Contract No. DTFH61-96-C-00077 Task Order 7718

Final Report
Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test

U.S. Department of Transportation
Federal Highway Administration

NHTSA
People Saving People

FMCSA
Federal Motor Carrier Safety Administration

for

U. S. Department of Transportation

Washington, D. C.

by

Battelle

505 King Avenue

Columbus, Ohio 43201-2693

May 2003

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U.S. Department of Transportation
Washington DC 20590

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List of Appendices

Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test

Executive Summary

The intent of the Intelligent Vehicle Initiative (IVI), sponsored by the U.S. Department of Transportation (USDOT), 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 cooperative agreements with four partnerships to conduct Generation 0 Field Operational Tests (FOTs) of advanced intelligent vehicle safety systems (IVSS). These systems, which were expected to begin production preparations before the end of fiscal year 2003, were designed for use in commercial trucks and specialty vehicles (e.g., snowplows and emergency vehicles).

An important activity of the IVI program is to evaluate the benefits and costs of IVSS as they are deployed in the FOTs and learn about factors that influence the future deployment and comercialization of IVSS. Thus, the USDOT contracted with Battelle to perform an independent evaluation for each of the four IVI FOTs. This report presents the evaluation results from one of the commercial truck FOTs, namely the Freightliner IVI FOT.

The Freightliner IVI FOT

Freightliner—in partnership with Praxair, the fleet operator; the University of Michigan Transportation Research Institute (UMTRI), the technology integrator; and Meritor-Wabco, the component supplier—tested two related but distinct functions of a new Roll Advisor and Control (RA&C) system. The RA&C is designed to assist commercial vehicle drivers, especially drivers of tanker trucks, in avoiding rollover crashes. The benefits of RA&C for helping to avoid single-vehicle roadway departure (SVRD) crashes were also evaluated. During the time of the FOT, Freightliner began offering the RA&C for sale.

The first component is the Roll Stability **Advisor** (RSA), which is intended as an educational tool for drivers. The RSA will not prevent any particular crash through direct intervention. Instead, it merely advises a driver, after a maneuver is finished, that the lateral forces on the vehicle were higher than might have been desirable. The RSA's advisory notices are provided to the driver as briefly worded messages appearing on the instrument panel display. The second component is the Roll Stability **Control** (RSC). This system takes partial, momentary control of the vehicle if it deems that a serious rollover threat is developing. The system's authority in the FOT was limited to reducing the throttle or applying engine braking. Only a minimal amount of deceleration is applied in this manner, but the hope is that a bad situation can be prevented from becoming worse.

As the independent evaluator, Battelle and a team of subcontractors analyzed the FOT data and conducted independent studies to estimate the safety benefits of the RA&C, assess driver acceptance of the new technology, and study the prospects for widespread deployment. Battelle participated in driver interviews and conducted independent track tests of the RA&C to support a system performance assessment and to validate the vehicle dynamic simulation models used in the safety benefits estimate.

Evaluation Goals and Methods

The goals for the Freightliner IVI FOT evaluation and the methods used were as follows:

Goal 1A. Achieve an In-Depth Understanding of Safety Benefits. The primary safety benefit expected from the deployment of the RA&C is a reduction in the number of heavy truck rollovers and the resulting injuries and fatalities. Three objectives under this goal are achieved by answering the following questions: (i) Do drivers drive more safely with RA&C than without it, in ways related to the system? (ii) Do vehicles equipped with RA&C have fewer crashes than those without it? (iii) If all vehicles in the national fleet were equipped with RA&C, would there be a decrease in the total number of crashes and crash-related injuries and fatalities? **Methods:** Data sources included historical crash data, engineering data collected in the course of the FOT, special track tests, and driver interviews. Time domain vehicle dynamic simulations and statistical models were used to estimate safety benefits (i.e., crash reductions).

Goal 1B. Achieve an In-Depth Understanding of Mobility Benefits. Transportation mobility refers to the ease of movement, or perceived ease of movement as viewed by the traveling public. Benefits are usually measured in terms of travel-time savings and reduced congestion. **Methods:** The mobility benefits of IVSS were estimated directly from the number of crashes avoided, as determined in Goal 1A, and literature-derived estimates of the effect of crashes on travel time and congestion.

Goals 1C and 1D. Achieve an In-Depth Understanding of Efficiency and Productivity Benefits. Efficiency generally refers to the amount of output (e.g., cargo ton miles) for a given input (driver or vehicle days). IVSS affects the efficiency of commercial fleet operations through reduction of the number of crashes or through operational effects that can be measured in terms of productivity gains or losses (cost savings or increases). Deployment of IVSS can result in productivity increases through cost savings from reduced numbers of crashes and lower insurance rates. **Methods:** Personal interviews with FOT participants and other key informants were performed to identify initial and recurring costs (e.g., purchase, installation, maintenance, and training) and determine the value of cost savings or other benefits. A comprehensive benefit-cost analysis was conducted, using cost values from the FOT and from the literature, combined with estimates of safety benefits.

Goal 1E. Achieve an In-Depth Understanding of Environmental Quality Benefits. A reduction in the number of crashes resulting from the deployment of RA&C system also benefits the environment in terms of fewer hazmat spills and reduced fuel consumption and air pollution from traffic congestion caused by crashes. **Methods:** These benefits were estimated as secondary benefits resulting from the estimated number of crashes prevented, and in turn were applied to the benefit-cost analysis.

Goal 2. Assess User Acceptance and Human Factors. This goal area focuses on understanding (i) how IVSS technologies affect the driving environment, and (ii) if and how human factors may play a role in the eventual acceptance and deployment of the systems. The four principal objectives are to assess usability of the system, its effect on the driver workload and stress, the effect on driver behavior, and the drivers' perceptions of value. **Methods:** Driver interviews before system activation and at the conclusion of the test and monthly questionnaires were used to assess driver acceptance. Driver responses were compared with objective driving data in the safety benefits analysis. An independent ergonomic assessment was performed from a human factors perspective.

Goal 3. Assess IVSS Performance and Capability Potential. This goal area deals with the ability of the IVSS to perform its functions according to design specifications and meet minimum reliability and maintainability criteria. **Methods:** Data sources for the performance assessment include FOT driving data, driver interviews, and special track tests. Reliability of the system was assessed by inquiring whether any of the units needed to be serviced during the FOT and searching the on-board data for self-diagnostic messages from the units.

Goal 4. Assess Product Maturity for Deployment. The objectives of this goal area were to assess the logistics and feasibility of large-scale production, production and installation costs, related infrastructure investments, and the need to achieve consistency with ITS standards and architecture. **Methods:** Five objectives under this goal were met by gathering information from the vendor and conducting interviews from key informants from external organizations.

Goal 5. Address Institutional and Legal Issues that Might Affect Deployment. Even though IVSS could effectively meet the performance and benefit goals established, institutional and legal issues could influence the adoption of the technology. Matters such as product liability, possible eventual regulation of the RA&C, and driver privacy were identified and discussed. **Methods:** Key informant interviews were conducted with manufacturers, trade groups, motor carriers, and other industry sources.

Findings

> Under conditions similar to those observed in the FOT, the RA&C is expected to prevent 20% of rollover crashes caused by excessive speed in a curve.

Safety Benefits (Goal 1A). There was a slight reduction in the overall risk-taking behavior by FOT drivers that can be attributed to the educational function of the RA&C. To estimate the *efficacy* of the RA&C at preventing rollover crashes, driving conflicts were defined as safety-critical driving scenarios that precede crashes. The driving conflict that is relevant to the RA&C is generally defined as a vehicle moving at excessive speed in a curve. These conflicts were identified in the onboard driving data, and rates at which driving conflicts occurred during the pre- and post-system activation phases of the FOT were estimated. Also, the corresponding conditional probabilities of a rollover crash (given that a particular driving conflict has occurred) were estimated using detailed onboard driving data from each driving conflict identified and a time domain vehicle dynamic simulation model, which was validated with data from test track maneuvers. The safety benefits methodology combines the estimated changes in conflict rates (exposure) and conditional crash probabilities (prevention) to estimate the efficacy of the RA&C at preventing rollover crashes. Because this particular conflict type (excessive speed in a curve) can also lead to single-vehicle roadway departure (SVRD) crashes, the RA&C is expected to achieve a similar efficacy for preventing SVRD crashes.

> For the national fleet of approximately 110,000 tanker trucks, we estimate that the RA&C will prevent 34 crashes, 21 injuries, and two to three fatalities per year.

Data from the U.S. DOT's General Estimates System (GES) and Fatality Analysis Reporting System (FARS) for the years 1995 through 2000 were used to determine the annual average numbers of rollover and SVRD crashes for various categories of heavy trucks. The estimated RA&C efficacy (percent reduction in relevant crashes) was then applied to the numbers of crashes, fatalities, and injuries, which occurred without the RA&C, to estimate the numbers of crashes, fatalities, and injuries that the deployment of the RA&C could help motor carriers avoid. The analysis was performed for four subsets of the national truck fleet (tractors + tanker trailers carrying hazardous materials, tractors + tanker trailers, tractors + trailers, and all large trucks over 10,000 pounds gross vehicle weight). It is straightforward and appropriate to apply the RA&C efficacy derived from this FOT to the fleet of truck tractors pulling tanker trailers, especially for fleets that haul hazardous materials. However, to illustrate the *potential* benefits under wider deployment, the findings from this FOT are extrapolated to the larger fleets, even though it was not possible to validate the applicability of RA&C efficacy beyond the fleet of tractors pulling tanker trailers. Table ES-1 shows the potential annual reductions of crashes, injuries, and fatalities for all four truck fleets. The potential reductions were calculated using RA&C efficacy estimates of 20% for rollover crashes and 33% for SVRD crashes caused by high speed in curves. These are the best estimates derived from driving data collected in the FOT.

There is some evidence to suggest that drivers drive more slowly on particular curves after they were advised by the RSA to slow down during a previous trip. The behavior may be specific to the curve on which the advisory was given or it may be the result of changes in overall driving behavior.

> On the test track, the RSC consistently triggered as the vehicle approached the limit of roll stability.

Examined in isolation, the Roll Stability Control (i.e., the portion of the RA&C that is able to take momentary control of the vehicle's speed) performed well during the planned tests on the closed course, but it showed little benefit during the operational test. In most of the tests performed, it prevented the outrigger (used to avoid an actual rollover) from touching the pavement. In the FOT, the RSC was triggered several times, but it actually slowed the vehicle in only a few cases. It was triggered only when the tank was empty and the truck was not actually in danger of rolling over. Meritor-Wabco reports that the system's weight-estimating method has been improved since the FOT. This is expected to improve the performance of the system in operation.

Table ES-1. Estimated Annual Reduction in Crashes, Injuries and Fatalities for Four Target Populations

		Annual Reductions[1]		
		Rollover – Fast Turn	SVRD – Fast Turn[2]	Potential Reduction[3]
Total Trucks in Crashes per Year	All Large Trucks[4]	157	661	819
	Truck-Tractor with Trailer[5]	94	408	502
	Truck-Tractor with Tanker Trailer[6]	9.3	25	34
	Truck-Tractor with Hazmat Tanker Trailer[7]	0.9	8.5	9.4
Total Injuries per Year	All Large Trucks	128	202	330
	Truck-Tractor with Trailer	65	110	175
	Truck-Tractor with Tanker Trailer	7.4	13	21
	Truck-Tractor with Hazmat Tanker Trailer	0.9	3.7	4.6
Total Fatalities per Year	All Large Trucks	4.5	9.0	13.5
	Truck-Tractor with Trailer	2.8	6.2	9.0
	Truck-Tractor with Tanker Trailer	1.2	1.3	2.5
	Truck-Tractor with Hazmat Tanker Trailer	0.5	0.6	1.1

1. Calculated using RA&C efficacy of 0.20 for rollover crashes and 0.33 for SVRD crashes caused by high speed in turns
2. SVRD = Single-vehicle roadway departure
3. Rows may not sum due to rounding
4. Class 3-8 trucks over 10,000 lbs. gross vehicle weight
5. Class 7 and 8 tractors with any trailing unit
6. Class 7 and 8 tractors with tanker trailer unit
7. Class 7 and 8 tractors with tanker trailer unit displaying hazmat placard

Benefit-Cost Analysis (Goals 1A – 1E). Benefits related to improvement in safety, mobility, efficiency, productivity, and environmental quality (Goals 1A through 1E) were combined and given monetary values to be used as inputs to a formal benefit-cost analysis. This analysis, performed from a national perspective, compared the total societal benefits of reduced crashes, fatalities, and injuries to the total societal costs of deploying the RA&C across the respective fleets of trucks. Benefit-cost analyses were performed for each of the four target deployment populations modeled in the safety benefit analysis (tractors + tanker trailers carrying hazardous materials, tractors + tanker trailers, tractors + trailers, and all large trucks). The benefit-cost analysis modeled the discounted costs and benefits of both maintaining the level of deployment and continuing to accrue crash-avoidance benefits over a period of 20 years. Results were calculated in terms of net present value, undiscounted and also separately at discount rates of 4 percent and 7 percent. The results assuming a 4 percent discount rate are presented in this summary.

The cost of purchasing an installed RA&C system is estimated to be $385 per vehicle. The system is expected to last 10 years, equal to the expected life of the tractor, with negligible maintenance and repair costs. The one-time cost for one hour of driver training is also included in the cost model. It is assumed in the baseline case that the vehicle already is equipped with a separate $400 traction control system (TCS), which is required for the operation of the RSC component of the RA&C. Our baseline (best estimate) cost model does not include the cost of the traction control system because (a) the RSC showed little or no benefit in the FOT, and (b) the benefits of the traction control system were not evaluated and, therefore, not included in the BCA.

The number of crashes avoided in each deployment scenario was calculated using baseline (best estimate) efficacies of 20% for rollover crashes and 33% for SVRD crashes caused by high speed in curves. The estimated value of each avoided crash included factors such as the cost of property damage, injuries, fatalities, cargo loss, reduced mobility, and environmental clean-up.

To assess the sensitivity of selected cost and benefit parameters on the overall BCA, alternative cost and benefit models were defined. The alternative cost model assumes that anyone purchasing RA&C would either have traction control on the truck or would be required to purchase traction control for an additional $400. Nationally, traction control is installed in only about 10 percent of large trucks. Thus, under the alternative cost model, the weighted average cost to purchase RA&C increased from $385 to $745.

Two alternative benefit models were also defined by considering both optimistic and pessimistic approaches to dealing with missing data or estimates that were not statistically significant. The pessimistic (worst-case) approach assumes that the RA&C efficacy is 20% for both SVRD and rollover crashes. The optimistic (best-case) approach assumes both efficacies are 33%.

The benefit/cost ratios under six different combinations of benefit and cost models (3 benefit models times 2 cost models) for each of the four deployment scenarios are shown in Table ES-2 and depicted graphically in Figure ES-1.

> Sensitivity analysis demonstrates that the deployment of RA&C on the fleet of tractors pulling tanker trailers and other fleets is economically justified under a variety of benefit and cost assumptions.

The ratios under the baseline assumptions (using "best estimate" cost and benefit models) are shown in the first column of Table ES-2 and displayed with an "X" in Figure ES-1. The most promising baseline application of the RA&C system, indicated by a benefit/cost ratio of 2.69, occurs for truck tractors pulling tankers. Even under the worst-case efficacy and cost assumptions the benefit/cost ratio for this fleet is greater than 1.0, indicating a net benefit to society. The benefit/cost ratio under the baseline assumptions (2.02) is slightly lower when the fleet is restricted to the fleet of tankers carrying hazardous materials. This occurs because, even with the higher costs of hazmat crashes (due to higher environmental cleanup costs), hazmat tankers have a smaller opportunity for crash avoidance benefits due to the fact that hazmat tankers are much less likely to be involved in a crash than non-hazmat tankers. Approximately 50% of tanker trailers carry hazardous materials; yet, they account for only 25% of the tanker trailer crashes. However, the benefit cost ratio is still greater than 1.0 under all but the worst-case combinations of efficacy and cost assumptions.

Table ES-2. RA&C Benefit-Cost Ratios for Four National Deployment Scenarios under Baseline and Alternative Assumptions

	Baseline Efficacy (20% and 33%)		Worst-Case Efficacy (20% and 20%)		Best-Case Efficacy (33% and 33%)	
TCS Costs[1]:	**Excluded[2]**	**Included**	**Excluded[2]**	**Included**	**Excluded[2]**	**Included**
HazMat Tankers	2.02	1.06	1.59	0.83	2.64	1.39
All Tankers	2.69	1.41	2.08	1.09	3.43	1.80
Tractor Trailers	1.08	0.58	0.79	0.42	1.32	0.70
Large Trucks	0.34	0.18	0.25	0.13	0.40	0.22

Note: Shaded cells indicate ratios >1 (positive net benefit to society).

1 TCS: Traction control system. When costs are excluded, the models assumed that all trucks would already have the TCS paid for at the time of purchasing the RA&C. When TCS costs are included, the models assumed that 10% of trucks would have TCS already paid for, and that 90% of truck purchasers would need to buy TCS in order to obtain the benefits of the RA&C technology.

2 Baseline scenario (i.e., best estimates of cost and efficacy parameters).

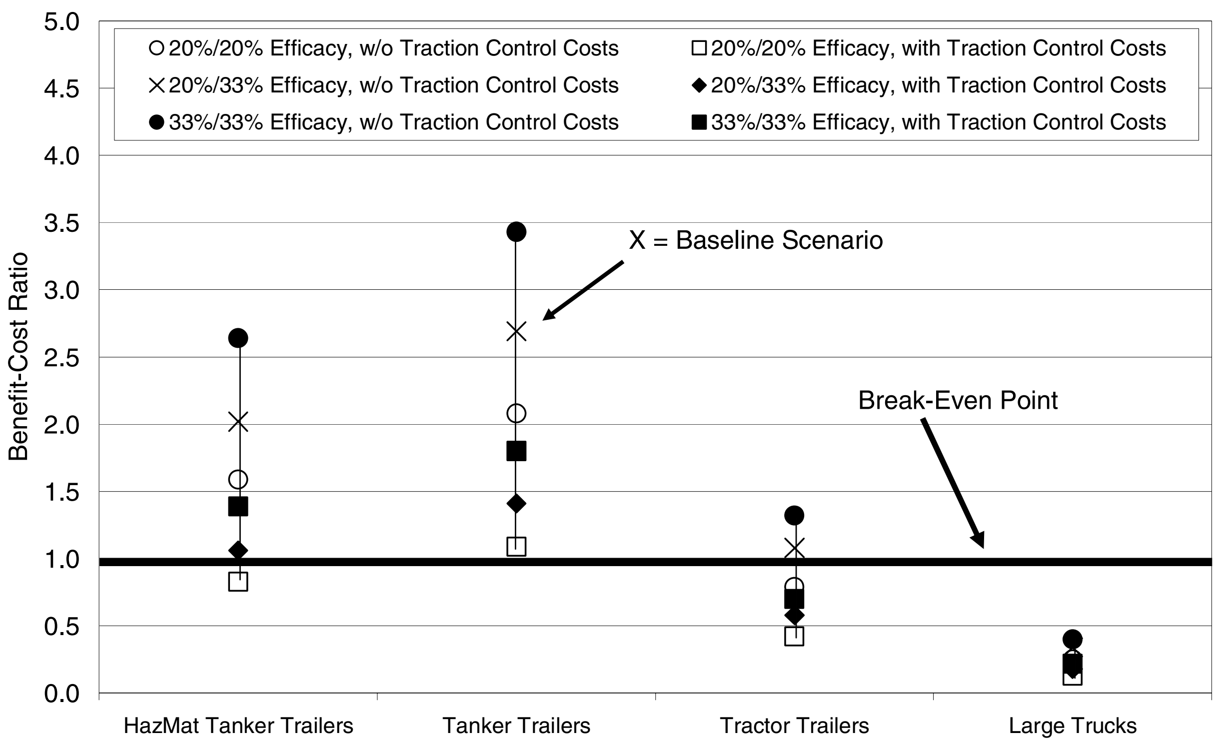

Figure ES-1. Benefit-Cost Ratios across All Scenarios under Baseline and Alternative Assumptions

The benefit/cost ratio for the fleet of all tractor-trailer combinations under the baseline assumptions (1.09) indicates a slightly positive benefit of deploying RA&C in the larger fleet. When the TCS costs are excluded, the ratio ranges from 0.79 to 1.32, depending on the efficacy assumptions. However, when TCS costs are included, the deployment of RA&C for all tractor-trailer combinations is not justified; unless it can be demonstrated that the additional benefits of TCS exceed the costs.

Under the most optimistic assumptions (33% efficacy for both rollover and SVRD crashes due to high speed in curves and TCS costs excluded), it is apparent that deployment of RA&C to the entire fleet of large trucks over 10,000 pounds gross vehicle weight is not economically justified. The maximum benefit cost ratio determined for this fleet was 0.40, indicating that the potential benefits are no greater than 40% of the anticipated costs.

User Acceptance and Human Factors (Goal 2). Key findings obtained concerning driver acceptance and human factors include:

- Before the start of the test, all of the drivers expected the RA&C to either greatly reduce or somewhat reduce their chances of a rollover. Drivers were optimistic that the systems could be useful to all types of drivers.
- Drivers indicated that the message center was a good way of delivering advisories, they could hear the tone, they could distinguish RSA advisories from other messages, and they did not find the RSA distracting.
- The training was viewed as adequate for the systems, and drivers experienced no problems in learning how to use the systems.

> The drivers approved of the message center design.
>
> Drivers showed a change in risk over time that can be attributed to the use of the RA&C system as a learning tool, as intended.
>
> The majority of drivers perceived the RSA messages to be useful, and this perception held over time.

- Having the systems did not lead to a perceived increase in workload or stress. A number of drivers even indicated a slight reduction in perceived workload due to the systems.
- Over time, drivers' responses indicated a change in awareness that they were driving differently as a result of the systems, even though many drivers had initially indicated no expectation that their driving would change as a result of the system.
- Most drivers preferred the RSA (advisory) function to the RSC (controller). Only a few preferred the RSA to a forward collision warning or a lane departure warning system.
- Drivers believe the benefit of the RA&C will be greater when it is deployed more widely, particularly with less experienced drivers. Independent analysis of the changes in conflict rates versus the experience level of the FOT drivers could not confirm this belief. The drivers might be expressing their feeling that younger drivers experience more conflicts and are more likely to be involved in rollover or SVRD crashes. Such benefits are accounted for in the safety benefits analysis.

Performance and Capability Potential (Goal 3). The repeatability of the RSA on the test track was good. In the uncontrolled conditions of the FOT, it occasionally issued messages in situations where the rollover risk was minimal and missed a few situations of higher risk. Drivers' opinions of the accuracy were mixed but generally positive. Most drivers indicated that at one time or another they received a message they thought was wrong. None of the units required maintenance during the year-long FOT, and no self-diagnostic messages were recorded. This experience provides confidence that the system can be as reliable as modern ABS technology.

> The RA&C system appears to be reliable. With minor exceptions, the RA&C seems to have been functioning as it was intended throughout the FOT.

Product Maturity for Deployment (Goal 4). There were two technical obstacles delaying the development of the RA&C for commercial introduction. One was an unexpected difficulty in accurately determining the mass of the vehicles as operated. The second technical obstable was a decision to change the method of retarding the vehicles from using engine braking to foundation braking. According to the Freightliner and Meritor-Wabco representatives, the two obstacles have been addressed and accommodated such that the system now functions at an accuracy level acceptable for production.

> Freightliner is currently offering the RA&C as an option on its high-end tractors.

Based on interviews, track testing, and engineering judgments, the RA&C device can be used with other types of truck operations and trailer loads. Freightliner and Meritor-Wabco are both open about the fact that the RA&C has no instruments on the trailer and, therefore, does not know the height of the load's center of gravity. The capability to estimate center of gravity height would be most important for drivers who carry loads with a different center of gravity height each day, such as bulky equipment or less than truckload.

Institutional and Legal Issues (Goal 5). Standardization of safety control layouts and driver interface is essential. Some drivers are in the same truck every day, while other drivers rotate frequently from one vehicle to another where controls and alerts are likely to differ. Safety systems must be intuitive such that drivers don't have to consciously think about them, especially in emergency situations. When the RA&C is deployed beyond the Freightliner Century class, the system's sights and sounds must be kept as consistent as possible and they should comply with ITS driver interface standards.

> Standardization of safety devices such as RA&C is needed to ensure that their control systems are logical and intuitive, and that their operation and use are properly regulated.

The "big brother" question arose even before the start of the FOT over the possibility of informing management of individual drivers' RA&C counts. Most drivers, though, had no objection to reporting RA&C events to management and viewed it as a benefit to safety. Those who voiced concerns over disclosure usually cited the inaccuracy of the yet immature system rather than opposition to the principle of reporting to management. As the RA&C was installed for the FOT, drivers could clear their count at the end of a shift, thereby protecting their privacy. Doing so would also clear a meter of miles and hours, so fleets choosing to implement management review would know when a driver has cleared the system.

> The legal issues deal primarily with the regulations and liability risks associated with product deployment and how they can best be anticipated and mitigated.

Legal issues can arise in conjunction with product failures, product inspection, and driver distractions. Documentation of due diligence in testing the product helps to mitigate some issues, as does compliance with industry standards on driver displays. It is critical for acceptance and use that this new technology be applied in both appearance and deed to focus on safety improvement rather than assessment of blame.

Implications of Findings

The RA&C was still in a developmental stage when it was deployed in the Field Operational Test. The drivers participating in the test were skilled and experienced. That the advisory function had any effect at all in improving drivers' practices bodes well for its larger deployment. Even in this study of 12 months, 15 drivers, and only six tractors, a statistically significant reduction in risky driving behavior was observed.

Organization of This Report

This report is arranged in seven 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. Results
6. Implications of the findings in the context of the larger safety issue
7. Recommendations for future FOTs.

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

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Other major contributors to the project were as follows:

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Surface Transportation Associates: Bjorn Klingenberg—Product Maturity

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Charles River Associates: Dan Brand and Mark Kiefer—Benefit Cost Analysis

Transportation Research Center: George DeShetler—Experiments on the Test Track

PBS&J: Craig Roberts—Legal Issues

We also thank those who gave their time for the interviews on Institutional and Legal Issues.

Abbreviations and Nomenclature

Term	Definition
ABS	Antilock braking system
ACC	Advanced cruise control
ATA	American Trucking Associations, Inc.
ATRI	American Transportation Research Institute
Ay	Lateral acceleration
B	Baseline period
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
CD	Compact disk
CG	Center of gravity
CVSA	Commercial Vehicle Safety Alliance
DAS	Data acquisition system
DMC	Driver Message Center
ECBS	Electronic control brake system
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FOT	Field Operational Test
g	Acceleration due to gravity, 9.8 m/s^2
GES	General Estimates System
GPS	Global Positioning System
GVW	Gross vehicle weight
HAZMAT	Hazardous material
HBED	Hard-braking event detector
HM	Hazardous material
Hz	Hertz, cycles per second
ITS	Intelligent Transportation System
IVI	Intelligent Vehicle Initiative
IVSS	Intelligent Vehicle Safety System(s)
LDW	Lane departure warning
MCMIS	Motor Carrier Management Information System
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
NPSRI	National Public Services Research Institute
NPTC	National Private Truck Council
O	Overall period (Baseline + System On)
OEM	Original equipment manufacturer
P	Principal data source
PAR	Police accident report
RA&C	Roll Advisor and Control (RSA + RSC)
RSA	Roll Stability Advisor
RSC	Roll Stability Control

Abbreviations and Nomenclature (Continued)

Term	Definition
S	Supplemental data source
SO	System On period
SVRD	Single-vehicle roadway departure
TCS	Traction control system
TIFA	Trucks Involved in Fatal Accidents
Tonne	Metric ton = 1000 kilograms ≃2200 pounds
TRC	Transportation Research Center, Inc.
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
UTC	Coordinated Universal Time (Greenwich Mean Time, or zulu)
VDANL	Vehicle Dynamics Analysis Non-Linear model
VKMT	Vehicle kilometers traveled
VMT	Vehicle miles traveled

FINAL REPORT

Evaluation of the Freightliner Intelligent Vehicle Initiative Field Operational Test

1.0 Introduction

The United States Department of Transportation (USDOT) has established an Intelligent Vehicle Initiative (IVI) as a major component of the Intelligent Transportation System (ITS) program. The intent of the IVI 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 cooperative agreements with four partnerships to conduct Generation 0 Field Operational Tests (FOTs) of advanced intelligent vehicle safety systems (IVSS). These systems are expected to begin production preparations before the end of fiscal year 2003. Although the scope of the IVI Generation 0 FOT program includes light passenger vehicles and transit vehicles, USDOT selected one FOT involving specialty vehicles and three FOTs involving commercial trucks:

- Minnesota DOT tested technologies designed to provide operators of snowplows, ambulances, and patrol cars a means to maintain desired lane position and avoid collisions with obstacles during periods of low visibility. Key among these technologies are vision enhancement, lateral guidance, and collision warning systems.

- Volvo Trucks North America, Inc., in partnership with U.S. Xpress, tested a forward collision warning system, a blind spot warning system (not under evaluation), an adaptive cruise control, and an advanced electronic braking system for commercial vehicles

- Mack Trucks, Inc., in partnership with McKenzie Tank Lines, will test a trucker safety advisory system and a lane departure warning system for commercial vehicles

- Freightliner Corporation, in partnership with Praxair, tested a roll stability advisor and a roll stability control to assist commercial vehicle drivers in avoiding rollover crashes.

Each team has planned or completed a separate operational test to demonstrate and evaluate advanced technologies. As part of this effort, the USDOT has selected a Battelle-led team to work with each partner to perform an independent evaluation of the technologies being tested. An Evaluation Plan was drafted and submitted to USDOT in 2001 for each of the tests.

In each case, the primary evaluation goal of the FOT is to determine the potential safety benefits of IVSS. Specifically, how many crashes, injuries, and fatalities could be avoided if all such vehicles were equipped with these technologies? It is also important to understand how these technologies affect driver performance. For example, do drivers drive more safely? And how do these technologies affect driver stress level and workload? The secondary goals of these evaluations include the estimation of other benefits (mobility, efficiency, productivity, and environmental quality), evaluation of system performance, and assessments of other factors that affect development and deployment of these technologies. These factors include user acceptance, product maturity, manufacturability, and institutional and legal issues.

1.1 The Freightliner IVI Field Operational Test

The Freightliner partnership comprised the following members:

Freightliner:	Major partner
UMTRI*:	Underlying technology, FOT logistics
Praxair:	Fleet operator.

*University of Michigan Transportation Research Institute

The component vendor was Meritor-Wabco. Freightliner and its partners tested two related but distinct functions of a new Roll Advisor and Control (RA&C) system. The first component was the Roll Stability ***Advisor*** (RSA), the system described in the original FOT application. Being an advisor, it is intended as an educational tool for drivers and not intended to prevent any particular crash through direct intervention. It merely advises a driver, after a maneuver is finished, that it was risky in terms of rollover, and it recommends a lower speed for the next time that curve is taken. The intent is that the driver will be better aware of the vehicle's capability in its current loading and more cautious on future maneuvers. The second component was the Roll Stability ***Control*** (RSC). In this capacity, the system can take partial, momentary control of the vehicle if it deems that a serious rollover threat is developing. The system's authority in the FOT was limited to reducing the throttle or applying engine braking. Only a minimal amount of deceleration can be applied in this manner, but continued acceleration can be prevented.

The RSA's advisory notices are provided to the driver as briefly worded messages appearing on the instrument panel. The system will display one of three messages depending on the level of severity. Messages are accompanied by an audible tone. The RSC is designed to intervene as soon as necessary. It does not provide an advance warning to the driver, but it does inform the driver when it activates. During the time of the FOT, Freightliner began offering the RA&C for sale.

Battelle served as independent evaluator of the FOT on behalf of the USDOT. Battelle communicated closely with the partnership, received the data from the FOT, and gathered other data relevant to the evaluation. Battelle analyzed the data to estimate the safety benefits of the RA&C, assess the users' acceptance of the new technology, and study the prospects for widespread deployment.

1.2 Organization of this Document

This report is divided into seven main sections:

- Section 1 gives introductory material and background on the overall program.
- Section 2 describes the IVI systems that were tested, the plan for deploying and evaluating these systems, and some operational issues that affected the evaluation.
- Section 3 contains a discussion of the evaluation goals and objectives and presents specific hypotheses that were to be tested.
- Section 4 presents our evaluation methods. We describe the data that were collected and the analyses that were performed to test specific hypotheses and achieve the goals and objectives.
- Section 5 applies the several analyses to the respective data. We present determinations as required by the objectives.
- Section 6 discusses the implications of the findings in the broader context of the larger safety issue, unlike Sections 3, 4, and 5, which are organized by evaluation objective.
- Section 7 presents recommendations for future FOTs.

References to bibliographic sources are included at the end of the report. Appendices giving more detailed information are presented in a separate volume.

2.0 Description of the IVI Technologies and the FOT

The RA&C measures the vehicle's lateral acceleration, estimates its mass, makes some assumptions about the trailer, and then decides whether to advise the driver or slow the truck. Section 2.1 describes the RA&C system being tested, and Section 2.2 presents the research plan, including information on the FOT design, drivers and trailers, delivery routes, and scheduling system. Section 2.3 identifies operational issues that influenced the evaluation of the FOT.

2.1 Description of the IVI Technologies

The RA&C continuously assesses both the vehicle's rollover threshold and the force tending to pull over the vehicle (Ehlbeck et al. 2000). The system compares the effective lateral force with the current threshold. After a maneuver where the force exceeds a predetermined fraction of the estimated rollover threshold, the system gives the driver an advisory message indicating the severity of the recent incident. If the threshold is approached too closely, the system reduces the throttle in an effort to keep the overturning force from growing.

Advisory messages are communicated via the Freightliner Driver Message Center (DMC). Messages imply increasing urgency as the potential for rollover increases. As shown in Figure 2-1, the RSA will give one of three messages depending on the severity of the maneuver. Messages include recommendations for lowering speed by specific amounts, which are calculated for every instance, independently of the advisory level. The RSC will give a message when it is slowing the truck. RSA messages are accompanied by audible tones of ½, 5, and 10 seconds for Levels 1, 2, and 3, respectively. The RSC message does not include a tone.

The RA&C system is incorporated as part of the tractor's antilock braking system (ABS) equipment.

A heavy truck rolls over when the sideways forces are too great. The vertical forces on the tires tend to resist the rolling. The lateral (sideways) force on the center can come from a high-speed curve or from gravity if the road is not level. The arrows in Figure 2-2 illustrate the force pulling on the center of gravity and the tire forces. The propensity of a vehicle to roll over depends on the height of its center of gravity, its track width (the left-to-right distance between the tires), and the lateral force on the tractor, which ordinarily comes from cornering. In its simplest form, the rollover threshold is the ratio of the half track width to the height of the center of gravity. The actual threshold is affected to a lesser degree by a number of other factors, many of which are related to the suspension. Because the track width of nearly all heavy trucks is the same, the RA&C needs only to measure the center of gravity height to estimate the rollover threshold. It does so by estimating the total weight of the vehicle, from a comparison of the engine output to the longitudinal acceleration. It then applies some general assumptions about the tare weights of trailers and the relationship between payload weights and the center of gravity height.

