Table 9, inflated from $(2000) to $(2005).
$/Fatality	3,358,240	3,022,840	Freightliner had used Pacific Institute Table 10. Volvo uses Revised Pacific Inst. Table 9, cost per fatality (minus delays and property damage), averaged across both fleets. Inflated by CPI from $(2000) to $(2005).
Property Damage $/crash (Truck-tractor, 1 trailer)	13,854 (SVRD) or 25,223 (Rollover)	7,758	Freightliner had used ATA/ATRI informal survey results; Volvo uses revised Pacific Inst. report Table 11 ($6,872 in 2000 dollars), inflated to year 2005 dollars).
Property Damage $/crash (All trucks)	6,350	6,813	Freightliner had used ATA/ATRI informal survey results; Volvo uses revised Pacific Inst. report Table 11 ($6,035 in 2000 dollars), inflated to year 2005 dollars).
Delays to Other Traffic, $/crash (Truck-tractor, 1 trailer)	9,064	5,280	Freightliner had used previous Pacific Inst. report (2000); Volvo uses revised Pacific Inst. report Table 11 ($4,677 in 2000 dollars, inflated to year 2005 dollars).
Delays to Other Traffic, $/crash (All Trucks)	9,355	5,419	Freightliner had used previous Pacific Inst. report (2000); Volvo uses revised Pacific Inst. report Table 11 ($4,800 in 2002 dollars, inflated to year 2005 dollars).
Annual Avg. Driver Wage	40,800	45,288	Inflated by CPI from $(2000) to $(2005). Factor = 1.11. Original value was based on ATA year 2000 Driver Compensation Study.

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, pg. 11).

These changes resulted in the aggregated per-crash delay costs used in the Volvo BCA (approximately $5,000) being less than the aggregated per-crash delay costs that had been used in the Freightliner BCA (approximately $9,000).

Because these changes in the crash cost assumptions were so substantial, a side analysis was performed to gauge the sensitivity of the life-cycle benefit-cost ratios to these costs, as described in the results section below.

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 analysis time (2005 to 2024), based on the U.S. Freight Transportation Forecast to 2008, published by the ATA, and covering the years 1998 to 2008. This growth rate was assumed to remain constant over the life cycle being modeled.

5.3.3 Benefit-Cost Results

Table 5.3-5 shows the societal benefit-cost ratios (BCRs), expressed in present (year 2005) dollars at a 4-percent discount rate over a 20-year deployment window, for each of the 24 scenarios modeled. As noted, values greater than 1 (printed in **boldface)** indicate an economic return on the investment required to deploy the various IVSS. BCR values less than one indicate that the deployment does not appear to be economically justified, based on the assumptions used in this analysis. The medium conflict threshold rows, representing the statistically most significant scenarios, are shaded.

The table shows that four of the 24 scenarios offer BCRs greater than 1, while the remaining 20 scenarios do not appear to be economically justified. All of the economically justified scenarios are for deployments on truck tractors pulling trailers. Two of the four economically justified scenarios used the medium threshold, and the other two used the aggressive threshold. The highest ratios are for the bundled system using the lower "alternative" first equipment cost assumption.

Only one of the 20 ratios that are not economically justified is between 0.8 and 1, indicating that, if some of the governing assumptions were to be modified, the BCR might move into the economically justified range. For example, if first cost or annual O&M costs could be reduced, then this marginal ratio might change to be greater than 1.

In four of the conservative conflict threshold scenarios, the BCRs are negative values, which appears anomalous. These results came about because the statistical modeling showed that the application of the IVSS under certain assumptions actually increased the rate of crashes. Thus the total benefits (expressed as a negative number, because the rate of crashes went up compared to the national rates prior to IVSS deployment for the given fleet and scenario) were divided by the costs for deploying the IVSS (expressed as a positive number), yielding a negative BCR.

Table 5.3-5. Benefit-Cost Ratios for All Scenarios Modeled in Volvo IVI FOT

(20-year Deployment; 4-Percent Discount Rate)

Fleet	IVSS Deployed[a]	Conflict Threshold	Equipment Cost Assumption	20-Year Societal BCR
All Large Trucks	CWS Only	Conservative	Low	–0.04
			High	–0.02
		Medium	Low	0.33
			High	0.23
		Aggressive	Low	0.41
			High	0.29
	Bundled	Conservative	Low	0.11
			High	0.04
		Medium	Low	0.40
			High	0.15
		Aggressive	Low	0.42
			High	0.16
Truck Tractors Pulling Trailers	CWS Only	Conservative	Low	–0.05
			High	–0.03
		Medium	Low	**1.08**
			High	0.76
		Aggressive	Low	**1.20**
			High	0.84
	Bundled	Conservative	Low	0.40
			High	0.15
		Medium	Low	**1.25**
			High	0.46
		Aggressive	Low	**1.32**
			High	0.48

a. CWS = Collision warning system
Bundled = CWS + adaptive cruise control + advanced brake system

Table 5.3-6 shows the modeled net present (2005) dollar values for all 24 scenarios. As in the previous table, boldface is used to show the scenarios where the life-cycle benefits exceed the costs.

Table 5.3-6. Net Present Dollar Value of 20-Year Benefits and Costs

(2005 Dollars; 4-Percent Discount Rate)

Fleet; Equipment; Conflict Threshold; Cost Assumption	Benefits, $	Costs, $
All Trucks; CWS Only; Conservative; Low	-1,364,122,561	38,506,495,418
All Trucks; CWS Only; Conservative; High	-1,364,122,561	54,571,101,654
All Trucks; CWS Only; Medium; Low	12,193,675,399	38,506,495,418
All Trucks; CWS Only; Medium; High	12,193,675,399	54,571,101,654
All Trucks; CWS Only; Aggressive; Low	15,614,161,805	38,506,495,418
All Trucks; CWS Only; Aggressive; High	15,614,161,805	54,571,101,654
All Trucks; Bundled; Conservative; Low	4,752,860,747	43,325,877,289
All Trucks; Bundled; Conservative; High	4,752,860,747	118,293,299,453
All Trucks; Bundled; Medium; Low	17,197,930,096	43,325,877,289
All Trucks; Bundled; Medium; High	17,197,930,096	118,293,299,453
All Trucks; Bundled; Aggressive; Low	18,355,097,895	43,325,877,289
All Trucks; Bundled; Aggressive; High	18,355,097,895	118,293,299,453
Tractor-Trailers; CWS Only; Conservative; Low	-393,374,893	8,552,432,808
Tractor-Trailers; CWS Only; Conservative; High	-393,374,893	12,120,440,333
Tractor-Trailers; CWS Only; Medium; Low	**9,206,785,188**	**8,552,432,808**
Tractor-Trailers; CWS Only; Medium; High	9,206,785,188	12,120,440,333
Tractor-Trailers; CWS Only; Aggressive; Low	**10,235,071,270**	**8,552,432,808**
Tractor-Trailers; CWS Only; Aggressive; High	10,235,071,270	12,120,440,333
Tractor-Trailers; Bundled; Conservative; Low	3,812,265,144	9,622,835,066
Tractor-Trailers; Bundled; Conservative; High	3,812,265,144	26,273,372,433
Tractor-Trailers; Bundled; Medium; Low	**12,062,307,505**	**9,622,835,066**
Tractor-Trailers; Bundled; Medium; High	12,062,307,505	26,273,372,433
Tractor-Trailers; Bundled; Aggressive; Low	**12,695,320,386**	**9,622,835,066**
Tractor-Trailers; Bundled; Aggressive; High	12,695,320,386	26,273,372,433

5.3.3.1 Sensitivity to First Cost and Annual O&M Costs

To gauge the sensitivity of the BCRs to potential future reductions in first costs and O&M costs, additional scenarios were modeled with sharply lower dollar values in these areas. It was found that, at a price point of $600 for the CWS and $1,000 for the bundled system, combined with reductions of 50 percent in annual operating and maintenance costs (to $20 and $40 per tractor per year for the CWS and the bundled system, respectively), the BCRs increase markedly. Table 5.3-7 shows the hypothetical results of this sensitivity analysis, based on cost points that are much lower than the ones currently assumed for the Volvo IVI FOT. Excluding the conservative conflict threshold scenarios, five of the eight remaining scenarios had BCRs greater than one, and all of the remaining tractor-trailer scenarios are economically justified.

The 20-year BCRs greater than one range from 1.21 to 3.56. One of the "all trucks" scenarios is greater than one, and another is at 0.98.

Table 5.3-7. Sensitivity Analysis for Hypothetical Reduced Equipment First Cost and Annual O&M Costs

(20-year deployment; 4-Percent Discount Rate)

Fleet	IVSS Deployed[a]	Conflict Threshold	20-Year Societal BCR
All Large Trucks	CWS Only	Conservative	–0.11
		Medium	0.98
		Aggressive	**1.21**
	Bundled	Conservative	0.21
		Medium	0.77
		Aggressive	0.82
Truck Tractors Pulling Trailers	CWS Only	Conservative	–0.14
		Medium	**3.20**
		Aggressive	**3.56**
	Bundled	Conservative	0.76
		Medium	**2.42**
		Aggressive	**2.55**

a. CWS = Collision warning system
Bundled = CWS + adaptive cruise control + advanced brake system

5.3.3.2 Summary of Benefit-Cost Ratios Using Various Equipment Cost Assumptions

Figure 5.3-1 illustrates the 20-year benefit-cost ratios across 36 of the scenarios modeled using low and high current cost estimates, and including additional scenarios from the sensitivity analysis assuming sharply reduced equipment and O&M costs in the future. To summarize these results:

- Very little difference was observed between the medium and aggressive conflict threshold criteria.
- The only positive societal returns on investment occur if CWS or the bundled system is deployed under the low current cost assumptions. (This includes the assumption that the benefits of the bundled system are not attributable to the AdvBS.)
- Deploying these systems on all large trucks does not appear to be economically justified under any current cost assumptions.
- A clear economic benefit of deploying these systems on tractor-trailers was observed, if costs can be lowered to the future levels used in the sensitivity analysis. There is still no—or very little—economic justification for deploying these system on all large trucks under any feasible current or future cost assumptions.

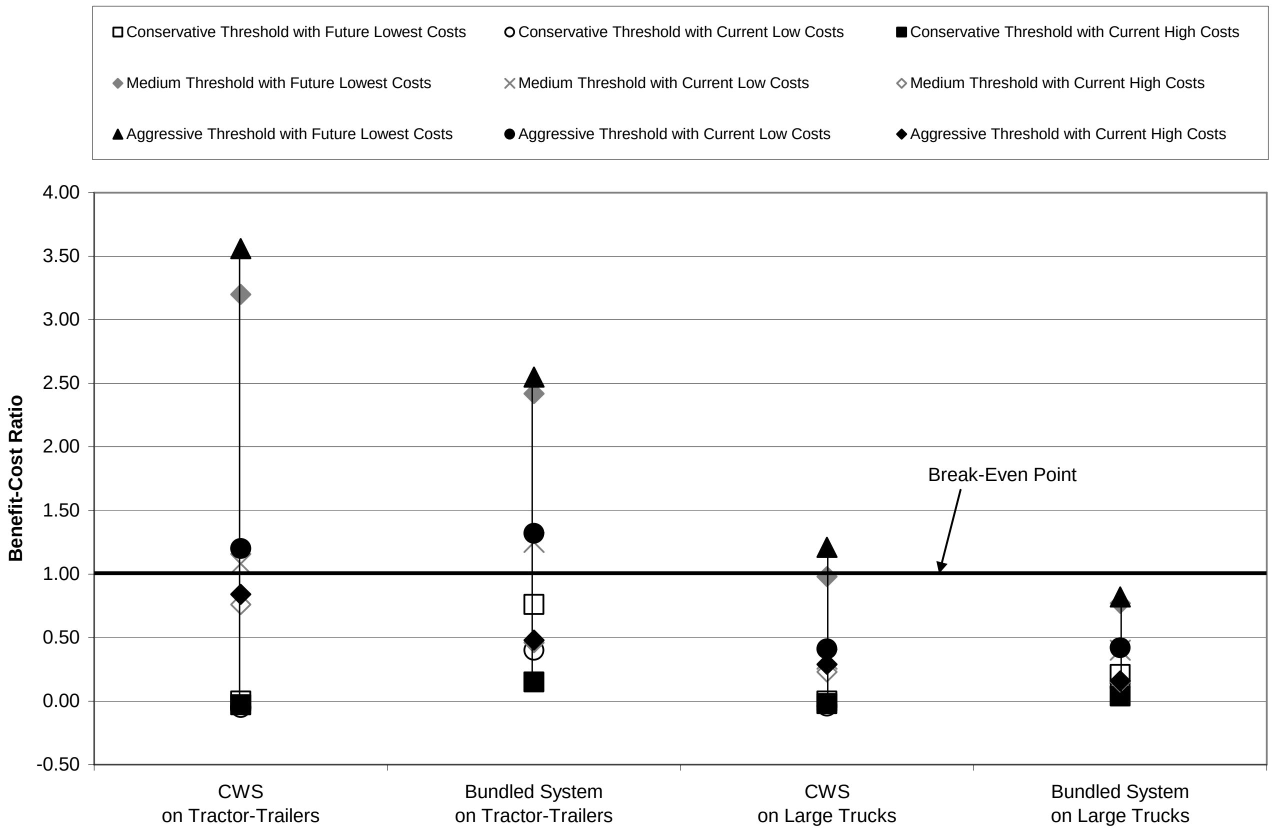


Figure 5.3-1. 20-year Benefit-Cost Ratios across Two National Fleets Using Various Equipment and Cost Assumptions and Conflict Threshold Criteria

5.3.3.3 Sensitivity to Crash Cost Assumptions

As noted above, the crash cost assumptions for injury, fatality, property damage, and delays to other traffic were based on values in an FMCSA-sponsored report that had been revised between the time of the Frieghtliner IVI FOT analysis (Pacific Institute 2000) and that of the Volvo IVI FOT Analysis (Pacific Institute 2002). The cost values included in the Volvo model were markedly lower for these categories. To gauge the sensitivity of the BCRs to these changes in crash cost assumptions, and to facilitate a hypothetical "apples-to-apples" comparison of the Freightliner to the Volvo IVSS, an analysis was conducted using the same values that had been input to the Freightliner BCA, inflated using the Consumer Price Index from $1999 to $2005, as shown in Table 5.3-8. All other cost and benefit inputs were held constant.

Table 5.3-8. Crash Cost Inputs for Sensitivity Analysis, $

Cost per Victim or Crash	Volvo IVI FOT	Freightliner Rpt. ($1999)	Freightliner Rpt. Inflated to $2005[b]
$/Injury, Tractor-Trailer	61,779	162,095	189,651
$/Injury, All Trucks	51,861	156,558	183,173
$/Fatality	3,022,840	3,358,240	3,929,141
$/Crash for Property Damage, Tractor-Trailer[a]	7,758	Avg. of 25,223 and 13,854 = 19,539	22,861
$/Crash for Property Damage, All Trucks	6,813	6,350	7,430
$/Crash for Delays, Tractor-Trailer	5,280	9,064	10,605
$/Crash for Delays, All Trucks	5,419	9,355	10,945

a. The Freightliner BCA (Battelle 2003b) used property damage values of $25,223 per rollover crash and $13,854 per single-vehicle roadway departure crash. For this Volvo sensitivity analysis, it was assumed for purposes of discussion that a rear-end crash might be midway between a rollover and an SVRD in property damage severity, so the mean of the two previous values was input into the BCA model.

b. Dollar values expressed in year 1999 were inflated to year 2005 dollars using the Bureau of Labor Statistics CPI Inflation Calculator, http://www.bls.gov/cpi/home.htm.

Table 5.3-9 shows the results of the crash cost sensitivity analysis in the last column. For comparison, the BCRs from the main Volvo analysis are repeated here from Table 5.3-5 above. This table shows that the 20-year BCRs approximately double their values compared with those used in the main Volvo IVI FOT analysis. Six of the 24 scenarios in the crash cost sensitivity analysis are greater than or equal to 1, and five other scenarios are between 0.8 and 0.99. As with the main Volvo IVI FOT analysis described above, the tractor-trailer scenarios and the medium and aggressive conflict threshold scenarios tend to have the highest BCRs. Changing the per-crash cost assumptions did not result in any of the ratios for the “all large truck” scenarios moving to greater than 1.

Table 5.3-9. Benefit-Cost Ratios for Volvo IVI FOT Crash Cost Sensitivity Analysis Using Inflation-Adjusted Freightliner Values

(20-year deployment; 4-Percent Discount Rate)

Fleet	IVSS Deployed[a]	Conflict Threshold	Equipment Cost Assumption	20-Year Societal BCR: Volvo Main Analysis	20-Year Societal BCR: Crash Cost Sensitivity Analysis
All Large Trucks	CWS Only	Conservative	Low	–0.04	–0.09
			High	–0.02	–0.06
		Medium	Low	0.33	0.74
			High	0.23	0.52
		Aggressive	Low	0.41	0.92
			High	0.29	0.65
	Bundled	Conservative	Low	0.11	0.23
			High	0.04	0.08
		Medium	Low	0.40	0.89
			High	0.15	0.33
		Aggressive	Low	0.42	0.96
			High	0.16	0.35
Truck Tractors Pulling Trailers	CWS Only	Conservative	Low	–0.05	–0.13
			High	–0.03	–0.09
		Medium	Low	**1.08**	**2.15**
			High	0.76	**1.51**
		Aggressive	Low	**1.20**	**2.46**
			High	0.84	**1.74**
	Bundled	Conservative	Low	0.40	0.75
			High	0.15	0.28
		Medium	Low	**1.25**	**2.53**
			High	0.46	0.93
		Aggressive	Low	**1.32**	**2.67**
			High	0.48	0.98

a. CWS = Collision warning system
Bundled = CWS + adaptive cruise control + advanced brake system

6.0 IMPLICATIONS OF FINDINGS

From a safety perspective, the most significant finding from this FOT is that the bundled system consisting of CWS + ACC + AdvBS on a tractor-trailer unit can help reduce the number of rear-end crashes by 28 percent. It appears that most of this benefit (21 percent) is due to the use of CWS, especially while driving at highway speeds; however, the estimated benefit of the CWS is only marginally significant at the 90 percent confidence level. If the CWS were to be deployed nationwide on all 1.8 million tractor-trailer units, approximately 4,700 rear-end crashes, 2,500 injuries, and 96 fatalities can be avoided each year. If all three systems were deployed on the same vehicles, the nation could realize reductions of 6,500 crashes, 3,400 injuries, and 122 fatalities. However, this FOT could not determine which of the two supplemental systems (ACC or AdvBS) is responsible for the additional safety benefit. This has significant implications on the costs of deployment.

Although additional studies may be needed to determine whether the ACC or AdvBS was responsible for the incremental benefits when both were added to a truck that already had CWS installed, it is clear that the cost of adding ACC (approximately $300 per truck) is substantially less than the cost of adding AdvBS (approximately $4,000 per truck). So, adding the ACC will have only a modest impact on the cost of deployment; but may produce substantial safety benefits.

The drivers participating in this FOT clearly recognized the value of the CWS—stating that it helped them to be more vigilant and maintain safer following distances. Driver feelings about the ACC were mixed, with about half of the drivers preferring to drive trucks with ACC and half preferring not to have ACC. Almost all of the drivers who used AdvBS agreed that it was beneficial.

6.1 All Large Trucks

Deployment of these systems on the larger population of 8 million large trucks (over 10,000 pounds) could result in additional crash savings; however, there are substantially fewer rear-end crashes per truck for this fleet (7 crashes per 1,000 large trucks versus 13 crashes per 1,000 tractor-trailers). Furthermore, more than three-fourths of the fatalities from rear-end crashes involving large trucks occur when tractor-trailers are involved. Thus, the safety benefit per unit deployed is substantially smaller for the larger fleet.

Thus, from an economic benefit-cost perspective, the deployment of bundled system on the fleet of all large trucks cannot be justified at a societal level under any scenario considered. This is partially driven by the high cost of the AdvBS. But, even under the most optimistic future cost assumptions, the economic benefits from deployment of the CWS on all large trucks would be approximately equal to the cost of deployment.

6.2 Tractor-Trailers

It appears that in a competitive market, the deployment of CWS on all tractor-trailers, on the other hand, can produce safety benefits that exceed the cost of deployment. Interviews with drivers also indicate that deployment of CWS will have positive benefits on driver morale. Deployment of ACC might produce additional safety benefits at a relatively small cost. However, the relative benefits and costs of deploying AdvBS require additional study. The drivers appear convinced that these braking systems improve driving safety; however, it was not possible to fully document these benefits in this FOT. Also, the future cost assumptions necessary to make these systems economically feasible ($1,000 per truck) may be overly optimistic in the near term.

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APPENDIX A.

TRUCK IN-SERVICE DATES

Appendix A.

Truck In-Service Dates

Fleet	Vehicle ID	USX ID	In-Service Date
Baseline	3932	10312	10-Jul-01
	3936	10316	Unknown
	3937	10317	29-Oct-01
	3938	10318	17-May-01
	3942	10322	20-Sep-01
	3943	10323	Unknown
	3946	10326	24-Oct-01
	3947	10327	22-May-01
	3953	10333	19-Jun-01
	3955	10335	25-Sep-01
	3958	10338	4-Jan-01
	3959	10339	Unknown
	3960	10340	5-Sep-01
	3961	10341	7-Aug-01
	3962	10342	Unknown
	3966	10346	Unknown
	3971	10351	19-Sep-01
	3972	10352	23-Oct-01
	3973	10353	28-Sep-01
	3974	10354	Unknown
Control	253975	10355	05-Jan-01
	253976	10356	24-Jan-01
	253977	10357	24-Jan-01
	253978	10358	05-Jan-01
	253970	10350	29-Dec-00
	253967	10347	24-Jan-01
	253968	10348	28-Dec-00
	253969	10349	28-Dec-00
	253963	10343	01-Dec-00
	253964	10344	15-Dec-00
	253965	10345	28-Dec-00
	253954	10334	01-Dec-00
	253956	10336	08-Dec-00
	253957	10337	01-Dec-00
	253952	10332	22-Dec-00
	253950	10330	01-Dec-00
	253951	10331	01-Dec-00
	253948	10328	01-Dec-00
	253949	10329	15-Dec-00
	253944	10324	01-Dec-00
	253945	10325	15-Dec-00
	253939	10319	01-Dec-00
	253940	10320	19-Jan-01
	253941	10321	24-Jan-01
	253934	10314	01-Dec-00
	253935	10315	01-Dec-00
	253933	10313	21-Dec-00
	253930	10196	01-Dec-00
	253931	10311	01-Dec-00
	253929	10195	01-Dec-00

Fleet	Vehicle ID	USX ID	In-Service Date
Test	247484	10159	13-Jun-01
	247482	10157	
	247483	10158	
	254009	10359	13-Jun-01
	254010	10360	03-Aug-01
	254011	10361	03-Aug-01
	254012	10362	11-Jul-01
	254013	10363	20-Jun-01
	254014	10364	25-Jun-01
	254015	10365	
	254016	10366	20-Jul-01
	254017	10367	20-Jul-01
	254018	10368	05-Jul-01
	254019	10369	27-Jun-01
	254020	10383	26-Jul-01
	254021	10384	27-Jul-01
	254022	10385	28-Jun-01
	254023	10386	
	254024	10387	
	254025	10388	13-Jun-01
	254026	10389	25-Jun-01
	254027	10390	25-Jun-01
	254028	10391	06-Aug-01
	254029	10392	09-Jul-01
	254030	10393	26-Jul-01
	254031	10394	
	254032	10395	24-Jun-01
	254033	10396	19-Jun-01
	254034	10397	19-Jun-01
	254035	10398	28-Jun-01
	254036	10399	20-Jun-01
	254037	10400	
	254038	10501	25-Jun-01
	254039	10502	05-Jul-01
	254040	10503	
	254041	10504	27-Jul-01
	254042	10505	27-Jun-01
	254043	10506	26-Jun-01
	254044	10507	06-Aug-01
	254045	10508	
	254046	10509	25-Jun-01
	254047	10510	03-Jul-01
	254048	10511	05-Jul-01
	254049	10512	25-Jun-01
	254050	10513	20-Jul-01
	254051	10514	11-Jul-01
	254052	10515	05-Jul-01
	254053	10516	27-Jul-01
	254054	10517	26-Jun-01
	254055	10518	26-Jun-01

APPENDIX B.

CODING SCHEME USED IN HISTORICAL CRASH DATA ANALYSIS (GES AND FARS)

Appendix B.

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 form. Both the name and alphanumeric name are given for the GES variables, while the SAS 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. In some cases, for the sake of simplicity, the coded SAS values that were excluded are provided, in which case the text describes what was omitted. Starting with the 2002 GES data sets, significant changes were made to the coding schemes of several variables used in the analysis. Those changes that affected how the variables of interest were defined are provided in parenthesis in the tables. An important change that should be mentioned is that the meaning of the "manner of collision" variable in FARS changed. Prior to 2002 the manner of collision variable was dependent on the direction of travel of the vehicles involved, where this was determined by the pre-crash condition direction of travel. Beginning in 2002, the manner of collision was dependent on the points of impact.

The analysis is performed on two categories of trucks: All large trucks (classes 3 through 8) and tractors (classes 7 and 8) pulling trailers. These subsets of trucks were used to create Excel tables, which give the relative frequency of predominant driving conflicts. The method used to define the truck categories from the GES and FARS data is provided in Table B-1.

A total of five crash types were determined from the GES and FARS data sets. Table B-2 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 for the GES data only since the necessary variables do not exist in FARS. Table B-3 provides the process used to determine predominant driving conflicts for rear-end crashes.

Table B-1. Determination of Truck Categories

Data Source	Category	Variables			
GES		**Hot-deck Imputed Body Type V5H**	**Tailing units V13**	**Cargo Body Type V33**	**Hazmat Placard V34**
	Large Truck	60- Step Van 64 – Single Unit Straight Truck 66- Truck-Tractor 78 – Unknown Medium/Heavy Truck	All All All All	All All All All	All All All All
	Tractor Trailer	66-Truck Tractor	2,3,4,5 – Trailing units	All	All
FARS		**Body_typ**	**Tow_veh**	**cargo_bt**	**haz_carg**
	Large Truck	60- Step Van 61-Single Unit Straight Truck low GVWR 62-Single Unit Straight Truck med GVWR 63-Single Unit Straight Truck high GVWR 64 – Single Unit Straight Truck 66- Truck-Tractor 71-Med. Single Unit Straight Truck or Combination Truck 72- Heavy Single Unit Straight Truck or Combination Truck 78 – Unknown Medium/Heavy Truck 79- Unknown Truck	All All All All All All All All All 1,2,3,4 – Trailing units	All All All All All All All All All All	All All All All All All All All All All
	Tractor Trailer	66-Truck Tractor	1,2,3,4 – Trailing units	All	All

Table B-2. Determination of Crash Type (Changes made due to variable recoding in 2002 in parenthesis)

Crash Type	GES			FARS				
	Accident type V23	**Rollover V30**	**Univariate Imputed Vehicle Role V22I**	**Man_col***	**Rel_road**	**Rollover**	**Impacts**	**J_knife**
SVRD	1-10	All	All	3 - Rear to rear	2 - Shoulder 4 – Roadside 6 – Off roadway	All All All	All All All	All All All
				6 - Sideswipe (Opp Direction)	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	1 or 3	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 Direction	All	All	Not 2 –Omit Struck	All
Untripped Rollover	98 –Other	10-Untripped Rollover	All	3 (10) – Rear to Rear	Not 2, not 4, and not 6	1 –first event	All	Not 2 –omit first event
				(09) – Rear to Side	Not 2, not 4, and not 6	1 –first event	All	Not 2 –omit first event
				6 (8) - Sideswipe -Opp Direction	Not 2, not 4, and not 6	1 –first event	All	Not 2 –omit first event
				(11) – Other	Not 2, not 4, and not 6	1 –first event	All	Not 2 –omit first event
				9 (99) – Unknown	Not 2, not 4, and not 6	1 –first event	All	Not 2 –omit first event
Other	Everything not categorized above			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 B-3. Determination of Rear-End Predominant Driving Conflicts from GES Data

Conflict Number	Accident Type V23	Rollover V30	Vehicles Involved A3	Univariate Imputed Vehicle Role V22I	Univariate Imputed Movement Prior to Critical Event V21I	Critical Event V26	Imputed Roadway Alignment A13I
Rear-End.1	20-43	All	<3	1 or 3	01 - Going Straight	051 – Other vehicle lower speed	All
Rear-End.2*	20-43	All	<3	1 or 3	02 – Decelerating	All except 050 – other vehicle stopped	All
Rear-End.3	20-43	All	<3	1 or 3	15,16 – Changing Lanes/ Merging	051 – Other vehicle lower speed	All
Rear-End.4*	20-43	All	<3	1 or 3	All	050 - Other vehicle stopped	All
Rear-End.5	20-43	All	<3	1 or 3	01 - Going Straight	052 – Other vehicle decelerating	All
Rear-End.9	20-43	All	All	1 or 3	Everything not categorized in Rearend.1-Rearend.5		

* Note: The accidents where the lead vehicle is stopped and the truck was decelerating are counted in both these categories. Removal of these accidents from the conflict total for 1992-1998 data did not alter the percentages reported.

APPENDIX C.

BENEFIT-COST ANALYSIS LIFE-CYCLE TABLES

Appendix C.

Benefit-Cost Analysis Life-Cycle Tables

This appendix presents supporting detail on the benefit-cost analysis. The first part shows annual cost and benefit values over the 20-year deployment being modeled, with various discount rate assumptions. The second part shows the total life-cycle costs and benefits per scenario, which were used to derive the benefit-cost ratios discussed in the text.

Tables C-1 through C-24 show representative examples of the detailed year-by-year forecasts for all the benefits and costs included in the BCA scenarios described in Section 5.3, including the present value for each benefit or cost at each future year, discounted at both 4 percent and 7 percent (real). Undiscounted dollar values are also shown. A table is presented for each combination of truck fleet, IVSS deployed, conflict threshold, and equipment cost assumption:

- All-truck scenarios—Tables C-1 through C-12
- Tractor-Trailer scenarios—Tables C-13 through C-24.

Examination of these tables can be helpful in understanding the relative importance of each category of project benefits and costs, how these are projected to increase over time, and how the arithmetic of discounting decreases the present value of a benefit or cost, the farther into the future it occurs. The present value of a benefit or cost that occurs *n* years into the future using discount rate *i* is equal to the future value divided by $(1+ i)^n$.

For example, assume that the base year is 2005, which makes the year 2008 into model year 3 (i.e., 2008 – 2005 = 3). Also, assume that the discount rate is 4%, or 0.04. If the undiscounted dollar benefit of crashes avoided in a given scenario during 2008 is $551,334,727, then the following equation is used to calculate that year's corresponding discounted value of $490,134,564.70:

$$[551{,}334{,}727 / (1 + 0.04)^3] = [551{,}334{,}727 / 1.124864] = 490{,}134{,}564.70.$$

Note that the discounted totals at the bottom of these tables are the same values used in computing the benefits and costs in the BCA summary tables for those scenarios summarized in Section 5.3.

Table C-1

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Conservative Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	-$74,809,754	$16,779,754,291	$393,580,498	-$74,809,754	$16,779,754,291	$393,580,498	-$74,809,754	$16,779,754,291	$393,580,498
2006	-$77,035,764	$0	$357,523,084	-$74,072,850	$0	$343,772,196	-$71,996,041	$0	$334,133,723
2007	-$79,328,010	$0	$368,161,402	-$73,343,205	$0	$340,385,911	-$69,288,157	$0	$321,566,426
2008	-$81,688,464	$0	$379,116,269	-$72,620,747	$0	$337,032,983	-$66,682,120	$0	$309,471,806
2009	-$84,119,154	$0	$390,397,106	-$71,905,405	$0	$333,713,082	-$64,174,100	$0	$297,832,083
2010	-$86,622,171	$0	$402,013,611	-$71,197,110	$0	$330,425,884	-$61,760,411	$0	$286,630,148
2011	-$89,199,667	$0	$413,975,772	-$70,495,792	$0	$327,171,066	-$59,437,504	$0	$275,849,536
2012	-$91,853,857	$0	$426,293,874	-$69,801,382	$0	$323,948,309	-$57,201,966	$0	$265,474,400
2013	-$94,587,025	$0	$438,978,509	-$69,113,813	$0	$320,757,297	-$55,050,510	$0	$255,489,489
2014	-$97,401,520	$21,847,065,143	$452,040,583	-$68,433,016	$15,349,458,181	$317,597,718	-$52,979,973	$11,883,355,908	$245,880,126
2015	-$100,299,762	$0	$465,491,327	-$67,758,925	$0	$314,469,262	-$50,987,313	$0	$236,632,187
2016	-$103,284,242	$0	$479,342,307	-$67,091,474	$0	$311,371,622	-$49,069,600	$0	$227,732,077
2017	-$106,357,528	$0	$493,605,430	-$66,430,598	$0	$308,304,495	-$47,224,015	$0	$219,166,714
2018	-$109,522,262	$0	$508,292,962	-$65,776,232	$0	$305,267,581	-$45,447,845	$0	$210,923,508
2019	-$112,781,164	$0	$523,417,530	-$65,128,312	$0	$302,260,581	-$43,738,480	$0	$202,990,342
2020	-$116,137,036	$0	$538,992,139	-$64,486,774	$0	$299,283,202	-$42,093,406	$0	$195,355,555
2021	-$119,592,765	$0	$555,030,179	-$63,851,555	$0	$296,335,151	-$40,510,207	$0	$188,007,925
2022	-$123,151,321	$0	$571,545,442	-$63,222,593	$0	$293,416,139	-$38,986,554	$0	$180,936,650
2023	-$126,815,763	$0	$588,552,126	-$62,599,827	$0	$290,525,880	-$37,520,208	$0	$174,131,337
2024	-$130,589,244	$0	$606,064,855	-$61,983,195	$0	$287,664,092	-$36,109,014	$0	$167,581,983
Total	-$2,005,176,473	$38,626,819,433	$9,352,415,004	-$1,364,122,561	$32,129,212,471	$6,377,282,947	-$1,065,067,177	$28,663,110,198	$4,989,366,514

Table C-2

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Conservative Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	-$74,809,754	$25,169,631,436	$393,580,498	-$74,809,754	$25,169,631,436	$393,580,498	-$74,809,754	$25,169,631,436	$393,580,498
2006	-$77,035,764	$0	$357,523,084	-$74,072,850	$0	$343,772,196	-$71,996,041	$0	$334,133,723
2007	-$79,328,010	$0	$368,161,402	-$73,343,205	$0	$340,385,911	-$69,288,157	$0	$321,566,426
2008	-$81,688,464	$0	$379,116,269	-$72,620,747	$0	$337,032,983	-$66,682,120	$0	$309,471,806
2009	-$84,119,154	$0	$390,397,106	-$71,905,405	$0	$333,713,082	-$64,174,100	$0	$297,832,083
2010	-$86,622,171	$0	$402,013,611	-$71,197,110	$0	$330,425,884	-$61,760,411	$0	$286,630,148
2011	-$89,199,667	$0	$413,975,772	-$70,495,792	$0	$327,171,066	-$59,437,504	$0	$275,849,536
2012	-$91,853,857	$0	$426,293,874	-$69,801,382	$0	$323,948,309	-$57,201,966	$0	$265,474,400
2013	-$94,587,025	$0	$438,978,509	-$69,113,813	$0	$320,757,297	-$55,050,510	$0	$255,489,489
2014	-$97,401,520	$32,770,597,714	$452,040,583	-$68,433,016	$23,024,187,271	$317,597,718	-$52,979,973	$17,825,033,861	$245,880,126
2015	-$100,299,762	$0	$465,491,327	-$67,758,925	$0	$314,469,262	-$50,987,313	$0	$236,632,187
2016	-$103,284,242	$0	$479,342,307	-$67,091,474	$0	$311,371,622	-$49,069,600	$0	$227,732,077
2017	-$106,357,528	$0	$493,605,430	-$66,430,598	$0	$308,304,495	-$47,224,015	$0	$219,166,714
2018	-$109,522,262	$0	$508,292,962	-$65,776,232	$0	$305,267,581	-$45,447,845	$0	$210,923,508
2019	-$112,781,164	$0	$523,417,530	-$65,128,312	$0	$302,260,581	-$43,738,480	$0	$202,990,342
2020	-$116,137,036	$0	$538,992,139	-$64,486,774	$0	$299,283,202	-$42,093,406	$0	$195,355,555
2021	-$119,592,765	$0	$555,030,179	-$63,851,555	$0	$296,335,151	-$40,510,207	$0	$188,007,925
2022	-$123,151,321	$0	$571,545,442	-$63,222,593	$0	$293,416,139	-$38,986,554	$0	$180,936,650
2023	-$126,815,763	$0	$588,552,126	-$62,599,827	$0	$290,525,880	-$37,520,208	$0	$174,131,337
2024	-$130,589,244	$0	$606,064,855	-$61,983,195	$0	$287,664,092	-$36,109,014	$0	$167,581,983
Total	-$2,005,176,473	$57,940,229,150	$9,352,415,004	-$1,364,122,561	$48,193,818,707	$6,377,282,947	-$1,065,067,177	$42,994,665,297	$4,989,366,514

Table C-3

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Medium Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$696,145,992	$16,779,754,291	$393,580,498	$696,145,992	$16,779,754,291	$393,580,498	$696,145,992	$16,779,754,291	$393,580,498
2006	$716,860,242	$0	$357,523,084	$689,288,694	$0	$343,772,196	$669,962,843	$0	$334,133,723
2007	$738,190,857	$0	$368,161,402	$682,498,943	$0	$340,385,911	$644,764,483	$0	$321,566,426
2008	$760,156,177	$0	$379,116,269	$675,776,074	$0	$337,032,983	$620,513,874	$0	$309,471,806
2009	$782,775,089	$0	$390,397,106	$669,119,427	$0	$333,713,082	$597,175,368	$0	$297,832,083
2010	$806,067,041	$0	$402,013,611	$662,528,351	$0	$330,425,884	$574,714,660	$0	$286,630,148
2011	$830,052,059	$0	$413,975,772	$656,002,199	$0	$327,171,066	$553,098,735	$0	$275,849,536
2012	$854,750,766	$0	$426,293,874	$649,540,333	$0	$323,948,309	$532,295,819	$0	$265,474,400
2013	$880,184,398	$0	$438,978,509	$643,142,118	$0	$320,757,297	$512,275,333	$0	$255,489,489
2014	$906,374,823	$21,847,065,143	$452,040,583	$636,806,928	$15,349,458,181	$317,597,718	$493,007,850	$11,883,355,908	$245,880,126
2015	$933,344,561	$0	$465,491,327	$630,534,142	$0	$314,469,262	$474,465,047	$0	$236,632,187
2016	$961,116,799	$0	$479,342,307	$624,323,146	$0	$311,371,622	$456,619,668	$0	$227,732,077
2017	$989,715,417	$0	$493,605,430	$618,173,330	$0	$308,304,495	$439,445,482	$0	$219,166,714
2018	$1,019,165,005	$0	$508,292,962	$612,084,092	$0	$305,267,581	$422,917,244	$0	$210,923,508
2019	$1,049,490,883	$0	$523,417,530	$606,054,835	$0	$302,260,581	$407,010,659	$0	$202,990,342
2020	$1,080,719,127	$0	$538,992,139	$600,084,969	$0	$299,283,202	$391,702,346	$0	$195,355,555
2021	$1,112,876,586	$0	$555,030,179	$594,173,908	$0	$296,335,151	$376,969,803	$0	$188,007,925
2022	$1,145,990,909	$0	$571,545,442	$588,321,073	$0	$293,416,139	$362,791,374	$0	$180,936,650
2023	$1,180,090,570	$0	$588,552,126	$582,525,891	$0	$290,525,880	$349,146,218	$0	$174,131,337
2024	$1,215,204,887	$0	$606,064,855	$576,787,793	$0	$287,664,092	$336,014,278	$0	$167,581,983
Total	$18,659,272,188	$38,626,819,433	$9,352,415,004	$12,693,912,235	$32,129,212,471	$6,377,282,947	$9,911,037,071	$28,663,110,198	$4,989,366,514

Table C-4

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Medium Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**
2005	$696,145,992	$25,169,631,436	$393,580,498	$696,145,992	$25,169,631,436	$393,580,498	$696,145,992	$25,169,631,436	$393,580,498
2006	$716,860,242	$0	$357,523,084	$689,288,694	$0	$343,772,196	$669,962,843	$0	$334,133,723
2007	$738,190,857	$0	$368,161,402	$682,498,943	$0	$340,385,911	$644,764,483	$0	$321,566,426
2008	$760,156,177	$0	$379,116,269	$675,776,074	$0	$337,032,983	$620,513,874	$0	$309,471,806
2009	$782,775,089	$0	$390,397,106	$669,119,427	$0	$333,713,082	$597,175,368	$0	$297,832,083
2010	$806,067,041	$0	$402,013,611	$662,528,351	$0	$330,425,884	$574,714,660	$0	$286,630,148
2011	$830,052,059	$0	$413,975,772	$656,002,199	$0	$327,171,066	$553,098,735	$0	$275,849,536
2012	$854,750,766	$0	$426,293,874	$649,540,333	$0	$323,948,309	$532,295,819	$0	$265,474,400
2013	$880,184,398	$0	$438,978,509	$643,142,118	$0	$320,757,297	$512,275,333	$0	$255,489,489
2014	$906,374,823	$32,770,597,714	$452,040,583	$636,806,928	$23,024,187,271	$317,597,718	$493,007,850	$17,825,033,861	$245,880,126
2015	$933,344,561	$0	$465,491,327	$630,534,142	$0	$314,469,262	$474,465,047	$0	$236,632,187
2016	$961,116,799	$0	$479,342,307	$624,323,146	$0	$311,371,622	$456,619,668	$0	$227,732,077
2017	$989,715,417	$0	$493,605,430	$618,173,330	$0	$308,304,495	$439,445,482	$0	$219,166,714
2018	$1,019,165,005	$0	$508,292,962	$612,084,092	$0	$305,267,581	$422,917,244	$0	$210,923,508
2019	$1,049,490,883	$0	$523,417,530	$606,054,835	$0	$302,260,581	$407,010,659	$0	$202,990,342
2020	$1,080,719,127	$0	$538,992,139	$600,084,969	$0	$299,283,202	$391,702,346	$0	$195,355,555
2021	$1,112,876,586	$0	$555,030,179	$594,173,908	$0	$296,335,151	$376,969,803	$0	$188,007,925
2022	$1,145,990,909	$0	$571,545,442	$588,321,073	$0	$293,416,139	$362,791,374	$0	$180,936,650
2023	$1,180,090,570	$0	$588,552,126	$582,525,891	$0	$290,525,880	$349,146,218	$0	$174,131,337
2024	$1,215,204,887	$0	$606,064,855	$576,787,793	$0	$287,664,092	$336,014,278	$0	$167,581,983
Total	$18,659,272,188	$57,940,229,150	$9,352,415,004	$12,693,912,235	$48,193,818,707	$6,377,282,947	$9,911,037,071	$42,994,665,297	$4,989,366,514

Table C-5

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Aggressive Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$856,295,203	$16,779,754,291	$393,580,498	$856,295,203	$16,779,754,291	$393,580,498	$856,295,203	$16,779,754,291	$393,580,498
2006	$881,774,791	$0	$357,523,084	$847,860,376	$0	$343,772,196	$824,088,589	$0	$334,133,723
2007	$908,012,539	$0	$368,161,402	$839,508,634	$0	$340,385,911	$793,093,317	$0	$321,566,426
2008	$935,031,008	$0	$379,116,269	$831,239,161	$0	$337,032,983	$763,263,826	$0	$309,471,806
2009	$962,853,427	$0	$390,397,106	$823,051,145	$0	$333,713,082	$734,556,270	$0	$297,832,083
2010	$991,503,720	$0	$402,013,611	$814,943,784	$0	$330,425,884	$706,928,449	$0	$286,630,148
2011	$1,021,006,520	$0	$413,975,772	$806,916,284	$0	$327,171,066	$680,339,755	$0	$275,849,536
2012	$1,051,387,194	$0	$426,293,874	$798,967,857	$0	$323,948,309	$654,751,103	$0	$265,474,400
2013	$1,082,671,863	$0	$438,978,509	$791,097,725	$0	$320,757,297	$630,124,881	$0	$255,489,489
2014	$1,114,887,427	$21,847,065,143	$452,040,583	$783,305,118	$15,349,458,181	$317,597,718	$606,424,890	$11,883,355,908	$245,880,126
2015	$1,148,061,584	$0	$465,491,327	$775,589,270	$0	$314,469,262	$583,616,294	$0	$236,632,187
2016	$1,182,222,859	$0	$479,342,307	$767,949,426	$0	$311,371,622	$561,665,564	$0	$227,732,077
2017	$1,217,400,623	$0	$493,605,430	$760,384,838	$0	$308,304,495	$540,540,436	$0	$219,166,714
2018	$1,253,625,124	$0	$508,292,962	$752,894,763	$0	$305,267,581	$520,209,857	$0	$210,923,508
2019	$1,290,927,506	$0	$523,417,530	$745,478,469	$0	$302,260,581	$500,643,944	$0	$202,990,342
2020	$1,329,339,844	$0	$538,992,139	$738,135,227	$0	$299,283,202	$481,813,935	$0	$195,355,555
2021	$1,368,895,164	$0	$555,030,179	$730,864,320	$0	$296,335,151	$463,692,153	$0	$188,007,925
2022	$1,409,627,478	$0	$571,545,442	$723,665,034	$0	$293,416,139	$446,251,960	$0	$180,936,650
2023	$1,451,571,806	$0	$588,552,126	$716,536,663	$0	$290,525,880	$429,467,719	$0	$174,131,337
2024	$1,494,764,213	$0	$606,064,855	$709,478,509	$0	$287,664,092	$413,314,761	$0	$167,581,983
Total	$22,951,859,892	$38,626,819,433	$9,352,415,004	$15,614,161,805	$32,129,212,471	$6,377,282,947	$12,191,082,908	$28,663,110,198	$4,989,366,514

Table C-6

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Effect of CWS Only Using Aggressive Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$856,295,203	$25,169,631,436	$393,580,498	$856,295,203	$25,169,631,436	$393,580,498	$856,295,203	$25,169,631,436	$393,580,498
2006	$881,774,791	$0	$357,523,084	$847,860,376	$0	$343,772,196	$824,088,589	$0	$334,133,723
2007	$908,012,539	$0	$368,161,402	$839,508,634	$0	$340,385,911	$793,093,317	$0	$321,566,426
2008	$935,031,008	$0	$379,116,269	$831,239,161	$0	$337,032,983	$763,263,826	$0	$309,471,806
2009	$962,853,427	$0	$390,397,106	$823,051,145	$0	$333,713,082	$734,556,270	$0	$297,832,083
2010	$991,503,720	$0	$402,013,611	$814,943,784	$0	$330,425,884	$706,928,449	$0	$286,630,148
2011	$1,021,006,520	$0	$413,975,772	$806,916,284	$0	$327,171,066	$680,339,755	$0	$275,849,536
2012	$1,051,387,194	$0	$426,293,874	$798,967,857	$0	$323,948,309	$654,751,103	$0	$265,474,400
2013	$1,082,671,863	$0	$438,978,509	$791,097,725	$0	$320,757,297	$630,124,881	$0	$255,489,489
2014	$1,114,887,427	$32,770,597,714	$452,040,583	$783,305,118	$23,024,187,271	$317,597,718	$606,424,890	$17,825,033,861	$245,880,126
2015	$1,148,061,584	$0	$465,491,327	$775,589,270	$0	$314,469,262	$583,616,294	$0	$236,632,187
2016	$1,182,222,859	$0	$479,342,307	$767,949,426	$0	$311,371,622	$561,665,564	$0	$227,732,077
2017	$1,217,400,623	$0	$493,605,430	$760,384,838	$0	$308,304,495	$540,540,436	$0	$219,166,714
2018	$1,253,625,124	$0	$508,292,962	$752,894,763	$0	$305,267,581	$520,209,857	$0	$210,923,508
2019	$1,290,927,506	$0	$523,417,530	$745,478,469	$0	$302,260,581	$500,643,944	$0	$202,990,342
2020	$1,329,339,844	$0	$538,992,139	$738,135,227	$0	$299,283,202	$481,813,935	$0	$195,355,555
2021	$1,368,895,164	$0	$555,030,179	$730,864,320	$0	$296,335,151	$463,692,153	$0	$188,007,925
2022	$1,409,627,478	$0	$571,545,442	$723,665,034	$0	$293,416,139	$446,251,960	$0	$180,936,650
2023	$1,451,571,806	$0	$588,552,126	$716,536,663	$0	$290,525,880	$429,467,719	$0	$174,131,337
2024	$1,494,764,213	$0	$606,064,855	$709,478,509	$0	$287,664,092	$413,314,761	$0	$167,581,983
Total	$22,951,859,892	$57,940,229,150	$9,352,415,004	$15,614,161,805	$48,193,818,707	$6,377,282,947	$12,191,082,908	$42,994,665,297	$4,989,366,514

Table C-7

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Conservative Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$260,651,318	$19,296,717,434	$393,580,498	$260,651,318	$19,296,717,434	$393,580,498	$260,651,318	$19,296,717,434	$393,580,498
2006	$268,407,158	$0	$357,523,084	$258,083,805	$0	$343,772,196	$250,847,811	$0	$334,133,723
2007	$276,393,777	$0	$368,161,402	$255,541,584	$0	$340,385,911	$241,413,029	$0	$321,566,426
2008	$284,618,043	$0	$379,116,269	$253,024,404	$0	$337,032,983	$232,333,104	$0	$309,471,806
2009	$293,087,027	$0	$390,397,106	$250,532,019	$0	$333,713,082	$223,594,689	$0	$297,832,083
2010	$301,808,011	$0	$402,013,611	$248,064,185	$0	$330,425,884	$215,184,940	$0	$286,630,148
2011	$310,788,493	$0	$413,975,772	$245,620,660	$0	$327,171,066	$207,091,495	$0	$275,849,536
2012	$320,036,194	$0	$426,293,874	$243,201,205	$0	$323,948,309	$199,302,457	$0	$265,474,400
2013	$329,559,067	$0	$438,978,509	$240,805,582	$0	$320,757,297	$191,806,378	$0	$255,489,489
2014	$339,365,299	$25,124,124,914	$452,040,583	$238,433,557	$17,651,876,908	$317,597,718	$184,592,237	$13,665,859,294	$245,880,126
2015	$349,463,321	$0	$465,491,327	$236,084,898	$0	$314,469,262	$177,649,432	$0	$236,632,187
2016	$359,861,816	$0	$479,342,307	$233,759,374	$0	$311,371,622	$170,967,756	$0	$227,732,077
2017	$370,569,724	$0	$493,605,430	$231,456,756	$0	$308,304,495	$164,537,389	$0	$219,166,714
2018	$381,596,253	$0	$508,292,962	$229,176,821	$0	$305,267,581	$158,348,879	$0	$210,923,508
2019	$392,950,883	$0	$523,417,530	$226,919,344	$0	$302,260,581	$152,393,127	$0	$202,990,342
2020	$404,643,377	$0	$538,992,139	$224,684,104	$0	$299,283,202	$146,661,381	$0	$195,355,555
2021	$416,683,788	$0	$555,030,179	$222,470,881	$0	$296,335,151	$141,145,215	$0	$188,007,925
2022	$429,082,469	$0	$571,545,442	$220,279,460	$0	$293,416,139	$135,836,521	$0	$180,936,650
2023	$441,850,081	$0	$588,552,126	$218,109,625	$0	$290,525,880	$130,727,495	$0	$174,131,337
2024	$454,997,600	$0	$606,064,855	$215,961,164	$0	$287,664,092	$125,810,628	$0	$167,581,983
Total	$6,986,413,700	$44,420,842,348	$9,352,415,004	$4,752,860,747	$36,948,594,342	$6,377,282,947	$3,710,895,285	$32,962,576,728	$4,989,366,514

Table C-8

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Conservative Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**
2005	$260,651,318	$52,856,226,015	$980,871,898	$260,651,318	$52,856,226,015	$980,871,898	$260,651,318	$52,856,226,015	$980,871,898
2006	$268,407,158	$0	$962,289,699	$258,083,805	$0	$925,278,556	$250,847,811	$0	$899,336,167
2007	$276,393,777	$0	$990,923,217	$255,541,584	$0	$916,164,217	$241,413,029	$0	$865,510,715
2008	$284,618,043	$0	$1,020,408,744	$253,024,404	$0	$907,139,658	$232,333,104	$0	$832,957,491
2009	$293,087,027	$0	$1,050,771,631	$250,532,019	$0	$898,203,994	$223,594,689	$0	$801,628,646
2010	$301,808,011	$0	$1,082,037,983	$248,064,185	$0	$889,356,349	$215,184,940	$0	$771,478,128
2011	$310,788,493	$0	$1,114,234,685	$245,620,660	$0	$880,595,857	$207,091,495	$0	$742,461,618
2012	$320,036,194	$0	$1,147,389,420	$243,201,205	$0	$871,921,659	$199,302,457	$0	$714,536,465
2013	$329,559,067	$0	$1,181,530,694	$240,805,582	$0	$863,332,905	$191,806,378	$0	$687,661,622
2014	$339,365,299	$68,818,255,200	$1,216,687,863	$238,433,557	$48,350,793,269	$854,828,754	$184,592,237	$37,432,571,109	$661,797,583
2015	$349,463,321	$0	$1,252,891,155	$236,084,898	$0	$846,408,372	$177,649,432	$0	$636,906,332
2016	$359,861,816	$0	$1,290,171,698	$233,759,374	$0	$838,070,933	$170,967,756	$0	$612,951,280
2017	$370,569,724	$0	$1,328,561,546	$231,456,756	$0	$829,815,622	$164,537,389	$0	$589,897,215
2018	$381,596,253	$0	$1,368,093,708	$229,176,821	$0	$821,641,628	$158,348,879	$0	$567,710,250
2019	$392,950,883	$0	$1,408,802,173	$226,919,344	$0	$813,548,152	$152,393,127	$0	$546,357,772
2020	$404,643,377	$0	$1,450,721,944	$224,684,104	$0	$805,534,399	$146,661,381	$0	$525,808,394
2021	$416,683,788	$0	$1,493,889,063	$222,470,881	$0	$797,599,584	$141,145,215	$0	$506,031,911
2022	$429,082,469	$0	$1,538,340,646	$220,279,460	$0	$789,742,931	$135,836,521	$0	$486,999,252
2023	$441,850,081	$0	$1,584,114,913	$218,109,625	$0	$781,963,668	$130,727,495	$0	$468,682,442
2024	$454,997,600	$0	$1,631,251,221	$215,961,164	$0	$774,261,034	$125,810,628	$0	$451,054,556
Total	$6,986,413,700	$121,674,481,215	$25,093,983,901	$4,752,860,747	$101,207,019,284	$17,086,280,169	$3,710,895,285	$90,288,797,124	$13,350,639,736