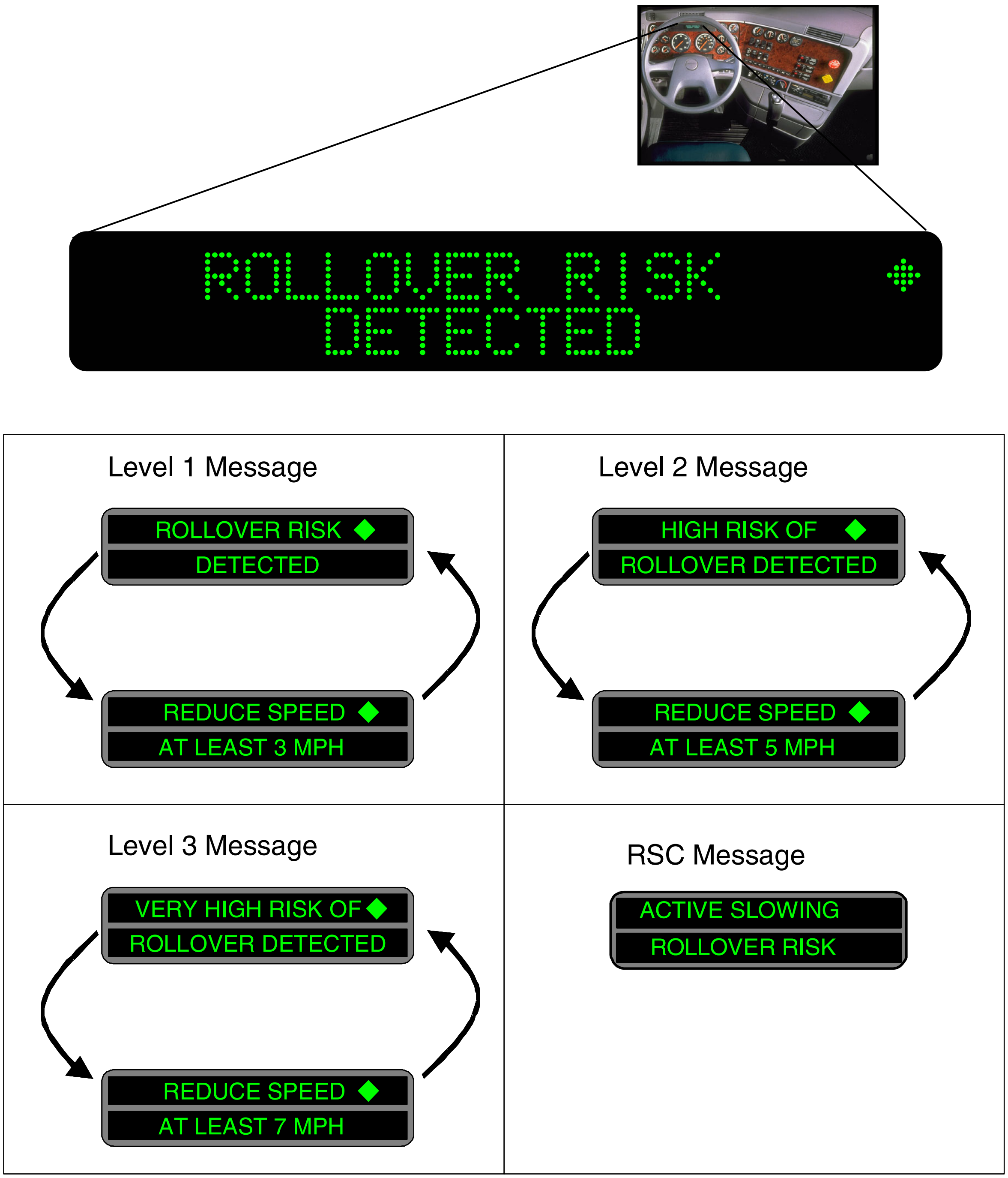


Figure 2-1. Driver Messages from the RA&C

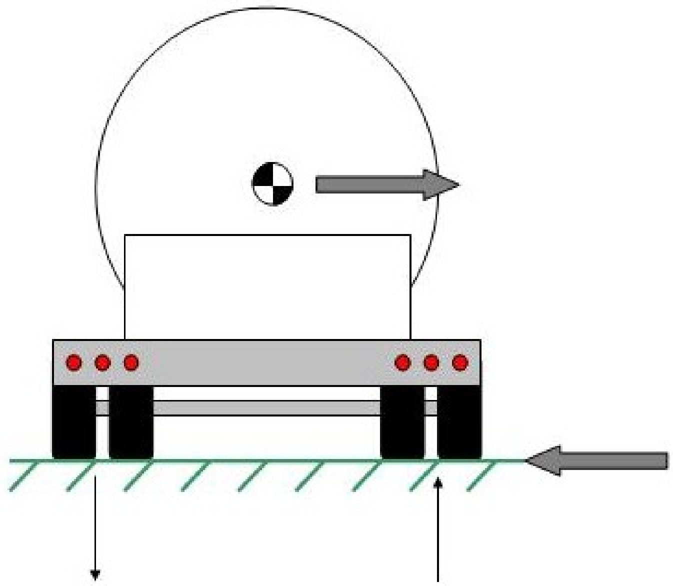


Figure 2-2. Roll-Plane Forces on a Tank Trailer

While wind and the road's cross slope can apply lateral forces that tend to tip the vehicle, the primary effect is from inertial centrifugal forces during cornering. The RA&C includes a lateral accelerometer from which the lateral force can be estimated. Because the RA&C is a new product, Freightliner considers details of the algorithms to be proprietary.

Table 2-1 lists three separate scales that were used for measuring a vehicle's proximity to rollover. They were used by different institutions for different purposes. A possibility for confusion exists because all are nondimensional scales from 0 to 100 or 0 to 1. Transforming from one scale to another is impossible because the three scales are calculated in different ways, some involving time dependence. (The Rollover Index is a relatively simple measure of how close a vehicle has come to rolling over. It was used as a preliminary screening tool because of the ease with which it can be calculated. When a better measure was needed, Battelle used a dynamic simulation, explained in Section 5.1.2, which was validated by test track experiments described in Appendix D.)

Research for the National Highway Traffic Safety Administration (NHTSA) has confirmed the intuitive expectation that a rollover system that includes instruments on the trailer can be more accurate than one confined to the tractor (Ervin et al. 1998). However, the RA&C is mounted entirely on the tractor. It has no instruments on the trailer and requires no cooperation from the trailer. Freightliner has chosen to limit the system to the tractor for two reasons. First, tractors in the nation's trucking fleet are replaced faster than are trailers, so the system can be deployed more quickly if it is strictly on the tractors. Second, cooperation between the tractor and trailer would inevitably require a means of communicating between the two, which would require an extra step whenever a tractor and trailer are mated.

Table 2-1. Three Nondimensional Scales for Measuring the Proximity of Rollover

Scale	Used by	Used for	Brief Description
RSA Score and RSC Score	Meritor-Wabco	The advisory level (1, 2, or 3) is determined by the peak RSA score in a maneuver.	(The formula is proprietary.)
Rollover Ratio	UMTRI	Comparing the risk of rollover under various conditions.	Ratio of current lateral acceleration (weighted average of tractor and trailer, calculated by a simple yaw-plane model) to current static roll threshold (adjusted for current weight) See section 4.2.4 of Winkler et al. (2002)
Rollover Index (R_I)	Battelle	Comparing the risk of rollover under various conditions and identifying "critical conflicts."	Ratio of current lateral acceleration (measured at the front axle) to current static roll threshold (adjusted for current weight.) Defined by Equation 4-1 in Section 4.3.1

Meritor-Wabco continued to develop the RA&C as the FOT proceeded. To ensure a consistent experiment, the design of the system in the FOT vehicles was not changed during the test. Therefore, the results in this report apply to the RA&C as it was in June 2001, or nearly two years before this writing. Battelle has been told that the weight estimation algorithm is greatly improved, so that the frequency of inappropriate RSA messages is greatly reduced. Also, the RSC can now apply the foundation brakes for greater effectiveness.

2.2 Research Plan

The FOT was conducted from Praxair's terminal in LaPorte, Indiana. Six tractors were equipped with the RA&C. The tractors pulled semitrailer tankers delivering liquid nitrogen to destinations primarily in Indiana, Michigan, Illinois, and Wisconsin. The FOT tractors did not have sleeper cabs, so they were used only on trips of a single driver shift.

The FOT plan was conducted over a 15-month period (Figure 2-3), which began in September 2000 (Gouse and Winkler 2000). During the Baseline period, the data collection instruments in the trucks recorded information on drivers' behavior, but the RA&C did not provide information to the driver or control the vehicle. (The first few months were a "shakedown" period. The first usable data were collected in November, 2000, and all six tractors were taking data by February, 2001.) The RA&C became fully operational on June 15, 2001. The original schedule included a third test period, where the RA&C's advisories were to be supplemented by periodic driver reviews by management. The "management feedback" portion of the test was not implemented. Driver consent for data collection was obtained at the beginning of the FOT, but drivers were unaware of the purpose of the study during the Baseline period. As described in Section 4, this approach was taken to minimize influences on their driving behavior. The drivers were given an orientation to the system before it was activated. The FOT data collection period ended on December 4, 2001.

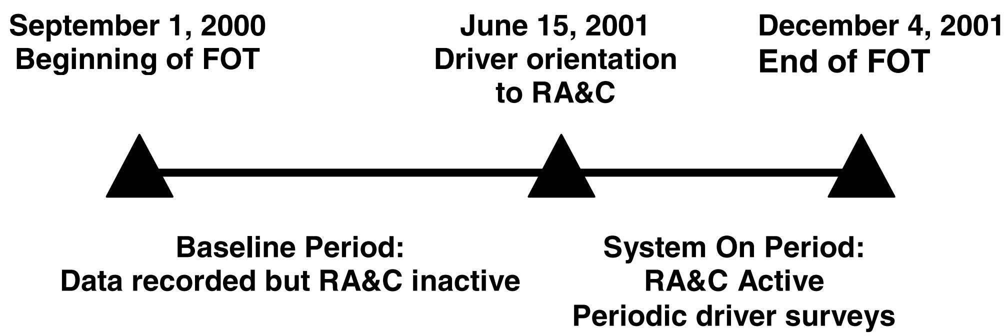


Figure 2-3. The Experimental Design Called for Two Periods. During the Baseline Period, Data was Recorded on Normal Driving. During the System On Period, Data was Recorded to Look for Any Effects of the RA&C

Battelle's evaluation project began in the fall of 1999. Before and during the FOT, Battelle developed tools for the analysis. Track testing at the Transportation Research Center (TRC) occurred in July through September, 2002, when a tractor for testing became available, to both verify the accuracy of the simulation model and perform an engineering assessment of the systems. The data analysis and results were completed in November 2002.

The study thus used a repeated-measures design; subjects served as their own control. Conclusions were drawn about the effect of RA&C on individual drivers and on the group of drivers as a whole.

The terminal had a total of about a dozen trucks during the study period. Drivers were randomly assigned to trucks according to each day's delivery schedule, so all drivers had ample opportunity to drive the equipped tractors. All 23 drivers who were working at the terminal at the beginning of the FOT enrolled in the study. Several drivers left employment during the study, and only 15 completed the entire study. No new drivers were hired.

Table 2-2 lists the demographics of the drivers who completed the study. Most of the analysis in this report includes the data from only these drivers.

Table 2-2. Driver Demographics for the Freightliner IVI FOT

	Driver Age, Yrs	Driving Experience, Yrs	Tanker Experience, Yrs
	37	14	5
	38	13	3
	38	17	4
	39	17	9
	43	23	13
	46	27	18
	47	20	6
	48	22	22
	50	8	3
	50	29	8
	50	31	15
	53	27	15
	55	23	23
	55	33	18
	56	22	8
Average	47	22	11
Median	48	22	9
Minimum	37	8	3
Maximum	56	33	23

2.3 Operational Characteristics Affecting the FOT

Operations at La Porte are conducted around the clock with staggered start times for drivers. Start times are determined by an annual bidding process in which the senior drivers get first choice. As nearly all the data were collected in calendar 2001, the driver schedule was virtually unchanged during the study. Product-delivery assignments are not given to drivers in any systematic way. When a request for a delivery is received, the task is assigned to the next available driver.

Vehicle assignment also varies unsystematically. Although the product request constrains the vehicle used (tankers are used for carrying a single kind of gas), only vehicle availability at the time of the request determines whether a driver will use a particular vehicle. Praxair endeavors to maintain an efficient operation with little excess delivery capacity. Drivers do not often have their pick of tankers since most tankers are in continual service. Therefore, all drivers at the terminal were expected to use the FOT vehicles on a frequent and fairly random basis throughout the study, and Table 4-7 shows that this expectation was borne out.

The drivers in the FOT were not representative of the broad spectrum of attitudes and skills present in the general fleet-driver population. Driver compensation levels are high, competition for a Praxair job is great, and driver turnover is much lower than the industry average. During the in-person interviews, drivers clearly exhibited an appreciation of the need for safety in their work. At the outset of the study, the expectation of both the partnership and the evaluator was that any increment in safety due to a training effect of the RA&C would be minor at best.

If the drivers began the FOT with at or near optimum performance, only small improvements would be possible. The unique characteristics of the FOT drivers and fleet (high skills and hazardous material tankers) limited the evaluator's ability to meaningfully extrapolate the FOT results to the general motor carrier industry.

Because the FOT was confined to day trips from a single terminal, the FOT occurred primarily in the four-state delivery area shown in Figure 2-4. Corresponding maps showing differences within the FOT are presented in Section 4.2.

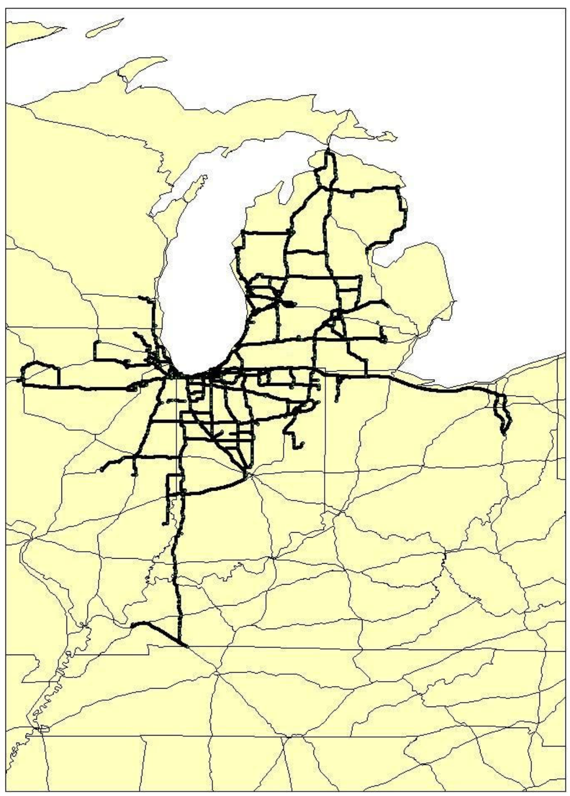


Figure 2-4. Routes Driven by FOT Trucks

The number of nitrogen customers in the area is fairly limited, and drivers are quite familiar with the routes.

Ordinarily a tractor and trailer remain together, but they were switched occasionally during the FOT when one or the other needed maintenance. A total of seven trailers were pulled by the tractors in the study. They were not exactly of the same design, but they were close enough that they were considered to be so.

In addition to the two components of the RA&C, which were the formal objects of the FOT, a hard-braking event detector (HBED) was active in the tractors, and the drivers were trained on it at the same time. The partnership's implicit assumption was that the HBED would not greatly affect the FOT. The HBED activated only 29 times during the FOT, all at its lowest level. At the exit interviews, most of the drivers seemed to understand the difference between the two systems, so the evaluator believes that the HBED did not affect the test of the RA&C.

The drivers were accustomed to driving without a forward collision warning system (Vorad), and the trucks in the FOT ran without the Vorad system. Near the end of the FOT, the terminal acquired two new tractors that did introduce the drivers to the Vorad collision warning system.

3.0 Evaluation Goals

This section defines the goals and objectives that guided the evaluation of the Freightliner Partnership Intelligent Vehicle Initiative (IVI) Generation 0 Field Operational Test (FOT). Section 3.1 describes the broad goal areas 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 several hypotheses were developed to suggest the types of data that would be needed during the FOT. The specific data collection and analysis methods for achieving the goals are described later in Section 4. These goals and objectives were established prior to developing the Evaluation Plan (Battelle 2001), and Battelle followed the plan during the evaluation, keeping all of the goals and their relative priority in mind.

Definitions and examples of key terms used in this section of the document are presented below.

Definition and Examples of Goal Areas, Objectives, Hypotheses, and Measures

Goal Area – Broad area of benefits, impacts, or factors to be evaluated
- **Example: Assess Safety Benefits**

Objective – Specific type of information to be obtained within a goal area
- **Example: Determine if drivers drive more safely with intelligent vehicle safety systems (IVSS).**

Hypothesis – A specific statement, related to an objective, which is to be tested using data and analyses. Sometimes hypotheses are stated in the form of Research Questions.
- **Example hypothesis: Drivers using a collision warning system (CWS) will maintain greater following distances from lead vehicles than drivers without CWS.**

Measure – A variable or parameter used to test hypotheses
- **Example: Expected number of rear-end crashes (derived from analysis)**
- **Example: Number of times a vehicle's following distance is less than a safe following distance threshold (a surrogate measure used to derive the expected number of rear-end crashes).**

3.1 Process of Establishing and Prioritizing Evaluation Goals

The USDOT (1999) suggested five goal areas along with some generic objectives for each goal. These objectives were to be tailored to meet the needs of each IVI FOT. The evaluation goals are summarized as follows:

Goal 1: Achieve an in-depth understanding of the benefits of intelligent vehicle safety systems (IVSS). Because the benefits of IVSS fall into five different categories (safety, mobility, efficiency, productivity, and environmental quality), this goal area is divided in five separate goals, labeled 1A to 1E, each corresponding to a different benefit category.

Goal 2: **Assess user acceptance and human factors. This rewording of Goal 2 (compared to the wording in the DOT Prospectus) reflects the focus on human factor issues. Evaluation of driver performance (in particular, answers to the question "Do drivers drive more safely with IVSS?") are considered under Goal 1A – Safety Benefits.**

Goal 3: **Assess IVSS performance and capability potential.**

Goal 4: **Assess product maturity for deployment.**

Goal 5: **Address institutional and legal issues that might affect deployment.**

These goals were discussed with the Freightliner Partnership and the USDOT during an Evaluation Workshop on January 18, 2000. The purpose of the workshop was to develop an initial framework (goals and methods) for conducting the evaluation and reach preliminary agreements on the priorities for the evaluation goals. The nine evaluation goal areas (Goal Areas 1A to 1E, corresponding to five benefit areas, plus Goals 2 through 5 listed above) were discussed and interpreted during the workshop, and priorities were established by polling the participants. Within each goal area, a number of specific objectives and hypotheses were proposed. To help define the scope and priorities of the evaluation project, participants were asked to rank each of the proposed goal areas based on several factors, including the perceived importance of the goal, feasibility of achieving the goal, and the resources required to obtain useful evaluation data during the FOT. The priority ratings established during the workshop are shown in Table 3-1.

Table 3-1. Evaluation Goal Priorities Established at the January 18, 2000, Evaluation Workshop

Goal Area	Priority Rating
1A – Assess Safety Benefits	49%
1B – Assess Mobility Benefits	Note 1
1C – Assess Efficiency Benefits	
1D – Assess Productivity Benefits	
1E – Assess Environmental Quality Benefits	
2 – Assess User Acceptance and Human Factors	23%
3 – Assess Performance and Capability Potential	17%
4 – Assess Product Maturity for Deployment	6%
5 – Address Institutional and Legal Issues that Might Impact Deployment	5%
Total	**100%**

Note 1: The four other benefit areas were not listed separately for the balloting.

3.2 Evaluation Goals, Objectives, and Hypotheses

The Goals and Objectives for the evaluation are summarized below. Table 3-2 lists all of the goals and the objectives under each goal, and it indicates the extent to which each goal was achieved. The complete list of evaluation Goals, Objectives, and Hypothesis from the Evaluation Plan is reproduced in this report as Appendix A. (The results themselves are in Section 5, Findings.)

Table 3-2. FOT Goals and Objectives, and the Extent to which They Were Achieved

Goal or Objective		Extent Achieved	Comments
1A	**Safety Benefits**		
1A.1	Drivers driving more safely	achieved	The majority of the evaluation effort was focused on this objective and the one following.
1A.2	Fewer crashes	achieved	
1A.3	All large trucks equipped	achieved	Involved considerable extrapolation from the FOT fleet
1A.4	Reductions in other types of crashes	not achieved	The partnership was collecting data on the performance of a lane tracker, which was providing no information to the drivers. The lane tracker did not work sufficiently well in curves to properly assess the propensity for run-off-road crashes
1B	**Mobility Benefits**		
1B.1	Better mobility from fewer crashes	achieved	Involved considerable extrapolation from the FOT fleet
1C and 1D	**Efficiency and Productivity Benefits**		
1D.1	Cost of deploying and maintaining	achieved	Drawn mostly by analogy from antilock brake systems (ABS).
1D.2	Cost savings	achieved	Calculated from estimated crash reductions
1D.3	Benefit-cost analysis	achieved	Several analyses were completed, assuming different levels of market penetration
1E	**Environmental Quality**		
1E.1	Environmental benefits	achieved	Follow from estimated crash reductions
2	**User Acceptance and Human Factors**		
2.1	Usability	achieved	
2.2	Effects on driving environment and workload	partially achieved	Drivers freely voiced their respective opinions on how the RA&C affects the environment in the cab. The drivers did not seem to understand the questions related to workload.
2.3	Vigilance reduction	achieved	

Table 3-2. FOT Goals and Objectives, and the Extent to Which They Were Achieved (Continued)

Goal or Objective		Extent Achieved	Comments
2.4	Perception of quality	achieved	
3	**System Performance**		
3.1	Performance	achieved	
3.2	Capability	achieved	
3.3	Reliability and Maintainability	achieved	
4	**Product Maturity**		
4.1	Price estimate	achieved	Freightliner provided the initial list price
4.2	Infrastructure needs	achieved	
4.3	Manufacturing availability	achieved	
4.4	ITS standards modification	achieved	
4.5	Widespread deployment	achieved	
5	**Institutional and Legal**		
5.1	Identify issues	achieved	

Goal 1A. Achieve an In-Depth Understanding of Safety Benefits. The primary safety benefit expected from the deployment of the RA&C is a reduction in the number of heavy truck rollovers and the resulting injuries and fatalities. This goal area comprises four objectives. The first three objectives under this goal are the primary indicators of whether any proposed countermeasure system improves safety. The evaluation sought to determine whether drivers drive more safely with the system than without it, whether vehicles with the RA&C will be have fewer crashes than those without it, and finally whether there would be a net overall benefit if all heavy trucks were so equipped. These objectives were all achieved, though, as expected at the beginning of the FOT, the effect was subtle. An auxiliary objective, examining crashes other than rollover, was not achieved. One anticipated sensor, a forward-looking radar, was not implemented, and another on-board sensor, the lane tracker, was not available sufficiently to use.

Goal 1B. Achieve an In-Depth Understanding of Mobility Benefits. Transportation mobility refers to the ease of movement, or perceived ease of movement as viewed by the traveling public. Benefits are usually measured in terms of travel-time savings, reduced congestion, and improvements in "customer" satisfaction. Reducing the number of crashes involving large trucks, an expected outcome of deploying IVSS, will produce a mobility benefit. The number of crashes avoided with full deployment of IVSS was used, along with information from the literature, to estimate the value of the mobility benefits.

Goals 1C and 1D. Achieve and In-Depth Understanding of Efficiency and Productivity Benefits. Efficiency generally refers to the amount of output (e.g., cargo ton miles) for a given input (driver or vehicle days). IVSS affects the efficiency of commercial fleet operations through reduction of the number of crashes or through operational effects that can be measured in terms of productivity gains or losses (cost savings or increases). Deployment of IVSS can result in productivity increases through cost savings from reduced numbers of crashes and lower insurance rates. Other indirect productivity benefits will be documented and valued. Of course there are cost increases associated with the purchase and maintenance of the systems, training costs for drivers and mechanics, and possibly operating costs. There were three cost-related objectives under these two goals, the most important of which was a comprehensive benefit-cost analysis. This analysis was carried out for several sets of assumptions and target fleets.

Goal 1E. Achieve an In-Depth Understanding of Environmental Quality Benefits. In addition to preventing injuries and fatalities, a reduction in the number of crashes resulting from the deployment of RA&C system also benefits the environment in terms of fewer hazmat spills and reduced air pollution from traffic congestion caused by crashes. These benefits were estimated as secondary benefits resulting from the estimated number of crashes prevented.

Goal 2. Assess User Acceptance and Human Factors. This goal area focuses on how IVSS technologies affect the driving environment and the acceptability of the systems by the drivers and fleet operators. While Goal 1A (Safety Benefits) deals with the objective assessment of the effects of IVSS on safe driving behavior, this goal focuses on understanding if and how human factors may play a role in the eventual acceptance and deployment of the systems. There were four objectives centered on the usability of the display, the effect on the driving task, adverse effects on driver behavior, and perceptions of value. The small cadre of test drivers, all operating from a single terminal, produced nearly 100% responses to all surveys and interviews. Good information was obtained for meeting these objectives.

Goal 3. Assess IVSS Performance and Capability Potential. This goal area deals with the ability of the IVSS to perform its functions according to design specifications and meet minimum reliability and maintainability criteria. Performance, reliability, and maintainability are necessary, but not sufficient, conditions for achieving the expected benefits. Performance consistency was evaluated both from the FOT data and from special maneuvers on a test track. Reliability of the system was assessed by inquiring whether any of the units needed to be serviced during the FOT and searching the on-board data for self-diagnostic messages from the units.

Goal 4. Assess Product Maturity for Deployment. Although tangible benefits (Goals 1A-1E) and user satisfaction (Goal 2) are necessary to achieve widespread deployment of IVSS, there are other factors that will determine success. In particular, it is important to consider the logistics and feasibility of large-scale production, production and installation costs, related infrastructure investments (if any), and the need to achieve consistency with ITS standards and architecture (as applicable). Five objectives under this goal were met by gathering information from the vendor and other outside sources.

Goal 5. Address Institutional and Legal Issues that Might Affect Deployment. Even though IVSS could effectively meet the performance and benefit goals established, institutional and legal issues could influence the adoption of the technology. Improper performance of any IVSS could result in legal actions by drivers of the trucks with the IVSS or other vehicles. Likewise, institutional issues, such as coordination with the many other in-cab sounds, could impair deployment.

4.0 Evaluation Methods

Battelle prepared a detailed plan for conducting the evaluation (2001). It lists the five broad goal areas for the evaluation that were established by the DOT (USDOT 1999) and, within each goal area, lists objectives that Battelle attempted to achieve during the course of the evaluation. The plan presented sources of data used by Battelle and the methods to be employed to analyze the data. The intent of this section is not to reproduce the entire Evaluation Plan but to highlight its important points.

4.1 Overview of Evaluation Approach

Battelle developed several hypotheses to test within the scope of each objective. Sources of data were identified for testing each hypothesis. Data came from many sources, some from the FOT itself, some previously existing, and some generated specifically for the evaluation. The sources are discussed in more detail in Section 4.2. To ensure that the objectives could be met, Battelle developed methods of analyzing the data and applying it to the evaluation. A few of the analysis methods were simple and straightforward; others involved sophisticated mathematical analysis. The methods are summarized in Section 4.3; they are presented in greater detail in Section 5, Findings.

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

Historical and FOT Crash/Incident Data. This source includes any available databases on truck crashes and relevant incidents. Primary sources were public databases—such as Trucks Involved in Fatal Accidents (TIFA) and the General Estimates System (GES)—and the fleet's crash history. In the estimation of safety benefits, this represented the crash incidence and distribution "without" the safety system.

Onboard Driving Data. The heart of the FOT, this source includes all data collected on the vehicles during the FOT. It was studied extensively to determine how often and under what circumstances possible precrash conflicts occur. Critical conflicts identified in GES as being relevant to rollovers were sought, as well as any instance where the lateral acceleration approaches the rollover threshold.

Surveys and Interviews. Opinions were solicited from personnel in the FOT (including drivers, mechanics, and corporate staff) and used to determine whether the messages are clear and to gauge the level of user acceptance, product maturity, and institutional and legal issues.

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

Special Tests and Supplemental Data. This category includes all sources of data outside the FOT itself. The most significant of the special tests were test track maneuvers with an instrumented tractor and a trailer equipped with outriggers. Other sources of data were interviews with representatives of various stakeholder groups, to ask what institutional or legal issues might affect deployment.

Table 4-1 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 Section 3.2. The next five columns identify the 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. The primary measure was the lateral acceleration of the truck. Supplemental data sources included any crashes or incidents that occurred, driver interviews, and fleet operations records such as violations. A brief summary of how these data were used is presented in the comment column.

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 we describe the data collection process and discuss 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 1995 through 2000. The host fleet, Praxair, also provided crucial information on its own rollover experience. Had any crashes or incidents occurred during the FOT, they would have been investigated, but, as expected, there were none.

The number of rollover crashes occurring per year outlines the scope of the rollover problem and thus defines the opportunities for crash reduction using RA&C. These data also identify which safety-critical situations (referred to as driving conflicts) lead to rollover crashes and provide estimates for the probability, with no IVSS, that a particular safety-critical situation (driving conflict) precedes a crash given that a rollover crash occurred. That is a crucial step in the safety benefits estimate of Section 5.1. The fleet crash statistics and safety data were used to assess the applicability of safety benefits estimates to fleets beyond those deployed in this FOT.

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. The Safety Benefits Estimation Methodology (Battelle, 2000) document 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 4-1. 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 used to identify relevant crash types, conflicts, and driving behaviors. Crash avoidance models are based on dynamic simulation. Surveys added driver perspectives concerning stress, nuisances, etc. Driver records and fleet safety records were used for extrapolating the results.
1A.1 Determine if drivers drive more safely	S	P	S	S		
1A.2 Estimate crash reductions	P	P			P	
1A.3 Estimate crash reductions at full deployment	P	P	S	S		
1A.4 Determine if RA&C affects other crashes	P	P	S			
Assess Mobility Benefits						Literature findings and historical crashes were used to estimate the effect of crash reductions (from 1A.3) on mobility
1B.1 Assess effect of reduced crashes on mobility	P				P	
Assess Efficiency and Productivity Benefits						Interviews were the source of cost data. The benefit-cost analysis combined literature results with FOT findings on specific costs and benefits to estimate total costs and benefits to society.
1D.1 Determine cost to deploy and maintain IVSS			S	P		
1D.2 Estimate cost savings (pos or neg) with IVSS			S	P		
1D.3 Conduct comprehensive benefit-cost analysis	S	S	P	P	P	
Assess Environmental Benefits						Literature findings and historical crashes were used to estimate the effect of crash reductions (from 1A.3) on the environment (from reduced congestion and hazmat spills).
1E.1 Assess effect of reduced crashes on environment	P				P	
Assess User Acceptance & Human Factors						Driving data were used to establish availability, determine alarm frequencies, and objectively characterize driving risks and behaviors. Surveys and interviews addressed driver perceptions of all aspects of IVSS.
2.1 Determine usability of IVSS		S	P			
2.2 Determine if drivers perceive increased stress/workload		S	P			
2.3 Determine perceived impacts on driver risks and vigilance		S	P			
2.4 Determine perceptions of product quality, maturity, etc			P			
Assess IVSS Performance and Capability Potential						Component performance, functionality, reliability, and maintainability were addressed with objective driving and maintenance data as well as interviews with drivers. Capability was addressed through special engineering tests and measurements.
3.1 Characterize performance/functionality of components		P	P	S	P	
3.2 Assess capability of components					P	
3.3 Determine reliability and maintainability of components		P	P	P		
Assess Product Maturity for Deployment						Interviews with the vendors gave roll-out plans. ITS standards were reviewed.
4.1 Determine if costs are reasonable for motor carriers			P	S		
4.2 Assess infrastructure investment needs			P			
4.3 Determine availability of manufacturing capabilities			P		P	
4.4 Assess need for modifications to ITS standards		P	P			
4.5 Determine if IVSS is suitable for widespread deployment			P		P	
Address Institutional and Legal Issues						Vendors and other industry representatives were interviewed.
5.1 Identify and determine impact of institutional and legal issues	P		P	S		

Tables 4-2 and 4-3 present the relative frequency with which the most prevalent safety critical situations precede rollover and SVRD crashes, respectively. Initially, this analysis was completed during the development of the safety benefits methodology in order to determine what types of conflicts need to be identified in the driving data. The original analysis determined conflict rates for two classes of trucks using data from the years 1992 through 1998. Later, the analysis was updated to include more recent data (1995 – 2000) and to calculate conflict rates for the three classes of trucks being considered in the safety benefits analysis. A fourth class of trucks, tanker trailers carrying hazardous materials (HM, or HAZMAT), is defined and discussed in the Benefit-Cost Analysis. This fourth fleet is a subset of the tanker-trailer fleet.

Note that many of the same safety critical situations precede rollover and SVRD crashes. Excessive speed in a curve, the behavior RA&C is designed to mitigate, precedes 55% of rollover and 9% of SVRD crashes involving tractors pulling tankers. SVRD crashes are much more common than rollovers, so the absolute number of SVRD crashes preceded by this conflict is more than the number of rollovers preceded by it.

The five stages used to identify driving conflicts within the 1995 through 2000 GES data were as follows:

1. Subset to relevant data
2. Parse data by crash type
3. Identify the predominant critical events that led to the truck's involvement in the crash for the crash type of interest
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.

Table 4-2. Dominant Driving Conflicts Leading to Untripped Rollover Crashes

Conflict Number	Conflict Definition	Relative Frequency		
		Heavy Truck[1]	Tractor Trailer[2]	Tanker Trailer[3]
Rollover.1	Truck is turning or negotiating a curve at excessive speed and loses control.	25%	25%	55%
Rollover.2	Truck loses control due to a vehicle related failure.	33%	32%	39%
Rollover.3	Truck is traveling at a constant speed and travels over the edge of the road.	8%	5%	3%
Rollover.4	Truck is turning or negotiating a curve and travels over the edge of the road.	3%	3%	0%
Rollover.5	Truck is traveling at a constant, excessive speed and loses control.	3%	3%	0%
Rollover.6	Truck is traveling at constant speed and loses control due to poor road conditions.	1%	1%	0%
Rollover.7	Truck is turning or negotiating a curve and loses control due to poor road conditions.	1%	2%	0%
Other		25%	29%	3%
Sum		100%	100%	100%

[1] Class 3-8 trucks over 10,000 lbs. gross vehicle weight
[2] Class 7-8 tractors with at least one trailing unit
[3] Class 7-8 tractors with at least one trailing tanker unit

Table 4-3. Dominant Driving Conflicts Leading to Single Vehicle Roadway Departure Crashes

Conflict Number	Conflict Definition	Relative Frequency		
		Heavy Truck[1]	Tractor Trailer[2]	Tanker Trailer[3]
SVRD.1	Truck is turning or negotiating a curve and travels over the edge of the road.	30%	37%	32%
SVRD.2	Truck is traveling at constant speed and travels over the edge of the road.	16%	14%	14%
SVRD.3	Truck loses control due to vehicle related failure.	15%	14%	18%
SVRD.4	Truck is traveling at constant, excessive speed and loses control.	4%	4%	3%
SVRD.5	Truck is turning or negotiating a curve at excessive speed and loses control.	6%	6%	9%
Other		29%	25%	25%
Sum		100%	100%	100%

4.2.2 On-Board Driving (Engineering) Data

UMTRI installed an automated data acquisition system (DAS) in each of the six FOT tractors. The DAS acquired data from several sources—vehicle condition from the vehicle data bus, location and time from the Global Positioning System (GPS), and several special transducers installed by UMTRI in the tractor. All sensors were on the tractor; there were none on the trailer in the FOT. Table 4-4, which was in the FOT test plan (Gouse and Winkler 2000), lists the channels that were recorded by the DAS.