Table C-9

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Medium Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$943,150,534	$19,296,717,434	$393,580,498	$943,150,534	$19,296,717,434	$393,580,498	$943,150,534	$19,296,717,434	$393,580,498
2006	$971,214,555	$0	$357,523,084	$933,860,149	$0	$343,772,196	$907,677,154	$0	$334,133,723
2007	$1,000,113,638	$0	$368,161,402	$924,661,278	$0	$340,385,911	$873,537,984	$0	$321,566,426
2008	$1,029,872,631	$0	$379,116,269	$915,553,019	$0	$337,032,983	$840,682,843	$0	$309,471,806
2009	$1,060,517,122	$0	$390,397,106	$906,534,480	$0	$333,713,082	$809,063,434	$0	$297,832,083
2010	$1,092,073,458	$0	$402,013,611	$897,604,777	$0	$330,425,884	$778,633,282	$0	$286,630,148
2011	$1,124,568,771	$0	$413,975,772	$888,763,035	$0	$327,171,066	$749,347,656	$0	$275,849,536
2012	$1,158,031,003	$0	$426,293,874	$880,008,388	$0	$323,948,309	$721,163,508	$0	$265,474,400
2013	$1,192,488,924	$0	$438,978,509	$871,339,977	$0	$320,757,297	$694,039,411	$0	$255,489,489
2014	$1,227,972,162	$25,124,124,914	$452,040,583	$862,756,953	$17,651,876,908	$317,597,718	$667,935,494	$13,665,859,294	$245,880,126
2015	$1,264,511,225	$0	$465,491,327	$854,258,475	$0	$314,469,262	$642,813,386	$0	$236,632,187
2016	$1,302,137,530	$0	$479,342,307	$845,843,710	$0	$311,371,622	$618,636,160	$0	$227,732,077
2017	$1,340,883,429	$0	$493,605,430	$837,511,833	$0	$308,304,495	$595,368,278	$0	$219,166,714
2018	$1,380,782,236	$0	$508,292,962	$829,262,029	$0	$305,267,581	$572,975,538	$0	$210,923,508
2019	$1,421,868,256	$0	$523,417,530	$821,093,489	$0	$302,260,581	$551,425,024	$0	$202,990,342
2020	$1,464,176,816	$0	$538,992,139	$813,005,412	$0	$299,283,202	$530,685,059	$0	$195,355,555
2021	$1,507,744,293	$0	$555,030,179	$804,997,005	$0	$296,335,151	$510,725,157	$0	$188,007,925
2022	$1,552,608,147	$0	$571,545,442	$797,067,484	$0	$293,416,139	$491,515,978	$0	$180,936,650
2023	$1,598,806,952	$0	$588,552,126	$789,216,072	$0	$290,525,880	$473,029,286	$0	$174,131,337
2024	$1,646,380,431	$0	$606,064,855	$781,441,999	$0	$287,664,092	$455,237,908	$0	$167,581,983
Total	$25,279,902,112	$44,420,842,348	$9,352,415,004	$17,197,930,096	$36,948,594,342	$6,377,282,947	$13,427,643,076	$32,962,576,728	$4,989,366,514

Table C-10

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Medium Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$943,150,534	$52,856,226,015	$980,871,898	$943,150,534	$52,856,226,015	$980,871,898	$943,150,534	$52,856,226,015	$980,871,898
2006	$971,214,555	$0	$962,289,699	$933,860,149	$0	$925,278,556	$907,677,154	$0	$899,336,167
2007	$1,000,113,638	$0	$990,923,217	$924,661,278	$0	$916,164,217	$873,537,984	$0	$865,510,715
2008	$1,029,872,631	$0	$1,020,408,744	$915,553,019	$0	$907,139,658	$840,682,843	$0	$832,957,491
2009	$1,060,517,122	$0	$1,050,771,631	$906,534,480	$0	$898,203,994	$809,063,434	$0	$801,628,646
2010	$1,092,073,458	$0	$1,082,037,983	$897,604,777	$0	$889,356,349	$778,633,282	$0	$771,478,128
2011	$1,124,568,771	$0	$1,114,234,685	$888,763,035	$0	$880,595,857	$749,347,656	$0	$742,461,618
2012	$1,158,031,003	$0	$1,147,389,420	$880,008,388	$0	$871,921,659	$721,163,508	$0	$714,536,465
2013	$1,192,488,924	$0	$1,181,530,694	$871,339,977	$0	$863,332,905	$694,039,411	$0	$687,661,622
2014	$1,227,972,162	$68,818,255,200	$1,216,687,863	$862,756,953	$48,350,793,269	$854,828,754	$667,935,494	$37,432,571,109	$661,797,583
2015	$1,264,511,225	$0	$1,252,891,155	$854,258,475	$0	$846,408,372	$642,813,386	$0	$636,906,332
2016	$1,302,137,530	$0	$1,290,171,698	$845,843,710	$0	$838,070,933	$618,636,160	$0	$612,951,280
2017	$1,340,883,429	$0	$1,328,561,546	$837,511,833	$0	$829,815,622	$595,368,278	$0	$589,897,215
2018	$1,380,782,236	$0	$1,368,093,708	$829,262,029	$0	$821,641,628	$572,975,538	$0	$567,710,250
2019	$1,421,868,256	$0	$1,408,802,173	$821,093,489	$0	$813,548,152	$551,425,024	$0	$546,357,772
2020	$1,464,176,816	$0	$1,450,721,944	$813,005,412	$0	$805,534,399	$530,685,059	$0	$525,808,394
2021	$1,507,744,293	$0	$1,493,889,063	$804,997,005	$0	$797,599,584	$510,725,157	$0	$506,031,911
2022	$1,552,608,147	$0	$1,538,340,646	$797,067,484	$0	$789,742,931	$491,515,978	$0	$486,999,252
2023	$1,598,806,952	$0	$1,584,114,913	$789,216,072	$0	$781,963,668	$473,029,286	$0	$468,682,442
2024	$1,646,380,431	$0	$1,631,251,221	$781,441,999	$0	$774,261,034	$455,237,908	$0	$451,054,556
Total	$25,279,902,112	$121,674,481,215	$25,093,983,901	$17,197,930,096	$101,207,019,284	$17,086,280,169	$13,427,643,076	$90,288,797,124	$13,350,639,736

Table C-11

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Aggressive Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$1,006,610,696	$19,296,717,434	$393,580,498	$1,006,610,696	$19,296,717,434	$393,580,498	$1,006,610,696	$19,296,717,434	$393,580,498
2006	$1,036,563,013	$0	$357,523,084	$996,695,205	$0	$343,772,196	$968,750,479	$0	$334,133,723
2007	$1,067,406,579	$0	$368,161,402	$986,877,385	$0	$340,385,911	$932,314,245	$0	$321,566,426
2008	$1,099,167,915	$0	$379,116,269	$977,156,274	$0	$337,032,983	$897,248,436	$0	$309,471,806
2009	$1,131,874,329	$0	$390,397,106	$967,530,920	$0	$333,713,082	$863,501,506	$0	$297,832,083
2010	$1,165,553,942	$0	$402,013,611	$958,000,380	$0	$330,425,884	$831,023,852	$0	$286,630,148
2011	$1,200,235,713	$0	$413,975,772	$948,563,718	$0	$327,171,066	$799,767,734	$0	$275,849,536
2012	$1,235,949,461	$0	$426,293,874	$939,220,012	$0	$323,948,309	$769,687,208	$0	$265,474,400
2013	$1,272,725,893	$0	$438,978,509	$929,968,344	$0	$320,757,297	$740,738,058	$0	$255,489,489
2014	$1,310,596,631	$25,124,124,914	$452,040,583	$920,807,809	$17,651,876,908	$317,597,718	$712,877,730	$13,665,859,294	$245,880,126
2015	$1,349,594,236	$0	$465,491,327	$911,737,508	$0	$314,469,262	$686,065,274	$0	$236,632,187
2016	$1,389,752,238	$0	$479,342,307	$902,756,553	$0	$311,371,622	$660,261,277	$0	$227,732,077
2017	$1,431,105,166	$0	$493,605,430	$893,864,064	$0	$308,304,495	$635,427,809	$0	$219,166,714
2018	$1,473,688,576	$0	$508,292,962	$885,059,170	$0	$305,267,581	$611,528,366	$0	$210,923,508
2019	$1,517,539,081	$0	$523,417,530	$876,341,006	$0	$302,260,581	$588,527,819	$0	$202,990,342
2020	$1,562,694,385	$0	$538,992,139	$867,708,720	$0	$299,283,202	$566,392,360	$0	$195,355,555
2021	$1,609,193,312	$0	$555,030,179	$859,161,466	$0	$296,335,151	$545,089,449	$0	$188,007,925
2022	$1,657,075,844	$0	$571,545,442	$850,698,405	$0	$293,416,139	$524,587,775	$0	$180,936,650
2023	$1,706,383,149	$0	$588,552,126	$842,318,708	$0	$290,525,880	$504,857,201	$0	$174,131,337
2024	$1,757,157,624	$0	$606,064,855	$834,021,554	$0	$287,664,092	$485,868,725	$0	$167,581,983
Total	$26,980,867,783	$44,420,842,348	$9,352,415,004	$18,355,097,895	$36,948,594,342	$6,377,282,947	$14,331,126,001	$32,962,576,728	$4,989,366,514

Table C-12

Benefits and Costs for Volvo FOT ($2005)
Scenario: All Trucks with Bundled System Using Aggressive Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$1,006,610,696	$52,856,226,015	$980,871,898	$1,006,610,696	$52,856,226,015	$980,871,898	$1,006,610,696	$52,856,226,015	$980,871,898
2006	$1,036,563,013	$0	$962,289,699	$996,695,205	$0	$925,278,556	$968,750,479	$0	$899,336,167
2007	$1,067,406,579	$0	$990,923,217	$986,877,385	$0	$916,164,217	$932,314,245	$0	$865,510,715
2008	$1,099,167,915	$0	$1,020,408,744	$977,156,274	$0	$907,139,658	$897,248,436	$0	$832,957,491
2009	$1,131,874,329	$0	$1,050,771,631	$967,530,920	$0	$898,203,994	$863,501,506	$0	$801,628,646
2010	$1,165,553,942	$0	$1,082,037,983	$958,000,380	$0	$889,356,349	$831,023,852	$0	$771,478,128
2011	$1,200,235,713	$0	$1,114,234,685	$948,563,718	$0	$880,595,857	$799,767,734	$0	$742,461,618
2012	$1,235,949,461	$0	$1,147,389,420	$939,220,012	$0	$871,921,659	$769,687,208	$0	$714,536,465
2013	$1,272,725,893	$0	$1,181,530,694	$929,968,344	$0	$863,332,905	$740,738,058	$0	$687,661,622
2014	$1,310,596,631	$68,818,255,200	$1,216,687,863	$920,807,809	$48,350,793,269	$854,828,754	$712,877,730	$37,432,571,109	$661,797,583
2015	$1,349,594,236	$0	$1,252,891,155	$911,737,508	$0	$846,408,372	$686,065,274	$0	$636,906,332
2016	$1,389,752,238	$0	$1,290,171,698	$902,756,553	$0	$838,070,933	$660,261,277	$0	$612,951,280
2017	$1,431,105,166	$0	$1,328,561,546	$893,864,064	$0	$829,815,622	$635,427,809	$0	$589,897,215
2018	$1,473,688,576	$0	$1,368,093,708	$885,059,170	$0	$821,641,628	$611,528,366	$0	$567,710,250
2019	$1,517,539,081	$0	$1,408,802,173	$876,341,006	$0	$813,548,152	$588,527,819	$0	$546,357,772
2020	$1,562,694,385	$0	$1,450,721,944	$867,708,720	$0	$805,534,399	$566,392,360	$0	$525,808,394
2021	$1,609,193,312	$0	$1,493,889,063	$859,161,466	$0	$797,599,584	$545,089,449	$0	$506,031,911
2022	$1,657,075,844	$0	$1,538,340,646	$850,698,405	$0	$789,742,931	$524,587,775	$0	$486,999,252
2023	$1,706,383,149	$0	$1,584,114,913	$842,318,708	$0	$781,963,668	$504,857,201	$0	$468,682,442
2024	$1,757,157,624	$0	$1,631,251,221	$834,021,554	$0	$774,261,034	$485,868,725	$0	$451,054,556
Total	$26,980,867,783	$121,674,481,215	$25,093,983,901	$18,355,097,895	$101,207,019,284	$17,086,280,169	$14,331,126,001	$90,288,797,124	$13,350,639,736

Table C-13

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Conservative Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	-$21,573,046	$3,726,844,511	$87,415,661	-$21,573,046	$3,726,844,511	$87,415,661	-$21,573,046	$3,726,844,511	$87,415,661
2006	-$22,214,965	$0	$79,407,178	-$21,360,544	$0	$76,353,056	-$20,761,650	$0	$74,212,316
2007	-$22,875,985	$0	$81,769,988	-$21,150,134	$0	$75,600,950	-$19,980,771	$0	$71,421,074
2008	-$23,556,674	$0	$84,203,104	-$20,941,798	$0	$74,856,252	-$19,229,263	$0	$68,734,815
2009	-$24,257,617	$0	$86,708,618	-$20,735,513	$0	$74,118,890	-$18,506,020	$0	$66,149,590
2010	-$24,979,418	$0	$89,288,686	-$20,531,261	$0	$73,388,792	-$17,809,980	$0	$63,661,599
2011	-$25,722,696	$0	$91,945,526	-$20,329,020	$0	$72,665,885	-$17,140,118	$0	$61,267,186
2012	-$26,488,090	$0	$94,681,421	-$20,128,772	$0	$71,950,099	-$16,495,451	$0	$58,962,831
2013	-$27,276,259	$0	$97,498,725	-$19,930,496	$0	$71,241,363	-$15,875,031	$0	$56,745,146
2014	-$28,087,881	$4,852,312,698	$100,399,859	-$19,734,173	$3,409,170,539	$70,539,609	-$15,277,946	$2,639,336,606	$54,610,871
2015	-$28,923,653	$0	$103,387,318	-$19,539,784	$0	$69,844,768	-$14,703,319	$0	$52,556,870
2016	-$29,784,294	$0	$106,463,671	-$19,347,310	$0	$69,156,771	-$14,150,304	$0	$50,580,123
2017	-$30,670,544	$0	$109,631,563	-$19,156,731	$0	$68,475,551	-$13,618,088	$0	$48,677,725
2018	-$31,583,165	$0	$112,893,717	-$18,968,030	$0	$67,801,041	-$13,105,891	$0	$46,846,879
2019	-$32,522,941	$0	$116,252,939	-$18,781,188	$0	$67,133,175	-$12,612,957	$0	$45,084,894
2020	-$33,490,681	$0	$119,712,116	-$18,596,187	$0	$66,471,889	-$12,138,564	$0	$43,389,180
2021	-$34,487,217	$0	$123,274,223	-$18,413,007	$0	$65,817,116	-$11,682,014	$0	$41,757,244
2022	-$35,513,405	$0	$126,942,323	-$18,231,632	$0	$65,168,793	-$11,242,635	$0	$40,186,689
2023	-$36,570,129	$0	$130,719,570	-$18,052,044	$0	$64,526,856	-$10,819,781	$0	$38,675,204
2024	-$37,658,295	$0	$134,609,211	-$17,874,224	$0	$63,891,242	-$10,412,832	$0	$37,220,568
Total	-$578,236,958	$8,579,157,210	$2,077,205,418	-$393,374,893	$7,136,015,050	$1,416,417,758	-$307,135,663	$6,366,181,118	$1,108,156,466

Table C-14

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Conservative Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	-$21,573,046	$5,590,266,767	$87,415,661	-$21,573,046	$5,590,266,767	$87,415,661	-$21,573,046	$5,590,266,767	$87,415,661
2006	-$22,214,965	$0	$79,407,178	-$21,360,544	$0	$76,353,056	-$20,761,650	$0	$74,212,316
2007	-$22,875,985	$0	$81,769,988	-$21,150,134	$0	$75,600,950	-$19,980,771	$0	$71,421,074
2008	-$23,556,674	$0	$84,203,104	-$20,941,798	$0	$74,856,252	-$19,229,263	$0	$68,734,815
2009	-$24,257,617	$0	$86,708,618	-$20,735,513	$0	$74,118,890	-$18,506,020	$0	$66,149,590
2010	-$24,979,418	$0	$89,288,686	-$20,531,261	$0	$73,388,792	-$17,809,980	$0	$63,661,599
2011	-$25,722,696	$0	$91,945,526	-$20,329,020	$0	$72,665,885	-$17,140,118	$0	$61,267,186
2012	-$26,488,090	$0	$94,681,421	-$20,128,772	$0	$71,950,099	-$16,495,451	$0	$58,962,831
2013	-$27,276,259	$0	$97,498,725	-$19,930,496	$0	$71,241,363	-$15,875,031	$0	$56,745,146
2014	-$28,087,881	$7,278,469,047	$100,399,859	-$19,734,173	$5,113,755,808	$70,539,609	-$15,277,946	$3,959,004,909	$54,610,871
2015	-$28,923,653	$0	$103,387,318	-$19,539,784	$0	$69,844,768	-$14,703,319	$0	$52,556,870
2016	-$29,784,294	$0	$106,463,671	-$19,347,310	$0	$69,156,771	-$14,150,304	$0	$50,580,123
2017	-$30,670,544	$0	$109,631,563	-$19,156,731	$0	$68,475,551	-$13,618,088	$0	$48,677,725
2018	-$31,583,165	$0	$112,893,717	-$18,968,030	$0	$67,801,041	-$13,105,891	$0	$46,846,879
2019	-$32,522,941	$0	$116,252,939	-$18,781,188	$0	$67,133,175	-$12,612,957	$0	$45,084,894
2020	-$33,490,681	$0	$119,712,116	-$18,596,187	$0	$66,471,889	-$12,138,564	$0	$43,389,180
2021	-$34,487,217	$0	$123,274,223	-$18,413,007	$0	$65,817,116	-$11,682,014	$0	$41,757,244
2022	-$35,513,405	$0	$126,942,323	-$18,231,632	$0	$65,168,793	-$11,242,635	$0	$40,186,689
2023	-$36,570,129	$0	$130,719,570	-$18,052,044	$0	$64,526,856	-$10,819,781	$0	$38,675,204
2024	-$37,658,295	$0	$134,609,211	-$17,874,224	$0	$63,891,242	-$10,412,832	$0	$37,220,568
Total	-$578,236,958	$12,868,735,815	$2,077,205,418	-$393,374,893	$10,704,022,575	$1,416,417,758	-$307,135,663	$9,549,271,676	$1,108,156,466

Table C-15

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Medium Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**	**Avoided Crashes Benefit**	**Purchase Cost for IVSS**	**Training Cost Plus Operating/ Maintenance**
2005	$504,908,691	$3,726,844,511	$87,415,661	$504,908,691	$3,726,844,511	$87,415,661	$504,908,691	$3,726,844,511	$87,415,661
2006	$519,932,558	$0	$79,407,178	$499,935,151	$0	$76,353,056	$485,918,278	$0	$74,212,316
2007	$535,403,469	$0	$81,769,988	$495,010,604	$0	$75,600,950	$467,642,125	$0	$71,421,074
2008	$551,334,727	$0	$84,203,104	$490,134,564	$0	$74,856,252	$450,053,367	$0	$68,734,815
2009	$567,740,029	$0	$86,708,618	$485,306,556	$0	$74,118,890	$433,126,150	$0	$66,149,590
2010	$584,633,481	$0	$89,288,686	$480,526,105	$0	$73,388,792	$416,835,592	$0	$63,661,599
2011	$602,029,608	$0	$91,945,526	$475,792,744	$0	$72,665,885	$401,157,748	$0	$61,267,186
2012	$619,943,367	$0	$94,681,421	$471,106,008	$0	$71,950,099	$386,069,572	$0	$58,962,831
2013	$638,390,161	$0	$97,498,725	$466,465,438	$0	$71,241,363	$371,548,886	$0	$56,745,146
2014	$657,385,851	$4,852,312,698	$100,399,859	$461,870,579	$3,409,170,539	$70,539,609	$357,574,346	$2,639,336,606	$54,610,871
2015	$676,946,769	$0	$103,387,318	$457,320,981	$0	$69,844,768	$344,125,411	$0	$52,556,870
2016	$697,089,734	$0	$106,463,671	$452,816,199	$0	$69,156,771	$331,182,311	$0	$50,580,123
2017	$717,832,066	$0	$109,631,563	$448,355,791	$0	$68,475,551	$318,726,022	$0	$48,677,725
2018	$739,191,598	$0	$112,893,717	$443,939,319	$0	$67,801,041	$306,738,233	$0	$46,846,879
2019	$761,186,697	$0	$116,252,939	$439,566,351	$0	$67,133,175	$295,201,325	$0	$45,084,894
2020	$783,836,272	$0	$119,712,116	$435,236,458	$0	$66,471,889	$284,098,337	$0	$43,389,180
2021	$807,159,800	$0	$123,274,223	$430,949,216	$0	$65,817,116	$273,412,950	$0	$41,757,244
2022	$831,177,334	$0	$126,942,323	$426,704,206	$0	$65,168,793	$263,129,458	$0	$40,186,689
2023	$855,909,524	$0	$130,719,570	$422,501,010	$0	$64,526,856	$253,232,744	$0	$38,675,204
2024	$881,377,636	$0	$134,609,211	$418,339,217	$0	$63,891,242	$243,708,261	$0	$37,220,568
Total	$13,533,409,371	$8,579,157,210	$2,077,205,418	$9,206,785,188	$7,136,015,050	$1,416,417,758	$7,188,389,805	$6,366,181,118	$1,108,156,466

Table C-16

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Medium Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$504,908,691	$5,590,266,767	$87,415,661	$504,908,691	$5,590,266,767	$87,415,661	$504,908,691	$5,590,266,767	$87,415,661
2006	$519,932,558	$0	$79,407,178	$499,935,151	$0	$76,353,056	$485,918,278	$0	$74,212,316
2007	$535,403,469	$0	$81,769,988	$495,010,604	$0	$75,600,950	$467,642,125	$0	$71,421,074
2008	$551,334,727	$0	$84,203,104	$490,134,564	$0	$74,856,252	$450,053,367	$0	$68,734,815
2009	$567,740,029	$0	$86,708,618	$485,306,556	$0	$74,118,890	$433,126,150	$0	$66,149,590
2010	$584,633,481	$0	$89,288,686	$480,526,105	$0	$73,388,792	$416,835,592	$0	$63,661,599
2011	$602,029,608	$0	$91,945,526	$475,792,744	$0	$72,665,885	$401,157,748	$0	$61,267,186
2012	$619,943,367	$0	$94,681,421	$471,106,008	$0	$71,950,099	$386,069,572	$0	$58,962,831
2013	$638,390,161	$0	$97,498,725	$466,465,438	$0	$71,241,363	$371,548,886	$0	$56,745,146
2014	$657,385,851	$7,278,469,047	$100,399,859	$461,870,579	$5,113,755,808	$70,539,609	$357,574,346	$3,959,004,909	$54,610,871
2015	$676,946,769	$0	$103,387,318	$457,320,981	$0	$69,844,768	$344,125,411	$0	$52,556,870
2016	$697,089,734	$0	$106,463,671	$452,816,199	$0	$69,156,771	$331,182,311	$0	$50,580,123
2017	$717,832,066	$0	$109,631,563	$448,355,791	$0	$68,475,551	$318,726,022	$0	$48,677,725
2018	$739,191,598	$0	$112,893,717	$443,939,319	$0	$67,801,041	$306,738,233	$0	$46,846,879
2019	$761,186,697	$0	$116,252,939	$439,566,351	$0	$67,133,175	$295,201,325	$0	$45,084,894
2020	$783,836,272	$0	$119,712,116	$435,236,458	$0	$66,471,889	$284,098,337	$0	$43,389,180
2021	$807,159,800	$0	$123,274,223	$430,949,216	$0	$65,817,116	$273,412,950	$0	$41,757,244
2022	$831,177,334	$0	$126,942,323	$426,704,206	$0	$65,168,793	$263,129,458	$0	$40,186,689
2023	$855,909,524	$0	$130,719,570	$422,501,010	$0	$64,526,856	$253,232,744	$0	$38,675,204
2024	$881,377,636	$0	$134,609,211	$418,339,217	$0	$63,891,242	$243,708,261	$0	$37,220,568
Total	$13,533,409,371	$12,868,735,815	$2,077,205,418	$9,206,785,188	$10,704,022,575	$1,416,417,758	$7,188,389,805	$9,549,271,676	$1,108,156,466

Table C-17

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Aggressive Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$561,300,859	$3,726,844,511	$87,415,661	$561,300,859	$3,726,844,511	$87,415,661	$561,300,859	$3,726,844,511	$87,415,661
2006	$578,002,709	$0	$79,407,178	$555,771,836	$0	$76,353,056	$540,189,448	$0	$74,212,316
2007	$595,201,533	$0	$81,769,988	$550,297,276	$0	$75,600,950	$519,872,070	$0	$71,421,074
2008	$612,912,119	$0	$84,203,104	$544,876,642	$0	$74,856,252	$500,318,862	$0	$68,734,815
2009	$631,149,694	$0	$86,708,618	$539,509,404	$0	$74,118,890	$481,501,080	$0	$66,149,590
2010	$649,929,940	$0	$89,288,686	$534,195,035	$0	$73,388,792	$463,391,065	$0	$63,661,599
2011	$669,269,003	$0	$91,945,526	$528,933,014	$0	$72,665,885	$445,962,196	$0	$61,267,186
2012	$689,183,511	$0	$94,681,421	$523,722,827	$0	$71,950,099	$429,188,854	$0	$58,962,831
2013	$709,690,588	$0	$97,498,725	$518,563,961	$0	$71,241,363	$413,046,384	$0	$56,745,146
2014	$730,807,866	$4,852,312,698	$100,399,859	$513,455,913	$3,409,170,539	$70,539,609	$397,511,058	$2,639,336,606	$54,610,871
2015	$752,553,501	$0	$103,387,318	$508,398,181	$0	$69,844,768	$382,560,040	$0	$52,556,870
2016	$774,946,191	$0	$106,463,671	$503,390,269	$0	$69,156,771	$368,171,353	$0	$50,580,123
2017	$798,005,189	$0	$109,631,563	$498,431,687	$0	$68,475,551	$354,323,848	$0	$48,677,725
2018	$821,750,322	$0	$112,893,717	$493,521,949	$0	$67,801,041	$340,997,169	$0	$46,846,879
2019	$846,202,005	$0	$116,252,939	$488,660,573	$0	$67,133,175	$328,171,727	$0	$45,084,894
2020	$871,381,264	$0	$119,712,116	$483,847,084	$0	$66,471,889	$315,828,671	$0	$43,389,180
2021	$897,309,746	$0	$123,274,223	$479,081,010	$0	$65,817,116	$303,949,856	$0	$41,757,244
2022	$924,009,747	$0	$126,942,323	$474,361,883	$0	$65,168,793	$292,517,822	$0	$40,186,689
2023	$951,504,222	$0	$130,719,570	$469,689,241	$0	$64,526,856	$281,515,766	$0	$38,675,204
2024	$979,816,813	$0	$134,609,211	$465,062,627	$0	$63,891,242	$270,927,513	$0	$37,220,568
Total	$15,044,926,823	$8,579,157,210	$2,077,205,418	$10,235,071,270	$7,136,015,050	$1,416,417,758	$7,991,245,638	$6,366,181,118	$1,108,156,466