Table 4-4. Channels Recorded by the Data Acquisition System

Name	Type	Units	Description
Gear	Byte	none	Calculated gear via engine speed and speed
CruiseEnable	Byte	none	Cruise Enable switch from J1939 VSC1
CruiseState	Byte	none	Cruise state from J1939 VSC1
ParkingBrake	Byte	none	Parking Brake status from J1939 VSC1
WiperState	Byte	none	Wiper state from digital input
WarningMessage	Byte	none	Warning message number from abs MID 226
DriverAcknowledge	Byte	none	Driver has acknowledge a rsa/rsc message by pressing the key
RscActive	Byte	none	On if ra&c is controlling torque
AtcActive	Byte	none	Automatic Traction Control active
OnScales	Byte	none	True if tractor is on the scales.
RsaScoreGe70	Byte	none	RSA score >= 70
RsaScoreGe80	Byte	none	RSA score >= 80
RsaScoreGe90	Byte	none	RSA score >= 90
RscScoreGe100	Byte	none	Rsc Score >= 100
TurnSignal	Byte	none	Filtered TurnSignalRaw to remove the blink.
Pto	Byte	none	True if pto governor is on
DeltaV	Single Float	kph	Delta v reported by abs rsa advisory message
SetSpeed	Single Float	kph	Set speed from J1939 VSC1 resolution = 1kph
RscCommand	Single Float	%	Torque limt command from TSC1_E 1939 message
AtcCommand	Single Float	%	Automatic Traction Control torque limit command
MaxRsaScore	Single Float	%	Maximum rsa score when rsa score goes above 70
SpeedHist	FloatHistogram	none	Histogram of speed
LeftOffsetHist	FloatHistogram	none	Histogram of LeftOffset from lane tracker.
RightOffsetHist	FloatHistogram	none	Histogram of RightOffset from lane tracker.
AccelPedalHist	FloatHistogram	none	Histogram of accelerator pedal
AyHist	FloatHistogram	none	Histogram of lateral accel. with large bins
AyCalcHist	FloatHistogram	none	Histogram of calculated lateral accel. with large bins
AyMeasuredHist	FloatHistogram	none	Histogram of measured lateral accel. with large bins
BrakePressureHist	FloatHistogram	none	Histogram of Brake pressure
EngineSpeedHist	FloatHistogram	none	Histogram of Engine speed
EngineTorqueHist	FloatHistogram	none	Histogram of engine torque
GpsSpeedHist	FloatHistogram	none	Histogram of GpsSpeed
LoadTransferHist	FloatHistogram	none	Histogram of load transfer
MassHist	FloatHistogram	none	Histogram of Mass
RSAScoreHist	FloatHistogram	none	Histogram of RSA score
RSCScoreHist	FloatHistogram	none	Histogram of RSC score
YawRateLt25Hist	FloatHistogram	none	Histogram of yaw rate for velocity below 25 kph
YawRate25to50Hist	FloatHistogram	none	Histogram of yaw rate for velocity btw 25 and 50 kph
YawRate50to75Hist	FloatHistogram	none	Histogram of yaw rate for velocity btw 50 and 75 kph
YawRateGe75Hist	FloatHistogram	none	Histogram of yaw rate for velocity above 75 kph
AirSpringHist	FloatHistogram	none	Histogram of filtered air spring pressure
Distance	Single Float	km	Integral of speed
TripDay	Double Float	none	Day of trip in access date/time format
DistanceWipers	Single Float	km	Distance with the wipers on
DistanceEngaged	Single Float	km	Distance with cruise on
TestTime	Long Integer	sec	Time since midnight utc in deciseconds
AccelPedal	Single Float	%	Accelerator Pedal from J1939 EEC2 resolution = .4%
Brake	Byte	none	Brake Pedal from J1939 VSC1
EngineSpeed	Single Float	rpm	Engine Speed from J1939 EEC1 resolution = .125 rpm
EngineTorque	Single Float	%	Engine torque from J1939 EEC1 resolution = .1% offset = -125%
Speed	Single Float	kph	Speed via corrected SpeedRaw
Ay	Single Float	g's	AyRaw corrected for temperature.
YawRate	Single Float	deg/sec	YawRateRaw - YawRateZero
AyTemperature	Single Float	deg C	Temperature of Ay sensor
AtmPressure	Single Float	bar	Atmospheric pressure via pressure transmitter
BrakePressure	Single Float	kpa	Brake treadle pressure measured by pressure transducer
LoadTransfer	Single Float	fsc	Lateral load transfer
AirSpringPressure	Single Float	kpa	Pressure of air spring
Distance	Single Float	km	Integral of speed
GpsTime	Long Integer	sec	Time since midnight utc in deciseconds

Table 4-4. Channels Recorded by the Data Acquisition System (Continued)

Name	Type	Units	Description
Longitude	Double Float	deg	Longitude from GPS
Latitude	Double Float	deg	Latitude from GPS
Height	Single Float	m	Height above the elipsoid from GPS
Heading	Single Float	deg	Heading from GPS
GpsSpeed	Single Float	kph	Ground speed from gps
GpsFix	Byte	none	Indicates type of position fix from POS message. Raw=0, Differential =1
NumberOfSats	Byte	none	Number Of Satellites used in fix
HDOP	Short Integer	none	Gps Horizontal Dilution of Precision times 10
VDOP	Short Integer	none	Gps Vertical Dilution of Precision times 10
TrackerStatus	Byte	none	Status byte from lane tracker
LeftOffset	Single Float	m	Offset from left lane edge - lane tracker message byte 5 - 2cm steps
RightOffset	Single Float	m	Offset from right lane edge - lane tracker message byte 6 - 2cm steps
AyCalculated	Single Float	g's	Lateral acceleration calculated in the ABS via J1587 PID 254
AyMeasured	Single Float	g's	Lateral acceleration measured in the ABS via J1587 PID 254
Mass	Single Float	tonne	Calculated Mass from ABS via J1587 PID 254
RsaScore	Single Float	none	Rsa score from the ABS via J1587 PID 254
RscScore	Single Float	none	Rsc score from the ABS via J1587 PID 254

Sources: Gouse and Winkler (2000); Winkler et al. (2002)

Tonne = metric ton, or approximately 2,200 pounds

Records in the database were uniquely identified by tractor, trip, and test time. The tractor number, 1 through 6, was fixed with the tractor throughout the FOT. The "trip" counter in the DAS was incremented every time the ignition was turned on. The test time was measured in deciseconds (0.1 s), so it corresponded with the 10-Hz sampling rate of the most frequently sampled channels. The test time was measured from midnight UTC (Coordinated Universal Time), and it continued to increment if a trip lasted through midnight UTC. (It did not wrap back to zero.) Data were collected at all times when the engine was running and the parking brake was not set.

When a truck returned to the terminal, it realized its location from the Global Positioning System (GPS) information and established communication with a server in the building via a wireless network. The truck transferred data from the trip to the server. The server then forwarded the data to UMTRI via a leased land line. UMTRI coordinated the vehicle number and departure times in the DAS data with Praxair's electronic delivery records to assign a driver number and other information to the records. (The driver numbers in the database were assigned by UMTRI to protect the drivers' anonymity.) After UMTRI formatted and processed the data, the data were transferred to a set of compact disks (CDs) or to a removable hard disk and mailed to Battelle, where the data were loaded on Battelle's server dedicated to the evaluations. Appendix H has details of Battelle's data management approach.

In several instances throughout the FOT, data were momentarily missing or invalid for one reason or another. Data from many trips on Tractor 1 were lost during the Baseline period because of a memory failure, and a similar failure occurred on Tractor 6 after the RA&C was activated. UMTRI and Battelle both checked the database for missing fields, inconsistent values, or obviously incorrect measurements. Also, some trips were excluded because, for example, the truck was driven to a shop for warranty maintenance and not revenue service. Battelle's practice was to exclude an entire trip if the trip failed one of 22 tests of validity. Overall, though, as shown in Figure 4-1, more than 90% of the distance traveled by all tractors, as recorded by their odometers and reported by Praxair, was represented by valid records in the database available for analysis by Battelle.

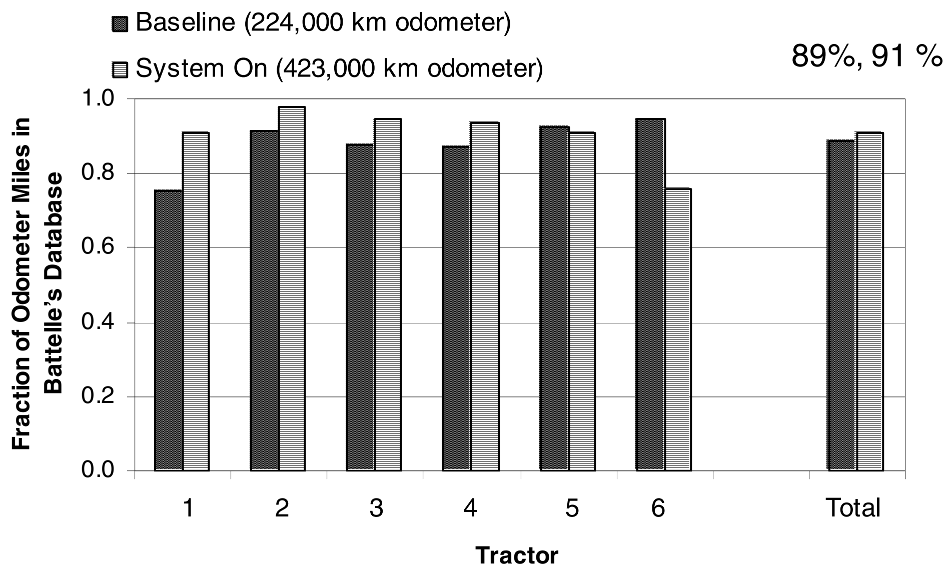


Figure 4-1. Validity of Driving Data

UMTRI processed two of the channels to produce data in a more useful form. First, the lateral acceleration measured at the drive axle was low-pass filtered to provide a smooth signal. Also, several "glitches," which had been independently discovered by UMTRI and Battelle, were removed, as exemplified in Figure 4-2. Battelle thoroughly checked UMTRI's processing on this channel and found it to be reasonable. UMTRI also developed a formula to calculate the total vehicle weight from the pressure in the drive-axle air bags and provided Battelle a table of weights at regular intervals throughout the FOT.

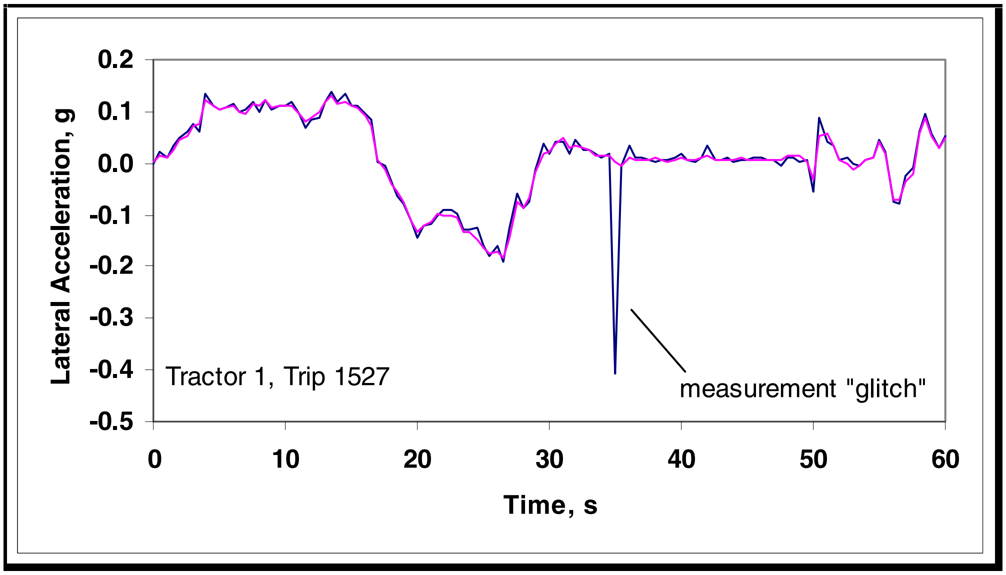


Figure 4-2. Data Processing and Smoothing

Table 4-5 and Figures 4-3 and 4-4 show the routes for the 15 most frequent trips taken during the Baseline and System On periods. Routes for the entire FOT were shown in Figure 2-4. The only difference in destinations shown in Figure 4-3 and 4-4 are South Haven (Baseline) and Whitehall (System On). Table 4-5 also shows the VKMT values and percentages for each of the most frequent trips. More than half of the distance accumulated was to these few destinations. This table suggests—and personal discussions with the drivers confirm—that the drivers were intimately familiar with the routes of the FOT.

Table 4-5. The 15 Most Frequent Trips

Rank			Route	Trips			1000 VKMT			Percent of VKMT		
B	SO	O		B	SO	O	B	SO	O	B	SO	O
1	1	1	Holland-LaPorte	368	302	670	62	49	111	18%	13%	15%
2	2	2	Kalkaska-LaPorte	63	74	137	26	31	58	8%	8%	8%
3	5	4	LaPorte-Terre Haute	43	42	85	14	14	29	4%	4%	4%
4	7	6	East Chicago-Holland	59	46	105	13	10	23	4%	3%	3%
5	8	7	East Chicago -LaPorte	150	135	285	11	10	21	3%	3%	3%
6	4	5	Kokomo-LaPorte	59	82	141	11	15	25	3%	4%	3%
7	6	8	LaPorte-South Bend	180	223	403	10	11	21	3%	3%	3%
8	9	9	Grand Rapids-LaPorte	43	47	90	9	10	18	3%	2%	3%
9	10	10	LaPorte-Marshall, IL	23	23	46	8	8	16	2%	2%	2%
10	13	13	LaPorte-Zeeland, MI	37	38	75	7	6	13	2%	2%	2%
11	12	12	Fruitport, MI-LaPorte	30	34	64	6	7	13	2%	2%	2%
12	11	11	Goshen-LaPorte	53	72	125	6	8	14	2%	2%	2%
13	3	3	Hemlock, MI-LaPorte	15	60	75	6	23	29	2%	6%	4%
14	16	15	LaPorte-Whitehall	16	20	36	4	5	8	1%	1%	1%
15	14	14	LaPorte-Muskegon	14	29	43	3	6	9	1%	2%	1%
			Total for Top 15 trips	1153	1227	2380	195	214	410	57%	55%	56%
			Total for All trips with Route Info	2346	2442	4788	326	336	662	96%	87%	91%
			Missing Route info	125	410	535	15	50	65	4%	13%	9%
			Total for All Trips*	2,471	2,852	5,323	341	386	727			

B: Baseline
SO: System On
O: Overall
* All trips over 1 km

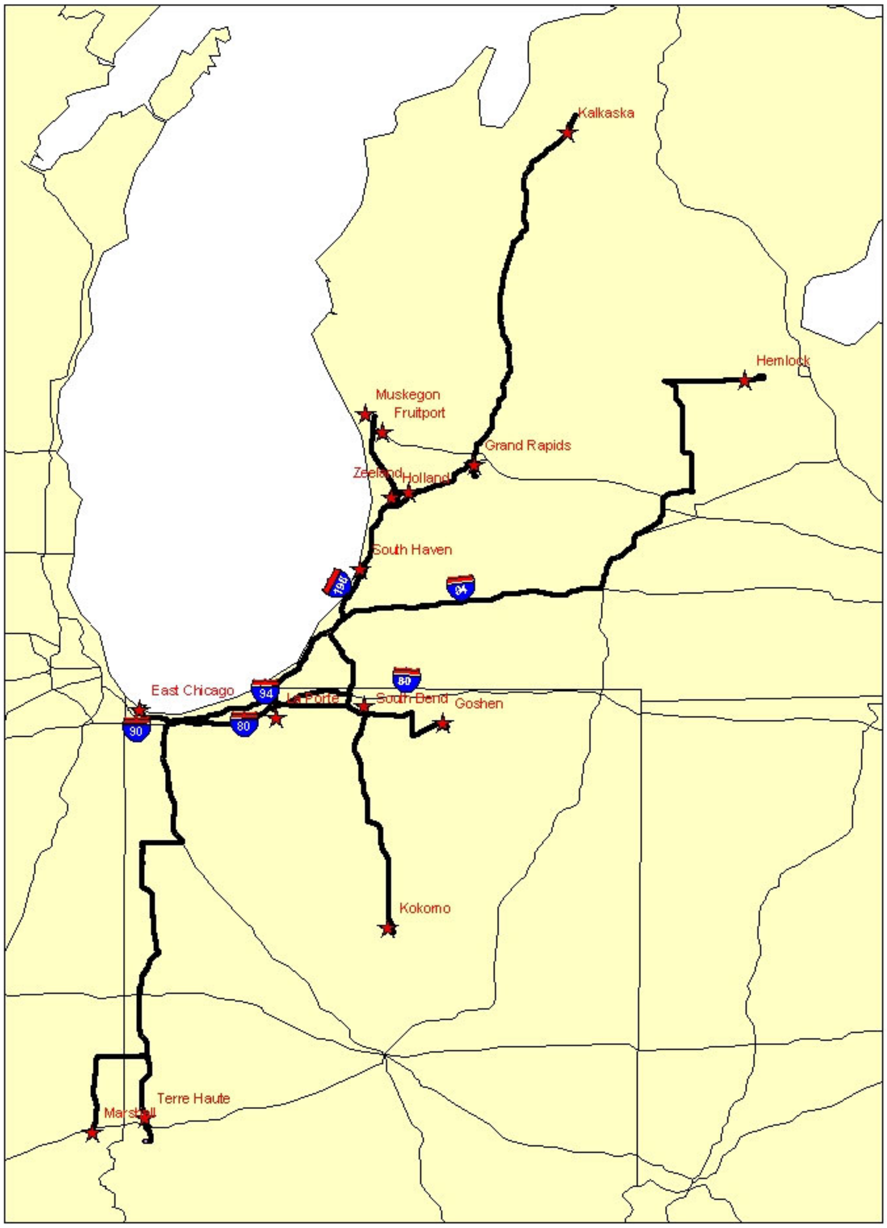


Figure 4-3. Most Frequent Trips during the Baseline Period

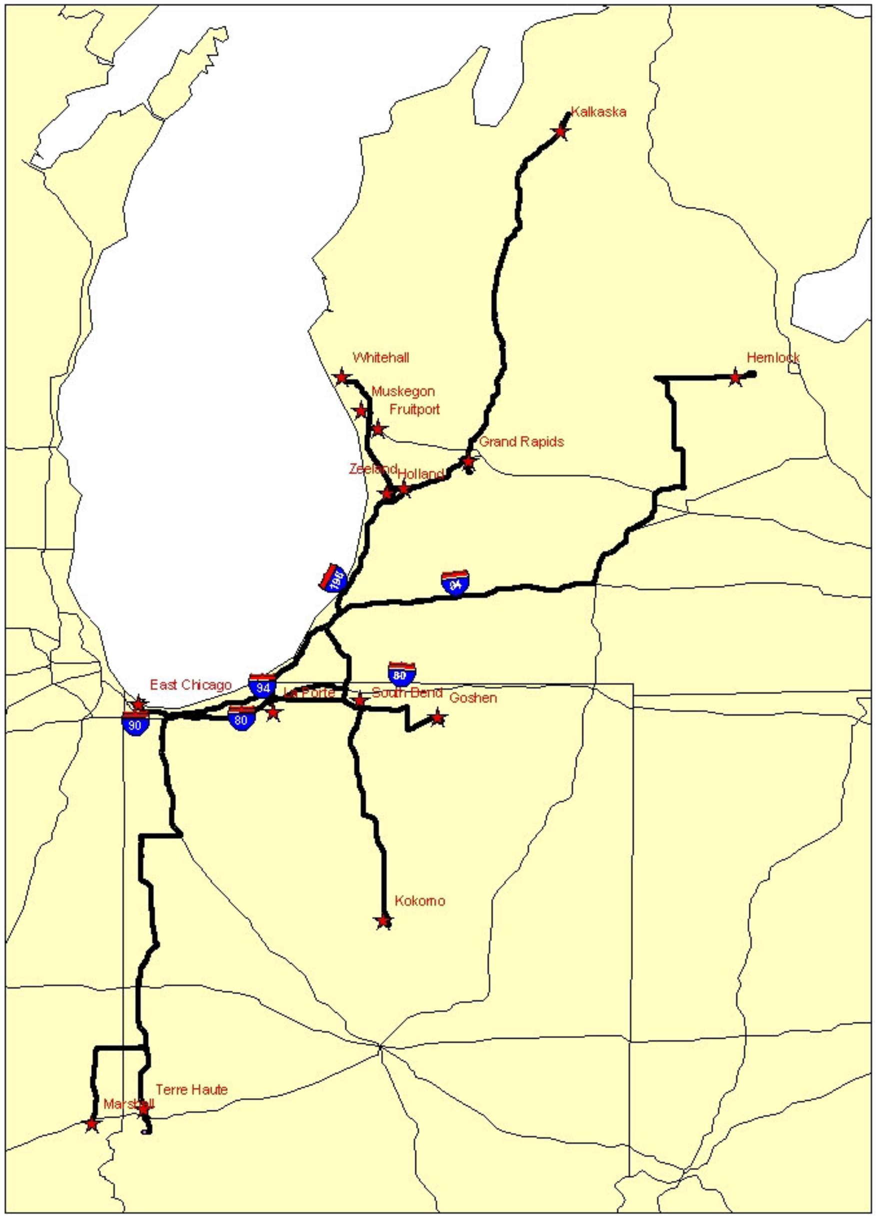


Figure 4-4. Most Frequent Trips during the System On Period

Table 4-6 shows the complete driving data by tractor for the Baseline and System On periods. Table 4-7 shows the corresponding driving data, organized by driver. This table lists the 15 drivers who completed the entire study. Drivers who began the study but did not finish are listed in the "Other" row. The category of "Missing" is for onboard data that could not be associated with an individual driver. These tables show that the exposure to the FOT was reasonably uniform across the drivers and tractors.

Table 4-6. Summary of Complete Driving Data by Tractor

Period	Tractor	Start date	End Date	Number of Trips (% of total)		Vehicle KM Traveled (% of total)	
				All	>1km	All trips	>1km
Baseline	1	8-Nov-00	18-Jun-01	626 (15%)	374 (15%)	51,582(15%)	51,519(15%)
	2	19-Dec-00	14-Jun-01	791 (20%)	494 (20%)	66,312(19%)	66,235(19%)
	3	19-Dec-00	15-Jun-01	865 (21%)	537 (22%)	77,207(23%)	77,116(23%)
	4	17-Jan-01	15-Jun-01	556 (14%)	334 (14%)	48,551(14%)	48,489(14%)
	5	2-Feb-01	15-Jun-01	714 (18%)	449 (18%)	60,579(18%)	60,511(18%)
	6	26-Feb-01	14-Jun-01	496 (12%)	283 (11%)	37,501(11%)	37,446(11%)
	Total	8-Nov-00	18-Jun-01	4,048	2,471	341,733	341,317
System On	1	19-Jun-01	4-Dec-01	816 (18%)	518 (18%)	67,253(17%)	67,164(17%)
	2	14-Jun-01	4-Dec-01	686 (15%)	444 (16%)	59,125(15%)	59,053(15%)
	3	20-Jun-01	4-Dec-01	736 (16%)	455 (16%)	64,804(17%)	64,714(17%)
	4	16-Jun-01	4-Dec-01	831 (18%)	513 (18%)	73,621(19%)	73,527(19%)
	5	16-Jun-01	3-Dec-01	896 (20%)	575 (20%)	76,570(20%)	76,468(20%)
	6	14-Jun-01	4-Dec-01	578 (13%)	347 (12%)	44,984(12%)	44,920(12%)
	Total	14-Jun-01	4-Dec-01	4,543	2,852	386,357	385,845

Table 4-7. Summary of Complete Driving Data by Driver

Driver	Baseline				System On			
	Number of Trips (%of total)		VKMT (%of total)		Number of Trips (%of total)		VKMT (%of total)	
	All	> 1km	All	> 1km	All	> 1km	All	> 1km
2019	11	9	1,547	1,546	85	49	6,833	6,821
	(0.3%)	(0.4%)	(0.5%)	(0.5%)	(1.9%)	(1.7%)	(1.8%)	(1.8%)
2034	154	110	13,919	13,905	163	136	18,965	18,956
	(3.8%)	(4.5%)	(4.1%)	(4.1%)	(3.6%)	(4.8%)	(4.9%)	(4.9%)
2033	109	80	14,222	14,213	210	147	21,327	21,307
	(2.7%)	(3.2%)	(4.2%)	(4.2%)	(4.6%)	(5.2%)	(5.5%)	(5.5%)
2032	151	104	14,611	14,596	164	120	17,361	17,344
	(3.7%)	(4.2%)	(4.3%)	(4.3%)	(3.6%)	(4.2%)	(4.5%)	(4.5%)
2021	149	91	15,105	15,091	232	144	27,692	27,661
	(3.7%)	(3.7%)	(4.4%)	(4.4%)	(5.1%)	(5.0%)	(7.2%)	(7.2%)
2029	177	130	15,242	15,228	305	210	23,140	23,106
	(4.4%)	(5.3%)	(4.5%)	(4.5%)	(6.7%)	(7.4%)	(6.0%)	(6.0%)
2025	180	130	15,845	15,831	146	120	17,098	17,090
	(4.4%)	(5.3%)	(4.6%)	(4.6%)	(3.2%)	(4.2%)	(4.4%)	(4.4%)
2028	191	140	16,635	16,623	327	229	27,785	27,754
	(4.7%)	(5.7%)	(4.9%)	(4.9%)	(7.2%)	(8.0%)	(7.2%)	(7.2%)
2030	160	111	16,919	16,902	270	175	22,702	22,675
	(4.0%)	(4.5%)	(5.0%)	(5.0%)	(5.9%)	(6.1%)	(5.9%)	(5.9%)
2035	154	104	17,016	17,000	289	180	27,534	27,499
	(3.8%)	(4.2%)	(5.0%)	(5.0%)	(6.4%)	(6.3%)	(7.1%)	(7.1%)
2023	178	127	17,916	17,900	301	188	24,619	24,579
	(4.4%)	(5.1%)	(5.2%)	(5.2%)	(6.6%)	(6.6%)	(6.4%)	(6.4%)
2026	277	174	17,997	17,977	266	171	14,664	14,646
	(6.8%)	(7.0%)	(5.3%)	(5.3%)	(5.9%)	(6.0%)	(3.8%)	(3.8%)
2022	180	131	18,063	18,053	202	144	21,580	21,560
	(4.4%)	(5.3%)	(5.3%)	(5.3%)	(4.4%)	(5.0%)	(5.6%)	(5.6%)
2020	190	130	18,104	18,086	286	189	26,826	26,791
	(4.7%)	(5.3%)	(5.3%)	(5.3%)	(6.3%)	(6.6%)	(6.9%)	(6.9%)
2031	257	167	23,690	23,665	348	205	29,918	29,875
	(6.3%)	(6.8%)	(6.9%)	(6.9%)	(7.7%)	(7.2%)	(7.7%)	(7.7%)
Other	1018	706	102659	102572	348	219	29029	28990
	(25%)	(29%)	(30%)	(30%)	(7.7%)	(7.7%)	(7.5%)	(7.5%)
Missing	512	27	2,242	2,128	601	226	29,283	29,190
	(13%)	(1.1%)	(0.7%)	(0.6%)	(13%)	(7.9%)	(7.6%)	(7.6%)
Total	4,048	2,471	341,733	341,317	4,543	2,852	386,357	385,845

4.2.3 Surveys and Interviews

The majority of surveys (written) and interviews (in-person) were with the drivers in the study to learn their opinions of the new system. A series of surveys and interviews were conducted during the FOT to track the evolution of the opinions as the test progressed. This was the primary means of gathering data for Goal 2, the assessment of user acceptance and human factors. Interviews were also conducted with other stakeholders in support of other goals.

Table 4-8 lists the surveys and interviews with the drivers and the purpose of each. The schedule for the surveys and interviews is shown with the overall FOT schedule in Figure 4-5. The Baseline period began in September 2000, and the System On period began in mid-June 2001. As shown in the figure, these were two sets of interviews and a total of seven surveys conducted during this test.

Table 4-8. Driver Interviews and Surveys

Tool	Purpose
Decision-Making Survey	To learn the decision–making style of the drivers.
Initial Stage Interview	To gather initial driver perceptions of the system. The interview provides qualitative information.
Initial Stage Survey	To gather baseline information from the drivers regarding their experiences with technology and their experience with and expectations of the systems.
Short-Form Surveys	To gauge driver perceptions primarily concerning usability issues in a brief, easily administered format. The survey was given two times.
Long-Form Surveys	To gather information from all four objectives. The survey was administered on three separate occasions.
Debriefing Interview	To collect final information on user acceptance over the four goal areas. In this interview, questions elicited both quantitative and qualitative responses.

Dr. John Sullivan of UMTRI was the primary contact with the drivers throughout the study. He introduced them to the study and obtained their informed consent for participation in August 2000. He explained what kinds of data would be collected, but, to minimize influences on their driving behavior, he did not at that time tell the drivers that the study concerned rollovers. Instead, the drivers filled out a written survey on their decision-making styles. The next direct contact with the drivers was during the week of June 11, 2001, when Dr. Sullivan again met with each driver and personally gave an orientation to the RA&C. The systems in the six tractors were activated June 14 through 18.

	2000		2001						
	Aug	Sep	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Driver Data Collection									
Informed Consent	▲								
Decision-Making Survey	▲								
Orientation to the RA&C			▲						
Activation Interview and Survey			▲						
Short Survey (given 2 times)				■	■				
Long Survey (given 3 times)						■	■	■	
Final Interview									▲
Truck-Based Data Collection									
Baseline		■	■						
System-On			■	■	■	■	■	■	

Figure 4-5. Schedule of Driver Surveys and Interviews for the Freightliner FOT

In the week following the orientation, personal interviews were conducted with each driver, by Dr. Hugh Clark of CJI Research, Mr. Doug Pape of Battelle, and Dr. Sullivan. Drivers also completed a short questionnaire at that time. The purpose was to gauge the drivers' experience with technology in general and with other safety systems and to learn their initial expectations for the new systems. Five additional written surveys were given to the drivers during the course of the study while the RA&C was active. The first two were "short" surveys, and the following three were "long" surveys. The surveys, designed by UMTRI with input from Battelle, were mailed as a package from UMTRI to the Praxair dispatcher in LaPorte, who gave them to each driver when he was available. When all of the surveys had been filled out, the dispatcher mailed them back to UMTRI. While this method had the advantage of ensuring 100% response to the surveys, the exact date on which any survey was filled out is not known, because the surveys themselves were not dated. Essentially, there was one survey each month during the five full months that the system was active.

Onboard data collection ended on December 4, 2001. Dr. Sullivan and Mr. Pape personally interviewed the drivers during the week of December 3 to learn their final assessment of the RA&C. Whereas the initial interviews in June were free flowing with mostly qualitative results, the final interview was more structured to provide quantitative results where possible. However, the individual, in-person format of the final interviews did allow follow-on questions, and many extra comments from the drivers were recorded.

The survey and interview instruments are in Appendices B and C, and the implications of the results are discussed in Section 5.5.

4.2.4 Operations Data

Daily fleet operations records are electronically recorded by Praxair, the fleet operator, and were integrated with the electronically recorded engineering data by UMTRI, who provided them to Battelle. The database contained driver assignments, destinations, fill levels, and mileages. Praxair also provided its historical rollover rate (about one rollover in 10 million miles driven) and brief descriptions of the rollovers that occurred in the three years before the FOT began. This historical information was used to calibrate the extrapolation from the FOT data to the entire fleet. Battelle also collected data on the availability and maintenance needs of the RA&C system.

4.2.5 Track Tests

To supplement the data from the FOT itself, Battelle ran a series of full-scale experiments at TRC (Transportation Research Center Inc., East Liberty, Ohio). The tractor for this activity was called the "seventh tractor." It was manufactured to be identical to the six in the FOT, and it was outfitted with the same sensors and data collection system. The trailer was a former Praxair nitrogen tanker that had been in a rollover that occurred prior to the FOT. (The trailer was roadworthy, but the suspension on one side had been damaged by the roll. Pages D-2 through D-4 show a slight side-to-side variability due to the damage.) Additional sensors, beyond those in the FOT vehicles, were mounted on the trailer for the experiments. As the purpose of many experiments was to take the vehicle to rollover conditions, outriggers were mounted at the trailer axle to limit the possibility of the trailer rolling completely over. Appendix D shows a photo of the outrigger configuration.

The Evaluation Plan listed four purposes for the test track effort, as summarized below. Separate plans were developed for each of the four purposes, plus two initial tests that were needed to finalize plans for subsequent tests. The four purposes and the six associated tests were as follows:

Purpose 1. Determine the actual conditions of rollover. This was the most important part of the test track work. These experiments were a key part of the safety benefits estimation.

Test 002	Initial Testing
Test 003	Testing of Advisories with 45% to 55% Rollover Index
Test 004	55% and Higher Rollover Index Testing

Tests 002 and 003 were to help ensure that Test 004, the major test, covered all of the appropriate regions of interest.

Purpose 2. Determine whether warnings are issued under appropriate circumstances. These experiments supported Goal 3, the assessment of the system performance. At the beginning and end of each day, simple maneuvers were run to determine the day-to-day consistency of the RSA.

Test 001	Daily Testing

Purpose 3. Challenge the system, especially the RSC. This was a special test of the RSC that could not be performed in revenue service. Identical maneuvers were attempted with and without the RSC active, to find situations where the RSC could and could not prevent a rollover.

Test 006	RSC Testing

Purpose 4. Determine adaptability to different configurations. This test supported Goal 4, the product maturity assessment, particularly the objective concerning suitability for widespread deployment. Unlike the other tests, for this test the trailer was a flatbed with a fixed load. Identical experiments were run with a high and low center of gravity.

Test 005 Flatbed Testing

Appendix D contains the six detailed test plans and the results of the respective tests. The implications of the tests and their application to the evaluation are discussed in appropriate places in Section 5, Findings.

4.3 Analysis Methods

To achieve certain evaluation goals and objectives, it was necessary to combine the results from various data sources into comprehensive analyses. Section 3.2 provided a high-level overview of the types of data and depth of analyses that were carried out, and Table 4-1 identified the principal and supplemental data sources that were employed. In this section, we describe the analyses that were performed to achieve each of the goals and objectives

4.3.1 Goal 1A: Safety Benefits

The most important aspect of evaluating the RA&C is quantification of the potential safety benefits of the systems. In particular, four safety objectives were identified for evaluation. They were to determine whether

1A.1. Drivers will drive more safely with the RA&C than without it,
1A.2 Rollover conflict and crash probabilities will be reduced; vehicles equipped with the RA&C will have fewer rollover crashes than those without
1A.3 Rollover crashes, injuries, and fatalities would be reduced nationwide if all such fleets are equipped, and
1A.4 SVRD conflict and crash probabilities will be reduced.

Between the two driving periods, Baseline (no RA&C), and System On (RA&C operating), comparisons of statistics calculated from the onboard driving data were used to evaluate some of the hypotheses under Objectives 1A.1, 1A.2, and 1A.4. These comparisons provided objective and quantitative information indicating if the RA&C system decreased rollover risks, decreased driving conflicts and crashes, caused drivers to take curves more slowly after they have received a message, or decreased SVRD crashes. Conclusions based on onboard driving data statistics from evaluations conducted under Objective 1A.2 were extrapolated using U.S. population crash statistics (GES data) in Objective 1A.3. These extrapolations provided estimates of the number of crashes that could be prevented nationwide under a number of deployment assumptions.

Survey and interview data were used to capture the drivers' *perceptions* of the effect of RA&C on their driving behaviors. These data were used to evaluate specific hypotheses under objectives 1A.1 and 1A.2, specifically to assess if warnings supplant the judgment of experienced drivers and if the system helped to identify routes with less rollover risk. Survey and interview data were also useful in evaluating Objective 1A.3, specifically to assess if drivers believe the RA&C modified their overall curve taking behavior or if it only shown them where to be more careful on routes they already knew. This information was useful in inferring an appropriate population to which conclusions from Objective 1A.2 could be extrapolated because it provided insight into whether the RA&C system assisted drivers who were not dispatched from a central facility on regularly scheduled day trips.

Track test data were used in the evaluation of Objective 1A.2, and, thus, indirectly in the evaluation of Object 1A.3. The test track data were necessary to benchmark the simulation experiments that were used to quantify the severity of specific near-crash scenarios. Test track data also assisted in the evaluation of the RSC.

Objective 1A.1 Determining whether drivers will drive more safely

Three hypotheses were evaluated under this objective:

1A.1-1 Drivers educated with the RA&C will take fewer rollover risks.
1A.1-3 The systems warnings will not supplant the judgment of experienced drivers.
1A.1-4 Drivers warned by the RSA on a given curve will take the curve more slowly or more carefully on future trips.

To evaluate rollover risks (1A.1-1), a *rollover risk index, R_I,* was defined as the percentage that the lateral acceleration of the vehicle is of the lateral acceleration that would be required to roll the truck at its current fill level in a static situation.

$$R_I = \frac{a_y}{a_y^*(f)} \tag{4-1}$$

where a_y is the lateral acceleration observed, f is the vehicle's fill level, and $a_y^*(f)$ is the lateral acceleration required to roll the truck at its current fill level in a static situation. [UMTRI has collected data and estimated the lateral acceleration required to roll the truck in a static situation for a number of fill levels. The complete description of the tilt table tests is in Appendix C of Winkler et al. (2002). See Figure 4-6 on the next page.] For calculating the rollover index, we used the lateral acceleration measured by the accelerometer mounted on the tractor's drive axle.

A rollover risk event is defined as an excursion of the rollover risk index above a certain threshold. Rollover risk rates were estimated using a number of event defining thresholds between 55% and 80% as the number of rollover risk events at that particular threshold per vehicle kilometer traveled (VKMT).

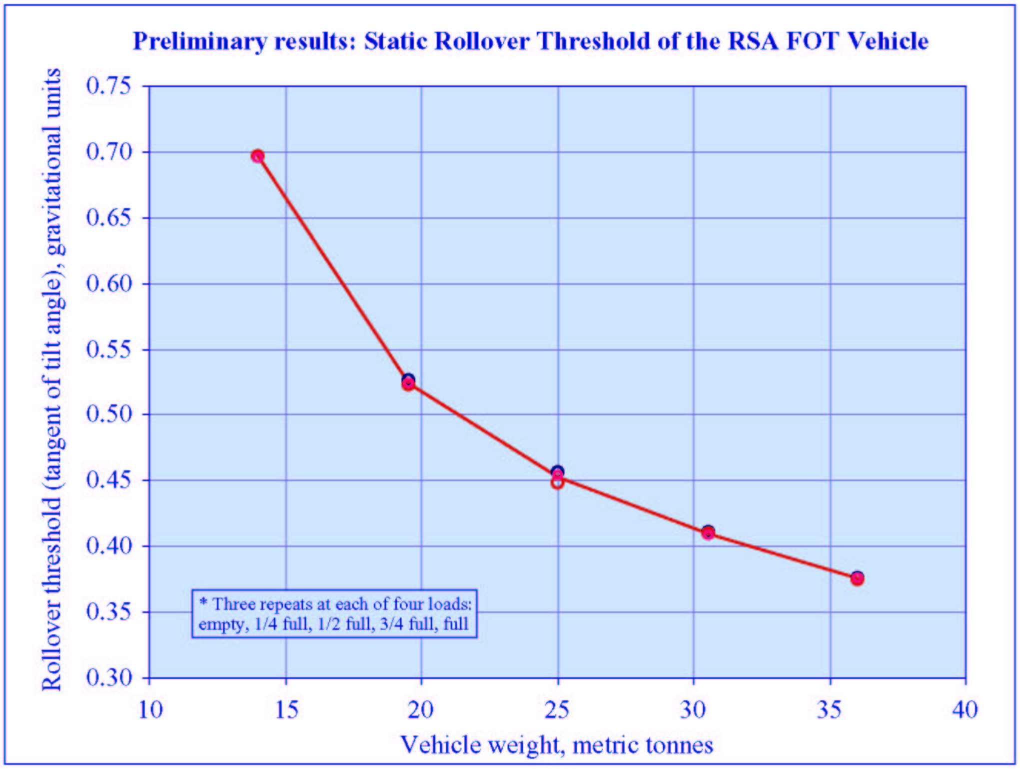


Figure 4-6. Static Lateral Acceleration Rollover Threshold (UMTRI)

Survey and interview data served to assess if the RA&C influenced the judgment of experienced drivers. This was a topic of discussion at the post-test interviews. We also examined the onboard data for evidence that the drivers occasionally reduced their safety margin.

To evaluate if drivers warned by the RSA on a given curve took the curve more slowly or more carefully on future trips, data from curves on which individual drivers received warnings were examined. Specifically, for each RSA warning issued, the subsequent *and prior* data from the warned driver were compared to determine if the maximum R_I during curve negotiation decreased. Daimler-Chrysler Research Center, as part of the Partnership's effort, assigned FOT travel to individual links, or road segments, in the commercial NavTech navigation database. These assignments were provided to the evaluator to aid in identifying repeated traversals of the same curve. The fact that Praxair drivers were dispatched from a central facility and were frequently dispatched to a limited number of destinations (Praxair customers who receive nitrogen on a regular schedule) made the chance that an individual driver traversed a given curve multiple times higher than it would be under less fixed dispatching plans.

<u>Objective 1A.2 Estimating reductions in rollover conflict and crash probabilities</u>

Estimating the reduction in the probability of a rollover crash under conditions encountered during the FOT was the primary emphasis of the assessment of safety benefits. The methodology used was similar to 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).

The potential reduction, R, in the probability of a rollover crash (the **Benefits Equation**) is

$$R = P_{wo}(C) — P_{w}(C) \qquad (4\text{-}2)$$

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

The methodology necessarily did not rely on analysis of crashes because it was anticipated that there would be no crashes during the Freightliner FOT, and, in fact, none occurred. Instead, the methodology partitions all crashes according to the *driving conflict* preceding each crash, and then looks simultaneously for a reduction in exposure to driving conflicts (exposure ratio) and in the chance of a crash after a driving conflict has occurred (prevention ratio).

Driving conflicts are determined to be particular safety critical driving scenarios, which precede crashes and are determined by the dynamic conditions of the test vehicle and the roadway. The vehicle dynamic situations that precede rollover crashes were identified based on analysis of GES data. (Section 4.2.1) Five types of rollover driving conflicts were identified, for example, *"truck is turning or negotiating a curve at excessive speed and loses control."* All crashes are preceded by a driving conflict, but all driving conflicts do not necessarily result in a crash, as conflicts are usually resolved before a crash occurs. Thus, driving conflicts, by definition, occur more frequently than crashes, and a significant number were anticipated, and, in fact, occurred, in the FOT.

The potential reduction, R, in probability of a rollover crash in Equation 4-2 can be manipulated with algebra and the rules of conditional probability to be expressed as

$$R = P_{wo}(C) \times \sum_{i} P_{wo}(S_i \mid C) \times \left[1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)}\right] \qquad (4\text{-}3)$$

where S_i is a driving conflict of type *i*, and $P_w(C \mid S_i)$ is the conditional probability that a rollover crash occurred with an active RA&C given that driving conflict S_i occurred. $P_w(S_i)$ is the probability that driving conflict S_i occurred with an active RA&C. Quantities subscripted with "wo" have the same interpretation, but for vehicles without (i.e., with inactive) RA&C. The probability that driving conflict S_i occurred prior to a crash given that a rollover crash occurred without (i.e., with an inactive) RA&C, $P_{wo}(S_i \mid C)$, is also required in the Benefits Equation.

There are two key ratios in the Benefits Equation, namely $\frac{P_w(S_i)}{P_{wo}(S_i)}$ and $\frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}$. The first ratio is the **Exposure Ratio**: the ratio of exposure to driving conflicts with and without an active

RA&C. Values of this ratio less than 1 indicate that an active RA&C will reduce exposure to potential crash situations. The second ratio, the **Prevention Ratio,** measures the ability of an RA&C to prevent crashes after a particular driving conflict has occurred. Again, if this ratio is less than 1, safety benefits can be inferred. The Benefits Equation is a robust approach to benefits estimation because each of the ratios used in computing benefits is based on a numerator and a denominator obtained by a consistent approach.

Four hypotheses, the first two of which relate to the Benefits Equation outlined above, were evaluated under this objective:

1A.2-1 Fewer rollover driving conflicts will be encountered with the RA&C.
1A.2-2 Probability of a rollover crash under conditions encountered in the FOT will be reduced with the RA&C.
1A.2-3 RSC equipped vehicles will have fewer rollover crashes.
1A.2-4 The RA&C will help identify routes with less rollover risk.

The effect of the RA&C on the rate of one rollover driving conflict type was evaluated (1A.2-1), specifically, *"truck is turning or negotiating a curve at excessive speed and loses control."* The quantities $P_w(S_1)$ and $P_{wo}(S_1)$, and, thus, the Exposure Ratio, was estimated from the onboard driving data. Driving conflicts are defined to be individual events during which the rollover risk index, R_I, exceeds 55%. Probability of a driving conflict, $P\,(S_i)$, is calculated as the number of driving conflicts identified within the onboard driving data divided by the number of miles driven.

Whereas the Exposure Ratio could be calculated from the driving data alone (specifically the lateral acceleration and the accumulated distance), calculation of the Prevention Ratio required the application of physical laws through a computer simulation. The lateral accelerometer was mounted on the tractor's steer axle, as shown in Figure 4-7, so it measured the sideways forces acting on the very front of the vehicle. Because the trailer is much higher than the tractor, the tendency to roll is determined by the sideways force acting on the trailer's center of gravity, as was shown in Figure 2-2 (shown previously). In a long, steady turn, the lateral acceleration at the two locations is nearly identical, but they can be quite different in the constantly-changing maneuvers encountered in the FOT. Therefore, a dynamic computer simulation of a five-axle articulated truck was used to infer the trailer's motion from the motion measured at the front axle. The computer simulation was validated through a series of test track experiments, where the actual acceleration of the trailer and the trailer's roll angle were measured.

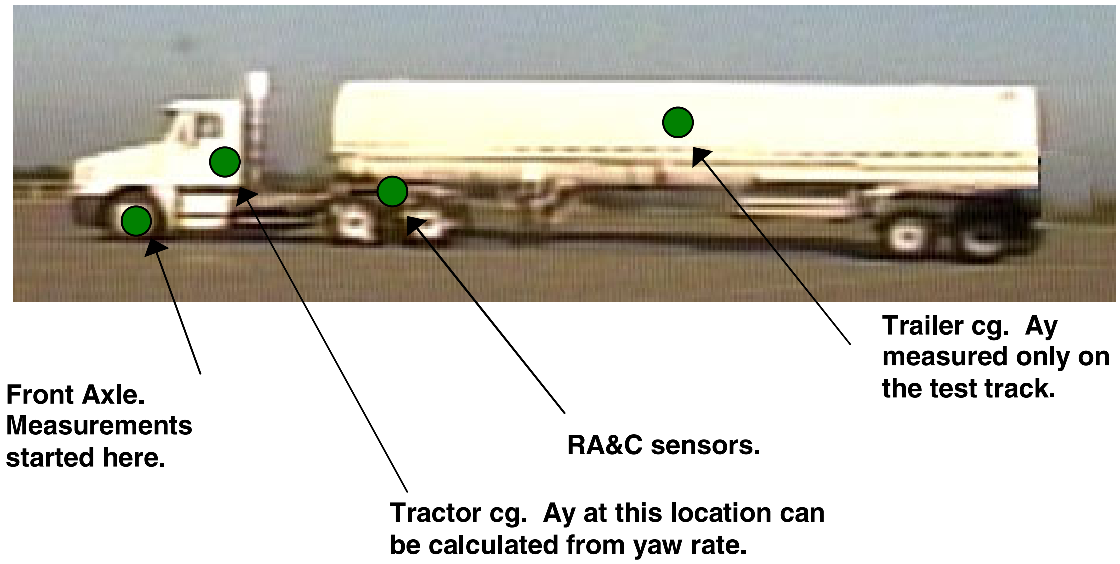


Figure 4-7. Lateral Acceleration (Ay) was Measured at the Steer Axle. Excessive Lateral Acceleration at the Trailer Center of Gravity (cg) Leads to Rollover.

Reduction in the probability of a rollover crash (1A.2-2) was evaluated by estimating the Prevention Ratio using $P_w(C \mid S_i)$ and $P_{wo}(C \mid S_i)$ the probability of a crash given that driving conflict S_i has occurred with and without RA&C, respectively. (Section 5.1.2.2) The Prevention Ratio and Exposure Ratio were combined using the Benefits Equations to estimate reduction in rollover crashes due to the RA&C.

The performance of the RSC was assessed by careful engineering examinations of events where it intervened and by maneuvers on the test track.

Routes or even specific locations with a high frequency of RSA notices or even RSC activations can be identified in the onboard driving data. In fact, the curve analysis, Section 5.1.1.3, has identified a number of links on which multiple drivers received warnings or on which individual drivers received multiple warnings. However, a normal fleet operator would not likely examine data in such detail. More likely, drivers would, over time, realize that certain locations more frequently yield notices. During the interviews after the FOT, drivers were asked whether this in fact happened, and results are presented in Section 5.5.

Objective 1A.3 Estimating reductions in crashes, injuries, and fatalities nationwide if all such fleets are equipped

The methodology that was used to address Objective 1A.2 permits estimation of the reduction in rollover crash probabilities under conditions encountered during the FOT. However, in order to extrapolate the results to estimate crash reductions under nationwide deployment, it was necessary to compare the conditions encountered during this FOT with typical driving conditions for drivers and vehicles in various target fleets. The four hypotheses specified under this objective assist in identifying the appropriate target fleet:

- 1A.3-1: Praxair-FOT drivers are typical of drivers across the country.
- 1A.3-2: Praxair is typical of fleets across the country.
- 1A.3-3: Praxair vehicles encounter rollover conflicts at similar rates to other fleets across the country.
- 1A.3-4: The reduction in rollover crash probabilities estimated for Praxair drivers is the same as for other drivers across the country.

To address the first three hypotheses, the Praxair fleet and its drivers were characterized in terms of the type of fleet operation (regional carrier of compressed gas in bulk tank trailers), location, truck type, cargo type, and carrier and driver safety records. SafeStat scores and other information from the Safety and Fitness Electronic Record (SAFER) system were used to determine the safety performance of Praxair and its drivers relative to other carriers. Demographic information on drivers in the Praxair and national flees were obtained from Praxair and Bureau of Labor Statistics records, respectively.

In addition to extrapolating the findings from this FOT to the entire Praxair fleet of 650 trucks, four potential target fleets were identified: (a) all class 7-8 truck tractors with tanker trailers carrying hazmat, (b) all class 7-8 truck tractors with tanker trailers, (c) all class 7-8 truck tractors with any type of trailer, and (d) all large commercial (classes 3 through 8) trucks greater than 10,000 lbs gross vehicle weight (GVW).

Although it is reasonable to extrapolate the findings from this FOT to the entire Praxair fleet, and possibly to the population of hazmat tanker fleets, and because of Praxair's exceptional safety record, it should be no surprise that the first three hypotheses were rejected when comparing Praxair to the larger populations of motor carriers. Nevertheless, the differences among fleets must be addressed when extrapolating the findings from this FOT.

Acceptance of the fourth hypothesis may be essential to estimating national safety benefits through extrapolation of findings from this FOT. However, there is no practical way to evaluate the hypothesis without performing similar FOTs on a variety of fleets. Therefore, this hypothesis merely serves as a reminder that the interpretation of the extrapolated findings from this FOT must consider not only differences in the characteristics and safety records of the motor carriers and their drivers, but also the variations in the efficacy of the IVSS for improving safety—even on a relative basis.

Although it may not be possible to fully validate and justify the extrapolation of safety benefits to all target fleets, it is still useful to perform the benefits calculations in order to illustrate the <u>potential</u> for crash, injury, and fatality reductions. For each target fleet to which the Objective 1A.2 benefit estimates are to be applied, the following equation was used to estimate the number of crashes avoided if all vehicles in the target fleet are equipped with RA&C:

$$B = E \times R$$

$$B = E \times P_{wo}(C) \times \sum_i P_{wo}(S_i \mid C) \times \left[1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)} \right] \qquad (4\text{-}4)$$

$$B = \qquad N_{wo} \times \sum_i P_{wo}(S_i \mid C) \times \left[1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)} \right]$$

where each term in R is as defined in the Benefits Equation 4-2 and E (exposure) is the vehicle kilometers traveled (VKMT) by the target fleet. $E \times P_{wo}(C) = N_{wo}$, the number of crashes by the target fleet, can be estimated from published or collected data.

Objective 1A.4 Estimating the incidence of crashes other than rollover

The methodology described to address Objective 1A.2 addresses this objective as well. The conflict identification and exposure ratio estimation methods are identical. The differences lie in the various methods used to estimate conditional crash probabilities (given a conflict) and the prevention ratio. Driving conflicts, particular safety critical driving scenarios, which precede crashes and are defined by the dynamic conditions of the test vehicle and proximate vehicles, were identified in the GES data. The rollover driving conflict investigated under Objective 1A.2 also led to 9% of single-vehicle roadway departure (SVRD) crashes involving tractors pulling tanker trailers (Table 4-3). Reduction in SVRD crashes by reduction in the driving conflicts leading to SVRD crashes is another potential benefit of RA&C. Due to inadequate lane tracking data in curves, it was not possible to estimate a prevention ratio for SVRD crashes. Therefore, the benefits calculations are performed with a prevention ratio equal to 1.0.

4.3.2 Goal 1B: Mobility Benefits

The effects of IVSS on mobility were evaluated, specifically to measure any mobility benefits to the general public that will accrue from the deployment of IVSS. Mobility was measured by the net benefits to travelers or other transportation consumers from a transportation improvement. Mobility benefits were applied to the benefit-cost analysis outlined in Section 5.9.

Reducing the number and/or severity of truck crashes reduces not only the direct costs to the vehicle owners and occupants involved, but also reduces the mobility costs. These include

- Traffic congestion and lost time for commuters and other on-the-clock travelers being stuck in traffic unexpectedly
- Secondary accidents because of increased traffic congestion
- Increased delivery times (and thus increased inventory costs for shippers and receivers)
- Reduced customer (shipper/receiver) satisfaction with the motor carrier involved.

The value of the lost mobility resulting from a truck crash was estimated from a literature review. Literature sources such as those of the Federal Motor Carrier Safety Administration (FMCSA) and the National Highway Traffic Safety Administration (NHTSA), both of which sponsor research on truck and bus accidents; the Pacific Institute for Research and Evaluation; and industry sources surveyed by the American Transportation Research Institute (ATRI) were used to determine the trends and costs of truck crashes.

4.3.3 Goals 1C and 1D: Efficiency and Productivity Benefits

In economics, "efficiency" means maximizing total net benefits from an investment or policy. To an economist, efficiency includes all the IVSS goals that have a dollar value to society. However, engineers tend to use the term "efficiency" much more narrowly to mean more output per unit of input. Engineering efficiency, rather than economic efficiency, is well accepted as one of the major IVSS goals. Measures of achievement of the engineering efficiency goal, however, do not enter into a benefit/cost analysis (BCA). This is because increased output per unit of input is best measured in transportation as increased throughput or capacity (e.g., vehicles per hour). Converting this benefit to a dollar value to society falls under the productivity goal in the form of cost savings. Thus efficiency and productivity were combined for purposes of this study.

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

The best available quantitative information on actual costs (one-time deployment costs and recurring operating and maintenance costs) incurred during deployment and operation of the IVSS were obtained from the FOT partners. The evaluation team attempted to itemize these costs so that future analysts can compare the costs reported in each FOT with cost elements for related IVSS deployments in the future.

Any potential cost savings were investigated using information from the safety benefits analysis and from the FOT partners.

4.3.4 Goal 1E: Environmental Quality Benefits

Energy savings in the form of decreased fuel use were included in the value of transit-time-related operating cost savings to motor carriers. The benefits to society of air and noise pollution reductions from IVSS were also calculated, based on the transit-time-related benefits input to the BCA. Cost values were obtained from literature sources. A summary of environmental benefits is presented as part of the formal benefit-cost analysis in Section 5.9.

4.3.5 Goal 2: User Acceptance and Human Factors

Goal Area 2 comprises four human factors objectives. These objectives focus on perception of usability, driving environment and workload, driving behavior, and product quality. These objectives help analysts understand if and how human factors play a role in the eventual acceptance and deployment of the systems. For each of the four objectives, we defined a series of hypotheses to be addressed through driver surveys, interviews, or the ergonomic assessment. In addition to the following four objectives, background and Baseline information were gathered to provide some historical information about the drivers' experience and to allow an understanding of what the drivers thoughts and perceptions of the system were before they had any contact with the RA&C.

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

This objective focuses on how RA&C is used and understood by the drivers. In particular, we were concerned with 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.

Objective 2.2: Determine how IVSS technologies affect the driving environment and driver workloads.

This objective focuses on how the RA&C affects the driving environment. Of particular interest are the effects of false alarms and the changes in driver workload. Driver perceptions of false alarm rates were compared with objective measures related to system performance established under Goal 3.

Objective 2.3: Determine the adaptability of the driver in terms of behavior risk modification and changes in driving vigilance.

While one of the objectives under Goal Area 1A (safety benefits) addressed whether drivers modify their driving behavior (and the degree to which modified behavior is safe), this objective was concerned with learning why drivers modify their driving behavior.

Objective 2.4: Determine perceptions of product quality, value, and maturity and establish customer willingness to pay.

Information on the perceived quality, value, and maturity of the IVSS from the perspective of the users (drivers, mechanics, and other fleet personnel) were obtained. Issues related to willingness to pay were addressed from the host fleet manager's perspective.

The surveys, questionnaires, and interviews were designed to satisfy each of the hypotheses and objectives. Some questions were designed to be asked over numerous phases of the survey process to gather longitudinal data representing the change in opinions or perceptions over time.

A number of the hypotheses also relate to issues that were addressed through the performance of the on-board ergonomic assessment of the system instrumentation. All of these hypotheses fall under the usability objective, since they concern how the IVSS are used and understood by the drivers, the robustness of the signals, and the ease of use and control.

All of the human factors data were combined to provide the insight into the nature of the relationship between the driver and the system interface. This insight aided in the determination of the advantages and disadvantages of the system from the viewpoint of the drivers, and contributed to the decision for future deployment of the intelligent systems on a larger scale.

4.3.6 Goal 3: Performance and Functionality

System performance was assessed using data from the FOT itself and data from the test track experiments. The consistency of the advisory messages was reviewed by examining the data from identical or nearly identical maneuvers on different days. The accuracy of the messages was judged by applying simple principles of physics to the RSA's recommendations and the known vehicle conditions. The FOT drivers' opinions on accuracy, expressed both in the surveys and the in-person interviews, were considered as well. Finally, the reliability of the system was judged on the maintenance requirements that were experienced during the FOT as reported by Praxair.

4.3.7 Goal 4: Product Maturity for Deployment

Investigation of product maturity for the Roll Advisor and Control (RA&C) System was accomplished primarily from interviews with vehicle manufacturers and original equipment manufacturers (OEMs) and comparison of the life cycle development and safety system introduction of comparable systems such as antilock brakes and conventional cruise control. Battelle complemented the interviews with a literature search for similar projects, track testing to evaluate system performance, and an engineering analysis.

It was assumed that an extensive analysis of product maturity was not needed for this technology since the complexity was minimal and there was already another similar product on the market in Europe and Australia. In addition, Freightliner already has introduced the Roll Advisor and Control System into its product line and it can be purchased as an option on selected tractor models. Commercial literature on these systems is presented in Appendix G. The Freightliner brochure in Appendix G was developed early in the project and is not necessarily representative of the current RA&C product.

4.3.8 Goal 5: Institutional and Legal Issues

The methodological approach to addressing institutional and legal issues was designed to identify important issues that could affect the success of the IVI program in general and the deployment of the specific IVI technologies being evaluated for Freightliner. Identification of institutional issues required an understanding of the relevant organizations, jurisdictions, and individuals as stakeholders in the outcome of this deployment, the adequacy of organizational procedures for managing the project components, and the perception of any potential problems due to the deployments that would need to be addressed and managed. Identification of legal issues involved an examination of laws and regulations that apply to the IVI program and the technologies being deployed, program consistency or conflict with these requirements, and an assessment of liability or privacy concerns. For both institutional and legal issues identified in this analysis, strategies for mitigating or avoiding problems were identified, and the most important issues were given greater attention.

A step-by-step approach to this analysis was conducted:

- Through expert and other stakeholder interviews, the elements of the IVI program deployment that have the potential to give rise to institutional or legal issues were identified, exposure of the stakeholders to liability risks was assessed, and the mechanisms by which the IVI program elements could give rise to these risks were identified.
- Current laws and regulations, along with experience in similar program deployments with institutional and legal issues were examined, both by reviewing case studies and by interviewing selected individuals familiar with these issues in comparable contexts. These individuals were affiliated with product vendors, public agencies involved in the deployment or regulation of the technologies, the insurance industry, and fleet operators and employees.
- The issues identified were prioritized by importance, as judged both by the stakeholders and by the analysts, and possible mitigation strategies were identified.

5.0 Findings

Results from the Freightliner IVI FOT are presented according to the evaluation goals, objectives, hypotheses, and measures as defined in the Freightliner Evaluation Plan (Battelle 2001). For reference, the planned goals are reprinted in Appendix A of this report and also summarized above in Table 3-2. The first eight section headings within this chapter correspond to the major goal areas of the evaluation. The ninth and final section contains the benefit-cost analysis.

5.1 Achieve an In-Depth Understanding of Safety Benefits

This section presents the safety related findings of the Evaluation according to the four safety objectives identified in Section 3.2 (Description of Goals and Objectives). On board driving data, surveys and interviews, and track test data were all used to evaluate these objectives.

This first objective (See Section 5.1.1) seeks to answer the question of whether **drivers with the RA&C drive more safely, in ways related to the system.** Because safety to avoid rollovers depends strongly on the speed of the vehicle in curves, where the RSA reminds drivers to drive more slowly, this analysis focuses on drivers' risk-taking behavior as measured by speeds in curves during the FOT. The analysis shows that there was a slight, but statistically significant, reduction in the overall speed in curves by drivers after the RA&C was activated.

The second objective (Section 5.1.2) is to **determine if vehicles equipped with the RA&C have fewer crashes than vehicles without the system**. This is accomplished by estimating the efficacy of the RA&C at preventing driving conflicts and crashes. Under the conditions observed in the FOT, it was estimated that RA&C can help prevent 20 percent of the untripped rollover crashes caused by high speeds in curves or turns.

The RSC activated several times during the FOT, but never when the vehicle was in apparent danger of rolling over. Evaluation of the test track data concluded that there are instances where the RSC can improve the stability of a vehicle. However, because (a) there is no evidence that the RSC actually activated during a risky maneuver during the FOT, and (b) none of the drivers reported that they were aware that the RSC activated, it was not possible to determine the contribution of the RSC in the overall safety benefit estimate for the RA&C system.

Drivers reported that the RA&C did not help them identify routes with less rollover risk. However, because these drivers operate within a limited delivery area and were intimately familiar with the routes before the FOT began, the findings do not imply that the RA&C could not be useful for this purpose. Not all drivers would be similarly familiar with their routes.

Because the third safety objective (estimation of crash, injury, and fatality reductions at full deployment) was expanded to include both untripped rollover and SVRD crashes, the findings related to fourth objective are presented first. Section 5.1.3 addresses the **potential for the RA&C to prevent SVRD crashes**. In addition to being the primary cause of rollover crashes, the conflict involving high speeds in turns can also lead to many SVRD crashes. Under the conditions observed during the FOT, we estimate that the RA&C will prevent 33% of SVRD crashes caused by excessive speed in a curve. However, because adequate data were not available to statistically estimate the prevention ratio for SVRD crashes, the crash reduction estimate was calculated using a prevention ratio of 1.0. A more conservative approach, which is considered as part of the benefit-cost sensitivity analysis, is to use the prevention ratio estimated for the untripped rollover crash type. This approach produces an efficacy estimate of 20%.

Section 5.1.4 presents findings involving the extrapolation of the RA&C efficacy estimate to **determine the decrease in the total number of crashes and crash-related injuries and deaths that would occur if all vehicles in target fleets were equipped with RA&C.** The analysis determined that 34 crashes, 21 injuries, and 3 deaths would be avoided each year if all large trucks with tanker trailers were equipped with RA&C. The potential reductions in rollover and SVRD crashes, injuries, and fatalities for three additional deployment scenarios (all tanker trailers carrying hazmat, all tractor-trailer trucks, and all large trucks) are also presented.

5.1.1 Do Drivers Drive More Safely with RA&C?

Four hypotheses were proposed to evaluate if drivers exhibit generally safer driving behaviors with the RA&C. Each of the individual hypotheses addresses a behavior change (either toward safer or less safe driving) that one might reasonably expect due to a driver's experiencing RA&C advisories or controller interventions.

Three hypotheses were concerned with

1. The effect of RA&C on the frequency with which drivers take rollover risks in curves, specifically via a measure of how near the truck is to a rollover condition,
2. The effect of RSA advisories on driver judgment, and
3. The effect of RSA messages on the drivers' future behavior on curves.

The hypotheses were evaluated using a combination of on board driving data and driver interview data. A fourth planned hypothesis, related to the effect of management feedback, was not addressed due to changes in the research design made by the FOT partners.

All analysis results indicate that the RA&C leads to either safer or unchanged driving behavior. No increased risks were identified. The results demonstrate that, on average, **drivers equipped with the RA&C do experience fewer rollover risks.** There is no evidence that the drivers are taking more rollover risks because they perceive the RA&C is permitting them to do so. No drivers with low advisory rates showed an increased rate of risky maneuvers in the driving data, and none reported a perceived change during the interviews.

Our analysis **did not produce conclusive evidence that all drivers receiving RSA warnings on a given curve will take the curve more slowly on future trips.** However, there are indications that drivers do heed the messages on subsequent trips through curves on freeways and arterial roads but not on ramps.

Each of these conclusions is supported by analyses presented below.

Frequency of Rollover Risks for Drivers Educated with the RA&C. Figure 5-1 illustrates how lateral acceleration behaves during a curve negotiation. The left panel of Figure 5-1 plots the path of a tanker making a right turn. The right panel plots the lateral acceleration behavior of the tanker whose path is depicted in the left panel.

The tanker whose path and lateral acceleration behavior are depicted in Figure 5-1 weighed 35 tonnes during this maneuver. Figure 4-6 from Section 4.3.1 indicates that the lateral acceleration required for rollover of a static Praxair tanker is 0.37g (dotted line in Figure 5-1). The peak lateral acceleration observed in Figure 5-1 is 0.24g. Thus, negotiation of this curve produced a rollover index, R_I, of 65% (0.24g/0.37g).

To understand the rate at which FOT tankers experienced various levels of the rollover risk index, occurrences of rollover risk index greater than 55% were identified. Many occurrences of R_I greater than 55% were during the same driving event. For example, in Figure 5-1, the tanker had R_I greater than 55% for many consecutive points as the data were measured at 10 Hz. Distinct events with R_I greater than 55% were identified, and the maximum R_I during the event was assigned to each. There were 903 events with R_I greater than 55% in the Baseline driving data (341,317 VKMT) and 949 in the RA&C (System On) driving (385,845 VKMT). Figure 5-2 presents the rate of events with rollover risk index greater than a range of thresholds between 55% and 80% for Baseline and System On driving. The Baseline rate is consistently higher than the RA&C rate. The greatest difference in Baseline and System On rates occurs for when the rollover risk index is 75%.

The diamond on the far right side of Figure 5-2 indicates Praxair's historical rollover rate. Specifically, Praxair reports that they experience about 1 rollover per 10,000,000 VMT (16,000,000 VKMT).

Table 5-1 presents the ratio of the System On to Baseline rates of occurrences of rollover risk index greater than 55%, 75%, and 80% thresholds. The 95% confidence intervals demonstrate that at rollover risk indices of 55% and 75%, the ratios of the System On rate to the Baseline rate are significantly different from 1 (i.e., the intervals do not include the value 1). In both cases, fewer rollover risks are indicated for the driving done with the RA&C.

Looking at individual drivers one at a time, Figure 5-3 presents confidence intervals for each driver's ratio of rollover risks at a 55% threshold. Most drivers' confidence intervals include unity. Similar plots for 75% and 80% thresholds do not reveal information, as many drivers have either no Baseline or no System On events at these high thresholds, and if no events occurred in one case or the other, the ratio of rates cannot be estimated.