Table C-18

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Effect of CWS Only Using Aggressive Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$561,300,859	$5,590,266,767	$87,415,661	$561,300,859	$5,590,266,767	$87,415,661	$561,300,859	$5,590,266,767	$87,415,661
2006	$578,002,709	$0	$79,407,178	$555,771,836	$0	$76,353,056	$540,189,448	$0	$74,212,316
2007	$595,201,533	$0	$81,769,988	$550,297,276	$0	$75,600,950	$519,872,070	$0	$71,421,074
2008	$612,912,119	$0	$84,203,104	$544,876,642	$0	$74,856,252	$500,318,862	$0	$68,734,815
2009	$631,149,694	$0	$86,708,618	$539,509,404	$0	$74,118,890	$481,501,080	$0	$66,149,590
2010	$649,929,940	$0	$89,288,686	$534,195,035	$0	$73,388,792	$463,391,065	$0	$63,661,599
2011	$669,269,003	$0	$91,945,526	$528,933,014	$0	$72,665,885	$445,962,196	$0	$61,267,186
2012	$689,183,511	$0	$94,681,421	$523,722,827	$0	$71,950,099	$429,188,854	$0	$58,962,831
2013	$709,690,588	$0	$97,498,725	$518,563,961	$0	$71,241,363	$413,046,384	$0	$56,745,146
2014	$730,807,866	$7,278,469,047	$100,399,859	$513,455,913	$5,113,755,808	$70,539,609	$397,511,058	$3,959,004,909	$54,610,871
2015	$752,553,501	$0	$103,387,318	$508,398,181	$0	$69,844,768	$382,560,040	$0	$52,556,870
2016	$774,946,191	$0	$106,463,671	$503,390,269	$0	$69,156,771	$368,171,353	$0	$50,580,123
2017	$798,005,189	$0	$109,631,563	$498,431,687	$0	$68,475,551	$354,323,848	$0	$48,677,725
2018	$821,750,322	$0	$112,893,717	$493,521,949	$0	$67,801,041	$340,997,169	$0	$46,846,879
2019	$846,202,005	$0	$116,252,939	$488,660,573	$0	$67,133,175	$328,171,727	$0	$45,084,894
2020	$871,381,264	$0	$119,712,116	$483,847,084	$0	$66,471,889	$315,828,671	$0	$43,389,180
2021	$897,309,746	$0	$123,274,223	$479,081,010	$0	$65,817,116	$303,949,856	$0	$41,757,244
2022	$924,009,747	$0	$126,942,323	$474,361,883	$0	$65,168,793	$292,517,822	$0	$40,186,689
2023	$951,504,222	$0	$130,719,570	$469,689,241	$0	$64,526,856	$281,515,766	$0	$38,675,204
2024	$979,816,813	$0	$134,609,211	$465,062,627	$0	$63,891,242	$270,927,513	$0	$37,220,568
Total	$15,044,926,823	$12,868,735,815	$2,077,205,418	$10,235,071,270	$10,704,022,575	$1,416,417,758	$7,991,245,638	$9,549,271,676	$1,108,156,466

Table C-19

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Conservative Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$209,068,178	$4,285,871,188	$87,415,661	$209,068,178	$4,285,871,188	$87,415,661	$209,068,178	$4,285,871,188	$87,415,661
2006	$215,289,129	$0	$79,407,178	$207,008,778	$0	$76,353,056	$201,204,794	$0	$74,212,316
2007	$221,695,189	$0	$81,769,988	$204,969,664	$0	$75,600,950	$193,637,164	$0	$71,421,074
2008	$228,291,865	$0	$84,203,104	$202,950,637	$0	$74,856,252	$186,354,165	$0	$68,734,815
2009	$235,084,829	$0	$86,708,618	$200,951,497	$0	$74,118,890	$179,345,091	$0	$66,149,590
2010	$242,079,922	$0	$89,288,686	$198,972,050	$0	$73,388,792	$172,599,639	$0	$63,661,599
2011	$249,283,158	$0	$91,945,526	$197,012,101	$0	$72,665,885	$166,107,894	$0	$61,267,186
2012	$256,700,731	$0	$94,681,421	$195,071,458	$0	$71,950,099	$159,860,314	$0	$58,962,831
2013	$264,339,018	$0	$97,498,725	$193,149,932	$0	$71,241,363	$153,847,715	$0	$56,745,146
2014	$272,204,588	$5,580,159,603	$100,399,859	$191,247,333	$3,920,546,120	$70,539,609	$148,061,260	$3,035,237,097	$54,610,871
2015	$280,304,202	$0	$103,387,318	$189,363,475	$0	$69,844,768	$142,492,443	$0	$52,556,870
2016	$288,644,825	$0	$106,463,671	$187,498,174	$0	$69,156,771	$137,133,077	$0	$50,580,123
2017	$297,233,628	$0	$109,631,563	$185,651,247	$0	$68,475,551	$131,975,286	$0	$48,677,725
2018	$306,077,997	$0	$112,893,717	$183,822,513	$0	$67,801,041	$127,011,487	$0	$46,846,879
2019	$315,185,535	$0	$116,252,939	$182,011,793	$0	$67,133,175	$122,234,384	$0	$45,084,894
2020	$324,564,073	$0	$119,712,116	$180,218,909	$0	$66,471,889	$117,636,956	$0	$43,389,180
2021	$334,221,676	$0	$123,274,223	$178,443,685	$0	$65,817,116	$113,212,445	$0	$41,757,244
2022	$344,166,646	$0	$126,942,323	$176,685,948	$0	$65,168,793	$108,954,346	$0	$40,186,689
2023	$354,407,535	$0	$130,719,570	$174,945,526	$0	$64,526,856	$104,856,401	$0	$38,675,204
2024	$364,953,148	$0	$134,609,211	$173,222,247	$0	$63,891,242	$100,912,587	$0	$37,220,568
Total	$5,603,795,872	$9,866,030,791	$2,077,205,418	$3,812,265,144	$8,206,417,308	$1,416,417,758	$2,976,505,625	$7,321,108,285	$1,108,156,466

Table C-20

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Conservative Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$209,068,178	$11,739,560,211	$217,855,219	$209,068,178	$11,739,560,211	$217,855,219	$209,068,178	$11,739,560,211	$217,855,219
2006	$215,289,129	$0	$213,728,045	$207,008,778	$0	$205,507,736	$201,204,794	$0	$199,745,837
2007	$221,695,189	$0	$220,087,654	$204,969,664	$0	$203,483,408	$193,637,164	$0	$192,233,080
2008	$228,291,865	$0	$226,636,497	$202,950,637	$0	$201,479,020	$186,354,165	$0	$185,002,891
2009	$235,084,829	$0	$233,380,204	$200,951,497	$0	$199,494,377	$179,345,091	$0	$178,044,640
2010	$242,079,922	$0	$240,324,575	$198,972,050	$0	$197,529,283	$172,599,639	$0	$171,348,101
2011	$249,283,158	$0	$247,475,580	$197,012,101	$0	$195,583,545	$166,107,894	$0	$164,903,428
2012	$256,700,731	$0	$254,839,367	$195,071,458	$0	$193,656,975	$159,860,314	$0	$158,701,150
2013	$264,339,018	$0	$262,422,268	$193,149,932	$0	$191,749,381	$153,847,715	$0	$152,732,149
2014	$272,204,588	$15,284,785,000	$270,230,804	$191,247,333	$10,738,887,197	$189,860,578	$148,061,260	$8,313,910,309	$146,987,652
2015	$280,304,202	$0	$278,271,686	$189,363,475	$0	$187,990,381	$142,492,443	$0	$141,459,215
2016	$288,644,825	$0	$286,551,831	$187,498,174	$0	$186,138,605	$137,133,077	$0	$136,138,711
2017	$297,233,628	$0	$295,078,356	$185,651,247	$0	$184,305,070	$131,975,286	$0	$131,018,319
2018	$306,077,997	$0	$303,858,593	$183,822,513	$0	$182,489,597	$127,011,487	$0	$126,090,513
2019	$315,185,535	$0	$312,900,091	$182,011,793	$0	$180,692,006	$122,234,384	$0	$121,348,050
2020	$324,564,073	$0	$322,210,625	$180,218,909	$0	$178,912,122	$117,636,956	$0	$116,783,958
2021	$334,221,676	$0	$331,798,199	$178,443,685	$0	$177,149,771	$113,212,445	$0	$112,391,529
2022	$344,166,646	$0	$341,671,057	$176,685,948	$0	$175,404,780	$108,954,346	$0	$108,164,307
2023	$354,407,535	$0	$351,837,689	$174,945,526	$0	$173,676,977	$104,856,401	$0	$104,096,077
2024	$364,953,148	$0	$362,306,835	$173,222,247	$0	$171,966,194	$100,912,587	$0	$100,180,859
Total	$5,603,795,872	$27,024,345,211	$5,573,465,174	$3,812,265,144	$22,478,447,408	$3,794,925,025	$2,976,505,625	$20,053,470,521	$2,965,225,686

Table C-21

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Medium Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$661,508,199	$4,285,871,188	$87,415,661	$661,508,199	$4,285,871,188	$87,415,661	$661,508,199	$4,285,871,188	$87,415,661
2006	$681,191,780	$0	$79,407,178	$654,992,096	$0	$76,353,056	$636,627,832	$0	$74,212,316
2007	$701,461,058	$0	$81,769,988	$648,540,180	$0	$75,600,950	$612,683,255	$0	$71,421,074
2008	$722,333,461	$0	$84,203,104	$642,151,817	$0	$74,856,252	$589,639,271	$0	$68,734,815
2009	$743,826,935	$0	$86,708,618	$635,826,382	$0	$74,118,890	$567,462,008	$0	$66,149,590
2010	$765,959,961	$0	$89,288,686	$629,563,255	$0	$73,388,792	$546,118,866	$0	$63,661,599
2011	$788,751,568	$0	$91,945,526	$623,361,821	$0	$72,665,885	$525,578,474	$0	$61,267,186
2012	$812,221,354	$0	$94,681,421	$617,221,475	$0	$71,950,099	$505,810,638	$0	$58,962,831
2013	$836,389,497	$0	$97,498,725	$611,141,613	$0	$71,241,363	$486,786,302	$0	$56,745,146
2014	$861,276,778	$5,580,159,603	$100,399,859	$605,121,640	$3,920,546,120	$70,539,609	$468,477,501	$3,035,237,097	$54,610,871
2015	$886,904,596	$0	$103,387,318	$599,160,966	$0	$69,844,768	$450,857,323	$0	$52,556,870
2016	$913,294,984	$0	$106,463,671	$593,259,007	$0	$69,156,771	$433,899,868	$0	$50,580,123
2017	$940,470,636	$0	$109,631,563	$587,415,184	$0	$68,475,551	$417,580,209	$0	$48,677,725
2018	$968,454,915	$0	$112,893,717	$581,628,925	$0	$67,801,041	$401,874,359	$0	$46,846,879
2019	$997,271,883	$0	$116,252,939	$575,899,663	$0	$67,133,175	$386,759,230	$0	$45,084,894
2020	$1,026,946,318	$0	$119,712,116	$570,226,837	$0	$66,471,889	$372,212,605	$0	$43,389,180
2021	$1,057,503,734	$0	$123,274,223	$564,609,890	$0	$65,817,116	$358,213,102	$0	$41,757,244
2022	$1,088,970,405	$0	$126,942,323	$559,048,271	$0	$65,168,793	$344,740,142	$0	$40,186,689
2023	$1,121,373,386	$0	$130,719,570	$553,541,437	$0	$64,526,856	$331,773,922	$0	$38,675,204
2024	$1,154,740,537	$0	$134,609,211	$548,088,848	$0	$63,891,242	$319,295,381	$0	$37,220,568
Total	$17,730,851,985	$9,866,030,791	$2,077,205,418	$12,062,307,505	$8,206,417,308	$1,416,417,758	$9,417,898,488	$7,321,108,285	$1,108,156,466

Table C-22

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Medium Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$661,508,199	$11,739,560,211	$217,855,219	$661,508,199	$11,739,560,211	$217,855,219	$661,508,199	$11,739,560,211	$217,855,219
2006	$681,191,780	$0	$213,728,045	$654,992,096	$0	$205,507,736	$636,627,832	$0	$199,745,837
2007	$701,461,058	$0	$220,087,654	$648,540,180	$0	$203,483,408	$612,683,255	$0	$192,233,080
2008	$722,333,461	$0	$226,636,497	$642,151,817	$0	$201,479,020	$589,639,271	$0	$185,002,891
2009	$743,826,935	$0	$233,380,204	$635,826,382	$0	$199,494,377	$567,462,008	$0	$178,044,640
2010	$765,959,961	$0	$240,324,575	$629,563,255	$0	$197,529,283	$546,118,866	$0	$171,348,101
2011	$788,751,568	$0	$247,475,580	$623,361,821	$0	$195,583,545	$525,578,474	$0	$164,903,428
2012	$812,221,354	$0	$254,839,367	$617,221,475	$0	$193,656,975	$505,810,638	$0	$158,701,150
2013	$836,389,497	$0	$262,422,268	$611,141,613	$0	$191,749,381	$486,786,302	$0	$152,732,149
2014	$861,276,778	$15,284,785,000	$270,230,804	$605,121,640	$10,738,887,197	$189,860,578	$468,477,501	$8,313,910,309	$146,987,652
2015	$886,904,596	$0	$278,271,686	$599,160,966	$0	$187,990,381	$450,857,323	$0	$141,459,215
2016	$913,294,984	$0	$286,551,831	$593,259,007	$0	$186,138,605	$433,899,868	$0	$136,138,711
2017	$940,470,636	$0	$295,078,356	$587,415,184	$0	$184,305,070	$417,580,209	$0	$131,018,319
2018	$968,454,915	$0	$303,858,593	$581,628,925	$0	$182,489,597	$401,874,359	$0	$126,090,513
2019	$997,271,883	$0	$312,900,091	$575,899,663	$0	$180,692,006	$386,759,230	$0	$121,348,050
2020	$1,026,946,318	$0	$322,210,625	$570,226,837	$0	$178,912,122	$372,212,605	$0	$116,783,958
2021	$1,057,503,734	$0	$331,798,199	$564,609,890	$0	$177,149,771	$358,213,102	$0	$112,391,529
2022	$1,088,970,405	$0	$341,671,057	$559,048,271	$0	$175,404,780	$344,740,142	$0	$108,164,307
2023	$1,121,373,386	$0	$351,837,689	$553,541,437	$0	$173,676,977	$331,773,922	$0	$104,096,077
2024	$1,154,740,537	$0	$362,306,835	$548,088,848	$0	$171,966,194	$319,295,381	$0	$100,180,859
Total	$17,730,851,985	$27,024,345,211	$5,573,465,174	$12,062,307,505	$22,478,447,408	$3,794,925,025	$9,417,898,488	$20,053,470,521	$2,965,225,686

Table C-23

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Aggressive Conflict Classes - Low Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$696,223,216	$4,285,871,188	$87,415,661	$696,223,216	$4,285,871,188	$87,415,661	$696,223,216	$4,285,871,188	$87,415,661
2006	$716,939,764	$0	$79,407,178	$689,365,157	$0	$76,353,056	$670,037,162	$0	$74,212,316
2007	$738,272,745	$0	$81,769,988	$682,574,653	$0	$75,600,950	$644,836,008	$0	$71,421,074
2008	$760,240,502	$0	$84,203,104	$675,851,038	$0	$74,856,252	$620,582,708	$0	$68,734,815
2009	$782,861,924	$0	$86,708,618	$669,193,653	$0	$74,118,890	$597,241,613	$0	$66,149,590
2010	$806,156,459	$0	$89,288,686	$662,601,846	$0	$73,388,792	$574,778,414	$0	$63,661,599
2011	$830,144,138	$0	$91,945,526	$656,074,970	$0	$72,665,885	$553,160,091	$0	$61,267,186
2012	$854,845,584	$0	$94,681,421	$649,612,387	$0	$71,950,099	$532,354,867	$0	$58,962,831
2013	$880,282,038	$0	$97,498,725	$643,213,463	$0	$71,241,363	$512,332,161	$0	$56,745,146
2014	$906,475,368	$5,580,159,603	$100,399,859	$636,877,570	$3,920,546,120	$70,539,609	$493,062,540	$3,035,237,097	$54,610,871
2015	$933,448,098	$0	$103,387,318	$630,604,088	$0	$69,844,768	$474,517,680	$0	$52,556,870
2016	$961,223,417	$0	$106,463,671	$624,392,403	$0	$69,156,771	$456,670,321	$0	$50,580,123
2017	$989,825,208	$0	$109,631,563	$618,241,904	$0	$68,475,551	$439,494,230	$0	$48,677,725
2018	$1,019,278,062	$0	$112,893,717	$612,151,991	$0	$67,801,041	$422,964,158	$0	$46,846,879
2019	$1,049,607,305	$0	$116,252,939	$606,122,065	$0	$67,133,175	$407,055,809	$0	$45,084,894
2020	$1,080,839,012	$0	$119,712,116	$600,151,537	$0	$66,471,889	$391,745,798	$0	$43,389,180
2021	$1,113,000,038	$0	$123,274,223	$594,239,820	$0	$65,817,116	$377,011,620	$0	$41,757,244
2022	$1,146,118,035	$0	$126,942,323	$588,386,336	$0	$65,168,793	$362,831,618	$0	$40,186,689
2023	$1,180,221,479	$0	$130,719,570	$582,590,511	$0	$64,526,856	$349,184,949	$0	$38,675,204
2024	$1,215,339,691	$0	$134,609,211	$576,851,777	$0	$63,891,242	$336,051,552	$0	$37,220,568
Total	$18,661,342,083	$9,866,030,791	$2,077,205,418	$12,695,320,386	$8,206,417,308	$1,416,417,758	$9,912,136,514	$7,321,108,285	$1,108,156,466

Table C-24

Benefits and Costs for Volvo FOT ($2005)
Scenario: Truck Tractor and Trailer with Bundled System Using Aggressive Conflict Classes - High Cost Estimate

	Undiscounted			Discounted at 4%			Discounted at 7%		
Year	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance	Avoided Crashes Benefit	Purchase Cost for IVSS	Training Cost Plus Operating/ Maintenance
2005	$696,223,216	$11,739,560,211	$217,855,219	$696,223,216	$11,739,560,211	$217,855,219	$696,223,216	$11,739,560,211	$217,855,219
2006	$716,939,764	$0	$213,728,045	$689,365,157	$0	$205,507,736	$670,037,162	$0	$199,745,837
2007	$738,272,745	$0	$220,087,654	$682,574,653	$0	$203,483,408	$644,836,008	$0	$192,233,080
2008	$760,240,502	$0	$226,636,497	$675,851,038	$0	$201,479,020	$620,582,708	$0	$185,002,891
2009	$782,861,924	$0	$233,380,204	$669,193,653	$0	$199,494,377	$597,241,613	$0	$178,044,640
2010	$806,156,459	$0	$240,324,575	$662,601,846	$0	$197,529,283	$574,778,414	$0	$171,348,101
2011	$830,144,138	$0	$247,475,580	$656,074,970	$0	$195,583,545	$553,160,091	$0	$164,903,428
2012	$854,845,584	$0	$254,839,367	$649,612,387	$0	$193,656,975	$532,354,867	$0	$158,701,150
2013	$880,282,038	$0	$262,422,268	$643,213,463	$0	$191,749,381	$512,332,161	$0	$152,732,149
2014	$906,475,368	$15,284,785,000	$270,230,804	$636,877,570	$10,738,887,197	$189,860,578	$493,062,540	$8,313,910,309	$146,987,652
2015	$933,448,098	$0	$278,271,686	$630,604,088	$0	$187,990,381	$474,517,680	$0	$141,459,215
2016	$961,223,417	$0	$286,551,831	$624,392,403	$0	$186,138,605	$456,670,321	$0	$136,138,711
2017	$989,825,208	$0	$295,078,356	$618,241,904	$0	$184,305,070	$439,494,230	$0	$131,018,319
2018	$1,019,278,062	$0	$303,858,593	$612,151,991	$0	$182,489,597	$422,964,158	$0	$126,090,513
2019	$1,049,607,305	$0	$312,900,091	$606,122,065	$0	$180,692,006	$407,055,809	$0	$121,348,050
2020	$1,080,839,012	$0	$322,210,625	$600,151,537	$0	$178,912,122	$391,745,798	$0	$116,783,958
2021	$1,113,000,038	$0	$331,798,199	$594,239,820	$0	$177,149,771	$377,011,620	$0	$112,391,529
2022	$1,146,118,035	$0	$341,671,057	$588,386,336	$0	$175,404,780	$362,831,618	$0	$108,164,307
2023	$1,180,221,479	$0	$351,837,689	$582,590,511	$0	$173,676,977	$349,184,949	$0	$104,096,077
2024	$1,215,339,691	$0	$362,306,835	$576,851,777	$0	$171,966,194	$336,051,552	$0	$100,180,859
Total	$18,661,342,083	$27,024,345,211	$5,573,465,174	$12,695,320,386	$22,478,447,408	$3,794,925,025	$9,912,136,514	$20,053,470,521	$2,965,225,686

Tables C-25 to C-32 provide 20-year total cost and benefit summaries of the BCA results for the 4% and 7% discount rates, across all scenarios:

All Large Trucks, CWS Only, Low Cost Estimate (Table C-25)
All Large Trucks, CWS Only, High Cost Estimate (Table C-26)
All Large Trucks, Bundled System, Low Cost Estimate (Table C-27)
All Large Trucks, Bundled System, High Cost Estimate (Table C-28)

Tractor-Trailers, CWS Only, Low Cost Estimate (Table C-29)
Tractor-Trailers, CWS Only, High Cost Estimate (Table C-30)
Tractor-Trailers, Bundled System, Low Cost Estimate (Table C-31)
Tractor-Trailers, Bundled System, High Cost Estimate (Table C-32)

Table C-25

Benefit/Cost Comparision for Volvo (Present Value in $2005) - Low Cost Estimate
All Trucks with Effect of CWS Only

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,693,912,235	$9,911,037,071
Total benefits	$12,693,912,235	$9,911,037,071
Costs		
Purchase Cost for Onboard IVSS	$32,129,212,471	$28,663,110,198
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$38,506,495,418	$33,652,476,712
Total (Net Present Value)	-$25,812,583,183	-$23,741,439,641
Benefit/Cost Ratio	0.33	0.29

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	-$1,364,122,561	-$1,065,067,177
Total benefits	-$1,364,122,561	-$1,065,067,177
Costs		
Purchase Cost for Onboard IVSS	$32,129,212,471	$28,663,110,198
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$38,506,495,418	$33,652,476,712
Total (Net Present Value)	-$39,870,617,980	-$34,717,543,889
Benefit/Cost Ratio	-0.04	-0.03

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$15,614,161,805	$12,191,082,908
Total benefits	$15,614,161,805	$12,191,082,908
Costs		
Purchase Cost for Onboard IVSS	$32,129,212,471	$28,663,110,198
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$38,506,495,418	$33,652,476,712
Total (Net Present Value)	-$22,892,333,614	-$21,461,393,804
Benefit/Cost Ratio	0.41	0.36

Table C-26

Benefit/Cost Comparision for Volvo (Present Value in $2005) - High Cost Estimate
All Trucks with Effect of CWS Only

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,693,912,235	$9,911,037,071
Total benefits	$12,693,912,235	$9,911,037,071
Costs		
Purchase Cost for Onboard IVSS	$48,193,818,707	$42,994,665,297
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$54,571,101,654	$47,984,031,811
Total (Net Present Value)	-$41,877,189,419	-$38,072,994,740
Benefit/Cost Ratio	0.23	0.21

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	-$1,364,122,561	-$1,065,067,177
Total benefits	-$1,364,122,561	-$1,065,067,177
Costs		
Purchase Cost for Onboard IVSS	$48,193,818,707	$42,994,665,297
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$54,571,101,654	$47,984,031,811
Total (Net Present Value)	-$55,935,224,215	-$49,049,098,988
Benefit/Cost Ratio	-0.02	-0.02

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$15,614,161,805	$12,191,082,908
Total benefits	$15,614,161,805	$12,191,082,908
Costs		
Purchase Cost for Onboard IVSS	$48,193,818,707	$42,994,665,297
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$54,571,101,654	$47,984,031,811
Total (Net Present Value)	-$38,956,939,849	-$35,792,948,903
Benefit/Cost Ratio	0.29	0.25

Table C-27

Benefit/Cost Comparision for Volvo (Present Value in $2005) - Low Cost Estimate All Trucks with Effect of Bundled System

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$17,197,930,096	$13,427,643,076
Total benefits	$17,197,930,096	$13,427,643,076
Costs		
Purchase Cost for Onboard IVSS	$36,948,594,342	$32,962,576,728
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$43,325,877,289	$37,951,943,242
Total (Net Present Value)	-$26,127,947,193	-$24,524,300,166
Benefit/Cost Ratio	0.40	0.35

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$4,752,860,747	$3,710,895,285
Total benefits	$4,752,860,747	$3,710,895,285
Costs		
Purchase Cost for Onboard IVSS	$36,948,594,342	$32,962,576,728
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$43,325,877,289	$37,951,943,242
Total (Net Present Value)	-$38,573,016,542	-$34,241,047,957
Benefit/Cost Ratio	0.11	0.10

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$18,355,097,895	$14,331,126,001
Total benefits	$18,355,097,895	$14,331,126,001
Costs		
Purchase Cost for Onboard IVSS	$36,948,594,342	$32,962,576,728
Training and O & M Cost	$6,377,282,947	$4,989,366,514
Total costs	$43,325,877,289	$37,951,943,242
Total (Net Present Value)	-$24,970,779,394	-$23,620,817,241
Benefit/Cost Ratio	0.42	0.38

Table C-28

Benefit/Cost Comparision for Volvo (Present Value in $2005) - High Cost Estimate
All Trucks with Effect of Bundled System

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$17,197,930,096	$13,427,643,076
Total benefits	$17,197,930,096	$13,427,643,076
Costs		
Purchase Cost for Onboard IVSS	$101,207,019,284	$90,288,797,124
Training and O & M Cost	$17,086,280,169	$13,350,639,736
Total costs	$118,293,299,453	$103,639,436,860
Total (Net Present Value)	-$101,095,369,357	-$90,211,793,785
Benefit/Cost Ratio	0.15	0.13

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$4,752,860,747	$3,710,895,285
Total benefits	$4,752,860,747	$3,710,895,285
Costs		
Purchase Cost for Onboard IVSS	$101,207,019,284	$90,288,797,124
Training and O & M Cost	$17,086,280,169	$13,350,639,736
Total costs	$118,293,299,453	$103,639,436,860
Total (Net Present Value)	-$113,540,438,706	-$99,928,541,576
Benefit/Cost Ratio	0.04	0.04

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$18,355,097,895	$14,331,126,001
Total benefits	$18,355,097,895	$14,331,126,001
Costs		
Purchase Cost for Onboard IVSS	$101,207,019,284	$90,288,797,124
Training and O & M Cost	$17,086,280,169	$13,350,639,736
Total costs	$118,293,299,453	$103,639,436,860
Total (Net Present Value)	-$99,938,201,558	-$89,308,310,859
Benefit/Cost Ratio	0.16	0.14

Table C-29

Benefit/Cost Comparision for Volvo (Present Value in $2005) - Low Cost Estimate
Truck Tractor and Trailer with Effect of CWS Only

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$9,206,785,188	$7,188,389,805
Total benefits	$9,206,785,188	$7,188,389,805
Costs		
Purchase Cost for Onboard IVSS	$7,136,015,050	$6,366,181,118
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$8,552,432,808	$7,474,337,583
Total (Net Present Value)	$654,352,380	-$285,947,778
Benefit/Cost Ratio	1.08	0.96

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	-$393,374,893	-$307,135,663
Total benefits	-$393,374,893	-$307,135,663
Costs		
Purchase Cost for Onboard IVSS	$7,136,015,050	$6,366,181,118
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$8,552,432,808	$7,474,337,583
Total (Net Present Value)	-$8,945,807,701	-$7,781,473,246
Benefit/Cost Ratio	-0.05	-0.04

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$10,235,071,270	$7,991,245,638
Total benefits	$10,235,071,270	$7,991,245,638
Costs		
Purchase Cost for Onboard IVSS	$7,136,015,050	$6,366,181,118
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$8,552,432,808	$7,474,337,583
Total (Net Present Value)	$1,682,638,462	$516,908,055
Benefit/Cost Ratio	1.20	1.07

Table C-30

Benefit/Cost Comparision for Volvo (Present Value in $2005) - High Cost Estimate
Truck Tractor and Trailer with Effect of CWS Only

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$9,206,785,188	$7,188,389,805
Total benefits	$9,206,785,188	$7,188,389,805
Costs		
Purchase Cost for Onboard IVSS	$10,704,022,575	$9,549,271,676
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$12,120,440,333	$10,657,428,142
Total (Net Present Value)	-$2,913,655,145	-$3,469,038,337
Benefit/Cost Ratio	0.76	0.67

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	-$393,374,893	-$307,135,663
Total benefits	-$393,374,893	-$307,135,663
Costs		
Purchase Cost for Onboard IVSS	$10,704,022,575	$9,549,271,676
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$12,120,440,333	$10,657,428,142
Total (Net Present Value)	-$12,513,815,226	-$10,964,563,805
Benefit/Cost Ratio	-0.03	-0.03

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$10,235,071,270	$7,991,245,638
Total benefits	$10,235,071,270	$7,991,245,638
Costs		
Purchase Cost for Onboard IVSS	$10,704,022,575	$9,549,271,676
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$12,120,440,333	$10,657,428,142
Total (Net Present Value)	-$1,885,369,063	-$2,666,182,504
Benefit/Cost Ratio	0.84	0.75

Table C-31

Benefit/Cost Comparision for Volvo (Present Value in $2005) - Low Cost Estimate Truck Tractor and Trailer with Effect of Bundled System

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,062,307,505	$9,417,898,488
Total benefits	$12,062,307,505	$9,417,898,488
Costs		
Purchase Cost for Onboard IVSS	$8,206,417,308	$7,321,108,285
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$9,622,835,066	$8,429,264,751
Total (Net Present Value)	$2,439,472,439	$988,633,737
Benefit/Cost Ratio	1.25	1.12

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$3,812,265,144	$2,976,505,625
Total benefits	$3,812,265,144	$2,976,505,625
Costs		
Purchase Cost for Onboard IVSS	$8,206,417,308	$7,321,108,285
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$9,622,835,066	$8,429,264,751
Total (Net Present Value)	-$5,810,569,921	-$5,452,759,126
Benefit/Cost Ratio	0.40	0.35

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,695,320,386	$9,912,136,514
Total benefits	$12,695,320,386	$9,912,136,514
Costs		
Purchase Cost for Onboard IVSS	$8,206,417,308	$7,321,108,285
Training and O & M Cost	$1,416,417,758	$1,108,156,466
Total costs	$9,622,835,066	$8,429,264,751
Total (Net Present Value)	$3,072,485,321	$1,482,871,764
Benefit/Cost Ratio	1.32	1.18

Table C-32

Benefit/Cost Comparision for Volvo (Present Value in $2005) - High Cost Estimate
Truck Tractor and Trailer with Effect of Bundled System

Medium Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,062,307,505	$9,417,898,488
Total benefits	$12,062,307,505	$9,417,898,488
Costs		
Purchase Cost for Onboard IVSS	$22,478,447,408	$20,053,470,521
Training and O & M Cost	$3,794,925,025	$2,965,225,686
Total costs	$26,273,372,433	$23,018,696,206
Total (Net Present Value)	-$14,211,064,928	-$13,600,797,719
Benefit/Cost Ratio	0.46	0.41

Conservative Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$3,812,265,144	$2,976,505,625
Total benefits	$3,812,265,144	$2,976,505,625
Costs		
Purchase Cost for Onboard IVSS	$22,478,447,408	$20,053,470,521
Training and O & M Cost	$3,794,925,025	$2,965,225,686
Total costs	$26,273,372,433	$23,018,696,206
Total (Net Present Value)	-$22,461,107,289	-$20,042,190,581
Benefit/Cost Ratio	0.15	0.13

Aggressive Conflict Classes

	Discounted at 4%	Discounted at 7%
Benefits		
Crashes avoided	$12,695,320,386	$9,912,136,514
Total benefits	$12,695,320,386	$9,912,136,514
Costs		
Purchase Cost for Onboard IVSS	$22,478,447,408	$20,053,470,521
Training and O & M Cost	$3,794,925,025	$2,965,225,686
Total costs	$26,273,372,433	$23,018,696,206
Total (Net Present Value)	-$13,578,052,047	-$13,106,559,692
Benefit/Cost Ratio	0.48	0.43

APPENDIX D.

SAFETY BENEFITS SUPPORTING DATA

Appendix D.

Safety Benefits Supporting Data

Appendix D1. Follow-On Time History Treatment

As noted in the Volvo Trucks Final Report (Volvo 2005), there are many follow-on threats, i.e., THs that start immediately after the end of a preceding TH. For this reason, threats were grouped into "follow-on groups" based on start times. Specifically, if the start time of threat A was within 15 seconds of the start time of threat B, threat B was assumed to be a follow-on of threat A. Groups of as many as seven follow-on threats (ABCDFEG) were identified by this process, but 80 percent of the follow-on groups contained only two triggered events (AB), and 14 percent consisted of three triggered events (ABC). Because the majority of the follow-on groups consisted of only two triggered events, only follow-on pairs were created. Longer events were broken into a series of driving conflicts using the process described below. Follow-on threats were important for determining the severity of the conflict.

First, driving conflicts with no follow-ons were identified and then driving conflict pairs were created. Driving conflicts with follow-on threats whose critical targets disappeared before the end of the driving conflict were identified as single driving conflicts and included in the single driving conflict group. The process of creating follow-on driving conflict pairs proceeded for the remaining driving conflicts by appending a single follow-on threat (whether it passes KME or not) to the preceding driving conflict. Using this approach, the initial threat must be a driving conflict, but the follow-on threat may or may not satisfy the KME equations. Only a single follow-on was appended to each driving conflict. However, if the follow-on threat was also a driving conflict, then a follow-on pair was also created for that driving conflict.

A method was implemented to avoid the situation of creating multiple driving conflicts from the same event. If the critical target was still present at the end of a follow-on driving conflict, indicating that the same target was probably present in the follow-on threat, then further driving conflict follow-on pairs were not created. If the last threat in a follow-on group was a driving conflict itself, it appears in the single driving conflict set. Table D1-1 gives examples of how follow-on groups were broken up to produce multiple single and follow-on pair driving conflicts.

Table D1-1. Examples of Creation of Single and Follow-on Pair Driving Conflicts

Original (A) and Follow-On (B,C) Time Histories	Conflicts Created				Number of:	
					Singles	Follow-On Pairs
A^{1} **B**^{1} **C**^{1}	→	AB	BC	—	0	2
A^{1} **B**^{1} **C**^{2}	→	AB	BC	C	1	2
A^{1} **B**^{2} **C**^{1}	→	AB	B	C	2	1
A^{1} **B**^{2} **C**^{2}	→	AB	B	C	2	1
A^{2} **B**^{1} **C**^{1}	→	A	BC	—	1	1
A^{2} **B**^{1} **C**^{2}	→	A	BC	C	2	1
A^{2} **B**^{2} **C**^{1}	→	A	B	C	3	—
A^{2} **B**^{2} **C**^{2}	→	A	B	C	3	—
A^{1} B^{1} **C**^{1}	→	AB	C	—	1	1
A^{1} B^{1} **C**^{2}	→	AB	C	—	1	1
A^{1} B^{2} **C**^{1}	→	AB	C	—	1	1
A^{1} B^{2} **C**^{2}	→	AB	C	—	1	1
A^{2} B^{1} **C**^{1}	→	A	C	—	2	—
A^{2} B^{1} **C**^{2}	→	A	C	—	2	—
A^{2} B^{2} **C**^{1}	→	A	C	—	2	—
A^{2} B^{2} **C**^{2}	→	A	C	—	2	—

Notes:

A, B, and C represent time histories (THs) collected in sequence called follow-on THs.
Boldface A, B, and C indicate a TH were the target satisfied the KME conditions.
Non-boldface indicates a TH that did not satisfy the KME conditions.

Key to superscripts in the Time History column:

1. Critical target present throughout the TH.
2. Critical target disappears before end of TH.

The main purposes of appending follow-on threats were to:

1. Improve driving conflict rate estimates by identifying unique, closely spaced driving conflicts as accurately as possible and

2. Aid the estimation of crash probabilities for each individual conflict with additional information for assessing the conflict severity.

The first purpose was addressed by the procedures described above for determining when follow-on THs represent separate driving conflicts and when they were continuations of other driving conflicts. It was anticipated that if the threat continued past the end of a TH, then additional driving data might be needed to assess the severity of the driving conflict. Thus, appending follow-on data to driving conflicts achieved the second purpose. The decision to limit the potential length of a driving conflict to two consecutive THs was based on both (a) the fact that over 80% of follow-on groups contained only one follow-on and (b) the crash probability, which indicates that 5 to 10 seconds of data after the point of conflict identification is typically sufficient to understand conflict resolution.

Appendix D2. Driver Assignments and Log Data

Unit tracking data and log data were processed by Battelle and combined with the on-board driving data. Figure D2-1 indicates the portion of the histogram data for which unit tracking data were available (95% of the 2.69 million VMT) and the portion for which both unit tracking and log data were available (59% of the 2.69 million VMT). Unit tracking data linked the driver to the vehicle. Thus, for all the histograms that have unit tracking data, it was possible to examine the effects of driver variables (age, gender, and experience).

Only two variables were constructed from the log data. The first variable captured the hours of driving the driver performed during the histogram. When two drivers both had driving data within one histogram period, the driving was assigned to the driver with the greater amount of driving during the histogram period. If no log information was available to determine which of the two drivers assigned to each truck did more of the driving during an individual histogram period, one of the two drivers was randomly assigned to that driving period. The second variable captured the driver's hours of service over the last 10-hour period prior to the start of the histogram.

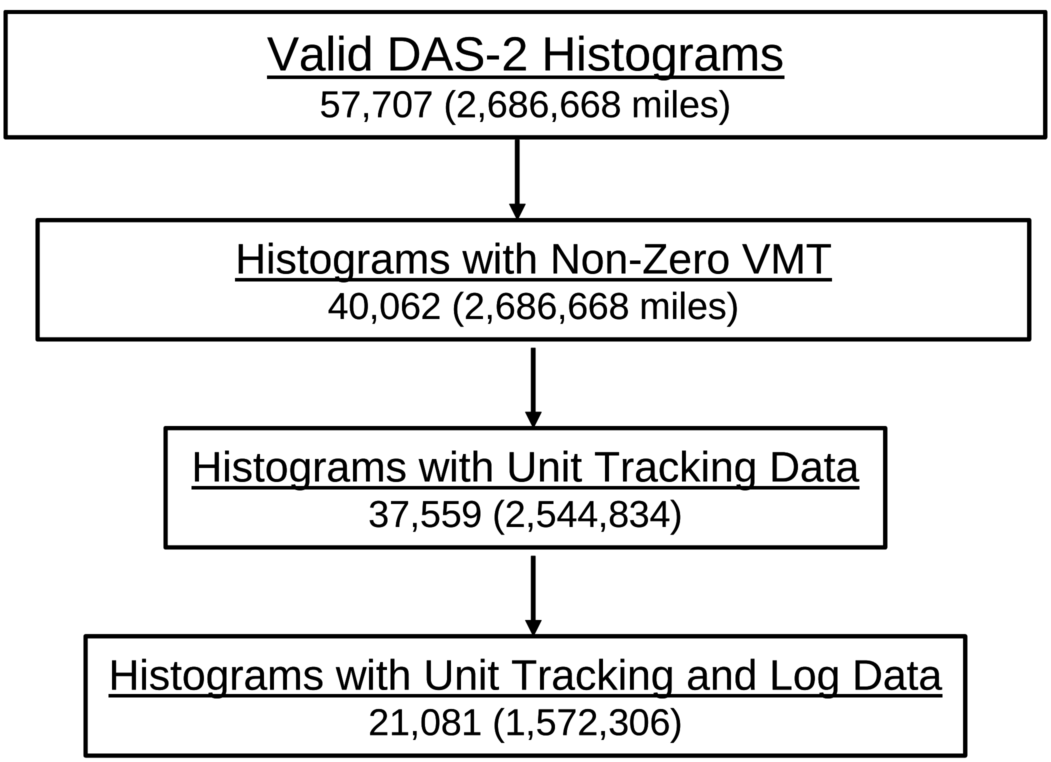

Figure D2-1. Process of Identifying Proper Histograms for Analyses

Figures D2-2, D2-3, and D2-4 show, for Baseline, Control, and Test trucks, respectively, a graphical summary of the overlap between on-board driving data and unit tracking/log data. On each plot, the x axis indicates the time period of the FOT. Each truck in that fleet has a row. To protect driver confidentiality, the identification numbers of the trucks are not shown. The key to the graphic is as follows:

- **Empty Row:** No data were collected
- **Yellow:** Unit tracking and log data only
- **Green Square:** On-board driving data were collected, but not DAS-2 data
- **Blue Square:** DAS-2 data were collected
- **Black Circle (DAS-1) or Red Circle (DAS-2):** Both on-board driving data for a particular day and unit tracking and log data.

Figures D2-2, D2-3, and D2-4 illustrate why there was a reduction in the number of histograms and the VMT when the histograms were combined with the unit tracking and log data. The information required for the conditional analysis of *exposure rates* is garnered from the histogram, unit tracking, and log data. Because of the reduction in available data when log data were required, conditional analyses of exposure rates were performed twice, once using information acquired from the histogram channels and unit tracking data and once using information from histogram channels, unit tracking, and log data.

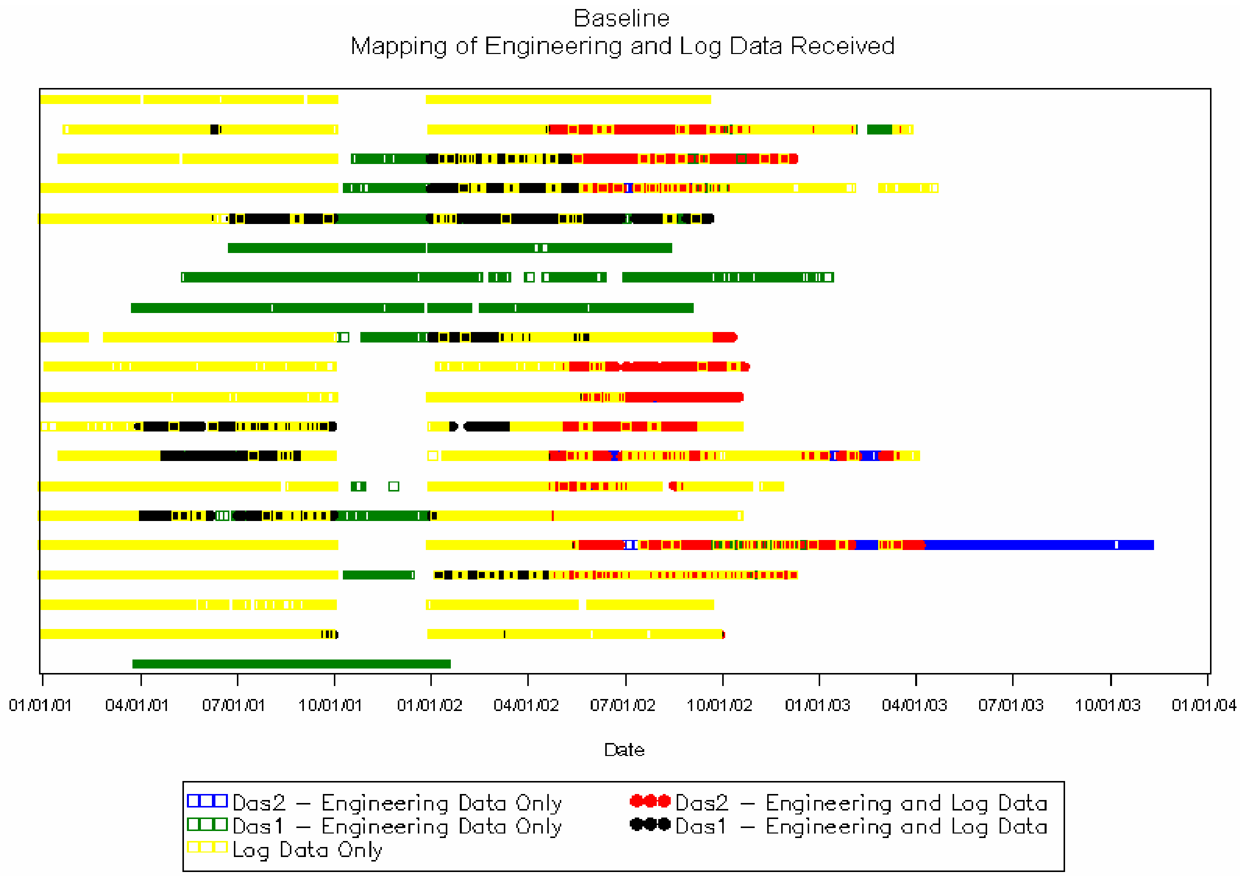

Figure D2-2. Overlap of On-Board Driving Data and Log Data for Baseline Trucks

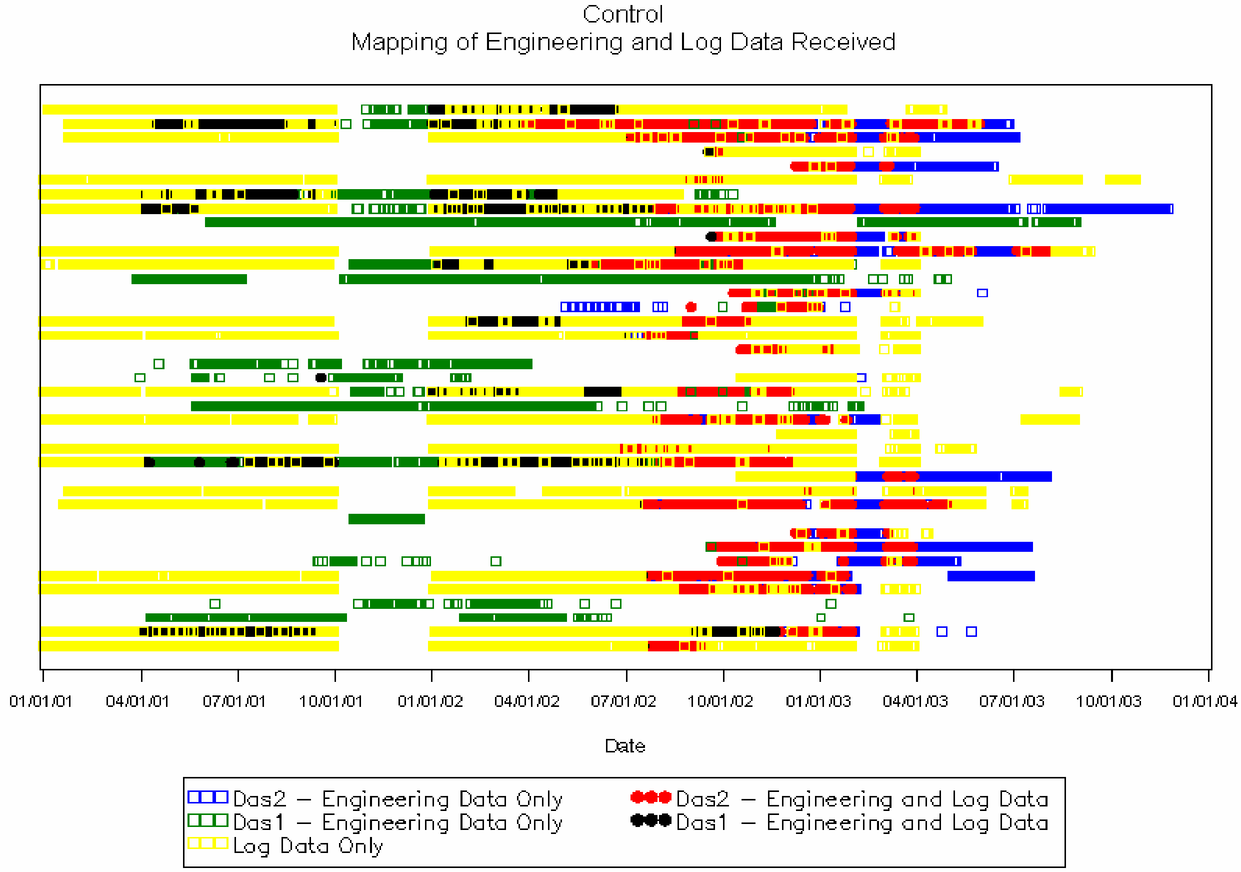

Figure D2-3. Overlap of On-Board Driving Data and Log Data for Control Trucks

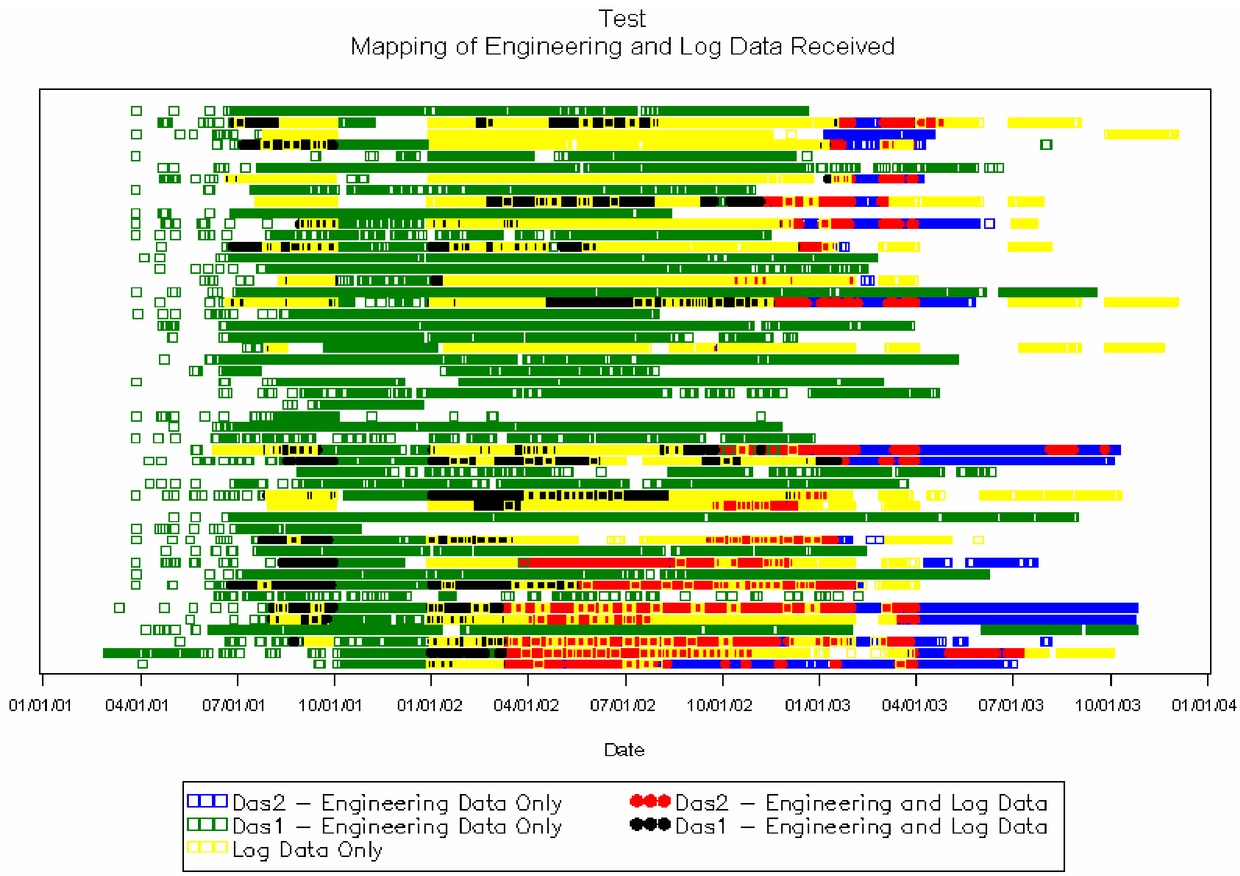

Figure D2-4. Overlap of On-Board Driving Data and Log Data for Test Trucks

Appendix D3. Supplemental Data Summaries

This appendix provides supplemental summaries of driver characteristics and driving data.

Driver Gender

Table D3-1 details the division of driving data by the gender of the driver. For the log data and the valid vehicle data available, there were more male drivers involved in the FOT, 131 men versus 56 women, and the males did a larger portion of the driving, 1,830,214 miles versus 714,478 miles.

Table D3-1. Distribution of VMT and Drivers by Gender

Gender	Fleet	Number of Drivers	Vehicle miles Traveled
Female	Baseline	14	132,114
	Control	19	268,225
	Test	27	314,139
	Tot. (F)	56	714,478
Male	Baseline	25	236,169
	Control	63	749,774
	Test	51	844,271
	Tot. (M)	131	1,830,214
Grand Total		187	2,544,692

Driver Age, Years of Experience, and Years with CDL

Figures D3-1 through D3-3 illustrate the spread of VMT and numbers of drivers over the range of driver ages, years of US Xpress experience, and years with a CDL. It appears from Figure D3-1 that driver ages were fairly evenly spread between 20 and 60 years of age, with a few drivers over 60, for the Baseline fleet. For the Control and Test fleets, however, drivers were centered in the 30 to 49 year old categories. Likewise, the VMT was spread over the age categories proportional to the number in that category. A majority of the driving was done by drivers with less than 1 year of experience at US Xpress (Figure D3-2). All baseline drivers, except one, had one year or less of experience with US Xpress as dictated by the FOT design. A large group of control vehicle drivers involved in the FOT had been with US Xpress 2 years. In general, Figures D3-2 and D3-3 indicate that US Xpress drivers were new to the driving business and new to US Xpress.