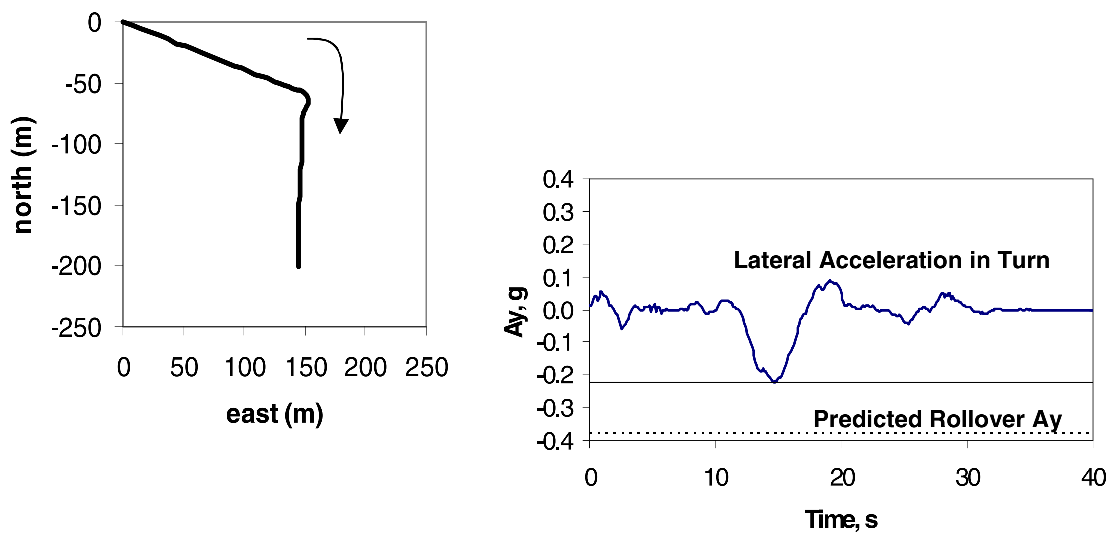


Figure 5-1. Lateral Acceleration Behavior of a Right Turning Tanker

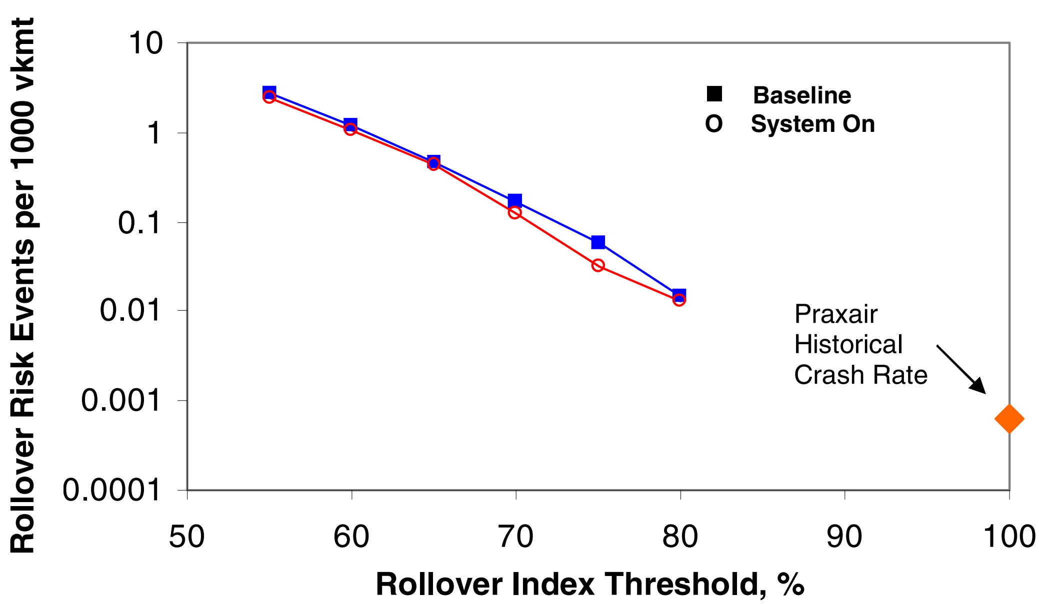


Figure 5-2. Comparison of Baseline and RA&C Rates of Rollover Risk Based on a Range of Thresholds

Table 5-1. Ratios of Rates of Rollover Risks at Three Thresholds

Rollover Risk Index Threshold	Ratio	95% Confidence Interval
55%	0.93	0.90 – 0.96
75%	0.53	0.38 – 0.68
80%	0.88	0.48 – 1.28

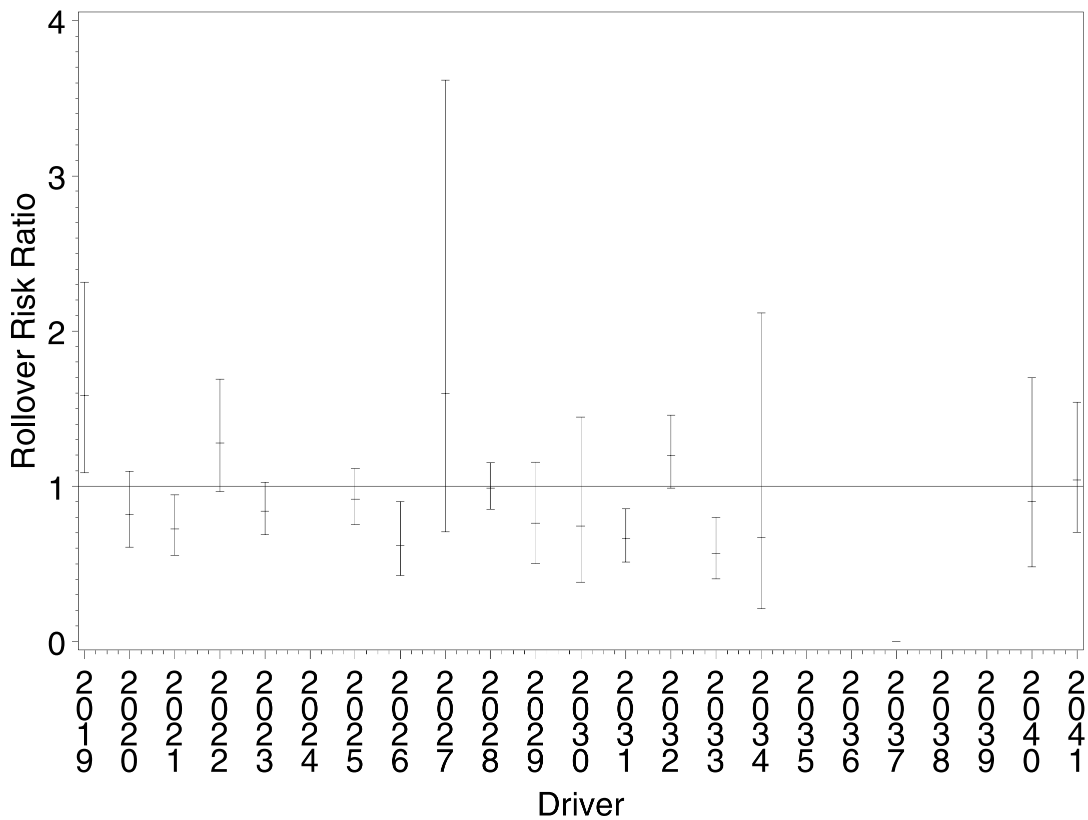


Figure 5-3. Confidence Intervals for Ratios of Rates of 55% Rollover Risks by Driver

Rollover risk events examined in this section are related to driving conflicts that are used in the safety benefits estimation methodology (see Section 5.1.2). Like rollover risk events, driving conflicts are defined based on the rollover risk index, R_I, except additional criteria are applied to declare a conflict.

Effect of RSA Warnings on the Judgment of Experienced Drivers. There is no evidence, either in the data recorded on the vehicles or in the driver interviews, that the drivers are taking more risks because they believe the RA&C is permitting them to do so. Opinions varied as to whether the system was too sensitive or too insensitive, and the drivers' remarks indicated that they trusted their own experience more than the device. None of the drivers, even in an offhand comment, suggested he had increased confidence for more aggressive driving. One driver, whose advisory count was near the average, said, "I've been erring on the cautious side, but I'm not changing anything. What do I save? Ten seconds? That ain't worth four or five stitches." The few who said they had intentionally generated a warning message said they did so with maneuvers they would not ordinarily do and gave no indication they would begin doing so.

To determine whether the drivers, perhaps subconsciously, are speeding up because they perceive the RA&C permits them to do so, consider Figure 5-4. Note that drivers with low advisory rates in the Baseline period (when the drivers were unaware of their rate) did not have substantially higher rates during the System On period, when they became aware of their low rate. (The Baseline rate is only approximate because the formula was changed during the period.) As a separate measure, to see if the drivers were driving just below the RSA threshold, consider Figure 5-5, where the Baseline and System On Risk Event rates for each driver are plotted as a function of System On advisory rate. Again those drivers with very low advisory rates (at the left side of the figure) show no trend toward higher conflict rates during the System On period.

Therefore, concerns that the drivers might "drive to the system" have not been borne out.

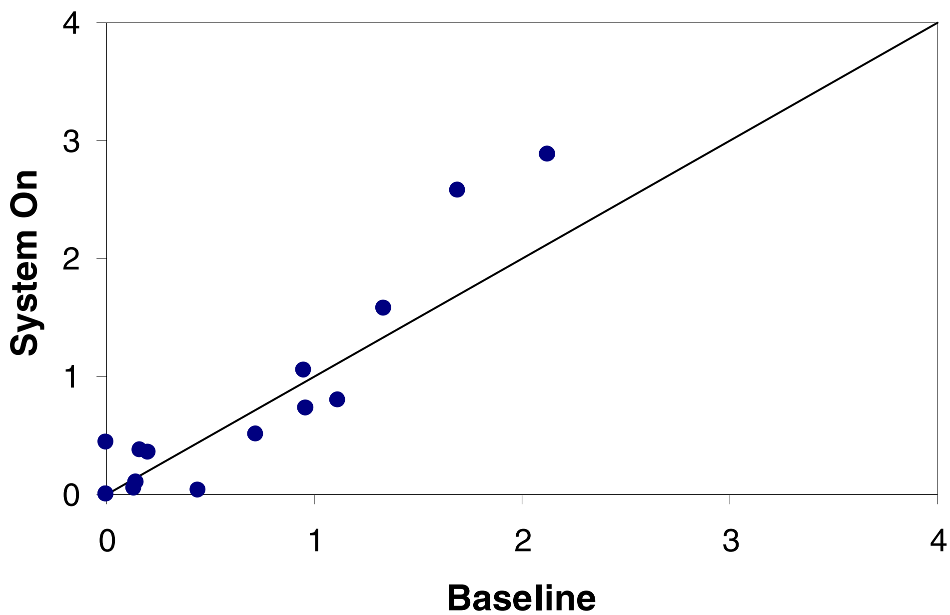


Figure 5-4. Advisory Rate for Each Driver (Number of Advisories per 1000 km) during the Baseline and System On Periods

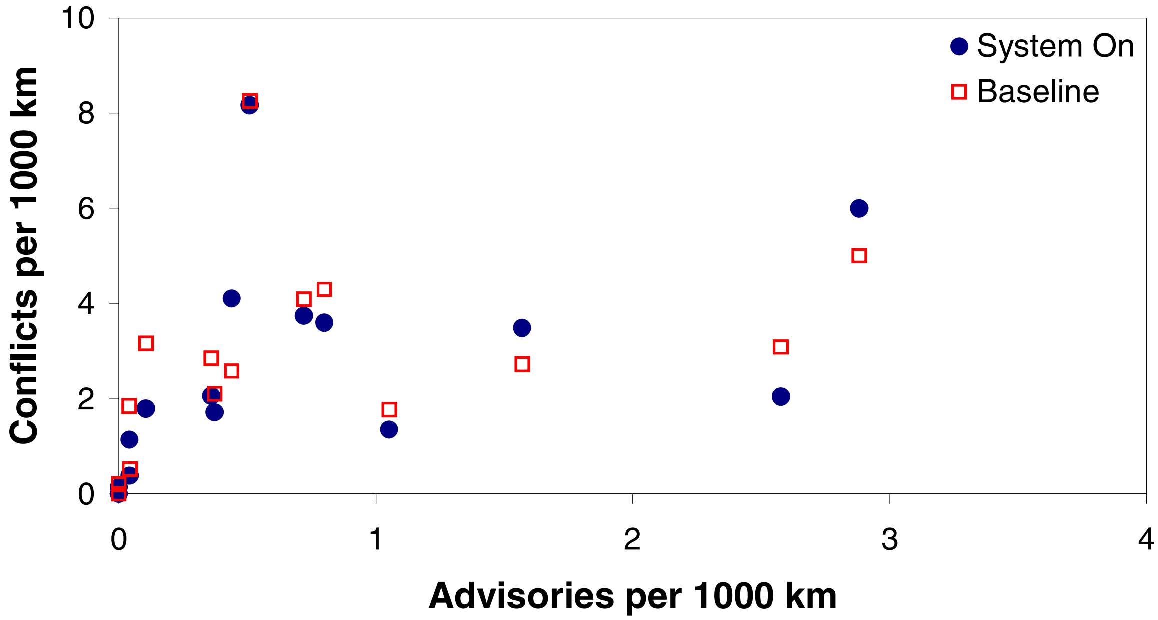


Figure 5-5. Baseline and System On Conflict Rates for Each Driver as a Function of System On Advisory Rate

Effect of RSA Messages on Drivers' Future Behavior on Curves. If a driver receives an advisory message on a particular curve and heeds the message, he may take that curve more carefully on later trips. This analysis compares the behavior of individual drivers at locations where they received RSA messages, before and after receiving the messages. It seeks to determine if rollover risk taking behavior, as measured by the rollover risk index, is reduced by RSA messages at the specific site at which the message was issued.[1] The discussion first examines behavior on specific sites before and after advisory messages, where evidence of changed behavior was found only in isolated cases. Secondly, groups of similar roadways were grouped together, and a statistically significant drop in risk-taking behavior was found in two classes of roadway. Finally, one particular ramp, on which many advisory messages were issued throughout the FOT, is analyzed. Changes in behavior at this particular ramp are inconsistent and are attributable to factors other than the RSA messages, such as traffic and weather.

Multiple trips through locations at which individual drivers received RSA messages were identified in the FOT driving data, and the vehicle locations at the time the messages were received were matched to links in the commercial NavTech database. For each driver, a list of unique RSA messages from the System On FOT driving data was compiled. A message was

[1] UMTRI answered this same question through a different analysis but arrived at a similar conclusion. There is a trend of improved behavior on passes through a curve after an advisory, but the trend is not statistically significant. See Section 8.7 of Winkler et al. (2002). UMTRI conducted an analysis to answer the related but distinct question of whether a driver's behavior is different immediately following an advisory than it was immediately prior. Section 8.6 of their report showed a temporary change in behavior within the first 250 km after an advisory. The change seemed to dissipate over time, as it was not as strong when longer intervals were considered.

considered unique if it occurred more than 5 seconds after the previous message. Of the 309 System On messages, 287 were classified as unique under this definition.

The RSA delivers its message shortly after a rollover risk event occurs. To ensure that the link where the event occurred was properly captured, the event's time was reckoned as 3 seconds prior to the message time. The timing of these unique events was then checked against the start and end times for all the links. An event time was matched to a link for 247 of the 287 unique events. Appendix I presents a series of plots of the NavTech links on which FOT drivers received RA&C messages.

For each of the 247 RSA messages, prior traversals on the same link by the same driver were extracted from the Baseline and System On FOT data. Similarly, subsequent traversals on the same link by the same driver were extracted from the System On data. Occasionally drivers received messages on more than one traversal of the same link. Therefore an indicator of the number of prior messages was incorporated into the analysis.

Only those instances where a driver traversed a roadway at least twice prior to the message and at least twice after the message were included in this analysis. Of the 247 matched advisories, 98 met this requirement. Table 5-2 lists the 28 links over which the 98 advisories were distributed. Also listed are the road classification, link number and road name, the count of the number of drivers who received a message on each link, the number of total unique messages on each link, and the total number of traversals of this link by all drivers.

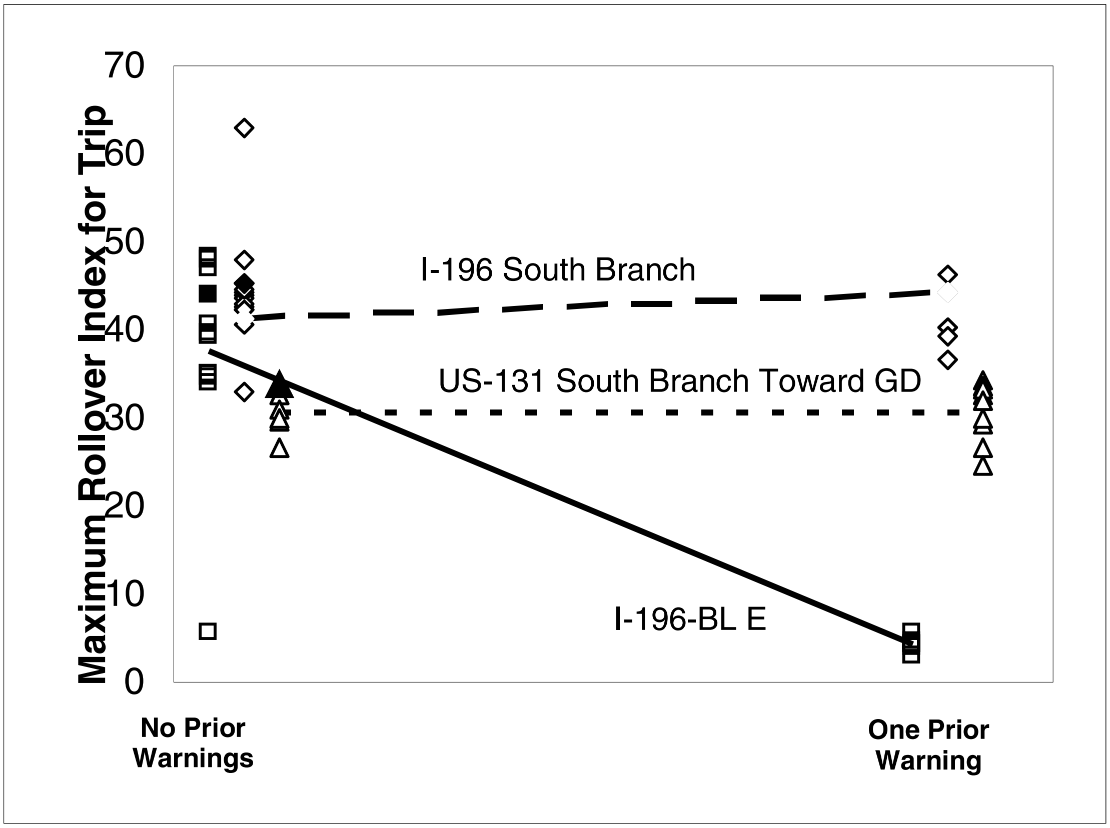
To evaluate whether a driver takes the same curve more carefully after an RSA message, a maximum rollover index (R_I) was calculated for each traversal or trip on a link, including the message trips. (See Section 4.3.1, Equation 4-1.) Figure 5-6 is a plot of the maximum R_I for driver 2021 for the 3 links on which he received a message and where sufficient prior and subsequent data existed. Each link is represented by a uniquely shaped symbol in the figure. Each open symbol on the plot represents the maximum R_I for a trip by this driver. A solid symbol corresponds to the maximum R_I for a trip on which the driver received an RSA advisory. The lines connect the average maximum R_I for all trips at the displayed number of prior messages. Driver 2021 does not appear to evidence more careful driving after the RSA messages on two of the links, but does appear to evidence more careful driving on the link named I-196-BL E.

Appendix I contains similar plots for all of the drivers. Each plot represents a different driver. Data from 13 drivers met the minimum requirements to be included in this analysis. Eight drivers received no more than one RSA message on the same link and three received no more than three. However, two drivers (ID numbers 2031 and 2032) are notably different from other drivers. Each of these drivers received a large number of advisory messages, including many messages on the same link. It is clear that these two were not driving differently in these locations because of the messages. The data for the remaining drivers were analyzed to search for subtle changes in behavior.

Table 5-2. Summary Information for NavTech Links on which Unique RSA Messages were Identified[1]

Road Classification	NavTech Link Number	Road Name	Number of Different Drivers Receiving Messages	Total Number of Unique Messages Received	Total Number of Traversals by All Drivers[2]
Local or Regional Road	39953003	IN-39	4	4	1066
	39953077	IN-39	3	5	1642
	39953085	IN-39	1	1	1623
	40106353	M-239	2	2	756
	40182039	E NAPIER AVE	1	1	28
Arterial Road	39972220	US-35	1	1	104
	40274262	US-35	1	1	136
Freeway	33751748	I-196-BL E	1	1	168
	39954598	US-35 N	1	2	111
	39954614	US-35 N	1	2	103
	39989477	UNNAMED RD	1	1	129
	40101088	UNNAMED RD	3	3	308
	40101090	CLINE AVE	8	25	309
	40140174	I-196-BL E	1	1	204
Motorway, Highway	39914143	I-196 W	1	2	189
	39952371	I-90 TOLL W	1	2	121
	39994187	I-196 S	1	1	801
Ramp to Local or Regional Road	39953082	I-80/I-90 Branch	1	1	391
	39953113	I-80 EAST/I-90 EAST Branch	2	2	288
	39953114	49	2	3	330
	39996446	I-94 EAST Branch	1	1	940
Ramp to Freeway	39989151	I-196 SOUTH Branch	4	8	197
Ramp to Motorway, Highway	39952350	I-80 WEST/I-90 WEST Branch	3	17	242
	39953829	US-31 NORTH Branch	1	3	42
	39996829	US-131 SOUTH Branch Toward GD	1	1	22
	40075370	12A	1	1	110
	40097602	I-90 WEST Branch Toward CHICAGO	1	4	118
	40109894	UNNAMED RD	2	2	250

[1] Minimum of two traversals before and after receiving the RSA message.
[2] Includes only those traversals that were matched by GPS to the NavTech link.



Note: Open symbols indicate trips through the indicated link. Solid symbols indicate trips after which an RSA warning was issued. Lines connect the before and after averages of trips.

Figure 5-6. Driver 2021 Maximum Rollover Index for Matched Links

A statistical analysis was conducted to investigate if there was a systematic response to messages. Although some drivers received multiple messages on individual links, link traversals in this analysis were only classified as before or after the first message. An Analysis of Variance (ANOVA) model of the maximum R_I on a link was specified. The model included terms for driver, road class, and whether or not the driver received a prior RSA message on the link. All two- and three-way interactions were included in the model. Road class was recoded from the values listed in Table 5-2 to capture three general classes of roads: 1. Ramps, 2. Local, Regional, or Arterial Roads, and 3. Motorways, Highways, and Freeways.

The goal of this analysis is to determine if the RSA messages received by drivers at particular locations have a significant effect on their risk-taking behaviors when they return to the same locations. All main effects and two- and three-way interactions were found to be statistically significant at the 0.05 level. Among other things, this implies that there are real differences in the maximum risk index before and after drivers receive RSA messages, and these differences vary among drivers and road classes in a non-systematic manner.

Figure 5-7 shows the average change in the maximum R_I by driver within each road class. The statistical uncertainty in these average changes is described in the form of 95% confidence intervals on the average changes. When the confidence interval does not include the value zero, we can state that the effect of the RSA message for that driver-road class combination is statistically significant.

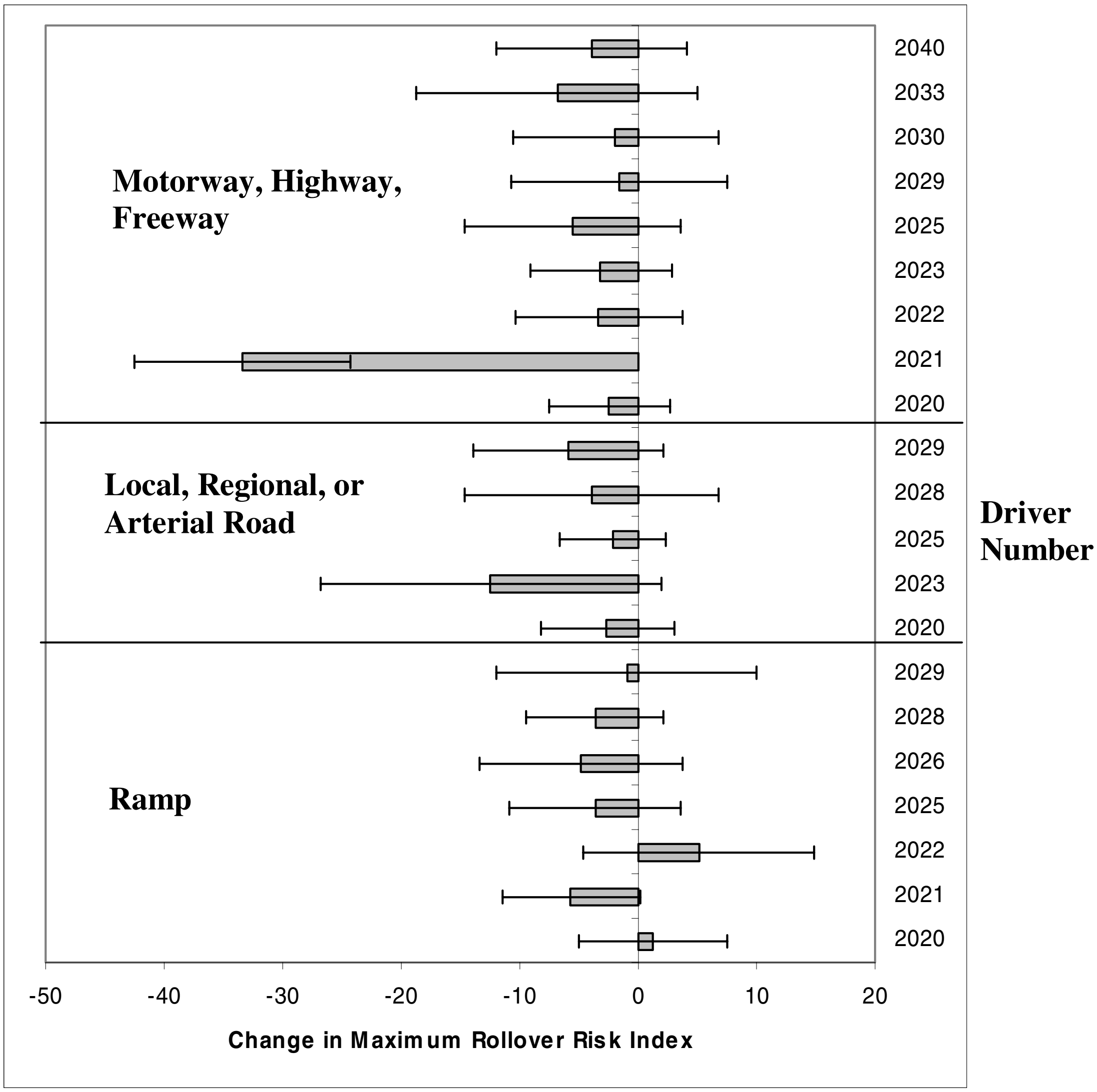


Figure 5-7. Change in Maximum Rollover Index after an RSA Message by Driver and Road Class (with 95% Confidence Limits)

Although the effects of RSA messages were found to be statistically significant for only one or two combinations of drivers and roadway class, the change in average maximum R_I is consistently negative for all road classes except ramps. In the ramp class, drivers 2020 and 2022 exhibited positive changes in maximum R_I, though these were not statistically significant.

Next, we looked at the average change in maximum risk index by roadway class and drivers. Figures 5-8 and 5-9 present average changes in maximum R_I after a message, along with 95% confidence intervals, by road class and driver, respectively. These averages weight each estimated change in maximum R_I equally across the set of road classes and drivers observed. Based on Figure 5-8, it can be concluded that across the set of drivers included in the data, advisories on Motorways, Highways, and Freeways, and advisories on Local, Regional, and Arterial Roads resulted in statistically significant reductions in maximum R_I on subsequent passes through the same roadway. The effect of advisories on ramps, though indicating a favorable trend, was not statistically significant. This could be because drivers were familiar with the rollover risks associated with ramps prior to this study. Figure 5-9 indicates that only one driver had statistically significant reductions in peak rollover index after hearing advisories, so no firm conclusions can be drawn.

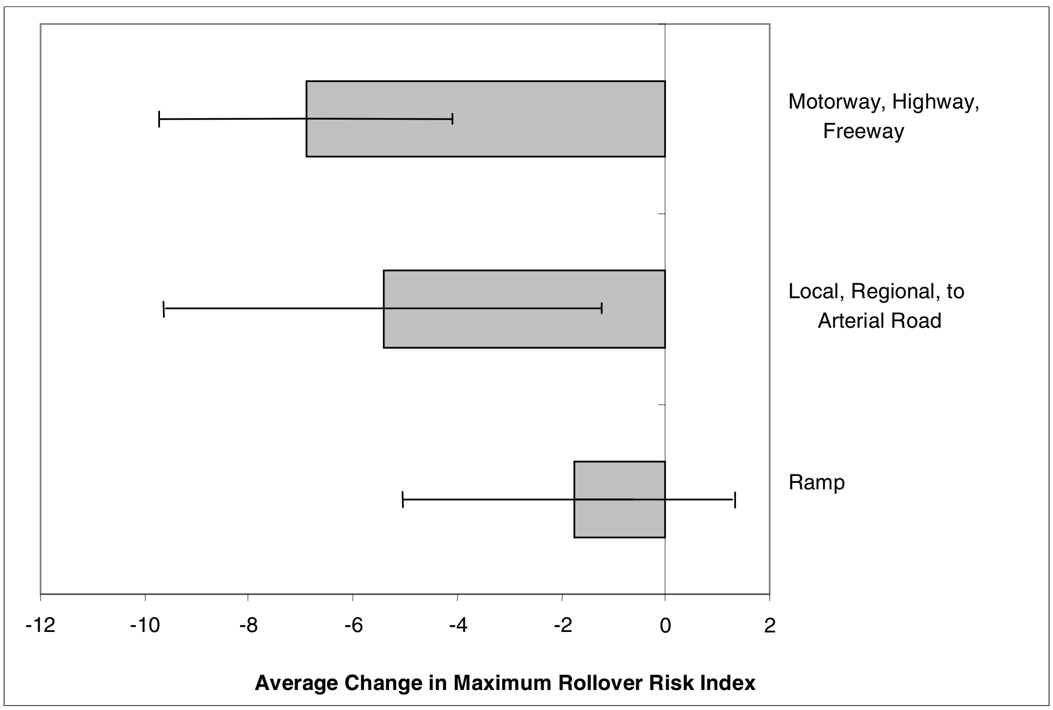


Figure 5-8. Change in Maximum Rollover Index after an RSA Message by Road Class—Averaged across Driver

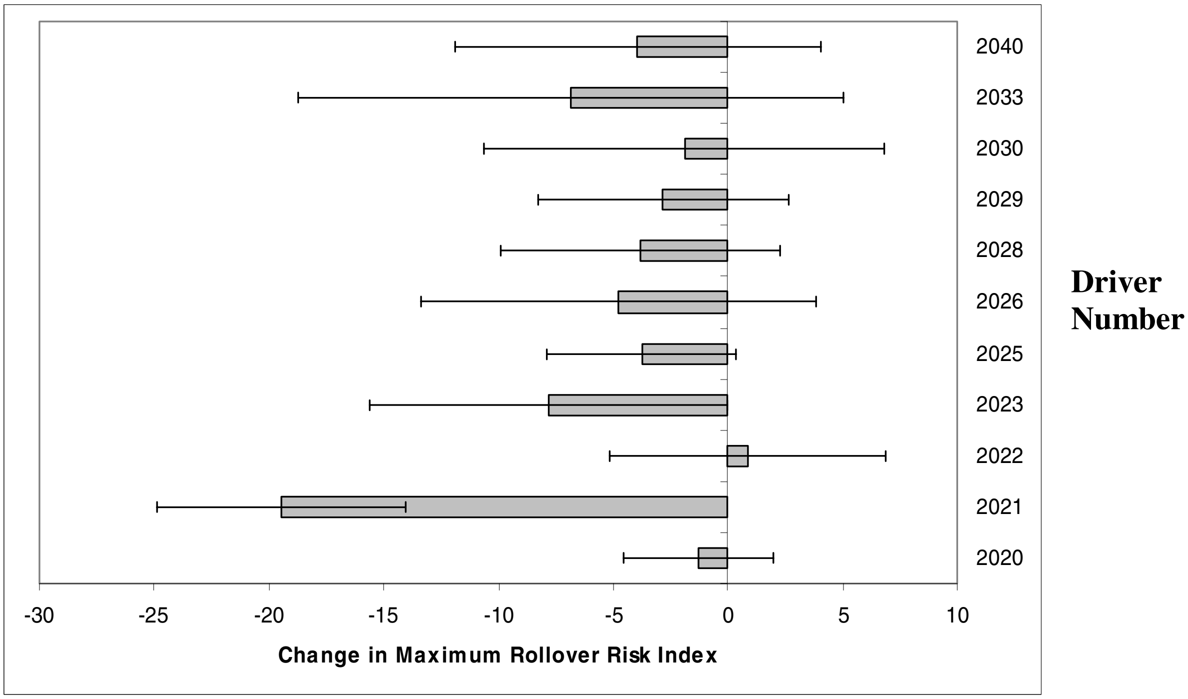


Figure 5-9. Change in Maximum Rollover Index after an RSA Message by Driver

The conclusion to be drawn from this analysis is that, on the average, drivers drive more safely at particular roadway locations after they receive an RSA message at that location. However, we cannot conclude whether the change in behavior is due to (a) the particular message or (b) some general change in behavior after using the RSA system. The analysis demonstrates that the RSA messages have a greater effect on driving behaviors on highways, curves, and local routes than on ramps. But this may be due to the drivers already being more aware of risks on the ramps.

The Freightliner Partnership concentrated on a particular ramp to answer a similar question through a different analysis. The ramp is the location that had the greatest number of RSA episodes as counted by the Partnership. It is a 270-degree ramp from US 31 to Interstate 80 (the Indiana Turnpike), west of South Bend. In Table 5-2 it corresponds to 39952350, I-80 WEST/ I-90 WEST Branch, the first of the Ramp to Motorway, Highway links. The ramp is quite commonly taken by empty trucks returning to the terminal. Praxair's vehicles are almost always empty when they are on this ramp.

An aerial photograph of the site along with a tracing of the ramp from GPS points are shown in Figure 5-10. The ramp is a 270-degree right-hand turn (clockwise direction). Note that the GPS was momentarily interrupted after the vehicles passed under the bridge as they entered the freeway. The ramp is divided into five segments, identified by A, B, C, D, and E in the figure. Each driver's average speed for all traversals through each segment was calculated. Separate averages were calculated for the Baseline and System On periods. Table 5-3 lists the change in average speed from the Baseline to the System On period; Figure 5-11 indicates the changes in averages graphically. Each shape of marker represents a different driver. A negative value indicates that the driver's average speed was lower after the RA&C was activated than it was before. Some drivers' average speed in certain segments did decrease after the RA&C was activated, but others' average speed increased.