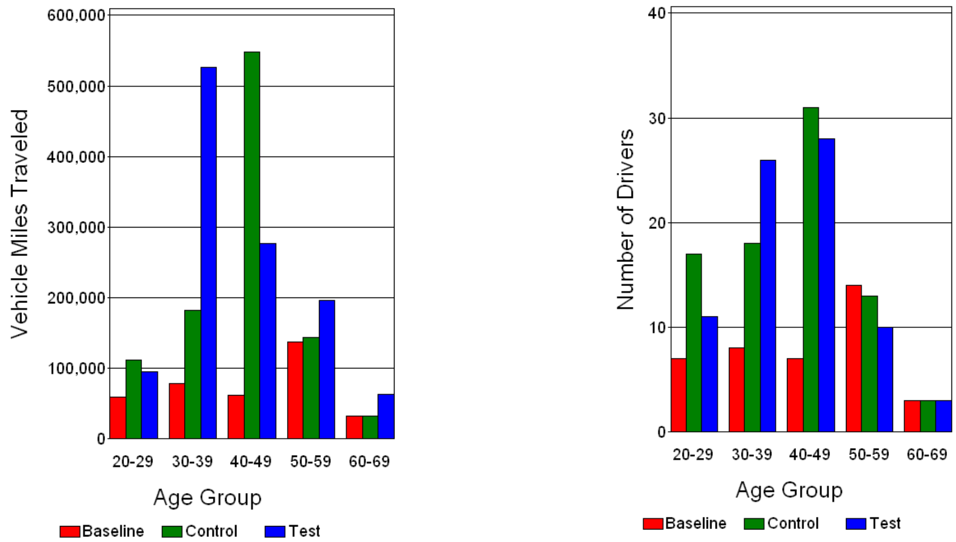

Figure D3-1. Distribution of VMT and Numbers of Drivers by Age Group

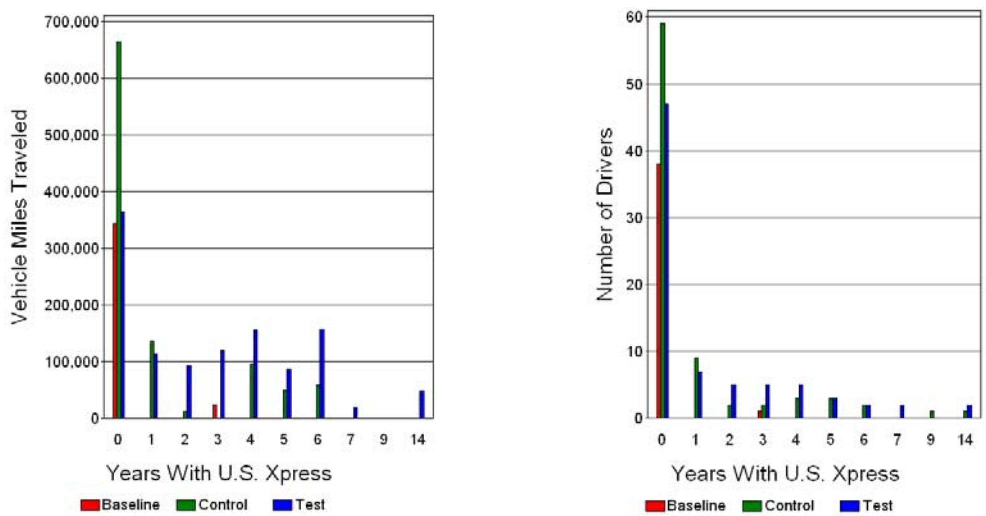

Figure D3-2. Distribution of VMT and Numbers of Drivers by Years of Service with US Xpress

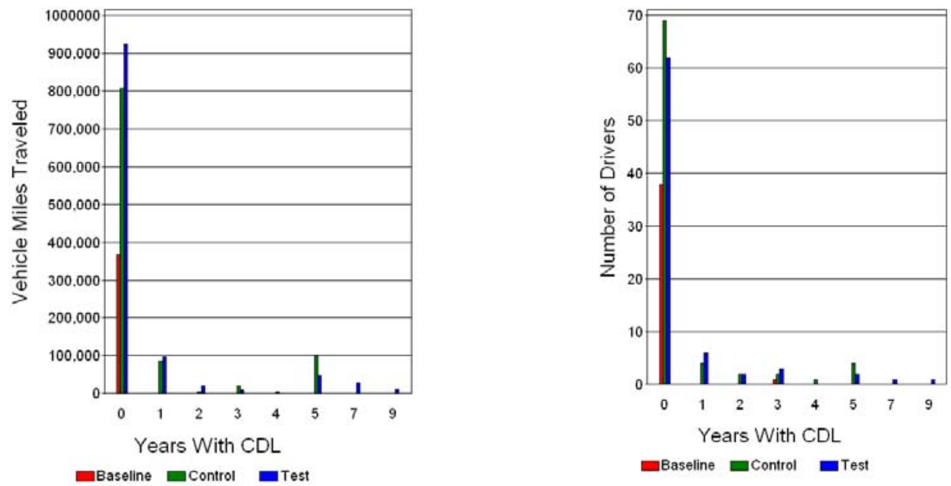

Figure D3-3. Distribution of VMT and Numbers of Drivers by Years with CDL

Distribution of Driving Speed

Figure D3-4 illustrates the breakdown of VMT by average road speed and percent of the time road speed is greater than 55 mph. To divide the VMT by these metrics, the average road speed and the percent of the time road speed was greater than 55 mph (80 fps) was calculated for each histogram reporting period. The VMT value from each histogram was then assigned to a bin along the horizontal axis of Figure D2-4. These bar charts demonstrate that the majority of the driving data was collected at speeds above 55 mph (80 fps). Analyses in Section 5.1.2 further examine the distribution of road speed demonstrated during the FOT by each fleet.

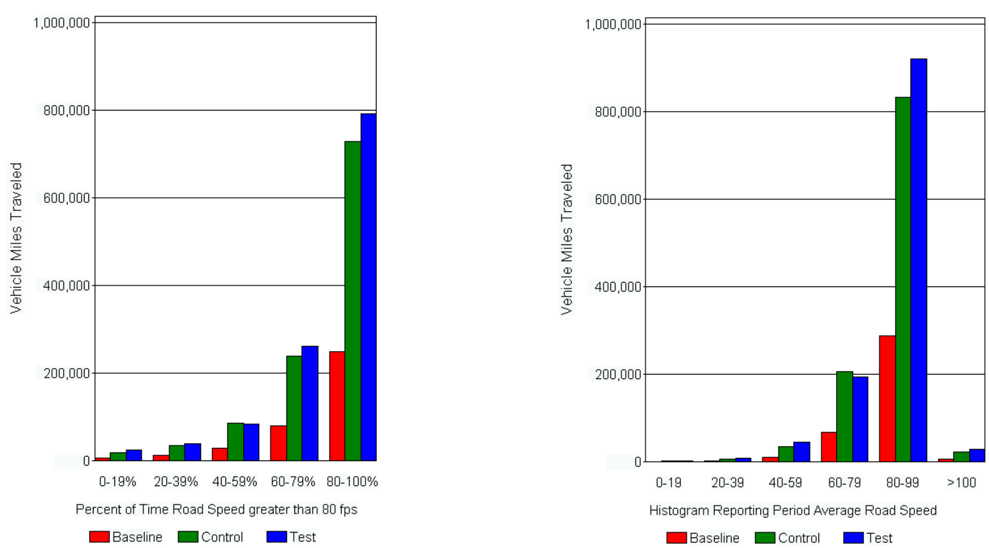

Figure D3-4. Breakdown of VMT by Road Speed (feet per second) Variables

Appendix D4. Calculating Standard Error for Estimating Conflict Rates

In this appendix, two methods for computing the variability of fleet average driving conflict rates are presented. The two methods were shown to produce similar standard errors. The simpler method was chosen for computing standard errors for rates in this report.

Table D4-1 presents the rate of driving conflicts by fleet. Standard errors were calculated for the fleet rates of driving conflicts by two methods. The first method assumed that all the trucks in a fleet should have the same driving conflict rate. Under this assumption, the number of driving conflicts experienced was assumed to have a Poisson distribution, with rate parameter equal to the rate of driving conflicts per unit distance times the total distance traveled by each fleet. In this distribution, the variance of the rate estimate is equal to the rate estimate divided by the total distance. The justification for viewing the number of driving conflicts as a Poisson process is based on a few concepts. First, conflicts are relatively rare events and no more than one conflict is expected in any one small unit of distance traveled. The driving conflicts can be viewed as a series of many binary trials (was there a conflict or not in a small unit of driving) with a small, constant probability of success. Under these conditions, the actual number of events occurring (conflicts) follows a Poisson distribution (Karlin and Taylor 1975).

The second method of calculating the uncertainty in the rate estimate assumed that each truck within a fleet could have a different driving conflict rate. Under this assumption, the variability among individual driving conflict rates estimated for each truck within a fleet is used to gauge the variability in the overall rate estimate. Figure D4-1 illustrates the variability of rates by truck. The second method produces slightly larger but very similar standard errors. The Poisson assumption was used to produce confidence intervals and determine statistical significance of differences in estimated conflict rates in this report.

Table D4-1. Number and Rate (Per 10,000 Miles) of Driving Conflicts by Truck Group

			Number of Driving Conflicts		
Fleet	VMT	Number of Trucks	Rate*	Poisson Standard Error	Standard Error w/ Truck Variability
Baseline	375,935	11	7.95	0.46	0.49
Control	1,108,674	31	8.10	0.27	0.32
Test	1,202,059	23	8.37	0.26	0.28
Total	2,686,668	59	8.20		

**** Rate is the number per 10,000 miles.***

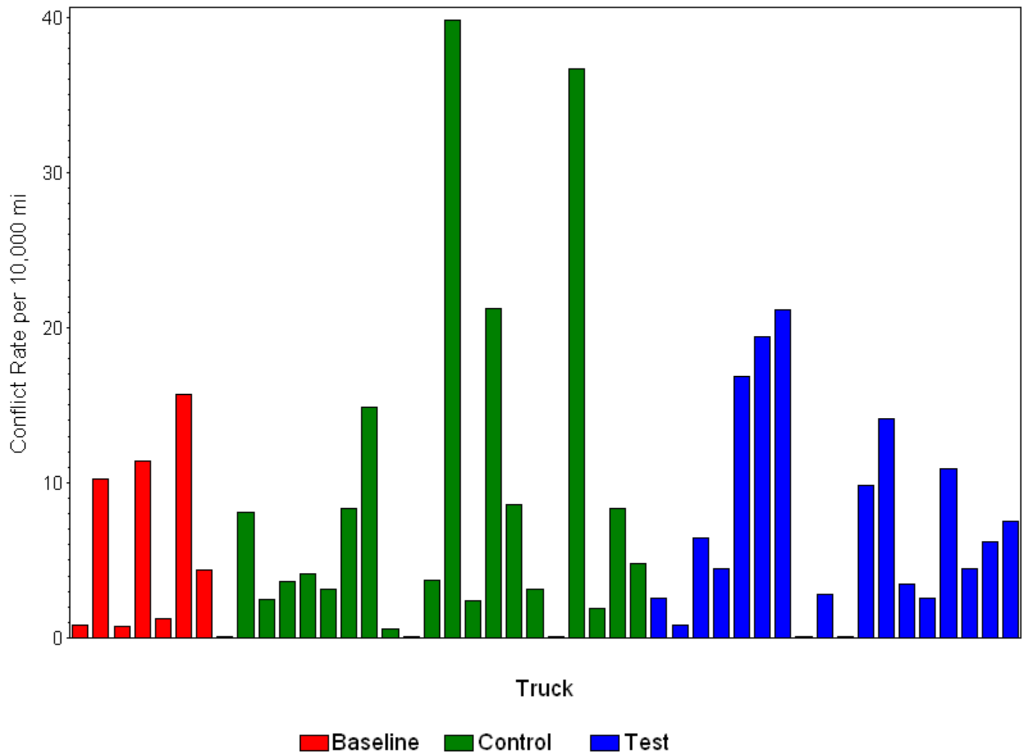

Figure D4-1. Overall Driving Conflict Rates by Truck

Appendix D5. Calculation of Vehicle Miles Traveled with Cruise Control On

The conditional analysis of conflict rates required the calculation of the vehicle miles traveled (VMT) during a 3-hour histogram period with cruise control on. This appendix describes how this calculation was performed.

The amount of time that the cruise control was on during a histogram period was included in the histogram file. Of interest for the Poisson regression was the VMT during which cruise control was on (in use). Additionally, the cruise control histogram channel recorded two cruise control states. The first was when the cruise control was on during driving conditions, and the second was when the cruise control was on and controlling engine speed during a high-idle state. The second cruise control mode occurred when the parking brake was set or when the vehicle was below some threshold speed (typically 5 mph).

In order to separate these two types of cruise control usage for use in the Poisson regression, allowing time to be converted into VMT, a linear regression was performed. The VMT in each histogram was split into VMT with cruise control on (VMT_{on}) and VMT with cruise control off (VMT_{off}) in the following manner:

1. The data were subset down to only driving with an average road speed greater than 50 mph with percent cruise control on greater than 0%. These higher average speeds made it likely that the drivers were using their cruise control in the driving mode only.

2. A regression equation was fit to the subset of the data that yielded an average speed with cruise control on (β_{CC} = 53 mph) and an average speed with cruise control off (β_{NOCC} = 41 mph):

$$VMT = \beta_{CC}\,(CC\ on\ time) + \beta_{NOCC}\,(CC\ off\ time)$$

3. The VMT in each histogram with an average road speed greater than 50 mph was then divided into cruise control on and off according to the proportion of the distance likely driven with cruise control on out of the total distance likely driven:

$$VMTon = \frac{\beta_{CC}(CC\ on\ time)}{\beta_{CC}(CC\ on\ time) + \beta_{NOCC}(CC\ off\ time)} \times VMT$$

$$VMToff = \frac{\beta_{NOCC}(CC\ off\ time)}{\beta_{CC}(CC\ on\ time) + \beta_{NOCC}(CC\ off\ time)} \times VMT$$

4. Average road speed with cruise control on was used to estimate the likely VMT_{on} for histograms with average road speed between 30 mph and 50 mph,

$$VMTon = \frac{\beta_{CC}(CC\ on\ time)}{\beta_{CC}(CC\ on\ time) + \beta_{NOCC}(CC\ off\ time)} \times VMT\ .$$

The minimum of this VMT_{on} and total VMT for the histogram was assumed to be VMT_{on}. This assumption was made because the sum of VMT_{on} and VMT_{off} must equal VMT, and neither can be negative.

5. Finally, any driving with an average road speed of less than 30 mph was assumed to be done without cruise control.

Appendix D6. Kinetic Motion Events Trigger

The Kinetic Motion Event (KME) triggers were implemented in order to capture time history data when a truck is in a situation where a high level of deceleration is required within a short period of time to avoid a collision. The KME trigger took its input from the collision warning system. The trigger criteria was that the following vehicle had to respond within 1.5 seconds at a deceleration of more than 0.25g (8 ft/s^2). Conservatively, the trigger criteria assumes that the following vehicle will not respond for the full 1.5 seconds.

Two trigger algorithms were used to account for different situations. The KME0 criteria uses measured lead vehicle deceleration, where the KME1 criteria assumes a constant deceleration for the lead vehicle. The following set of equations and logic describe the KME triggers.

It should be noted that the KME criteria found elsewhere in the report refers to the LVCS/LVS and LVD equations using various threshold parameters. This should be considered separately from the KME trigger criteria discussed here which cast a wider net to capture more situations of interest.

KME0:

If $|a_L| <= 0.25$ ft/s^2, (Lead Vehicle Constant Speed)

$$a_{F,req} = \frac{-\dot{R}^2}{2\left(R + \dot{R}t_{react}\right)}$$

If $a_L < -0.25$ ft/s^2, (Lead Vehicle Decelerating)

$$a_{R,req} = \frac{V_F^2}{2\left(V_L^2 \big/ 2a_L + V_F t_{react} - R\right)}$$

KME1:

If $a_L > -6.4$ ft/s^2, (Lead Vehicle Constant Speed)

$$a_{F,req} = \frac{-\dot{R}^2}{2\left(R + \dot{R}t_{react}\right)}$$

If $a_L < -6.4$ ft/s^2, (Lead Vehicle Decelerating)

$$a_{R,req} = \frac{V_F^2}{2\left(V_L^2 \big/ 2(-6.4\,ft/s^2) + V_F t_{react} - R\right)}$$

F = Following Vehicle
L = Lead Vehicle
t_{react} = reaction time (1.5 seconds)
$a_{F,req}$ = required deceleration

Appendix D7. Time of Critical Target Appearance

Analysis of the time history data focused on the period during which the critical target was present. The critical target is defined as the target under track when the trigger condition first occurs (Following Interval $\leq$ 0.5 sec, KME0, KME1, or Time to Collision $\leq$ 4 sec). Since the trigger condition was required to be present for 4 time steps (4/6 sec), the critical target was the target present just before the time history trigger at time zero. The time at which the critical target was first tracked is defined as the time of critical target appearance. This time is defined to be between -10 seconds and zero seconds in the time history (the first time step to the sixty-first).

Because the VORAD tracking system could rapidly switch between two targets due to a lane change, an algorithm was developed in coordination between the Volvo Partnership and Battelle to determine when a target switched within a time history. Generally, the VORAD could switch between targets or between target and no target. The algorithm used to determine the time of target switches is show below.

- For consecutive time steps, calculate range threshold as

  ΔR_{Thr} = max [|2 * previous Relative Velocity * 1/6|, 8]

  - (Previous Relative Velocity * 1/6) is the projected increase or decrease in range over one time step
  - Multiplication by the factor of two allows for range variability
  - Setting minimum value to 8 allows for VORAD range errors
  - The absolute value function accounts for negative relative velocities

- If $|\Delta R_{actual}| \geq \Delta R_{Thr}$, then a target switch has occurred.

The most difficult situations to determine a target switch were those in which a one time step drop-out of the track occurred. The Volvo Partnership analyzed video data and determined that some one step drop-outs were due to target switches and were correctly handled by the algorithm, while other drop-outs were due to a temporary loss of track by the VORAD system. Because these situations occurred in equal proportions in the analyzed data, no effort was made to distinguish between the two in the whole data set.

Appendix D8. Graphical Representation of Kinematic Analysis

The kinematic analysis is described fully in Step 5 of section 4.3.3. The kinematic analysis of a time history is designed to assign a numerical measure of severity to each FOT driving conflict. The measure of severity for this analysis is the additional time that a following vehicle driver could have waited to take action and still avoid a crash. This analysis assumes that the driver would react in the same manner as they did in the event. It also assumes that they maintain their kinematic profile throughout the additional time. Finally, the analysis assumes that the lead vehicle also behaves in the same way as it did during the actual time history.

Two time histories are shown here as an example of the results of the kinematic analysis. First, a time history is presented where the kinematic analysis predicts a lag time of 2 seconds. Figure D8-1 presents a Range/Range-Rate and following vehicle speed plot for this time history. Also shown on the plot are the range profiles predicted by the kinematic analysis. One profile is shown for 1 second and another for a 2 second lag. The 2 second lag profile reaches zero and therefore, would have resulted in a collision if the following driver had waited 2 seconds to react. The reaction in this case was braking at the 9 second mark. Second a time history is presented in Figure D8-2 where a lag time of longer than 15 seconds is predicted. This plot also shows the predicted range at 1 second time intervals. In this case, the predicted range by the kinematic analysis does not indicate a collision.

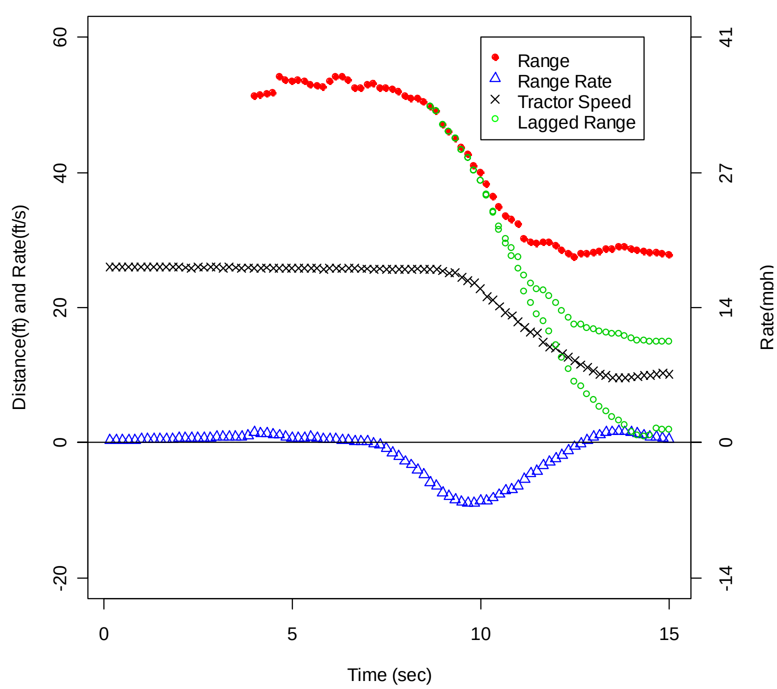

Figure D8-1. Range/Range-Rate/Speed Plot

The green range profile is the range that is predicted by the kinematic analysis at 1 second intervals with a collision at the 2 second lag time.
(UUID = 2F23284807072002544D00D0810000F4)

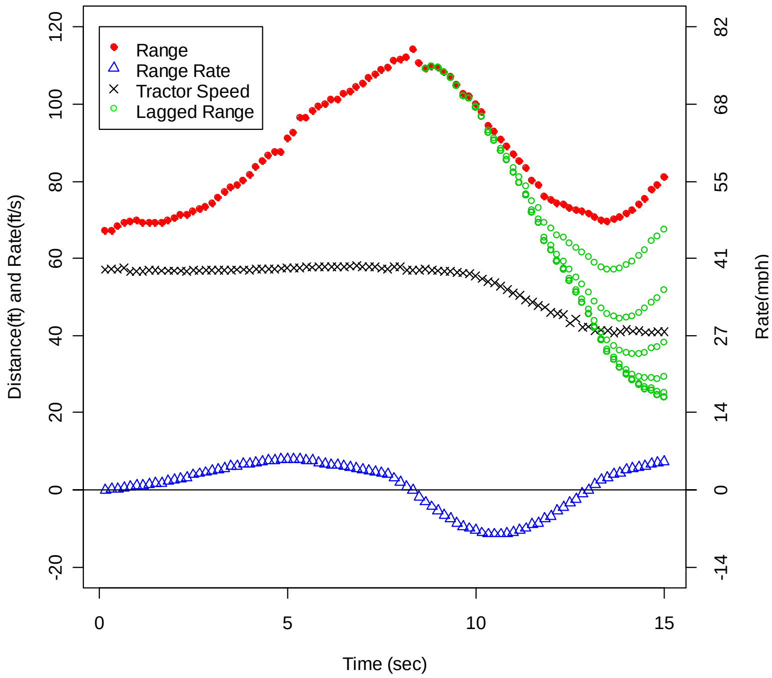

Figure D8-2. Range/Range-Rate/Speed Plot

The green range profile is the range that is predicted by the kinematic analysis at 1 second intervals up to 15 seconds. No collision is predicted. (UUID = 3C23090703192003544D00D081000102)

Appendix D9. Selected Time Histories

One area of concern in this study was the treatment of time histories which were not KME triggered. All time histories were treated in the same manner regardless of their initial triggering condition. Each time history was analyzed using the LVS/LVCS and LVD equations (KME equations). Then each time history that satisfied the conservative threshold of the KME equations was analyzed using a kinematic analysis. The kinematic analysis calculated the additional time that a driver could have waited to react (lag time) and still not collide with the lead vehicle. Once non-threats were removed from the set of time histories (time histories with a 1/6 second lag time), the remaining time histories were included in the KME Conflict Definition set. Of that group, time histories with a lag time less than 15 seconds were included in the Restricted KME Conflict Definition set. Full details of the process are found in Section 4.

Eight time histories selected for additional analysis are contained in Table D9-1. Two time histories did not have complete channel data and therefore could not be fully analyzed. Two time histories satisfied the KME criteria for the conservative threshold even though they were not triggered by a KME event, while the rest did not. One time history was included in the Restricted KME Conflict Definition. Also included in Table D9-1 is the conflict description and conflict category assigned to that time history. The determination of the type of trigger (FI, TTC, or KME) and the determination of the conflict description were performed by the Volvo Partnership. Conflict category assignments were done according to Section 4.

Table D9-1. Characteristics of Selected Time Histories

Time History UUID	Complete Data	KME Conflict Definition	Restricted KME Conflict Definition	FI Trigger	TTC Trigger
0018095908152002544D00D081000134	X			X	
0101051404142003544D00D0810001E3				X	
0101440905102002544D00D0810001E7	X				X
0101565401142003544D00D0810001AF	X			X	
0104560505122002544D00D0810000F4	X				X
0115291806142002544D00D0810000F7	X	X	X		X
0123404707222002544D00D081000124				X	
5701054706232003544D00D081000178	X	X		X	

Time History UUID	Conflict Description	Conflict Category
0018095908152002544D00D081000134	LV constant or decel and FV decel	2
0101051404142003544D00D0810001E3	LV & FV constant and no lane change	1
0101440905102002544D00D0810001E7	LV & FV constant and lane change	3
0101565401142003544D00D0810001AF	LV & FV constant and lane change	3
0104560505122002544D00D0810000F4	LV & FV constant and no lane change	1
0115291806142002544D00D0810000F7	LV constant or decel and FV decel	2
0123404707222002544D00D081000124	LV decel and FV constant	1
5701054706232003544D00D081000178	LV stopped and FV constant or decel	2

Each time history in Table D9-1 was examine using a Range/Range-Rate/Speed plot and an overhead X-Y plot. In order to give an indication of time and relative position of the vehicles in the X-Y plot, the size of the data points are increased each second. Each time history ends in a unique three letter identifier (indicating that eight different trucks are represented). The unique identifier will be used in the discussion for brevity.

Time history "134" did not meet the conservative KME criteria and was therefore excluded from the KME Conflict Definition group. Although the following vehicle did brake during the time history, at no time during the time history was the conflict severe enough to meet the KME criteria. Figure D9-1 gives the Range/Range-Rate/Speed plot and X-Y plot for "134".

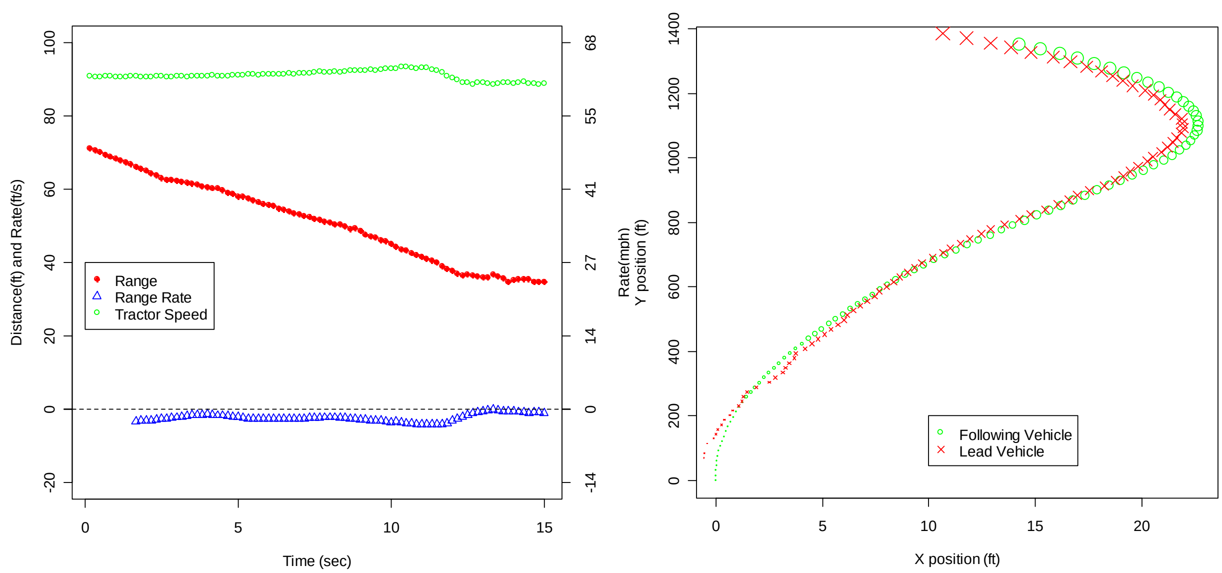

Figure D9-1. Range/Range-Rate/Speed Plot and Overhead X-Y plot for a Time History (UUID=0018095908152002544D00D081000134)

Time history "1E3" did not have complete data, and therefore was not analyzed. Time history "1E7" did not satisfy the conservative KME criteria. Figure D9-2 gives the profile for time history "1E7". In this time history, the conflict is resolved at 11 seconds due to the critical target disappearance. Although range is steadily decreasing over the time history, during the last time step in which the target was present, the required deceleration using the LVCS equation with a 1.5 second reaction time was 5.6 ft/s^2 (less than the 8 ft/s^2 required for the conservative criteria).

Time history "1AF" also did not satisfy the conservative KME criteria. Figure D9-3 shows this time history. Although there is decreasing range throughout the time history until the target disappears at 13.5 seconds, the driver did not recognize that his vehicle was in a conflict as he was accelerating from just before the FI trigger.

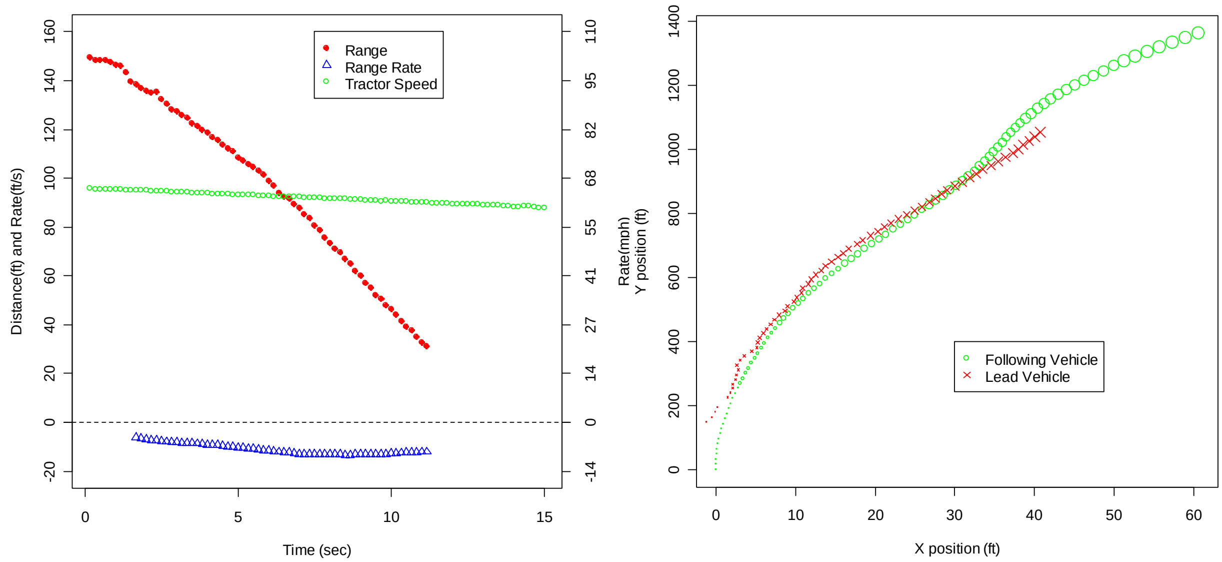

Figure D9-2. Range/Range-Rate/Speed plot and overhead X-Y plot for a Time History (UUID=0101440905102002544D00D0810001E7)

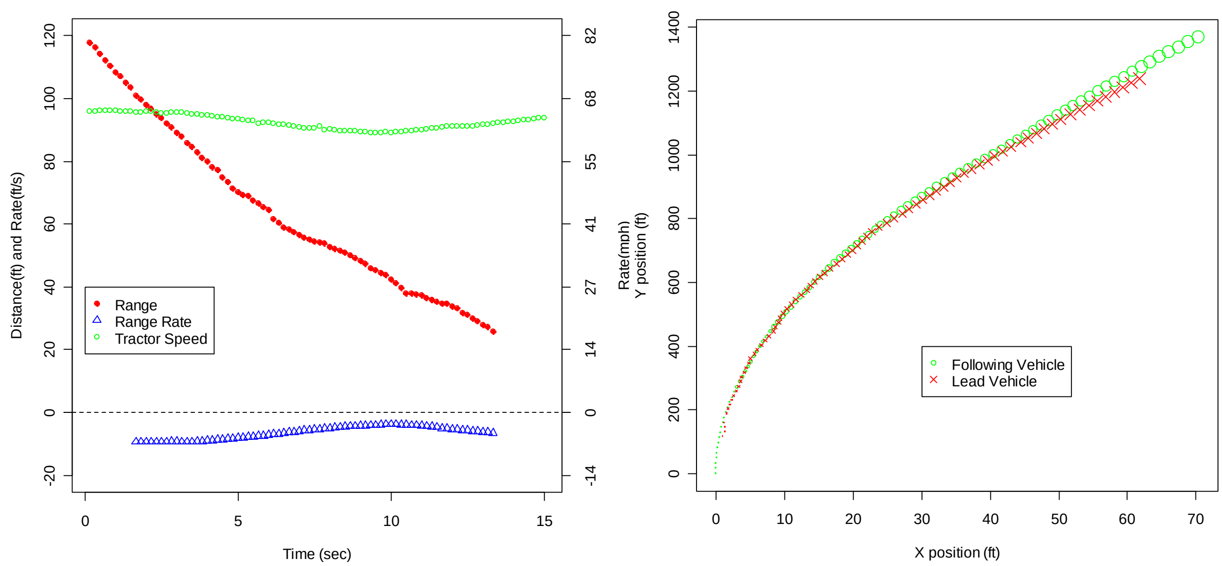

Figure D9-3. Range/Range-Rate/Speed plot and overhead X-Y plot for a Time History (UUID=0101565401142003544D00D0810001AF)

Time history “0F4” was excluded from the KME Conflict Definition group because it did not meet the conservative KME criteria. Figure D9-4 shows that there was a constant negative range rate and a steadily decreasing range. The conflict was most likely resolved by the lead vehicle as the driver did not react by braking or changing lanes during this time history.

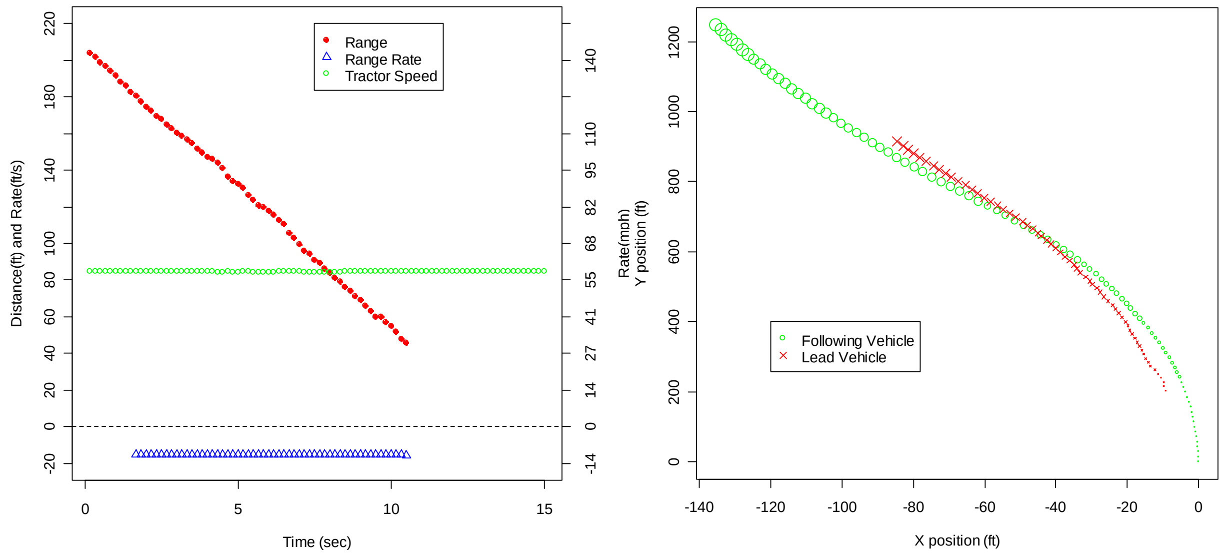

Figure D9-4. Range/Range-Rate/Speed plot and overhead X-Y plot for a Time History (UUID=0104560505122002544D00D0810000F4)

Time history “0F7” was considered a conflict in both the KME Conflict Definition and the Restricted KME conflict Definition. The kinematic analysis predicted that this event would have resulted in a crash if the driver had lagged his reaction (in this case, braking at the 4 second mark). Time history “0F7” is shown in Figure D9-5.

Another time history was selected with incomplete data, “124”. No analysis was performed on it.

Finally, time history “128” was also considered a conflict, but only according to the KME Conflict Definition. The kinematic analysis predicted that there would not have been a collision, even if the driver had delayed his reaction for 15 seconds (in this case, a lane change at time 1.2 sec). Figure D9-6 shows that this was actually a short presence target which the Volvo Partnership identified as a possible radar return phantom, but did not exclude from their set of threats.

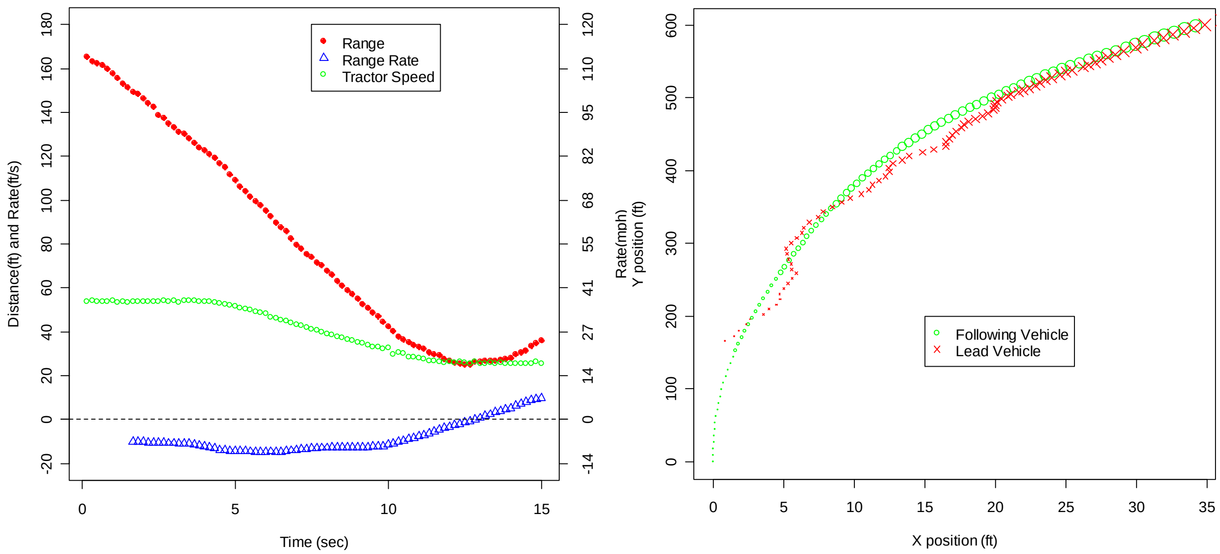

Figure D9-5. Range/Range-Rate/Speed plot and overhead X-Y plot for a Time History (UUID=0115291806142002544D00D0810000F7)

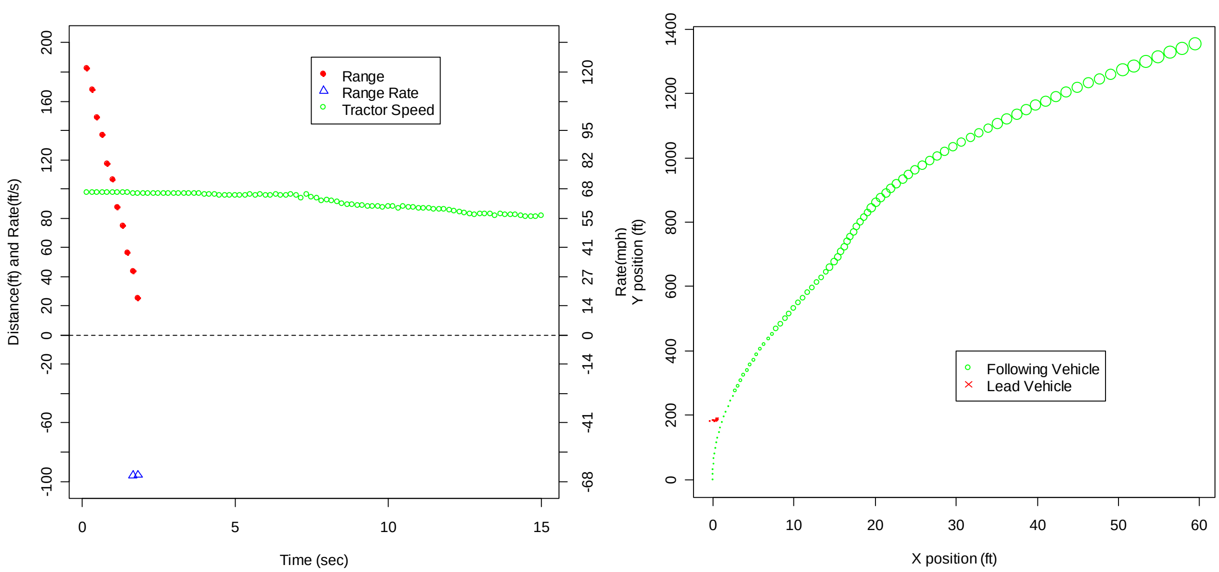

Figure D9-6. Range/Range-Rate/Speed plot and overhead X-Y plot for a Time History (UUID=5701054706232003544D00D081000178)

Appendix D10. Percent Reduction in Rear-End Crashes Simulation

The calculation of the percent reduction in Rear-End crashes involves the combination of four terms with different distributions. In the exposure ratio, the rate of conflicts with an IVI technology (numerator) and the rate of conflicts without an IVI technology (denominator) are Poisson distributed random variables. In the prevention ratio for the Restricted KME Conflict Definition, the lag times with and without an IVI technology are approximately lognormally distributed. In the KME Conflict Definition, the probability of a crash given a conflict category is approximately gamma distributed. The ratios and products of these distributions do not follow any standard, closed form distribution. Therefore, a simulation approach was employed to estimate the distribution of the percent reduction in rear-end crashes. The goal of this analysis is to assess the normality of the estimate of the percent reduction in rear-end crashes. If the distribution is not far from normal, then the standard assumptions about 2 standard deviations from the mean encompassing a 95% confidence interval is appropriate. However, if the distribution is not normally distributed, then calculating p-values based on a normal assumption is not valid.

Exposure Ratio

The rate of conflicts per mile times the VMT is assumed to be Poisson distributed with a rate parameter equal to the number of conflicts for a category. For example, Table 5.1-10a shows that the number of conflicts for the Restricted KME Conflict Definition, conservative threshold, baseline fleet, constant speed category is 31. The VMT associated with the baseline fleet is 395,935.

$$P(S)_{Threshold,Fleet,Category} \cdot VMT \sim \text{Poisson}(\lambda_{Threshold,Fleet,Category})$$
$$P(S)_{Conservative,Baseline,Constant\ Speed} \cdot 395{,}935 \sim \text{Poisson}(\lambda = 31)$$

In the simulation, one million samples are taken from the appropriate Poisson distribution, each sample is divided by the appropriate VMT, and then the appropriate ratios are constructed to create one million samples of the Exposure Ratio.

Prevention Ratio

Restricted KME Conflict Definition

In the Restricted KME Conflict Definition, the mean lag times calculated in the kinematic analysis are assumed to be lognormally distributed. The median of that distribution is equal to the geometric mean lag time. For example, Table 5.1-1 gives the geometric mean lag time for the Baseline fleet, conservative threshold, and constant speed conflict category as 1.220. In practice, it is easier and computationally equivalent to work with natural log transformed values. In this case, the mean of the transformed lag times is 0.198964, the variance is 0.506294, and the number of observations is 41. The calculation of the a_i parameter is omitted because it cancels from the numerator and denominator of the prevention ratio.

$$\overline{\tau}_{Threshold,Fleet,Category} \sim \text{LogNormal}\left(\overline{\ln \tau_{Threshold,Fleet,Category}}, \frac{V(\ln \tau_{Threshold,Fleet,Category})}{N}\right)$$

$$\overline{\tau}_{Conservative,Baseline,Constant\ Speed} \sim \text{LogNormal}\left(\overline{\ln \tau} = 0.198964, \frac{V(\ln \tau)}{N} = 0.506294/41\right)$$

In the simulation, one million samples are taken from the appropriate lognormal distribution and then the appropriate ratios are constructed to create one million samples of the Prevention Ratio.

KME Conflict Definition

In the KME Conflict Definition, the probabilities of a crash given a conflict category are assumed to be gamma distributed. A gamma distribution was chosen because it best fit the data. Table 5.1-2 gives the mean probability of a crash given the constant speed category for the conservative threshold and Baseline fleet as 0.009 and the number of observations as 734. The variance is 0.00206 (calculated separately). The parameters of the gamma distribution are found by the method of moments.

$$\overline{P_{Threshold,Fleet}(C \mid S_i)} \sim \text{Gamma}\left(\frac{N\left(\overline{P_{Threshold,Fleet}(C \mid S_i)}\right)^2}{V(P_{Threshold,Fleet}(C \mid S_i))}, \frac{V(P_{Threshold,Fleet}(C \mid S_i))}{\overline{P_{Threshold,Fleet}(C \mid S_i)}}\right)$$

$$\overline{P_{Conservative,Baseline}(C \mid S_1)} \sim \text{Gamma}\left(\frac{N\left(\overline{P_{Conservative,Baseline}(C \mid S_1)}\right)^2}{V(P_{Conservative,Baseline}(C \mid S_1))} = 31.50, \frac{V(P_{Conservative,Baseline}(C \mid S_1))}{\overline{P_{Conservative,Baseline}(C \mid S_1)}} = 0.22\right)$$

Again, one million samples are taken from the appropriate gamma distribution and then the appropriate ratios are constructed to create one million samples of the Prevention Ratio.

Percent Reduction in Crashes

Finally, the one million samples from each ratio are combined according to the same method as in Section 5.1 for calculating the percent reduction in crashes. Figures D10-1 and D10-2 reproduce Figures 5.1-12 and 5.1-13 for the Restricted KME Conflict Definition and the KME Conflict Definition respectively. Added to these figures are the non-parametric 95% confidence intervals from the results of the simulation. These confidence intervals are not intended to replace the confidence intervals from Section 5.1. However, these confidence intervals do give information about the normality assumption for the confidence intervals in Section 5.1. Similar conclusions are drawn from both Figures D10-1 and D10-2. First, the assumption of normality for the conservative and medium threshold is reasonable. Although differences exist, they are not extreme enough to reject the normality assumption of the percent reduction in crashes. However, for the aggressive threshold, there is evidence that the assumption of normality is not valid. For this reason, Tables 5.1-17 and 5.1-19 do not provide p-values based on the normal assumption for the aggressive threshold.

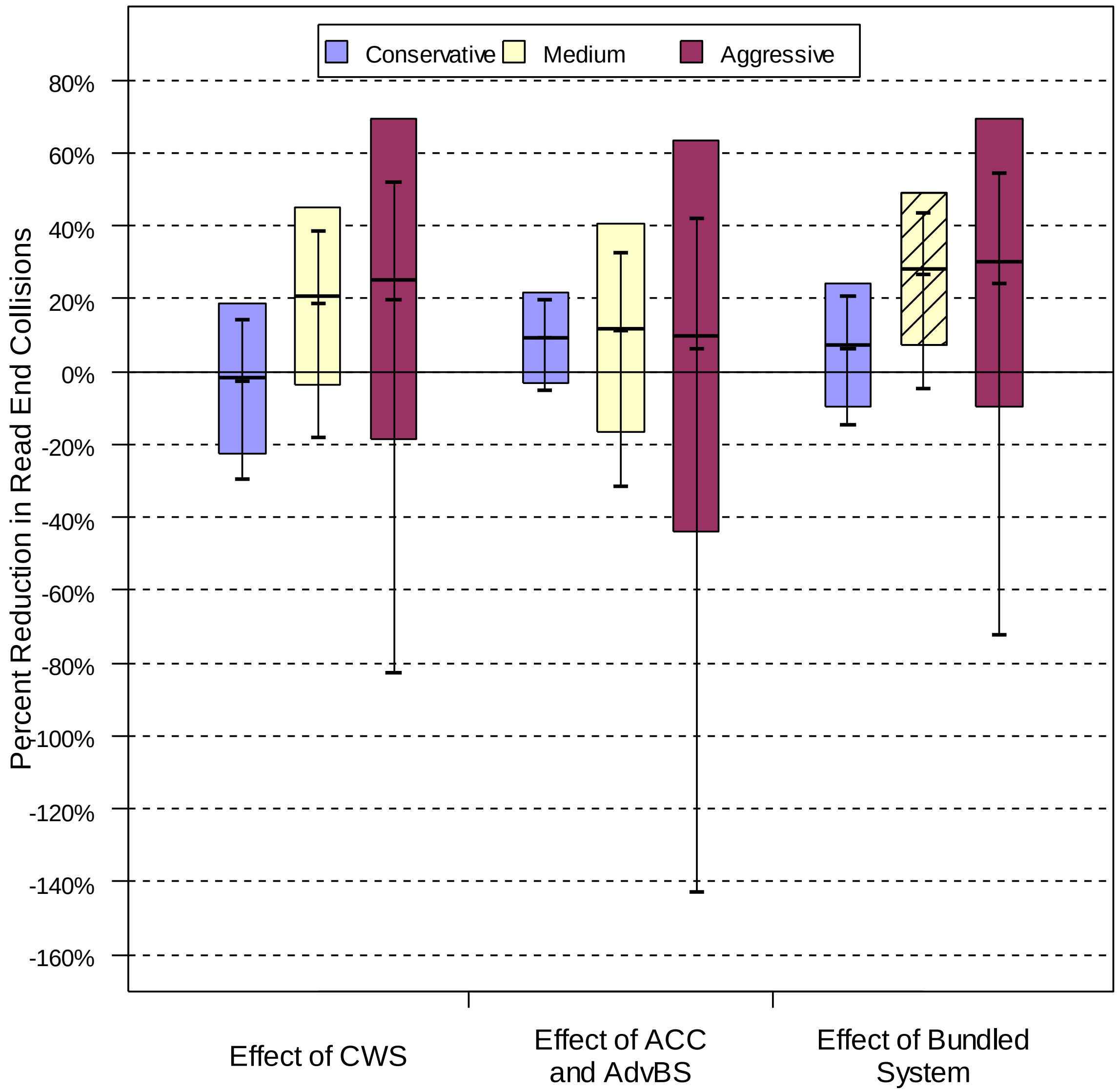

Figure D10-1. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies (Restricted KME Conflict Definition)

Colored error bars represent +/- two standard deviations

The thin, black error bars represent the results of the simulation

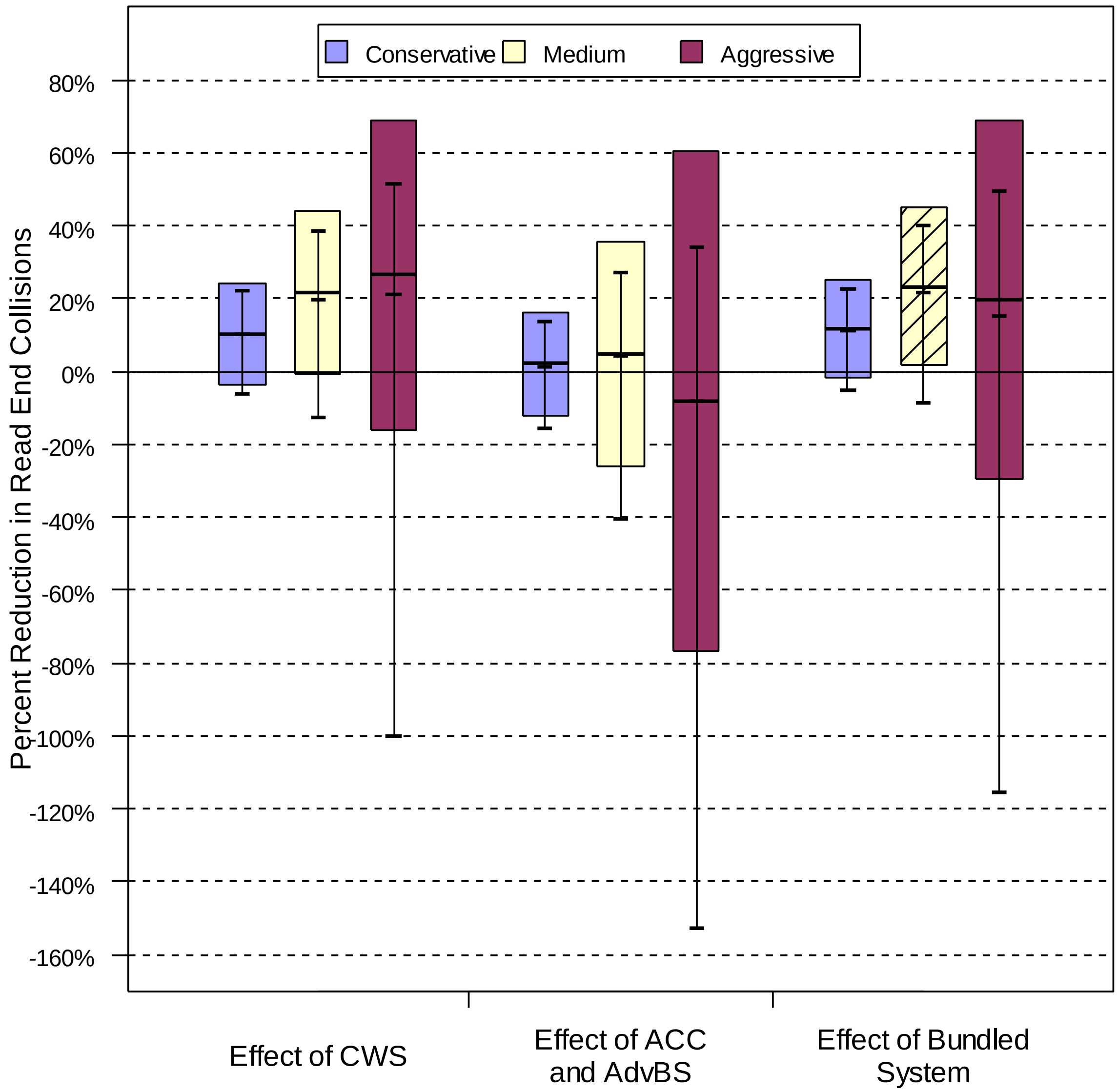

Figure D10-2. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies (KME Conflict Definition)

Colored error bars represent +/- two standard deviations

The thin, black error bars represent the results of the simulation

Appendix D11. Variance Estimates

The calculation of the variance of non-linear combinations of random variables is often accomplished with a Taylor series approximation, also known as the delta method (Hogg and Craig 1995). The prevention ratio and exposure ratio are both non-linear combinations of random variables, and an estimate of their variance can be calculated in this manner.

The result of the Taylor series approximation is that the variance of a function of a random variable, *f(X)*, is approximated by

$$Var(f(X)) \approx Var(X)\left[f'(\overline{X})\right]^2$$

where *f'(●)* is the first derivative, and $\overline{X}$ is the mean of the random variable.