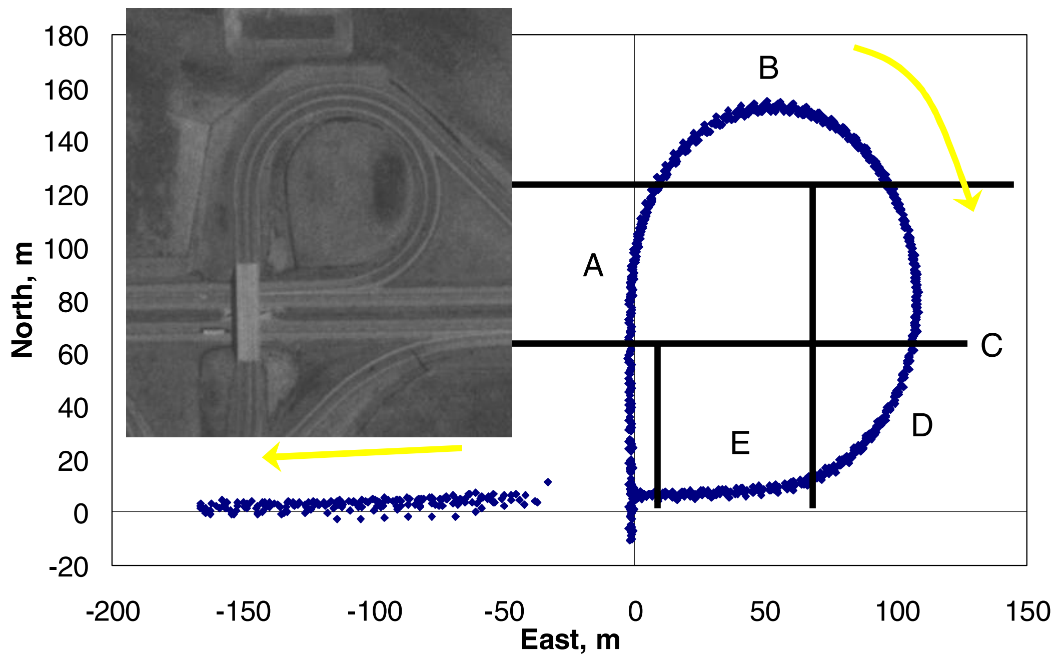


Figure 5-10. Plan View of the Ramp from US 31 to the Indiana Turnpike Westbound, West of South Bend

Table 5-3. Change in Average Speed (kph), from the Baseline Period to the System On Period, in Each Segment of the Ramp for All Drivers who Traversed the Ramp in Both Periods

Symbol	Driver	Ramp Segment					Entire Ramp
		A	B	C	D	E	
♦	2020	2.7	0.3	0	0.9	1.9	2.4
◇	2021	-0.7	-1.1	1.4	0.4	-0.4	0.2
▲	2022	1.2	-0.9	-0.7	-1.1	0.2	0.7
△	2025	-1.3	-1.9	-2	-1.9	-1.4	-0.2
■	2026	-2.3	-4	-4.6	-4.8	-2.5	-1.6
□	2028	-2.6	-3.9	-1.9	-1.5	-1.9	-1.3
+	2029	2.7	-3	-3.5	-3.7	-0.6	0
X	2031	2.4	2.4	3.4	3	3	4.2
–	2032	1	1.3	0.6	-0.4	0.1	1.9

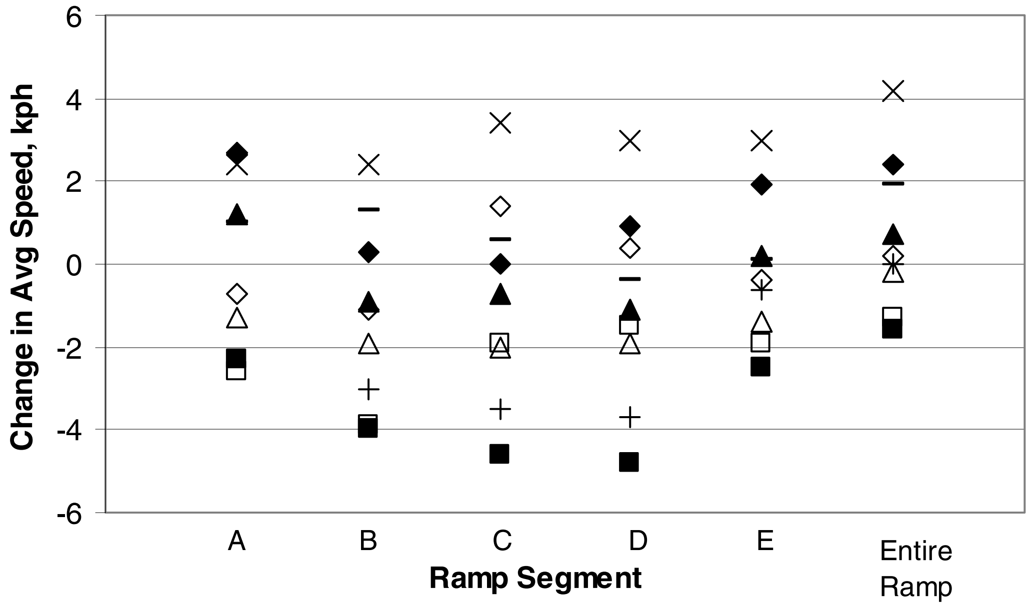


Figure 5-11. Graphical Representation of the Data in Table 5-3

To better understand the reasons for the changes, the speed time histories on all traversals were examined for the drivers with notable increases or decreases. For example, consider Figure 5-12, which shows the time history of the speed for every time Driver 2031 passed through this ramp. The upper portion of the figure is for the twelve traversals during the Baseline period, and the lower portion is for the thirteen traversals during the System On period. Driver 2031 was one whose speed apparently was increased by the RA&C. The speeds on all traversals are concatenated, with each traversal appearing as a "U" as the driver slowed on entering the curve and then accelerated to merge at the end of the ramp. The upper portion of the figure shows the speeds for the trips during the Baseline period. The speed on all trips is roughly the same, but the speed was lower on three trips. (The total weight of the vehicle in all of these trips was less than 18 tonnes; heavy load was not the reason for the few slow trips. Perhaps traffic, weather, or other factors were affecting the truck's speed.) During the System On period, shown in the lower portion of the figure, the trip-to-trip variation was much less, giving a higher average and an apparent increase in risky behavior.

In conclusion, these two approaches to the data both have evidence that some drivers in some situations did appear to reduce their speed when returning to a particular curve after the RA&C was activated. However, the evidence is weak, and sporadic conditions such as traffic or weather appear to be better explanations for the apparent changes.

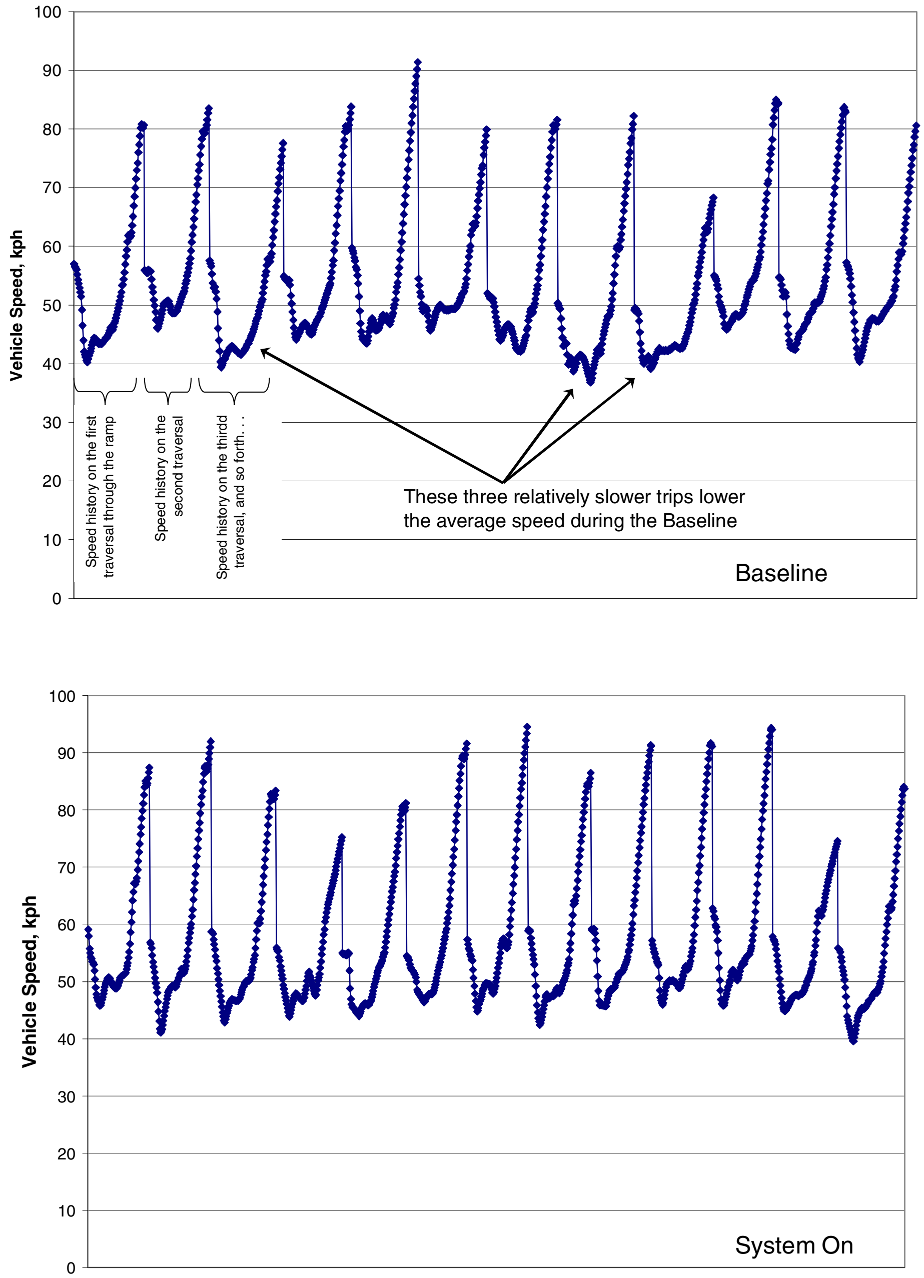


Figure 5-12. Time Histories of Speed for Every Traversal of Driver 2031 through the Ramp in Figure 5-10

5.1.2 Do Vehicles Equipped with RA&C Have Fewer Rollover Crashes?

The second objective under the safety benefits goal is to answer the question, "Will vehicles equipped with the technology have fewer crashes than those without it?" Whereas the previous objective focused on the RSA's effect on prevalence of risky behavior, this section goes a step further to examine the likely change in the number of crashes.

This section begins with an analysis of the driver behavior as observed in the FOT. It then combines the results of the FOT with a test-track-validated vehicle model to estimate the number of crashes that can be prevented by the RSA's advisory messages. Secondly there is a separate discussion of the effects of the RSC. Finally, the question of whether the RA&C can help drivers or a carrier identify routes with high rollover risk is addressed.

The results of the safety benefits analysis are extrapolated to segments of the national trucking fleet in the Section 5.1.3.

Fewer Rollover-Related Conflicts: Estimating the Exposure Ratio. The exposure ratio is a measure of the ability of the RA&C to reduce exposure to situations known to precede crashes, i.e., driving conflicts. It is calculated as the ratio of two probabilities. The probability that a driving conflict will occur per vehicle kilometer traveled (VKMT) during the RA&C (System On) phase is in the numerator, and the probability that a driving conflict will occur per VKMT during the Baseline driving period is in the denominator,

$$ER_1 = \frac{P_w(S_1)}{P_{wo}(S_1)} \qquad (5\text{-}1)$$

Values of the exposure ratio less than one indicate that the RA&C is effective at reducing exposure to driving conflicts. The exposure ratio is one of the elements necessary to calculate the number of crashes that can be prevented by widespread deployment of the RA&C. (See Section 5.1.3)

In Section 4.3.1 the rollover risk index (R_I) was introduced as an objective measure of when a truck has taken a curve too fast. Recall that the most common driving conflict leading to a rollover crash is *Truck is turning or negotiating a curve at excessive speed and loses control*.

Analyses described in Section 5.1.1 have determined that R_I exceeds 55% during the Baseline driving period 2.6 times per 1000 VKMT on average. This R_I threshold was chosen as representing a balance between events severe enough to be justifiably called driving conflicts but frequent enough for accurate rates of occurrence to be estimated. Figure 5-13 presents a comparison of the raw rate of rollover risk index 55% threshold exceedences during the Baseline period and the raw rate during the System On period.

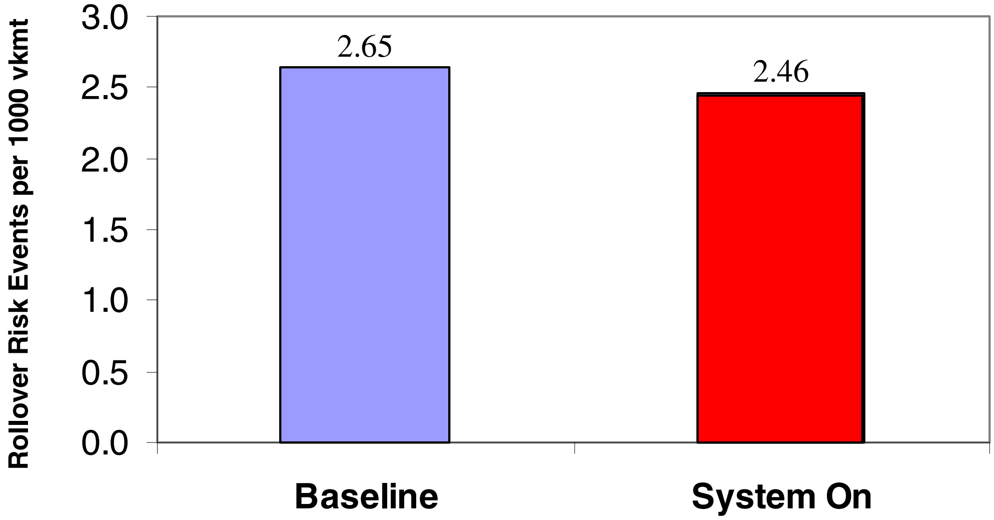


Figure 5-13. Comparison of Baseline and RA&C 55% Rollover Index Exceedences

Of the 1,852 potential driving conflicts (55% threshold) identified in the FOT driving data, many occurred at very low speeds. Figure 5-14 plots the truck's speed at peak rollover index versus curvature for all FOT driving events in which rollover risk index exceeded 55%. Test 002 at the Transportation Research Center (presented in Appendix D) showed that the chance of a rollover is substantially lower below 25 kph, so only events during which the vehicle's speed was greater than 25 kph were defined to be driving conflicts. As illustrated in Figure 5-14 by the horizontal line at 25 kph, this eliminated the vast majority of potential driving conflicts (1,653), leaving only 199.

The vertical reference lines in Figure 5-14 indicate curvature bins to which driving conflicts were assigned. Six curvature bins have been defined. Curvature bin 0 (radius of curvature greater than 4000 m) includes all straight driving and cannot be seen clearly in Figure 5-14 as it is essentially on the y-axis of the plot. Curvature bins 1 through 5 step along the plot from left to right above the 25 kph horizontal line, specifically

Curvature bin 0 – radius of curvature greater than 4000 m (essentially straight)
Curvature bin 1 – radius of curvature greater than 400 m,
Curvature bin 2 – radius of curvature greater than 200 m,
Curvature bin 3 – radius of curvature greater than 100 m,
Curvature bin 4 – radius of curvature greater than 50 m, and
Curvature bin 5 – radius of curvature less than 50 m.

Curvature bin 5 includes all driving during which the radius of curvature is less than 50 m. Note that no driving conflicts occur during "straight" or curvature bin 1 driving, which is the leftmost bin.

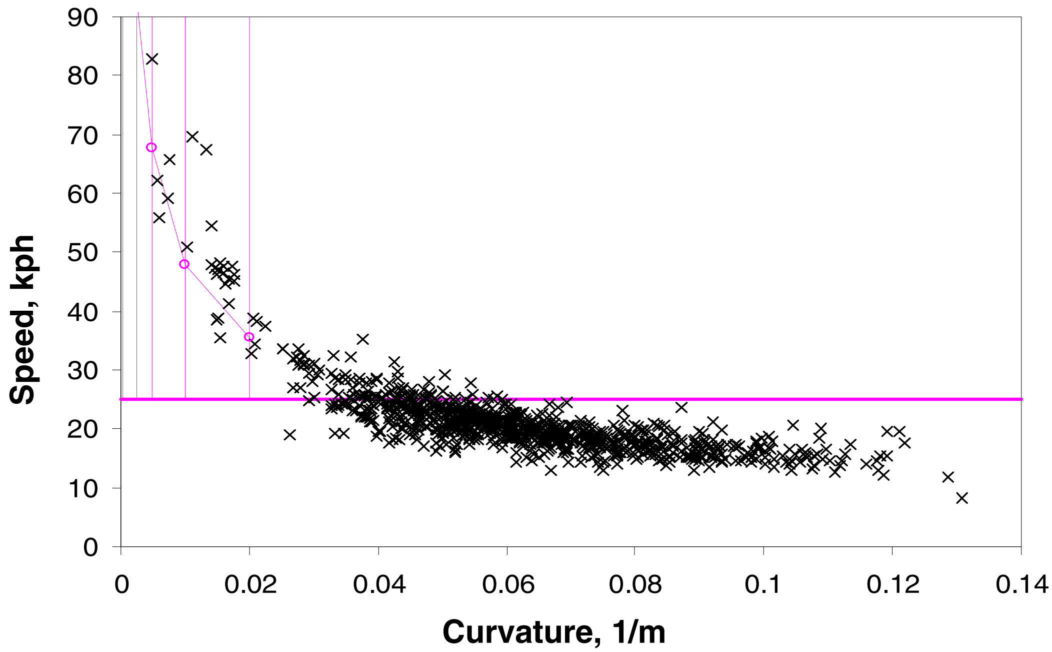


Figure 5-14. Speed Versus Curvature for Driving Events during which Rollover Index Exceeded 55%

The Freightliner FOT was designed as a repeated measures experiment, i.e., each driver drove under both the Baseline condition and the RA&C condition so that each driver could serve as his own control when assessing the effect of the RA&C. Of the 199 potential driving conflicts, 137 belonged to the 15 drivers who completed the entire study, those listed in Table 4-7. Drivers 2030, 2034, and 2035 did not have any conflicts.

Two methods have been considered for estimation of the exposure ratio. The first is the ratio of unadjusted empirical rates of occurrence observed in the FOT driving data by the drivers with data during both study periods. There were 71 driving conflicts during the Baseline-driving period (236,617 km) and 66 driving conflicts during the RA&C period (327,662 km), resulting in an exposure ratio of

$$ER_1 = \frac{66/327{,}662}{71/236{,}617} = \frac{0.20}{0.30} = 0.67 \,. \qquad (5\text{-}2)$$

and an associated standard error of 0.083. Thus, the exposure ratio is significantly below unity at the 95% confidence level.

To illustrate a potential issue associated with the empirical exposure ratio estimate, Figure 5-15 plots driving conflict rate by month of study, highlighting driving done during the Baseline period versus that done during the System On period. June, when the system was turned on, is not separated in the figure. Figure 5-15 illustrates the potential confounding of RA&C use with seasonality, possibly due to changing driving conditions during winter and spring (Baseline) as compared to summer and fall (System On). The data of this year-long study do not permit the separation of the seasonal effect from the RA&C effect. One explanation for the dip around month 10 is that driving is somehow safer in August. Another, equally valid, explanation is that there was a gradual improvement due to the RA&C that “wore off” after two or three months.

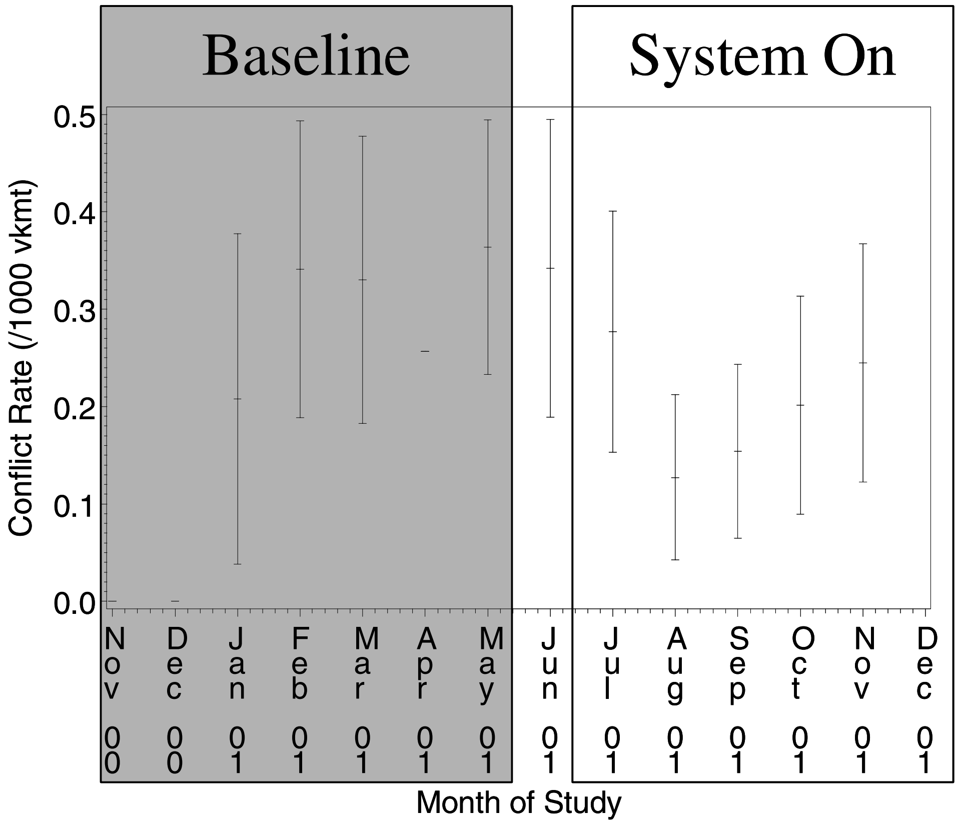


Figure 5-15. Effect of Covariates on Rate of Driving Conflicts With and Without RA&C (Monthly Rates with 95% Confidence Intervals)

Both seasonal and RA&C effects were tried in the model. The fit to the data was better with the RA&C effect included and the seasonal effect excluded, so we attribute the improvement to training by the RA&C.

In order to account for different driving conditions that were encountered during the two phases of the Freightliner FOT and also to assess the conditional effect of various driving conditions on the effectiveness of RA&C, a Poisson regression analysis of the rate at which driving conflicts occur was performed. The Poisson regression model states that the expected number of driving conflicts during any interval of driving is proportional to the distance driven during that driving interval. The constant of proportionality is a function of conditions describing the driving interval, specifically,

$$E(Y_i) = e^{X_i \beta} D_i \tag{5-3}$$

where Y_i is the number of driving conflicts during driving interval i, X_i are covariates describing driving conditions during driving interval i, β is a vector of regression parameters, and D_i is the distance driven during interval i. The notation $E(Y_i)$ indicates the expected value of the number of driving conflicts. Poisson regression of driving conflicts assumes that observed numbers of driving conflicts experienced during each driving interval are independent and follow a Poisson distribution with the designated mean value.

To fit the described Poisson regression model, the FOT driving data were parsed into contiguous driving intervals during which driving conditions were constant. Specifically, the data were blocked into 1-hour segments. Each 1-hour segment was further subdivided into portions driven at distinct levels of curvature, cruise control status, wiper intensity, and fill level. The six curvature bins described in relation to Figure 5-14 were used. Two levels of cruise control were considered, on and off. Seven levels of windshield wiper intensity settings were considered, which are described in Table 5-4. Fill level was assigned between 0 and 1 at $1/8^{th}$ intervals based on truck weight.

Table 5-4. Levels of Windshield Wiper Intensity to which Driving Segments were Assigned

Level	Raw Measurement	Interpretation
0	0	Windshield wipers off
1	<0.25	Windshield wipers on intermittent, less than 25%
2	<0.5	Windshield wipers on intermittent, between 25% and 50%
3	<0.75	Windshield wipers on intermittent, between 50% and 75%
4	<1	Windshield wipers on intermittent, between 75% and 100
5	<2	Windshield wipers on low
6	2	Windshield wipers on high

In the Poisson regression of driving conflicts, each of the described variables was considered as well as the effect of RA&C. By incorporating interactions into the Poisson regression model, differential effects of the driving conditions on the effectiveness of the RA&C were considered. Backwards variable selection was used to identify a Poisson regression model with statistically significant predictor variables. Table 5-5 lists all of the driving condition variables considered in the Poisson regression model and indicates which were statistically significant.

Cruise control status is not a variable in the Poisson regression model because all driving conflicts occurred with cruise control off. Thus, the Poisson regression model is fitted only to that data and characterizes the rate of driving conflicts during negotiation of appreciable curves with cruise control off.

Table 5-5. Driving Condition Variables Considered in Driving Conflict Poisson Regression

Driving Condition	Description	Interactions with "Test Period" Evaluated**
Test Period (Baseline vs. RA&C Active)*	Indicator of Baseline or RA&C was considered.	
Curvature Bin*	Class effect for curvature bins 2 through 5 was considered.	Across the four curvature bins.
Driver*	Class effect for twelve drivers was considered.	Across the sixteen drivers.
Windshield Wiper*	Class and linear windshield wiper effects were considered	As windshield wiper intensity changes.
Fill Level*	A linear fill level effect was considered	As fill level changes.
Day	Both sinusoidal (seasonal) effects across the FOT period and quadratic day (training) effects within the FOT phases were considered.	Between the FOT phases.
Quadratic Day		
Service Hours	A linear service hour effect was considered	Depending on the service hours of the driver.
Sine Hour of Day*	Both sinusoidal (circular) and quadratic hour effects were considered.	Over time within a day.
Cosine Hour of Day*		

* Variables which were statistically significant in the Poisson regression model of rate of driving conflicts.
** None of the interaction terms were statistically significant. Significant interactions would have indicated a differential effect of RA&C across the levels of the driving condition variable.

No interaction terms were significant in the final Poisson regression model selected using backward variable selection. The driving condition variables that remained in the model are designated in Table 5-5 with asterisks. Figure 5-16 illustrates the effect of each of the driving condition variables on the rate of driving conflicts (during curve negotiation, with cruise control off). Based on the Poisson regression model specified, each of the driving condition variables has a multiplicative effect on the rate of driving conflicts, as was assumed in Equation 5-3.

The multiplicative effect is equal to the exponentiated value of the driving condition variable times the parameter estimated for that condition and is graphed for both the Baseline and System On conditions in Figure 5-13.

The fact that none of the RA&C interaction terms were significant indicates that the effectiveness of the RA&C at reducing the rate of driving conflicts is constant across levels of the driving condition variables. The Poisson regression model yields an estimate of the exposure ratio that is

$$e^{\beta_{RA\&C}} = e^{(-0.2946)} = 0.745. \qquad (5\text{-}4)$$

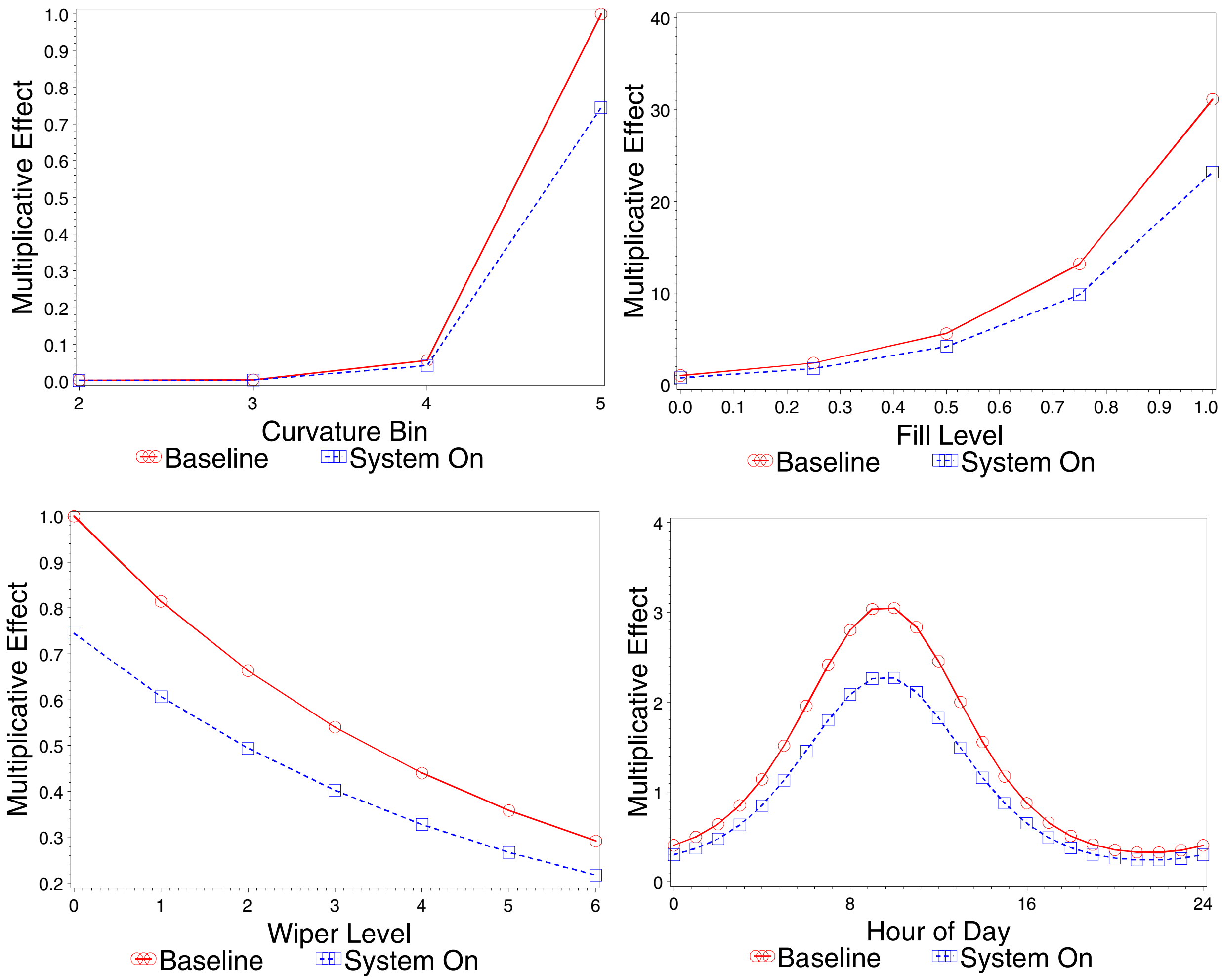


Figure 5-16. Effects of Driving Condition Variables on the Rate of Driving Conflicts

A 95% upper confidence bound for this estimate can be constructed based on the standard error of the RA&C parameter estimate, 0.1736, specifically

$$e^{\beta_{RA\&C}} = e^{(-0.2946+1.65*0.1736)} = 0.992. \quad (5\text{-}5)$$

Thus, a 95% upper confidence bound for the exposure ratio does not include 1, so the effect is statistically significant. Under conditions in which driving conflicts occur (negotiation of curves with radius of curvature less than 400 m and with cruise control off) and accounting for the different driving experiences observed during the two phases of the FOT, the RA&C reduces exposure to driving conflicts.

The empirical and model-based estimates of the exposure ratio both indicate an RA&C safety benefit but produce slightly different estimates of the exposure ratio. The model-based estimate does not account for differences in which the rate of conditions that can lead to driving conflicts occur. For example, suppose that a larger proportion of the driving experience is less than 25 kmph in the RA&C phase. This benefit is not accounted for in the model-based estimate of the exposure ratio, but is in the strictly empirical estimate. During the Baseline phase, 1.2% of the driving experience was under conditions that can lead to driving conflicts (cruise off and curvature bins 2 through 5). During the System On phase, 1.1% of the driving experience was under conditions that can lead to driving conflicts.

The Poisson regression analysis provides additional information about the rate of driving conflicts that is not provided by the empirical estimates. Specifically, the regression analysis indicates that the RA&C is equally effective at reducing exposure to driving conflicts across the four curvature bins, at all fill levels and wiper intensities, and during the entire day. The absolute rates of driving conflicts are affected by these driving condition variables, but the RA&C's effectiveness is not affected by them.

Either estimate of the exposure ratio, empirical or model-based, could be carried forward to the safety benefits calculations. Because the empirical estimate accounts for the different rates at which driving conditions conducive to driving conflicts occur between the two phases, the empirical estimate is used in further safety benefit analysis. Table 5-6 summarizes the results of the two methods of estimating exposure ratio.

Table 5-6. Summary of Exposure Ratio Results

Estimation Approach	Exposure Ratio		Equation Number
	Estimate	Upper Confidence Bound	
Empirical	0.67	0.807	5-2
Model	0.745	0.992	5-4

Reductions in Crash Probabilities with RA&C. The exposure ratio was calculated almost entirely from the FOT data, drawing only on the tilt table results for a rough indication of the proximity to rollover. The next element in the benefits equation (Equation 4-1 in Section 4.3.1) is the Prevention Ratio, which needs a more realistic measure of rollover proximity and a "calibration" point from known historical data. The more realistic measure was a dynamic vehicle simulation that was validated by test track maneuvers with a tanker. The "calibration" point was Praxair's historical rollover rate.

This section introduces the dynamic model, explains how it was validated, and uses it to assign a realistic measure of severity to each of the 137 conflicts. Next, this set of severity measures is used to estimate the Prevention Ratio for the RA&C. Finally, the safety benefits equation can be completed, and the number of crashes prevented by the RA&C is estimated.

Simulations to Determine the Actual Rollover Threshold. The purpose of the simulations was to provide an objective and quantitative calculation of the probability of a crash. This section describes the simulation model and presents sample results. The calculation of the crash probabilities using these data is described the following section entitled "Prevention Ratio."

We know that none of the conflicts actually resulted in crashes, as all trucks returned safely home during the FOT. However, if each event occurred thousands and thousands of times, each time would be a little different from the others. The speed may be slightly higher, driver alertness may vary, the load may be a little fuller, or the path may be slightly different. All these differences can be considered as perturbations of the actual event in the FOT. Some small fraction of the combinations of these perturbations will result in a rollover crash. It is this fraction we seek.

The simulations determined, for each conflict, the minimum amount of perturbation that leads to a rollover. The next section determines the level of perturbation that can be expected and calculates the probability of a crash given that a conflict occurred.

The method for determining the amount of perturbation that leads to rollover was to duplicate the 137 conflicts, one at a time, with the simulation program. Each conflict was then run again at successively higher speeds until it either rolled over or the vehicle could not reasonably maintain its path. Thus, the perturbation was in only one parameter—speed.

Vehicle Model Description. The commercially available Vehicle Dynamics Analysis, Non-Linear (VDANL) version 6.0 computer simulation was used in this study.[2] This rigid-body model incorporates equations of motion that explicitly describe vehicle dynamics in the longitudinal, lateral, and vertical directions in addition to independent wheel spin modes. The sprung and unsprung mass motions are modeled separately in the pitch, roll, heave, and lateral modes. The longitudinal motions are for the total vehicle, while the sprung and unsprung masses rotate together in yaw. The model also allows simulation of a two-axle trailer connected to the tractor through a fifth wheel.

The wheelbase and track widths of the truck were measured. Axle loads were also measured during the test. The height of the vehicle's center of gravity and inertias were estimated. Some of the parameters such as roll stiffness, throttle and steering lags, and steering geometry were taken as typical of five-axle trucks.

Vehicle parameters are defined in several parameter files. VDANL incorporates a driver model with access to the gains of the closed-loop system. These can be modified to achieve the appropriate velocity, steering, or curvature input response. VDANL allows time-varying throttle, brake, velocity, steer, or curvature inputs to be specified.