In the case of a ratio of random variables, *X* and *Y*, this gives the following approximation

$$Var\left(\frac{X}{Y}\right) \approx Var(X)\left(\frac{1}{\overline{Y}}\right)^2 + Var(Y)\left(\frac{\overline{X}}{\overline{Y}^2}\right)^2$$

where the bar notation over the random variable indicates a mean value.

Exposure Ratio

For the exposure ratio, the variance is approximately equal to

$$Var(ER_i) = Var\left(\frac{P_W(S_i)}{P_{WO}(S_i)}\right) \approx Var(P_W(S_i))\left(\frac{1}{\overline{P}_{WO}(S_i)}\right)^2 + Var(P_{WO}(S_i))\left(\frac{\overline{P}_W(S_i)}{\overline{P}_{WO}(S_i)^2}\right)^2$$

where ER_i is the exposure ratio for conflict category *i*, $P_W(S_i)$ is the probability that driving conflict S_i occurred with a safety system, and the subscript WO indicates without a safety system. Because the probability that a conflict occurs is a Poisson random variable, the mean and variance are estimated by

$$\overline{P}_W(S_i) = \frac{N_i}{VMT_W}$$

$$Var(P_W(S_i)) = \frac{N_i}{VMT_W^2}$$

where N_i is the number of conflicts in category *i* which occurred in VMT_W vehicle miles traveled with the safety system. Similar calculations yield $P_{WO}(S_i)$.

Prevention Ratio

For the prevention ratio, KME conflict definition, the variance is approximately equal to

$$Var(PR_i) = Var\left(\frac{\overline{P}_W(C \mid S_i)}{\overline{P}_{WO}(C \mid S_i)}\right) \approx Var\left(\overline{P}_W(C \mid S_i)\right)\left(\frac{1}{\overline{P}_{WO}(C \mid S_i)}\right)^2 + Var\left(\overline{P}_{WO}(C \mid S_i)\right)\left(\frac{\overline{P}_W(C \mid S_i)}{\overline{P}_{WO}(C \mid S_i)^2}\right)^2$$

where $P_W(C|S_i)$ is the conditional probability that a rear end collision occurred given that a driving conflict in category *i* occurred with the safety system. $\overline{P}_W(C \mid S_i)$ and $Var\left(\overline{P}_W(C \mid S_i)\right)$ are calculated from the data obtained in Step 6 of section 4.3.3.

For the RKME conflict definition, the inverse of the geometric mean lag time was used to calculate the prevention ratio.

$$PR_i = \frac{\overline{P}_W(C \mid S_i)}{\overline{P}_{WO}(C \mid S_i)} = \frac{1/\overline{\tau}_W}{1/\overline{\tau}_{WO}}$$

where τ_W is the geometric mean lag time with a safety system.

Algebraic manipulation of this definition indicates

$$\ln(PR_i) = \ln(\overline{\tau}_{WO}) - \ln(\overline{\tau}_W)$$

Assuming independence between the geometric mean lag times

$$Var\left(\ln(PR_i)\right) = Var\left(\ln(\overline{\tau}_{WO})\right) + Var\left(\ln(\overline{\tau}_W)\right)$$

The $Var\left(\ln(\overline{\tau}_{WO})\right)$ is calculated from the variance in the natural logarithm of each lag time simulation.

Again, using the Taylor series approximation:

$$Var(PR_i) = e^{2\ln(PR)} Var\left(\ln(PR_i)\right)$$

Crash Reduction Ratio and Percent Reduction in Crashes

Finally, to find the variance in the crash reduction ratio

$$Var(CRR_i) = Var(ER_i PR_i) \approx ER_i^2 Var(PR_i) + PR_i^2 Var(ER_i)$$

where CRR_i is the crash reduction ratio for conflict category *i*. Assuming independence between the various conflict categories, the variance in the percent reduction in crashes (B) can be calculated in the following manner.

$$Var(B) = Var\left(\sum_{i=1}^{3} P_{WO}(S_i \mid C)(1 - CRR_i)\right) = \sum_{i=1}^{3} P_{WO}(S_i \mid C)^2 Var(CRR_i)$$

where CRR_i is the crash reduction ratio for conflict category i and $P_{WO}(S_i \mid C)$ are the percentages of each conflict category given a collision from GES.

Appendix D12. Comparison of Time History Filtering with the Volvo Partnership Report

A different data filtering procedure was used in the Volvo Partnership Report than is discussed in this report. Figure 6.2-1 of the Volvo Partnership Report shows the data reduction process used in that report. Figure D12-1 gives a comparison between the filtering processes in the two reports.

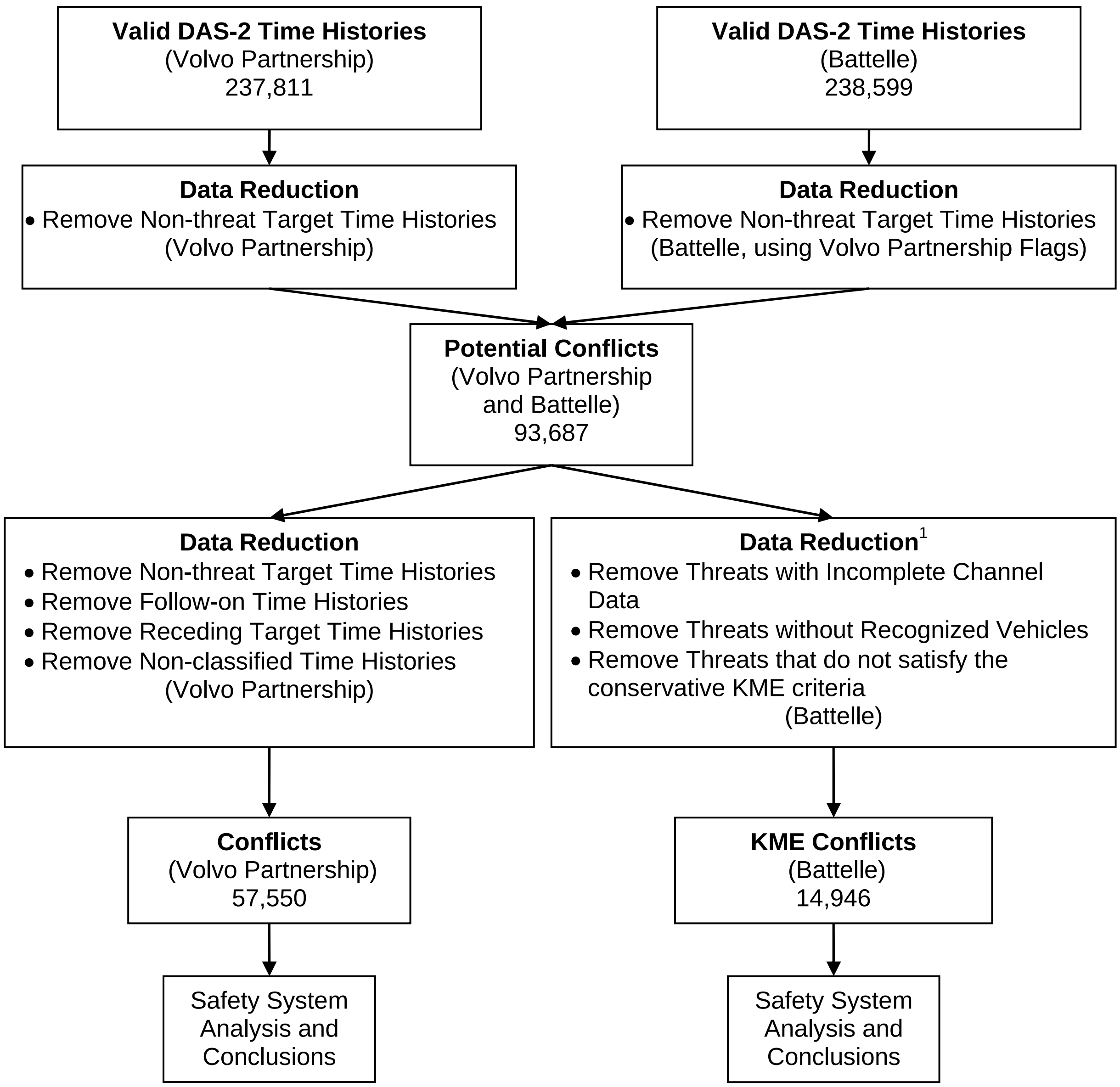

Figure D12-1. Comparison of Data Reduction Procedures in the Volvo Partnership Reports and Battelle Report

[1] See figure 4.3.5 and the associated text for the details of this process.

Both the Volvo Partnership and Battelle reports begin with the set of valid DAS-2 time histories. Valid DAS-2 time histories were identified by Battelle using data validation flags provided by the Volvo Partnership. No explanation for the small difference in reported numbers of valid DAS-2 time histories is given here. Battelle removed the non-threat target time histories using flags provided by the Volvo Partnership. Despite the differences in the starting sets of Valid DAS-2 time histories, both the Volvo Partnership and Battelle found 93,687 time histories before additional data reduction was undertaken.

Figure 6.2.1 of the Volvo Partnership report details the additional data reduction steps that were undertaken by the Volvo Partnership; those steps are summarized in Figure D12.1. The Volvo Partnership report had 57,550 time histories which it used to draw conclusions about the systems. Battelle's data reduction followed a different path as described in Section 4.3.3. The main distinguishing feature between the two methods was that Battelle did not exclude all follow-on time histories and Battelle used the conservative KME criteria to determine if a time history was in the set of time histories to be used to evaluate the safety systems. The 14,946 conflicts that Battelle used were a subset of the 57,550 conflicts in the Volvo Partnership Report.

Appendix D13. Sensitivity of the Lag Time Kinematic Algorithm to Following Vehicle Lane Changes

One of the important features of the kinematic algorithm described in Step 5 of Section 4.3.3 is that when the lead vehicle disappears before the end of a time history, the position of the lead vehicle is not extrapolated beyond that time when calculating the additional lag time available before the following vehicle needs to brake or steer to avoid a crash. If the lead vehicle disappears due to the actions of the lead vehicle, then those same actions are kept constant in the lag process. However, if the lead vehicle disappears due to the actions of the following vehicle, then it would have been more appropriate to predict the position of the lead vehicle when lagging the lane change time of the following vehicle. This analysis was not performed in creating the main results. This appendix explores the effect that these situations (following vehicle lane changes) might have on the results.

The first step was to identify the time histories which may have been excluded due to following vehicle lane changes in the Restricted KME Conflict Definition. Conflicts of interest were those with a lag time equal to 15 seconds, where the following vehicle executed a lane change and where there was a lead vehicle present prior to the lane change. These conflicts were then divided appropriately into fleets, kinematic thresholds, and conflict categories and then were added to the Restricted KME Conflict Definition exposure rates. In all, 1800 conflicts were added to the 2,203 conflicts in the Restricted KME Conflict Definition. The exposure ratio estimates are shown in Figure D13-1. There is no change in the exposure ratios for the KME Conflict Definition, since these 1,800 conflicts are already included in the 12,360 conflicts used to calculate those exposure ratios. Table D13-1 gives the percent increase in the conflict rate for each fleet and conflict category for the Restricted KME Conflict Definition and the conservative threshold.

Table D13-1. Percent Increase in the Conflict Rate for each Fleet and Conflict Category due to Following Vehicle Lane Changes (Restricted KME Conflict Definition, Conservative Threshold)

Fleet	Constant Speed	Slowing	Lane Change	Overall
Baseline	113%	84%	21%	79%
Control	107%	91%	34%	85%
Test	200%	88%	46%	92%

The exposure ratios shown in Figure D13-1 are different from those in Figure 5.1-8. Most notably, the ACC and AdvBS exhibit a significant dis-benefit for the constant speed category for all thresholds in Figure D13-1. Also, the effect of the CWS is significant in Figure D13-1 for the lane change category at the aggressive threshold.

The prevention ratios for both conflict definitions remain unchanged in this analysis. Future work can be performed to change the kinematic algorithm to project the lead vehicle position during following vehicle lane changes after the target has disappeared from the radar. A new algorithm would be able to estimate the lag time for these conflicts, and this new set of lag times could be used to better estimate the prevention ratios.

Without the additional analysis to estimate the prevention ratios for both the KME and Restricted KME Conflict Definitions for the wider set of time histories considered to be conflicts in this appendix, it is difficult to infer safety benefits. However, the effect of the altered exposure ratios on the overall safety benefits are shown in Figure D13-2. There are two major differences between this figure and Figure 5.1-12. First, Figure D13-2 shows a consistent, although not statistically significant, dis-benefit for the effect of the ACC and AdvBS. Second, the effect of the bundled system is no longer significant for the medium threshold.

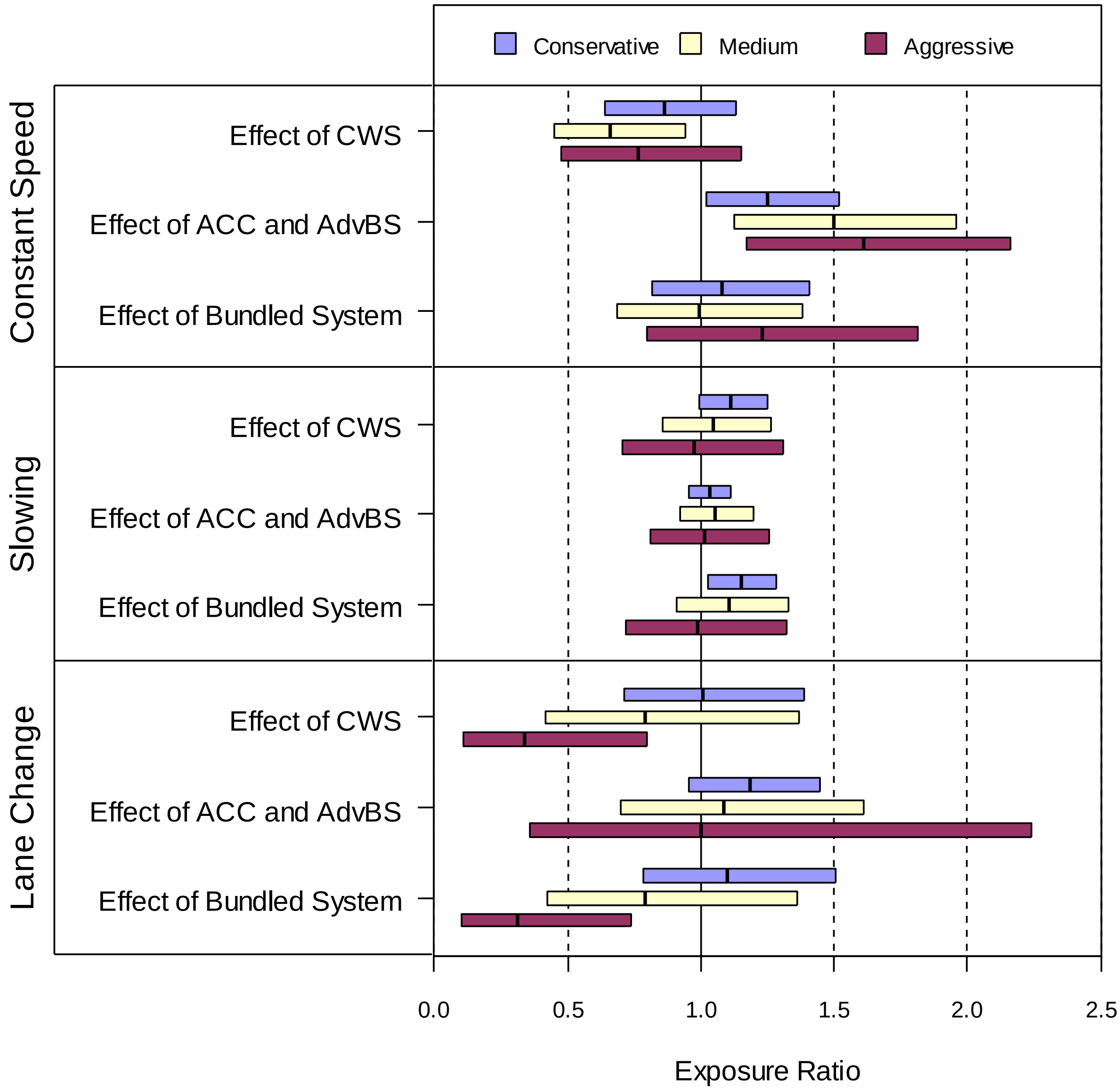

Figure D13-1 Exposure Ratios by Conflict Category, Fleet, and Threshold with 95% Confidence Intervals Including Time Histories where the Following Vehicle Executes a Lane Change to Avoid the Lead Vehicle.

Error bars denote +/- two standard errors; benefits are to the left of 1.00; disbenefits are to the right

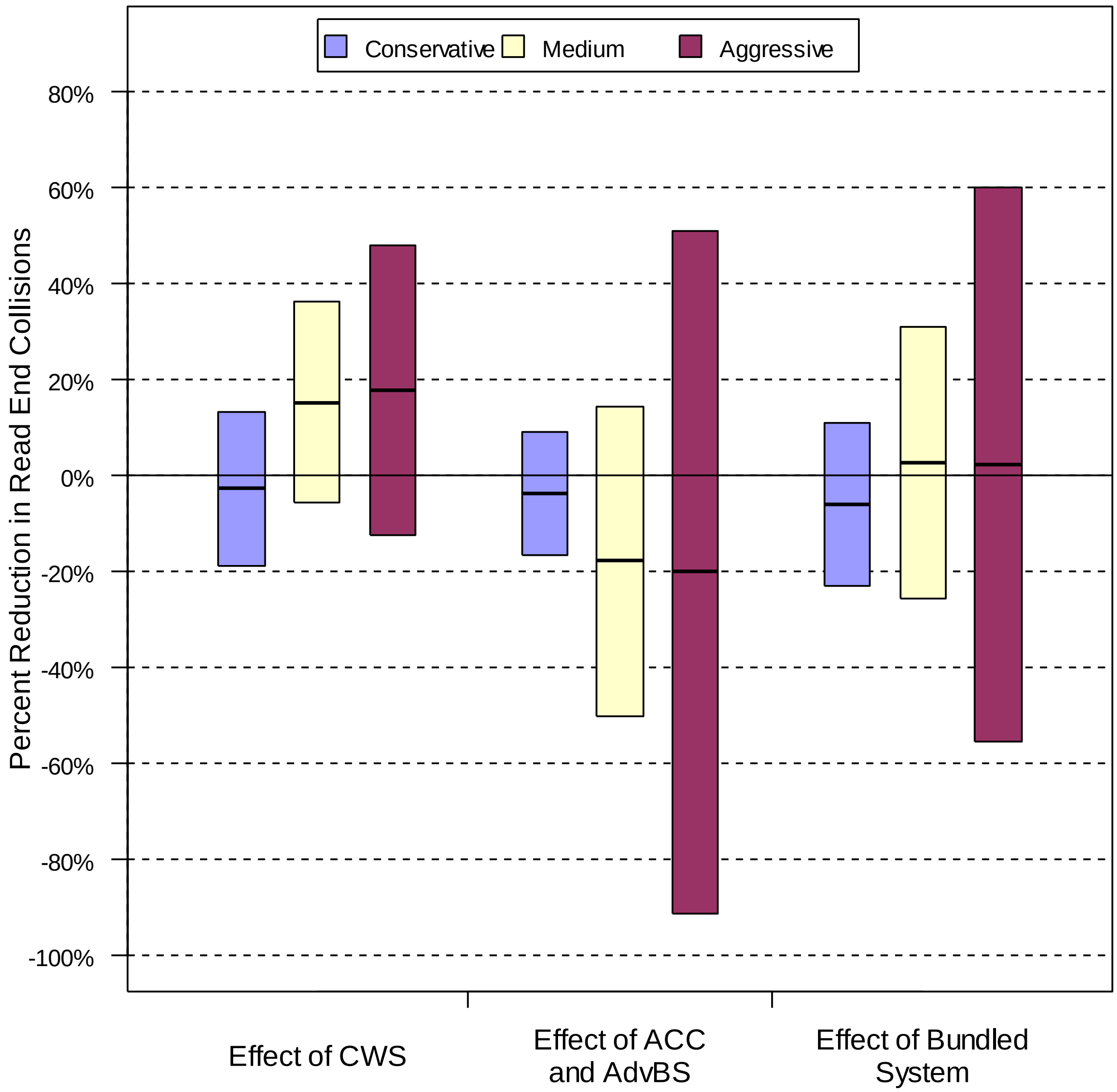

Figure D13-2. Estimated Percent Reduction in Rear-End Crashes Attributable to Deployment of Selected IVSS Technologies using the Restricted Kinetic Motion Equation (RKME) Conflict Definition Method Including Time Histories where the Following Vehicle Executes a Lane Change to Avoid the Lead Vehicle.

(Error Bars Represent Approximate 95% Confidence Intervals)

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APPENDIX E.

ENGINEERING DATA SUPPORTING DOCUMENTATION

Appendix E.

Engineering Data Supporting Documentation

Some of the changes that occurred during the FOT affected the collection of data onboard the vehicles. The Evaluation Team took these changes into consideration in the analyses conducted. However, to assist the readers in understanding the whole process, this appendix summarizes the changes, and documents how they may have impacted the Evaluation. The appendix also presents detailed information on vehicle data management.

Data Changes

The histogram data collected during the Volvo FOT remained consistent over the course of the FOT. The time history data collection triggers as well as the time history data channels changed a number of times due to requests for additional triggers and channels from Battelle and USDOT. When a new configuration file became available, some changes in time history triggers and channels were implemented through simple configuration file changes. All trucks did not receive the new configuration files at the same time. Trucks that called in, got all of their data uploaded, and still had time for a configuration download received the new configuration file. Because the channel azimuth—which was required for inferring the lateral motion of the lead vehicle—was not introduced until the configuration file released on May 31, 2001, only time history data collected based on that configuration file or a later one is appropriate for the safety benefits analysis.

During the course of the Volvo FOT, USDOT, in cooperation with the Volvo Partnership, implemented some changes to the data acquisition system (DAS) for trucks. This effort was initiated to gather new data to evaluate certain performance characteristics of the CWS, as well as to correct errors in the original DAS (referred to as DAS-1). This section details the data collected with the original DAS (DAS-1) as well as data collected with the updated DAS (DAS-2). Differences in time history channels between DAS-1 and DAS-2 are documented in Section 4.2.2.

Decisions concerning the data to be collected by DAS-1, such as which data elements to include and triggering mechanisms, were made jointly by USDOT, ATC, Mitretek, Volpe, and Battelle. The DAS was initially designed to trigger data collection in the form of 15-second time histories every time a VORAD alarm sounded. However, not only was this too costly to implement, due to the volume of data, it was also inadequate because it would not have included situations where a conflict existed but no alarm sounded. In the end, it was agreed that time history data collection would be triggered based on lateral and longitudinal acceleration, steering rate, time to collision, following interval, and kinematic motion equations derived by Battelle and Volpe. Only one of these criteria—less than 0.5-second following interval—corresponds to a VORAD alarm. Time history data collection triggers were not changed between DAS-1 and DAS-2.

Vehicle Data Management

1. Vehicle data bus: Vehicle data bus failures were identified when the ambient temperature reading was -273ºC. These failures caused all data elements collected from the data bus (e.g., vehicle speed) to be missing.

2. VORAD CWS data bus: Failures of the VORAD CWS data bus or sensor were indicated by constant target range data. In such instances, time history files triggered by VORAD conditions (Table 4.2-7) were not created, VORAD data elements recorded in time history files created by other triggers were invalid or missing, and events based on VORAD information could not appear in histogram data.

3. Steering angle sensor: Several measures were used to identify failures of the steering angle sensor.

    a. The primary failure mode for a steering angle sensor was identified by a nearly constant value for an entire time history, resulting in the standard deviation of the steering angle data collected in a history file being zero. The algorithm calculated the standard deviation of steering angle data for each time history file. All time history files collected during a histogram period were also flagged if more than 7% of the files had a standard deviation below 4 degrees.

    b. The steering sensor failure could also be identified by artificial spikes or other noncontinuous events, which would trigger a large number of time history files under the "Steering angle rate >120 deg/s" triggering condition. If 20% or more of the time history files created during a histogram period were triggered by "Steering angle rate >120 deg/s," the files were flagged.

    c. Another characteristic of the data collected by steering angle sensor was a drift over time. The drift was corrected by artificially recentering the steering angle data on a monthly basis prior to use in analyses.

    d. Steering angle data were derived from the VORAD yaw rate data element, when available.

4. Biaxial accelerometer sensor (fore/aft and lateral): Accelerometer failures were indicated by large constant accelerations, which led to the continuous triggering and recording of time history data.

Additional validation checks were performed by the Battelle Team to identify data inconsistency using information stored in the headers of histograms and time history files. Table E-1 summarizes header information for histograms and time history files.

- The Vehicle Miles Traveled (VMT) of each histogram reporting period was calculated by subtracting starting mileage (odometer start) from stopping mileage (odometer stop). When these calculations resulted in negative or unreasonably large numbers, mostly because either starting or stopping mileage was erroneously reported as zero, the VMT for the period was calculated by integrating the speed histogram.

- Header information was also used to match time history data to the histogram period during which the time history file was created.

Table E-1. Header Data Elements for Histogram and Time History Data Files

Channel	Time History	Histogram	
	Start	Start	Stop
Odometer	Yes	Yes	Yes
GPS Coordinates/Time	Yes	Yes	Yes
Ambient Temperature	Yes	Yes	Yes
VORAD Data Snapshots (Range, Azimuth & Relative Speed) for All Identified Targets	Yes	-	-

Various changes implemented throughout the FOT included:

- Changes in the original DAS design (referred to as DAS-1) to correct errors. The new DAS design was referred to as DAS-2.

- Changes in the list of measurement channels collected in time history files (Table 4.2-8):
    - "Target azimuth" data were added to infer the lateral motion of the lead vehicle
    - "ABS Active" data were added
    - "DDU Display Message Update" data were added and replaced "DDU Light" and "DDU Audio" data channels
    - "Following interval" and "Time to collision" data channels were deleted
    - "VORAD yaw rate" data were added to identify steering maneuvers.

- Collection of ATH files to evaluate certain performance characteristics of the CWS.

Because of the multiple requests for changes and because of the limited access to tractors, these changes were not all implemented at the same time. These changes also had consequences on the data analyses performed by the Evaluation Team. For example, only time history data files collected with azimuth information were appropriate for the safety benefits analysis.

DAS-1 Yaw Rate Calculations

Because the yaw rate became the primary measure used to assess lateral movement of the vehicle, only data collected with DAS-2 were validated and analyzed by the Volvo partnership and, thus, are the only data included in this report. DAS-1 utilized steering position for capturing the lateral movement of the truck. The algorithm below (labeled Steering to Yaw Conversion Algorithm) was developed for computing yaw rate from steering position prior to the decision to analyze only DAS-2 data.

Steering to Yaw Conversion Algorithm

1. Centered steering position was computed for each truck by subtracting off average steering position by truck and month

2. Variable calculated yaw was computed as follows:

   Yaw = –(centered steering position)(truck velocity)/(18*truck wheelbase)*

   where truck wheelbase was 18.3 feet

3. A 9-point moving average of calculated yaw was computed

4. This variable was lagged 4 time steps (2/3 of a second) and multiplied by 0.82492.

Average steering position was calculated by month as well as by truck because drift in average steering position over time was noted for many trucks. The 4 time step lag, the damping factor of 0.82492, and the moving average window of 9 were all chosen based on the analysis of an interim dataset available early in the FOT. This dataset consisted of data from trucks that were recording both yaw rate and steering position.