Model Validation. The model and parameter set were validated through comparison with data from the full-vehicle tests at the Transportation Research Center (TRC). The scope of the test track effort was not a full validation of the entire model but rather an assurance that the simulation had suitable fidelity for predicting rollover. The TRC Test 004 was designed specifically to produce data for validating the model. (Tests 002 and 003 were initial tests to aid

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[2] VDANL was developed by Systems Technology, Inc., in Hawthorne, California. Phone 310-679-2281 ext. 61. http://www.systemstech.com/vdanl1.htm.

in planning Test 004.) Maneuvers in the FOT that produced critical conflicts were sorted in three broad classes according to their geometry—an S turn, a ?-shaped turn, and ordinary bends of different curvature. Whereas the FOT events were perturbed only in speed in the simulation, the starting TRC maneuvers were perturbed in both speed and path to provide a more thorough measure of the simulation model's fidelity. Details of the TRC procedures and results are in Appendix D.

The test vehicle at the TRC was instrumented identically to those in the FOT, but with some extra sensors. Most notably, the FOT vehicles had instruments only on the tractor, but the TRC trailer had several instruments, including a roll angle sensor, critical for predicting rollover. Also, the TRC tractor had a steer angle sensor so TRC maneuvers could be more easily reproduced in the simulation.

The actual roads driven during the FOT were, of course, superelevated according to common engineering practice, but the test track had no superelevation, and superelevation was not modeled in the simulation. The lateral accelerations predicted by the simulation agreed reasonably well with those measured in the FOT, so the absence of superelevation was judged to have minimal effect.

The trailer had outriggers during the test track work at TRC. Experimental observations indicate that the outriggers make contact with the ground at about 8 degrees trailer roll angle. This coincides in most maneuvers with trailer wheel liftoff.

The first set of figures shows a comparison of vehicle response during simulation to a specific test track run. The maneuver is defined by the steer angle and vehicle speed time histories, which were measured at the test track and were used as inputs to the model. Figures 5-17 and 5-18 show the global x-y positions of the truck during the test track run and simulation respectively. The difference in orientation is due to the fact that the heading of the truck was not due east during the test run as it was in the simulated case. Figure 5-19 gives an indication of how well the model tracks the speed measured during the actual run. The comparison of the path curvatures in the two cases is in Figure 5-20. While the lateral acceleration of the tractor seen during the simulation is comparable to that measured and calculated during the test run (Figure 5-21), the roll angle is lower in the simulated case (Figure 5-22). Some of this can be attributed to the fact that the steering of the test track run is given as an input to the model and this just serves as the steering command to the vehicle. The steering part of the model is thus open-loop control. Whereas Figures 5-17 through 5-22 demonstrate the fidelity with which a typical single TRC maneuver could be reproduced with the VDANL simulation, Figure 5-23 shows the reliability over all maneuvers. The peak roll angles from all TRC maneuvers are plotted as a function of the peak angle predicted by the corresponding simulation. The VDANL model consistently underpredicts the peak roll angle, but the variability of the predictions is actually quite small. Near the point of wheel liftoff, 6 to 8 degrees measured angle, the exact behavior of the trailer depends nonlinearly on minute details of the properties, which are difficult to capture in the model. This is why the spread in Figure 5-23 increases around 6 degrees measured angle. The actual trailer's roll is limited by the outriggers, while the model has no such restriction. This agreement was judged to be suitable for use in examining the 137 critical conflicts.

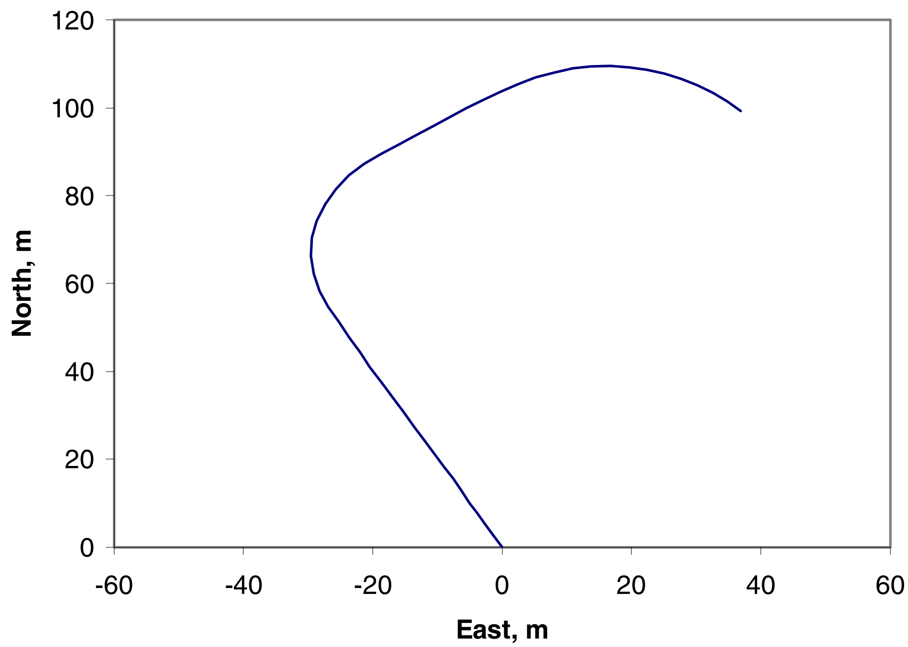

Figure 5-17. Bird's Eye View of the Actual Vehicle Path in a Test Track Maneuver, Measured by GPS

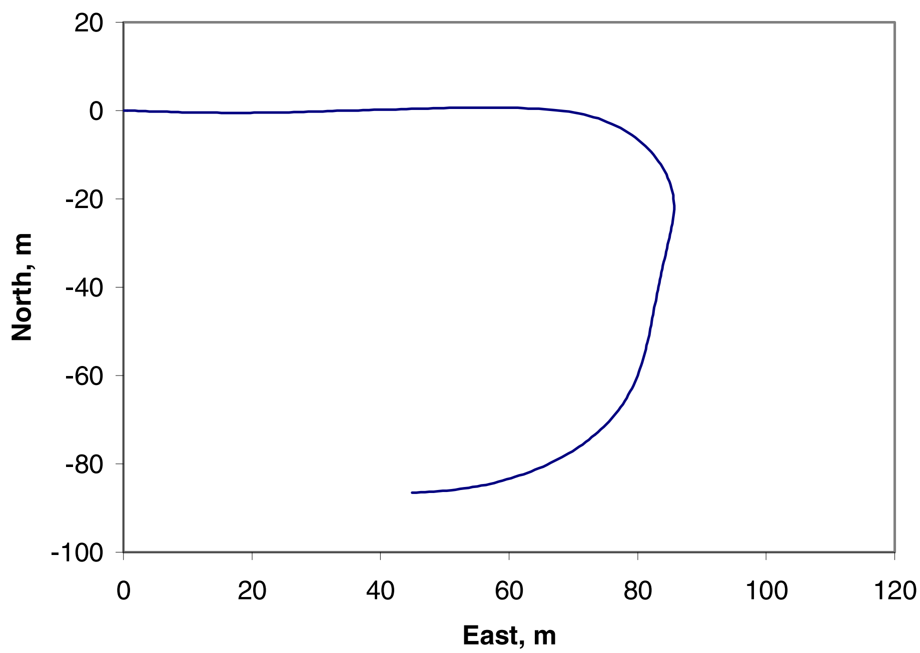

Figure 5-18. Bird's Eye View of the Simulated Vehicle Duplicating the Path of Figure 5-17

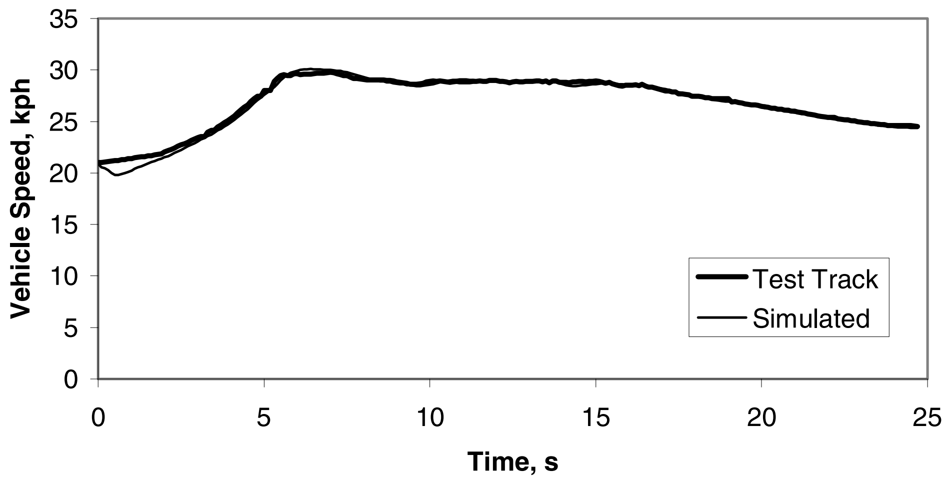

Figure 5-19. Comparison of Vehicle Speed Measured at the Test Track with Simulated Vehicle Speed

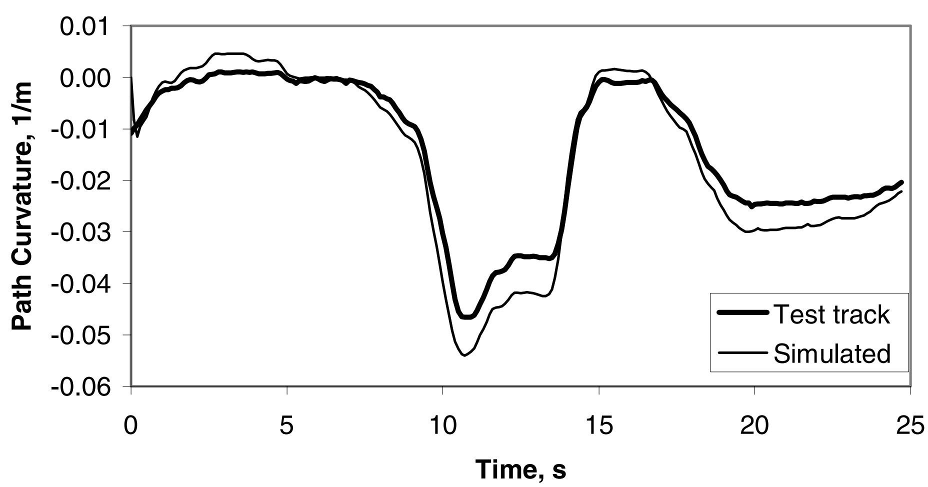

Figure 5-20. Comparison of Calculated Tractor Path Curvature at the Test Track with that Calculated during Simulation

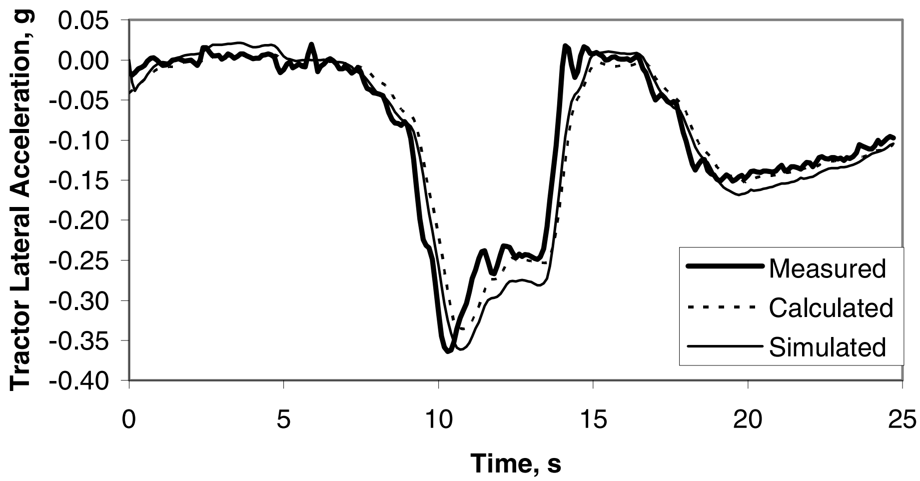

Figure 5-21. Comparison of the Measured (Steer Axle) and Calculated (Approximate CG) Lateral Accelerations of the Tractor during the Test Track Run with the Simulated Tractor CG Lateral Acceleration

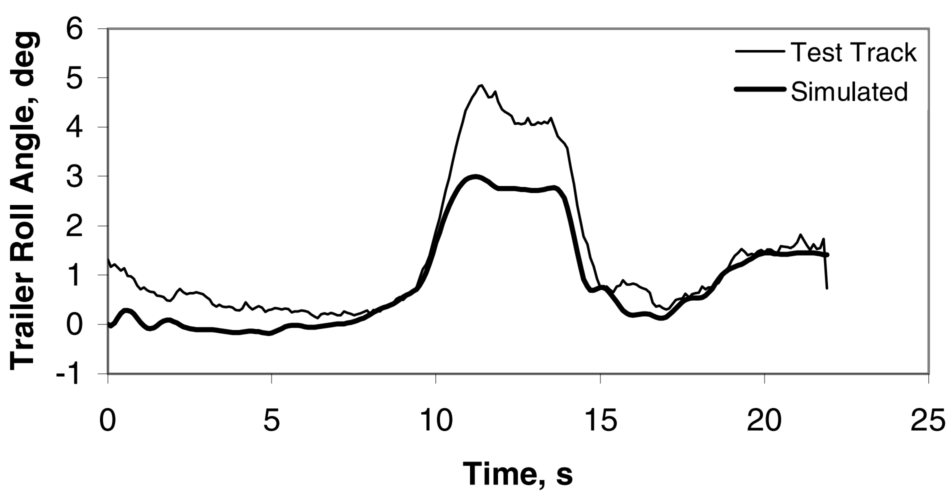

Figure 5-22. Roll Angle Variation of the Trailer as Measured during the Test Track Run Compared to the Trailer Roll Angle during Simulation

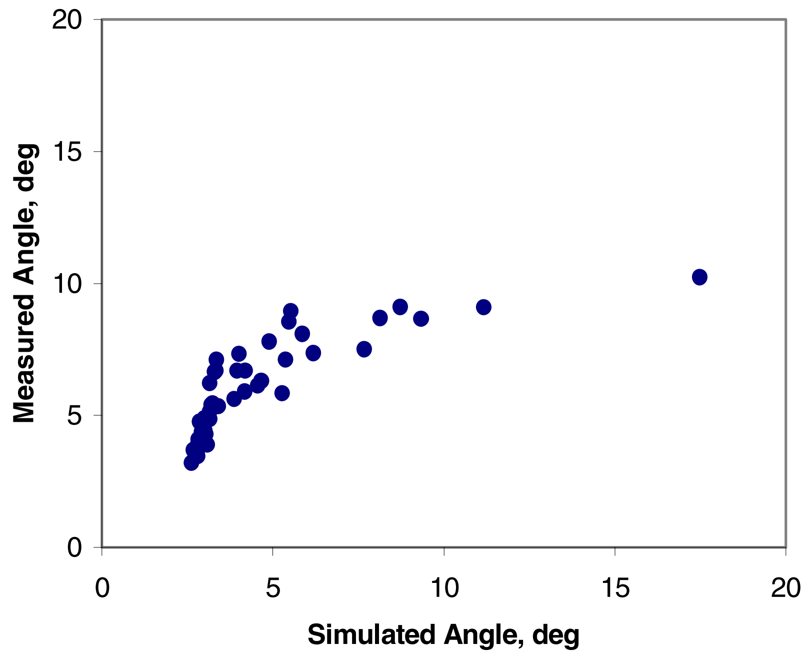

Figure 5-23. Comparison of the Simulated and Measured Peak Trailer Roll Angle over Several Maneuvers. Each Dot Represents One Maneuver that was Carried Out at the TRC and Reproduced in the VDANL Simulation.

The second step of the validation was to show the model's ability to duplicate paths measured in the FOT. Since no data were collected on vehicle steering position during the FOT, inputs to the model were curvature data calculated from the vehicle speed and yaw rate. When duplicating TRC paths, the model's inputs were steer angle and speed; the inputs for duplicating FOT paths were path curvature and speed. The gains of the driver model in VDANL were adjusted to yield a response from the model that was close to that seen during the FOT. Figures 5-24 through 5-29 show the measurements of a representative FOT maneuver where the vehicle was in a conflict situation. These data are comparisons with the corresponding simulated case. It can be seen that the vehicle paths traversed were similar (Figures 5-24 and 5-25) with comparable speeds, Figure 5-26. The curvature and acceleration comparisons (Figures 5-27 and 5-28) definitely show agreement in magnitude even though the peak values occur at slightly different times. The roll of the trailer was not measured during the FOT, so the VDANL output is plotted for reference in Figure 5-29, but there is no standard for comparison.

The gross vehicle weight was not the same for each of the 137 conflict cases. Most of the conflict cases, 113, occurred when the truck was full or almost full. The mass of the vehicle modeling these cases was 36 tonnes (i.e., 36 metric tons). In the remaining 24 cases the truck was either partially empty or near empty. These 24 cases were split into two different gross

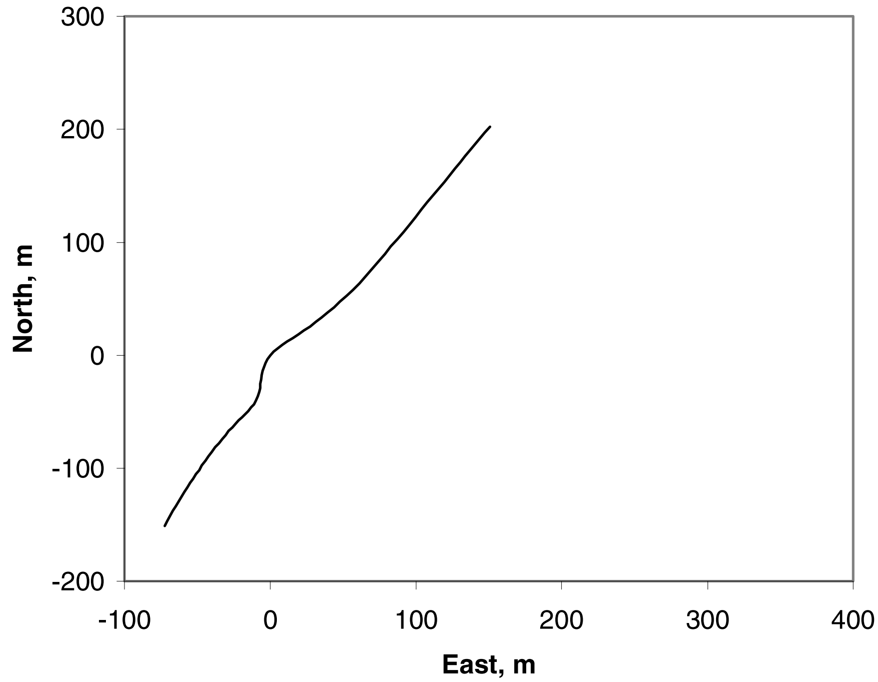

Figure 5-24. Bird's Eye View of the Actual Vehicle Path in an FOT Conflict Maneuver, Measured by GPS

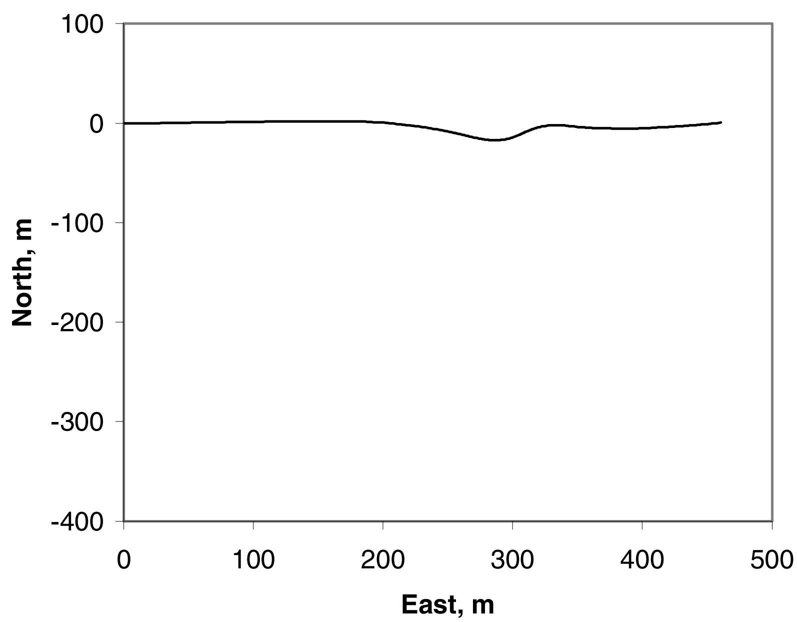

Figure 5-25. Bird's Eye View of the Simulated Vehicle Duplicating the Path of Figure 5-24

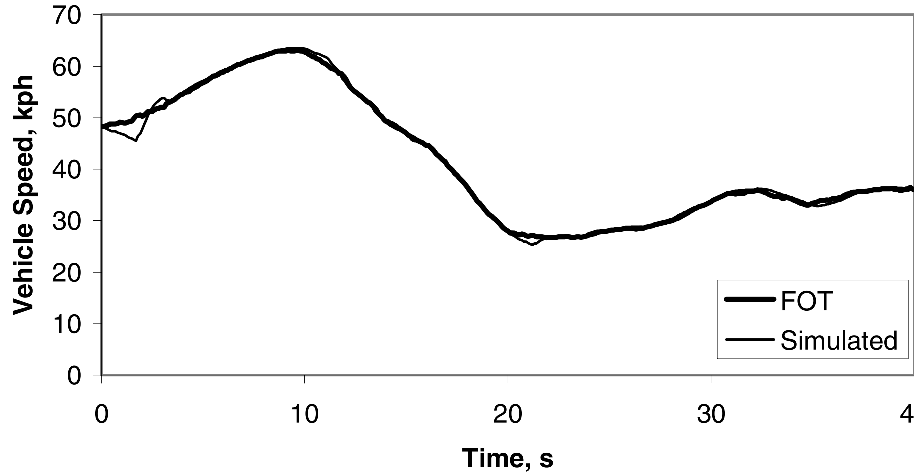

Figure 5-26. Comparison of Vehicle Speed Measured during the FOT Conflict of Figure 5-24 Maneuver with Simulated Vehicle Speed

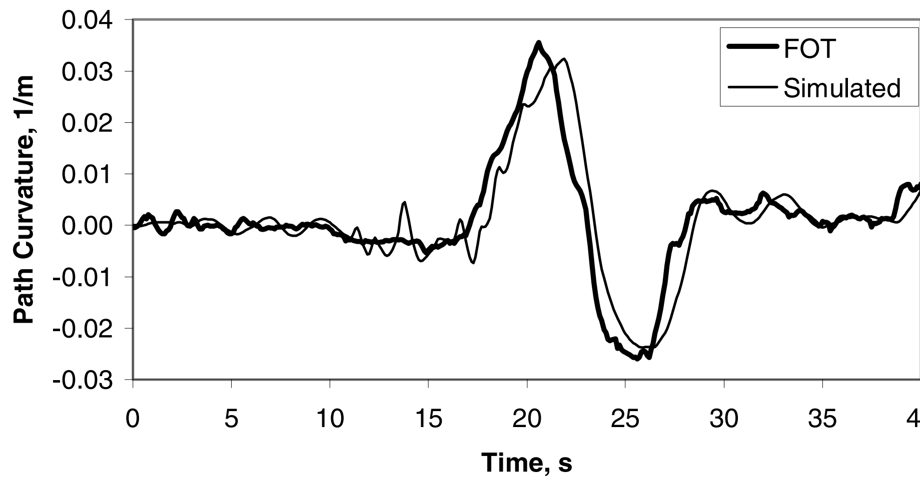

Figure 5-27. Comparison of Calculated Tractor Path Curvature during the FOT Conflict Maneuver with that Calculated during Simulation

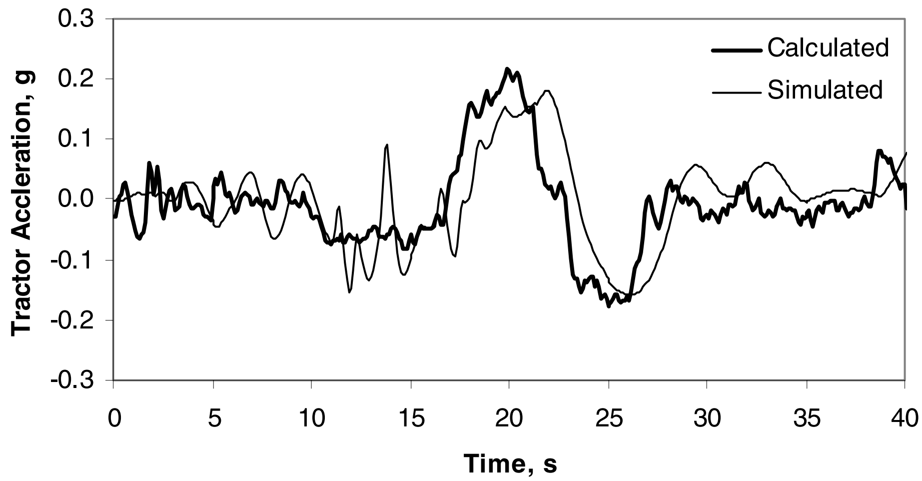

Figure 5-28. Comparison of the Lateral Accelerations Calculated at the Tractor CG during the FOT Conflict Maneuver with the Simulated Tractor CG Lateral Acceleration

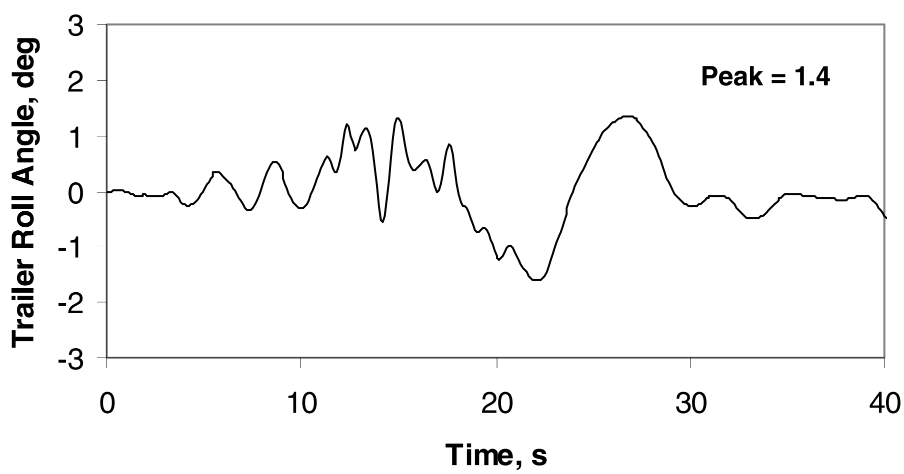

Figure 5-29. Roll Angle Variation of the Trailer during Simulation of the Path in Figure 5-24

vehicle weight categories based on the average separation of the vehicle weights (28 and 19 tonnes). With separation into three such categories all the vehicle weights were within 3 tonnes of the means chosen for each of the categories. Three separate parameter sets for the vehicle model were created to account for the differences in the weights. The primary differences in the parameters are in the vehicle sprung and unsprung mass weights, center-of-gravity heights, and the vehicle inertias. Minor variation in some of the driver model feedback parameters was made between models to obtain good speed and curvature tracking.

The model was exercised using inputs from several representative test track maneuvers and several representative FOT maneuvers. In addition, some of the FOT runs were also simulated using the different gross vehicle weight models. The agreement of the simulations presented in these figures are typical of the other vehicle model validation runs. The broad agreement of the simulation results with those of the test track runs gave us confidence that the truck modeled has response similar to an actual truck performing standard maneuvers. Close agreement of the simulation and representative maneuvers from the FOT gave confidence that the simulation could be used for simulating the FOT conflict cases.

Use of the Vehicle Model to Quantify Conflict Severity. The goal of the simulation analysis was to establish the dynamic envelope that separates a conflict from a definite rollover. The peak Rollover Index (defined in Section 4.3.1) was used to identify potential near-rollover or “conflict” cases. In all, 137 such instances were observed. Each of these cases was the starting point for a series of simulation runs.

For each of the conflict cases, vehicle speed was perturbed to induce a vehicle rollover. Starting with the speed record for the conflict, the speed was incremented by 1 ft/s (about 1.1 kph) for the entire maneuver. The simulation was repeated with this speed input. If no rollover was observed, the speed file was incremented by 1 ft/s again (2 ft/s higher than the conflict case) and the simulation repeated. In this fashion the speed was perturbed until a vehicle rollover was observed. This process was repeated for each of the 137 conflict cases observed during the FOT.

The results of the unperturbed FOT conflict case have been illustrated in Figures 5-24 through 5-29. To show the effect of the speed increment, these figures are duplicated where the conflict was simulated again but with the input velocity about 4.5 kph higher. With this velocity input, the speed and curvature tracking is still very good. The effect of the higher speed is seen in the lateral acceleration of the tractor and the increased roll of the trailer. The comparison of accelerations of the tractor in simulation is with the acceleration seen in the unperturbed FOT conflict case. A slight increase can be observed in the lateral acceleration of the tractor (Figure 5-30 versus Figure 5-28). The increase is more visible in the roll angle of the trailer, as can be seen in Figure 5-31 (as compared to the trailer roll in Figure 5-29) where the roll angle increased from 1.4 to 2.6.

Twelve of the 137 driving conflicts did not result in a rollover in the simulations. Despite having been identified as being near a rollover in the FOT data, these cases, all with light loads, did not roll even as the simulation’s speed was increased. Instead, the simulated path was not able to track the FOT path at higher speeds, which is the expected failure mechanism for a lightly loaded

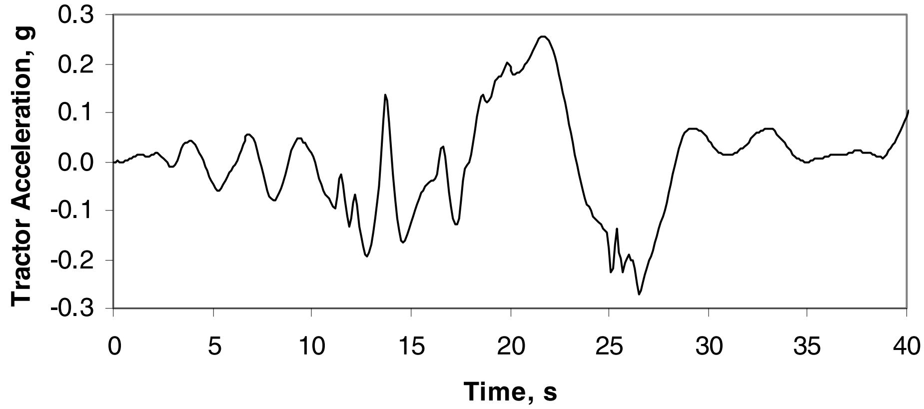

Figure 5-30. Lateral Accelerations of the Tractor when the FOT Conflict Maneuver of Figure 5-17 is Simulated at an Increased Speed

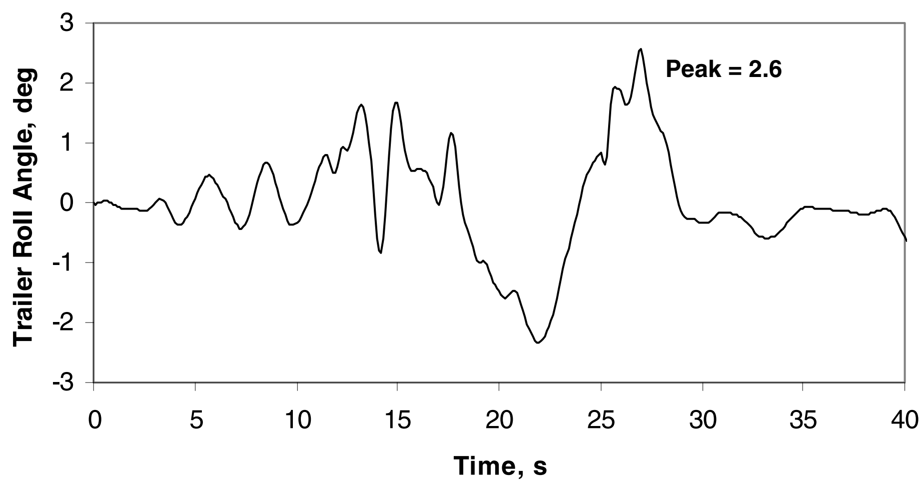

Figure 5-31. Roll Angle Variation of the Trailer during Simulation of the Vehicle Performing the Same Maneuver at an Increased Speed

trailer. Seven were in the Baseline period, and five were in System On. In the analysis that follows, the probability of a rollover was set to zero for these cases. The remaining 125, with partial and full loads, did roll at higher speeds. About 2/3 of the speed increments were between 5 and 10 mph. The simulation was not an exact duplication of the FOT vehicles. This is a valid relative but not an exact absolute indication of how close the vehicles came to rolling over.

The result of this simulation exercise was a list of 125 speed increments. These are the increments above the respective speeds, originally observed in the FOT, of the 125 non-empty conflicts. At these incremented speeds, the 125 conflicts became 125 crashes. These speed increments that were necessary to produce rollovers were used as one of the inputs to the Prevention Ratio analysis that follows.

Estimating the Prevention Ratio. The prevention ratio is a measure of the ability of the RA&C to prevent crashes given that a driving conflict has already occurred. It is calculated as the ratio of two conditional crash probabilities. The probability that a System On driving conflict will culminate in a crash is in the numerator, and the probability that a Baseline driving conflict will culminate in a crash is in the denominator,

$$PR_1 = \frac{P_w(C|S_1)}{P_{wo}(C|S_1)}. \tag{5-6}$$

S_1 represents the first scenario leading to a rollover as described in Table 4-2, which is "turning or negotiating a curve at excessive speed." **Values of the prevention ratio less than 1 indicate that the RA&C is effective at preventing crashes given that a driving conflict has occurred.** If the prevention ratio is greater than unity, that does not necessarily mean that the RA&C is ineffective at preventing crashes, only that any conflicts that occur with the RA&C tend to be more severe than those without. The prevention ratio is one of the elements necessary to calculate the number of crashes that can be prevented by widespread deployment of the RA&C (See Section 4.3.1). Together, the exposure and prevention ratios characterize the ability of the RA&C to prevent crashes.

Estimation of $P_w(C|S_1)$ and $P_{wo}(C|S_1)$, the two components of the prevention ratio, is based on the 137 driving conflicts identified in the FOT driving data. In particular, 71 driving conflicts were identified in the Baseline driving data and 66 in the System On driving data. The 71 Baseline driving conflicts are used in the estimation of $P_{wo}(C|S_1)$ and the 66 System On conflicts are used in the estimation of $P_w(C|S_1)$. Thus, the severity of the Baseline driving conflicts as compared to the severity of the System On driving conflicts governs the prevention ratio.

Praxair informed Battelle that the corporate rate of bulk liquid rollovers from all causes is typically one in ten million miles. That is, $P_{wo}(C) = 1 \times 10^{-7}$ per mile or 6.21×10^{-8} per km. If we assume that Praxair experiences the same distribution of scenarios leading to rollovers as the national tanker fleet (Table 4-2), then 55% of these rollovers will have been preceded by the scenario of "too fast around a curve." Thus,

$$P_{wo}(C, S_1) = 0.55 \times P_{wo}(C) = 3.42x10^{-8} \text{ perVKMT.} \tag{5-7}$$

Based on Baseline FOT driving data, the probability of an S_1 driving conflict, $P_{wo}(S_1)$ is 0.300 per 1,000 VKMT (71 conflicts in 236,617 km driving). The rules of conditional probability determine that

$$P_{wo}(C\,|\,S_1) = \frac{P_{wo}(C, S_1)}{P_{wo}(S_1)} = \frac{0.0342/1{,}000{,}000}{0.300/1{,}000} = 0.000114\,. \quad (5\text{-}8)$$

Of course, not enough miles have yet been driven with the RA&C to directly calculate the probability of a crash with the system in the way that was done without in Equation 5-8.

A method based on vehicle dynamic simulations centered about the 66 System On driving conflicts has been used to calculate $P_w(C|S_1)$. The method was calibrated using the 71 Baseline driving conflicts. In essence, the method is based on transforming the severity of each individual driving conflict to a probability of crashing specific to that driving conflict. The individual probabilities of crashing are averaged separately for Baseline and System On conflicts to create estimates of $P_{wo}(C|S_1)$ and $P_w(C|S_1)$. The transformation of severity to probability of crashing is scaled so that $P_{wo}(C|S_1)$ matches the value prescribed by Equation 5-8.

To heuristically understand the transformation from severity to probability of a rollover, consider Figure 5-32, in which a Gaussian perturbation distribution is specified around V_j, the speed of conflict number j at its peak lateral acceleration. In Figure 5-32, there is a small tail probability (the shaded area under the curve) beyond V_{jR}, the lowest speed (at the same point in time) at which the simulated vehicle in a perturbed conflict would roll over. This tail probability is the probability of a rollover for conflict number j.

The perturbation distribution of Figure 5-32 must be scaled through its variance, i.e., as the perturbation distribution gets wider the probability that an individual conflict results in a crash increases. As indicated in Figure 5-32, the variance of the perturbation distribution was defined to equal a scaling parameter, σ^2, times the square of the unperturbed velocity, V_j^2. Thus, the probability conflict number j will result in a crash, $P(C|S_{1,j})$, is a function of quantities measured from the conflict data and σ^2. The value of σ^2 is determined by Equation (5-8), i.e., the average probability of a rollover over the 71 Baseline driving conflicts must equal 0.000114.

To evaluate and average the tail probabilities as discussed above, it is convenient to define the severity of a conflict as the relative increase in speed required to roll the vehicle during the conflict,

$$s_j = \frac{V_{j,R} - V_j}{V_j}\,. \quad (5\text{-}9)$$

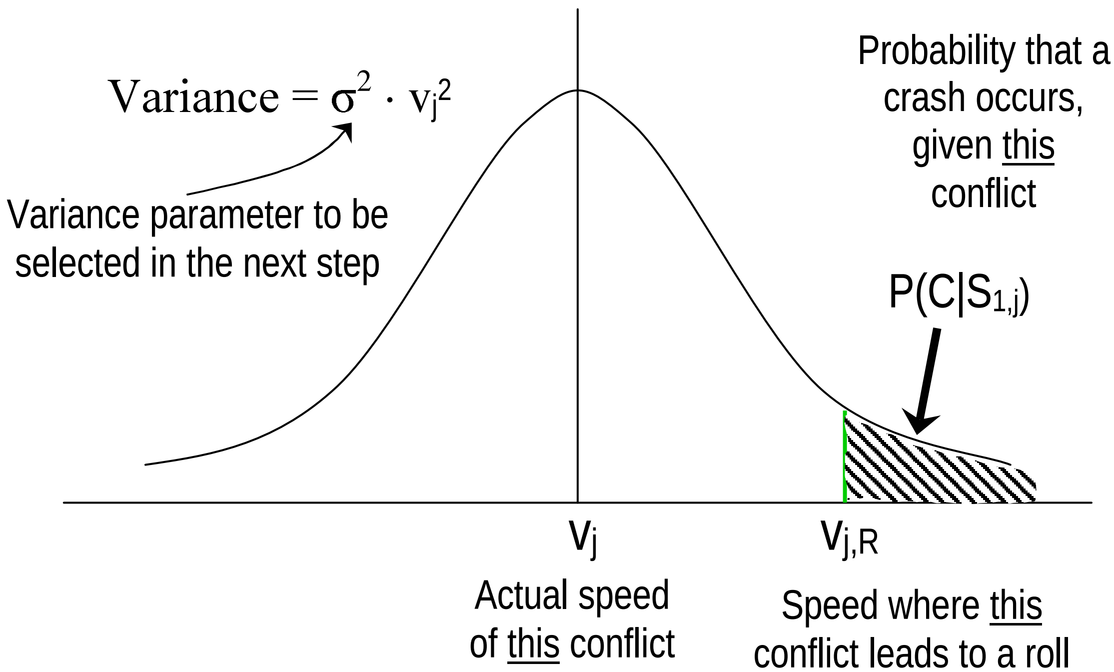

Figure 5-32. Hypothetical Distribution of Perturbed Speed around the Actual Speed of a Conflict

Smaller values of this severity metric indicate conflicts that are closer to rollover. The probability metric for consistently translating driving conflict severity to the probability of a crash for each specific driving conflict as described in Figure 5-32 is

$$P(C \mid S_{1,j}) = 1 - \Phi\left(\frac{V_{j,R} - V_j}{\sqrt{\sigma^2} \bullet V_j}\right), \tag{5-10}$$

where Φ is the standard Gaussian cumulative distribution. The parameter σ^2 scales the variance of the speed perturbation so that the average of $P(C|S_{1,j})$ over the Baseline driving conflicts equals the value prescribed by the Praxair historical data and Baseline FOT driving conflict rate in Equation 5-8.

The severity statistic calculated from vehicle dynamic simulations for each driving conflict is the data governing estimation of the prevention ratio. Figure 5-33 compares the cumulative distribution of driving conflict severity between Baseline and System On periods. Figure 5-33 includes only the 125 driving conflicts that resulted in rollover events during the simulation study. Figure 5-33 indicates that there are similar percentages of Baseline and System On driving conflicts at all severity levels. The most severe conflicts, those with the smallest severity measures, have much larger conditional crash probabilities ($P(C|S_{1,j})$), however, and dominate the computation of average conditional crash probabilities for both the Baseline and System On periods ($P_{wo}(C|S_1)$ and $P_w(C|S_1)$).

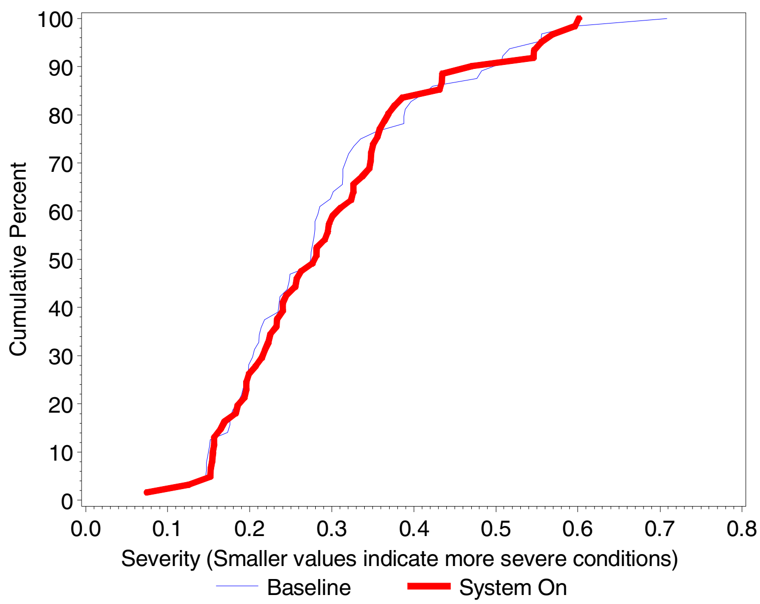

Figure 5-33. Baseline and System On Cumulative Distribution of Driving Conflict Severity (Defined in Equation 5-9)

Figure 5-34a presents $P_{wo}(C|S_1)$ calculated from the Baseline driving data for a range of perturbation variance scaling constant (σ^2) values. The horizontal line in the figure represents the historical $P_{wo}(C|S_1)$ from Equation 5-8. The appropriate proportionality constant of Figure 5-32, σ_0^2, is selected from Figure 5-34a as the point on the x-axis where the Baseline estimate of $P_{wo}(C|S_1)$ crosses the Praxair historical estimate of $P_{wo}(C|S_1)$, $\sigma_0^2 = 0.0010$.

Figure 5-34b has the same $P_{wo}(C|S_1)$ and the probability of a crash given a conflict calculated from the System On data, $P_w(C|S_1)$. Estimates of $P_{wo}(C|S_1)$ and $P_w(C|S_1)$ do not cross back and forth as the cumulative distribution of severity from the Baseline and System On data did (Figure 5-33). In the range of perturbation variance scaling constant values considered, both $P_{wo}(C|S_1)$ and $P_w(C|S_1)$ are dominated by the most severe Baseline and System On conflicts, respectively. Figure 5-33 indicates that there are more of the most severe conflicts in the System On data. Thus, $P_w(C|S_1)$ stays consistently above $P_{wo}(C|S_1)$ over the range of perturbation variance scaling constant values plotted.

Asymmetric 95% confidence intervals are presented for $P_{wo}(C|S_1)$ and $P_w(C|S_1)$ in Figure 5-34b as, clearly, negative probabilities do not make sense. When constructing confidence intervals for small probabilities, a standard method is to assume that the logarithmic transform of the probability is normal. This is the approach taken in Figure 5-34b. The Baseline and System On $P(C|S_1)$ estimates are nearly identical, and the confidence intervals overlap considerably. This means that the conflicts observed after the RA&C was activated were not significantly more or less severe than those before it was activated. Mathematically, at the selected σ_0^2, the prevention ratio (the System On value divided by the Baseline value) is **1.19** with an associated standard error of 1.19.

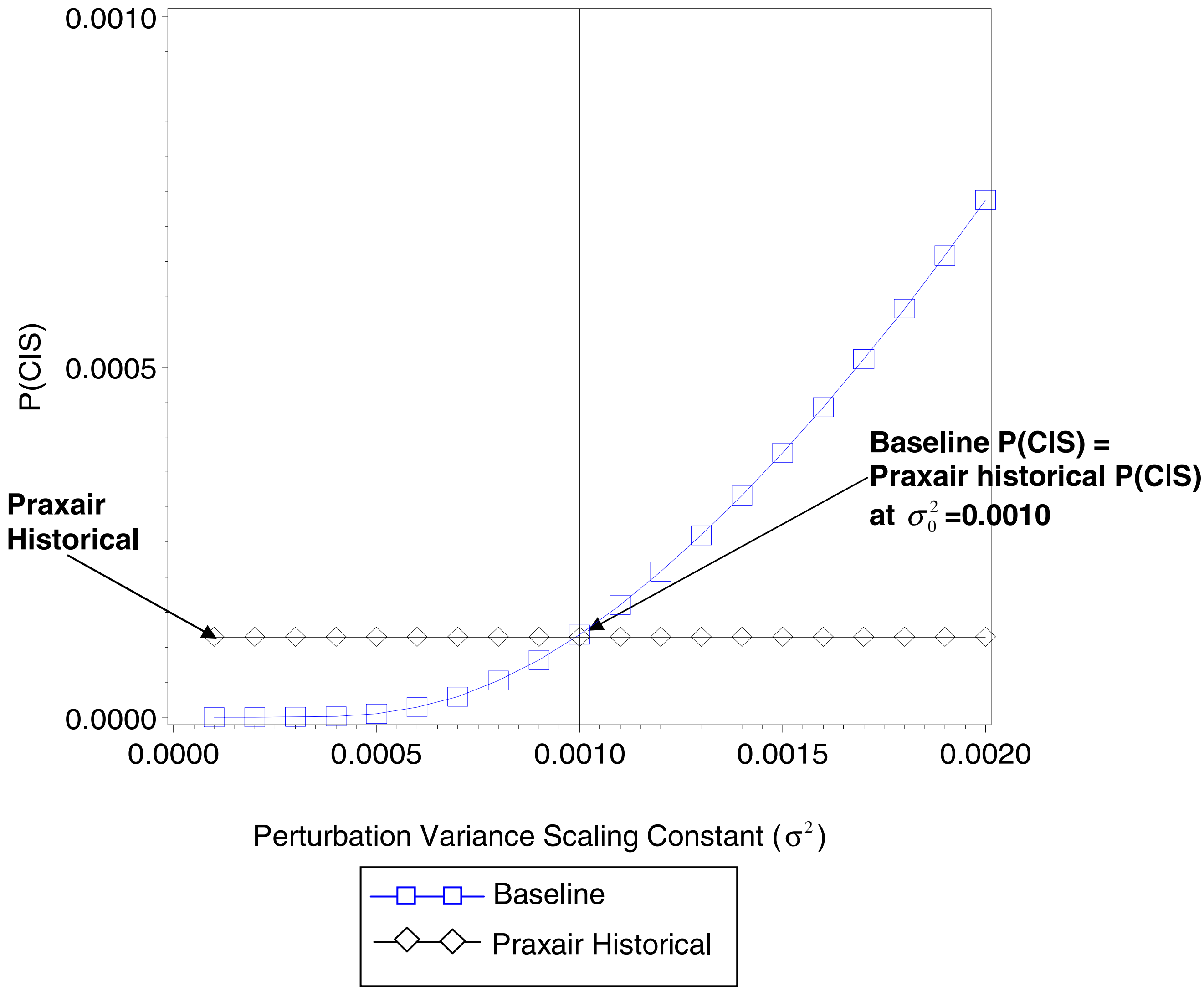

Figure 5-34a. Selection of Perturbation Variance Scaling Constant Using Praxair Historical and Baseline $P_{wo}(C|S_1)$

Note: The probability of a rollover crash given a conflict in Figure 5-32 depends on the variance of the speed perturbation, as indicated here by the line with boxes. The horizontal line with diamonds is the historical rollover rate reported by Praxair. The variance scaling constant is chosen so that the estimated probability of a rollover crash during the Baseline period matches the historical Praxair rate.

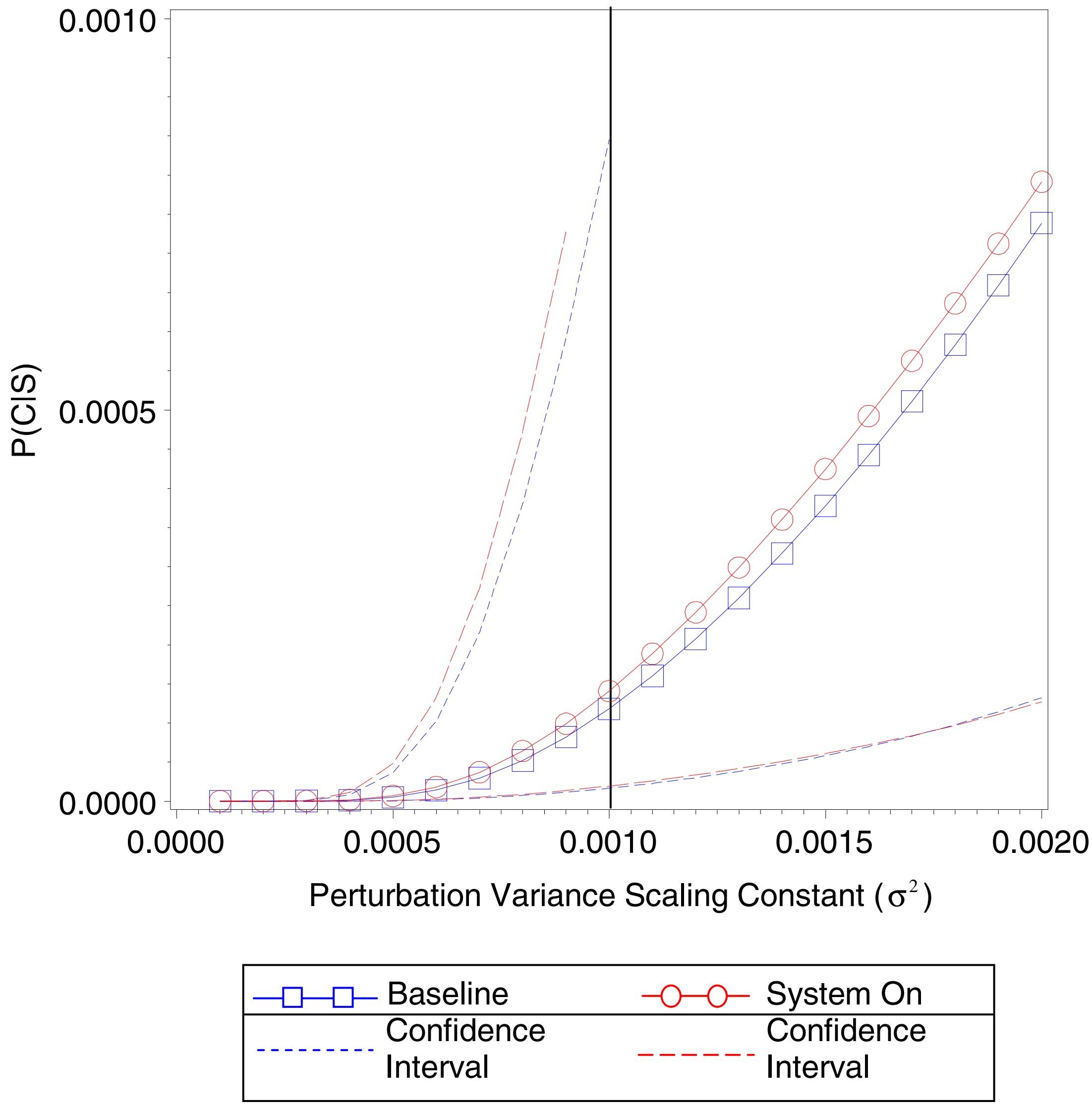

Figure 5-34b. Comparison of Baseline and System On P(C|S$_1$)

Note: The estimated probabilities of a crash during the Baseline and System On periods were nearly identical. The dotted lines indicate the 95% confidence intervals for the two estimates. The regions overlap almost entirely.

One concern associated with any model-based inference technique is sensitivity of the result to the model assumed. Figure 5-35 illustrates how selection of σ_0^2 affects the prevention ratio as well as the 95% confidence interval. The prevention ratio remains relatively constant around unity for a wide range of σ_0^2 values. Confidence intervals about the prevention ratio are wider for small values of σ_0^2, but regardless of the σ_0^2 selected, the prevention ratio is not significantly different from one.

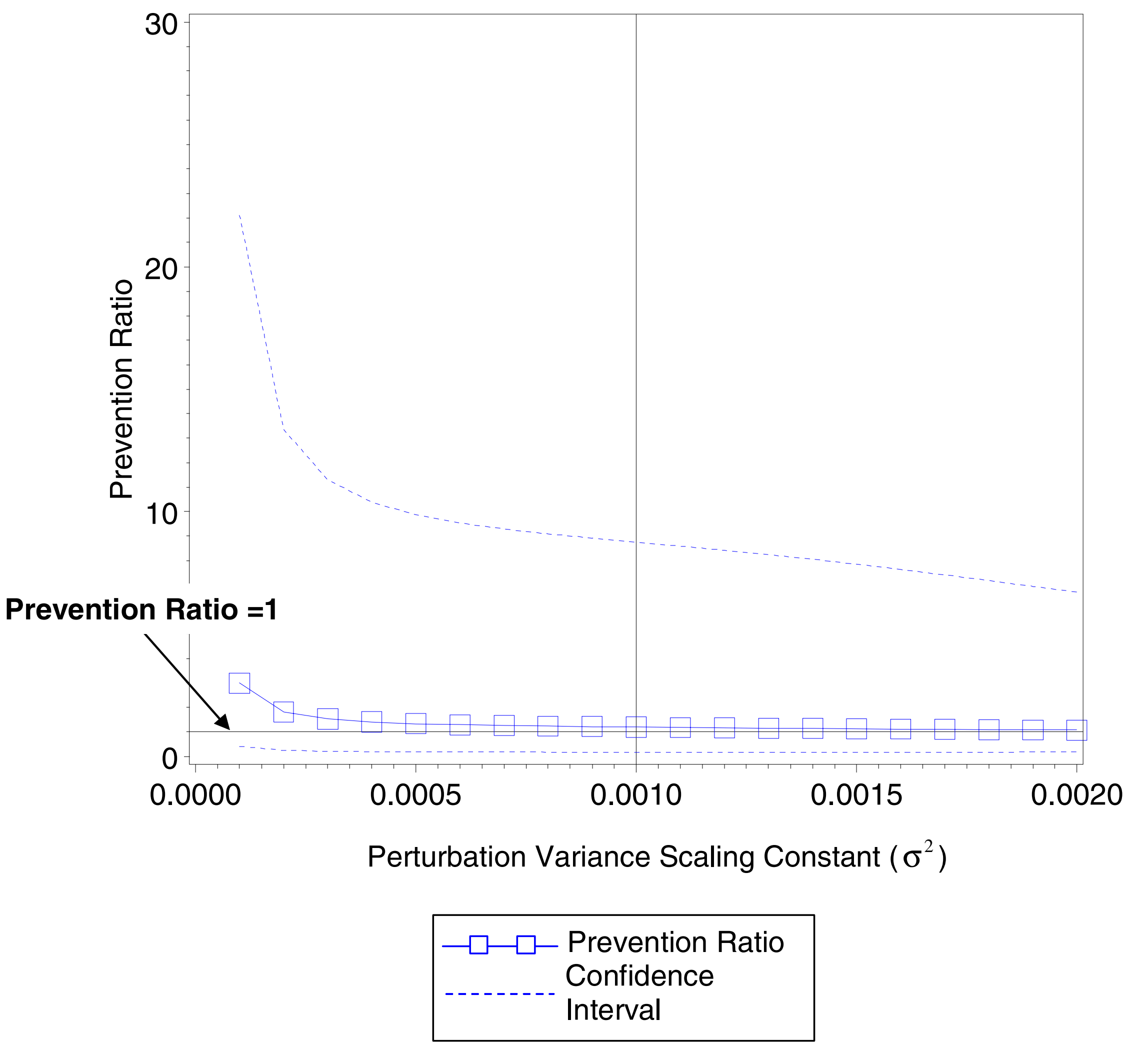

Figure 5-35. Sensitivity of the Prevention Ratio to Selection of σ_0^2

The severity measure selected in Equation 5-9 was reasonable but arbitrary. To evaluate the extent to which the prevention ratio estimate (1.19) is sensitive to the selected severity measure, an alternative severity measure has been considered. The alternative severity measure does not scale the speed increase required to produce a rollover, as it did in Equation 5-9; it is simply

$$s_j = V_{j,R} - V_j \,. \qquad (5\text{-}11)$$

The alternative severity measure modifies the interpretation of the perturbation variance scaling constant. Previously, it was controlling the variance of a distribution about the *relative* change in speed required for a conflict to result in a rollover (a dimensionless quantity). Now, it is controlling the variance of a distribution about the *absolute* change in speed required (as measured in kmph). Under this definition, different conflicts are considered to be severe. Specifically, low speed conflicts are made relatively more severe than before and high speed conflicts less.

If we repeat the procedure of Figures 5-32 through 5-35 for this alternative measure instead of the original one, we arrive at a scaling parameter of 0.7. Figure 5-36 has the same interpretation as Figure 5-35, but it is plotted with the alternative scaling parameter on the x-axis.

The alternative prevention ratio estimate is 1.05 with an associated standard error of 1.05. Thus, similar prevention ratio estimates result from both severity measures, and both approaches are largely invariant to selection of the perturbation variance scaling constant. This reinforces the observation that the severity of conflicts was not significantly different during the Baseline and System On periods.

Estimating the Safety Benefit. Previous work, summarized in Section 4.3.1, has determined that the reduction in number of rollover crashes due to deployment of RA&C can be calculated using the **Benefits Equation** which originally appeared as Equation 4-4:

$$B = N_{wo} \times \sum_i P_{wo}(S_i \mid C) \times \left[1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)} \right]. \qquad (5\text{-}12)$$

In the Benefits Equation, S_i are the driving conflicts, which partition the normal driving space. The conditional probability $P_w(C \mid S_i)$ is the probability that a rollover crash occurred with an active RA&C given that driving conflict S_i occurred. $P_w(S_i)$ is the probability that driving conflict S_i occurred with an active RA&C. Quantities subscripted with "wo" have the same interpretation, but for vehicles without RA&C. The probability that driving conflict S_i occurred prior to a crash given that a rollover crash occurred without (i.e., with an inactive) RA&C, $P_{wo}(S_i \mid C)$, is also required in the Benefits Equation.

There are two key ratios in the Benefits Equation, namely $\frac{P_w(S_i)}{P_{wo}(S_i)}$ and $\frac{P_w(C \mid S_i)}{P_{wo}(C \mid S_i)}$. The first ratio is the **Exposure Ratio**: the ratio of exposure to driving conflicts with and without an active RA&C. Values of this ratio less than 1 indicate that an active RA&C will reduce exposure to

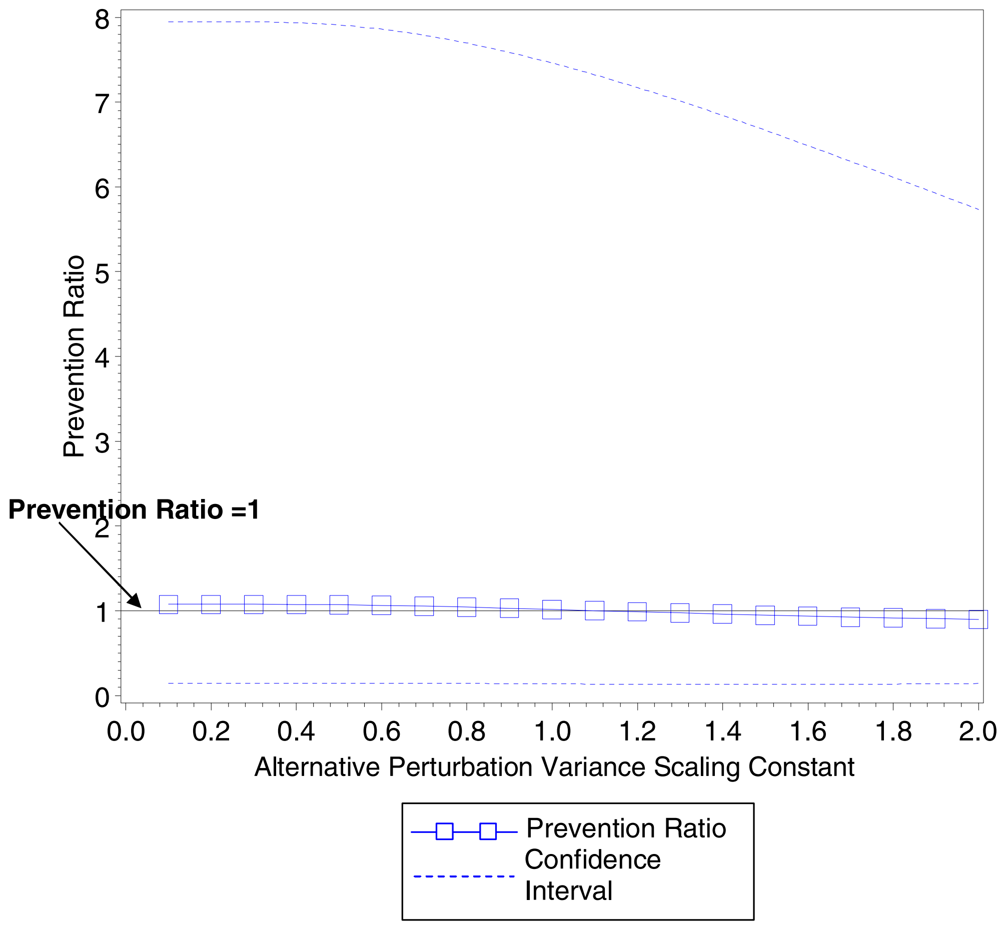

Figure 5-36. Calculation of the Prevention Ratio Using the Alternative Severity Measure of Equation 5-11

potential crash situations. The second ratio measures the efficacy of an active RA&C at preventing crashes after a particular driving conflict has occurred. It is the **Prevention Ratio**. Again, if this ratio is less than 1, safety benefits can be inferred. The estimated exposure and prevention ratios for the relevant rollover driving conflict (too fast through a curve) and their estimated standard errors are provided in Table 5-7.

Table 5-7. Inputs to the Safety Benefit Estimate

Ratio	Estimated Value	95% Confidence Interal		Reference
		Lower Confidence Bound	Upper Confidence Bound	
Exposure	0.67	0.51	0.83	Equation 5-2
Prevention	1.19	0.16	8.75	Figure 5-35

Simplifying of the Benefits Equation for the case where there is only one driving conflict, which the RA&C affects, results in:

$$B = N_{wo}(S_1|C) \times \left[1 - \frac{P_w(C|S_1) \times P_w(S_1)}{P_{wo}(C|S_1) \times P_{wo}(S_1)}\right] = N_{wo}(S_1|C) \times [1 - PR_1 \times ER_1] \qquad (5\text{-}13)$$

where $N_{wo}(S_1|C)$ is the number of rollover crashes preceded by the first rollover driving conflict encountered without the RA&C, and $[1 - PR_1 \times ER_1]$ measures the efficacy of the RA&C at preventing crashes of this type. Substituting the values of the Exposure and Prevention ratios of Table 5-7 into the efficacy measure results in an efficacy value of **0.20** with an approximate standard error of 0.95. Thus, the safety analysis indicates that the RA&C can prevent 20% of untripped rollover crashes caused by taking a turn too fast. This result is not, however, statistically significant. The calculated efficacy will be applied to the number of rollover crashes of various fleets in Section 5.1.3.

Effect of RSC on Reducing Rollover Crashes. The Roll Stability Control performed well during the planned tests on the closed course, but it showed little benefit during the operational test.

Figures 5-37, 5-38, and 5-39 show three typical outcomes of RSC activations. In Figure 5-37, the RSC functions properly and keeps the vehicle's lateral acceleration from becoming to great. The upper part of the figure shows the engine torque over a ten-second period. The heavy line shows the momentary torque limit imposed by the RSC, beginning about 3.7 s into the window. The RSC reduces the engine torque for about one second, and then the limit is lifted. The lateral acceleration measured at the steer axle during this same period is shown in the lower part of the figure. The truck is accelerating as it prepares to come out of a right-hand turn. The lateral acceleration approaches 0.3 g, which would be fairly high if the truck were fully loaded. The acceleration levels off and does not increase further when the RSC activates. The lateral acceleration returns to about zero when the truck leaves the curve, and the RSC's torque limit is no longer needed. Figure 5-38 shows another case where the RSC decides to limit the engine torque. However, the actual torque is below the RSC's commanded limit, so there is no direct effect. Interestingly, the accelerometer pedal was released immediately after the RSC activated.

It is difficult to say whether the driver was reacting, perhaps subconsciously, to the RSC's intervention or whether the driver himself perceived too much lateral acceleration and released the pedal independently. The time delay between the RSC and the pedal release is about 0.5 s, which is a plausible response time. There are a few instances of RSC activation where the RSC's torque limit was above the actual engine torque and the driver did not respond, so there was no effect, direct or indirect, of the RSC. The final example, Figure 5-c, is one such case. The truck was already in a curve and the speed, in fact, was already decreasing when the RSC activated. The engine torque was zero, so the RSC torque limit was at all times above the requested torque. The engineering data did not record whether the retarder was engaged, but the speed of the vehicle did not show any changes while the RSC was limiting the torque. The

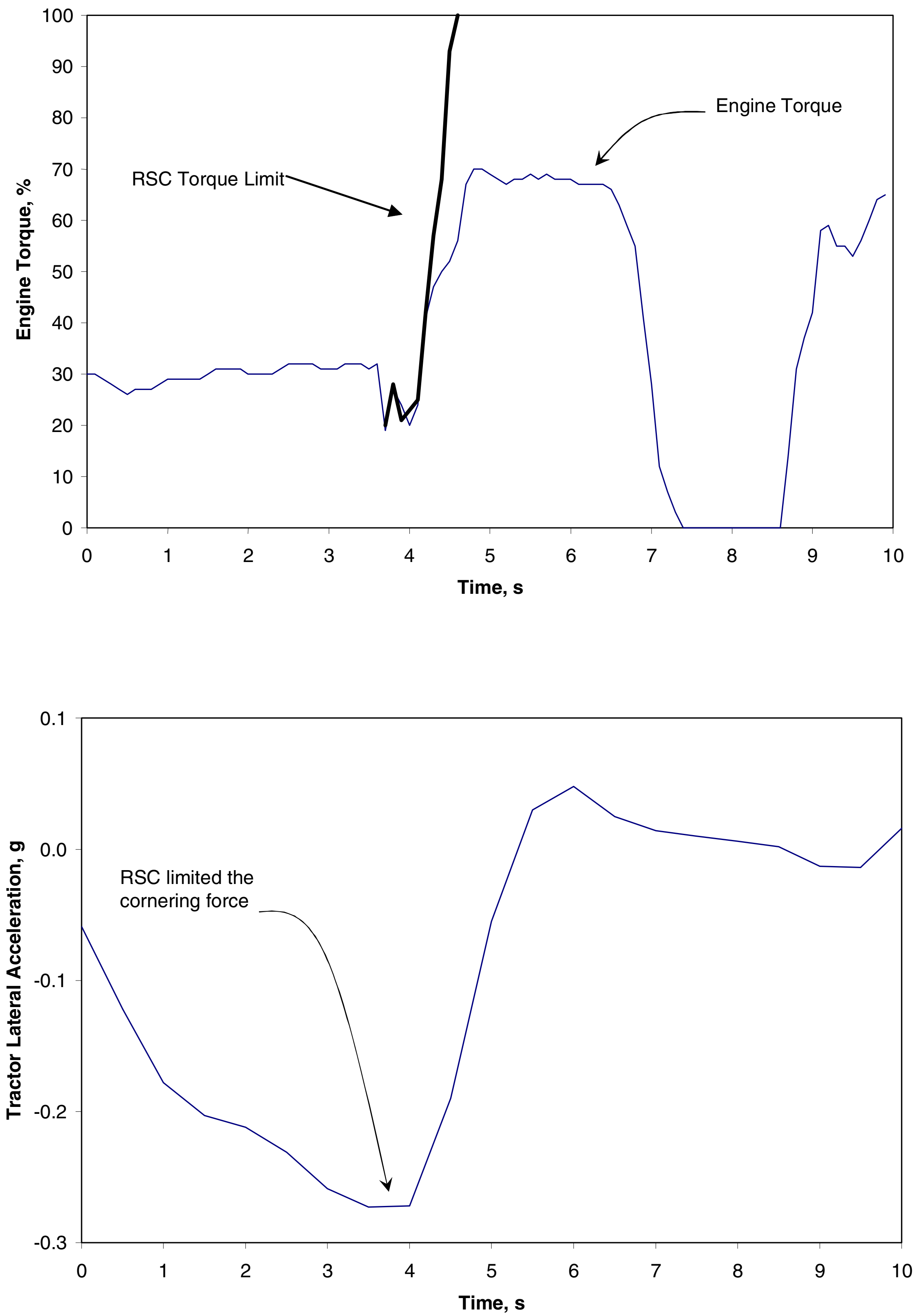

Figure 5-37. An Instance where the RSC Worked Effectively to Limit the Engine Torque and Prevent the Lateral Acceleration from Increasing Beyond a Safe Limit

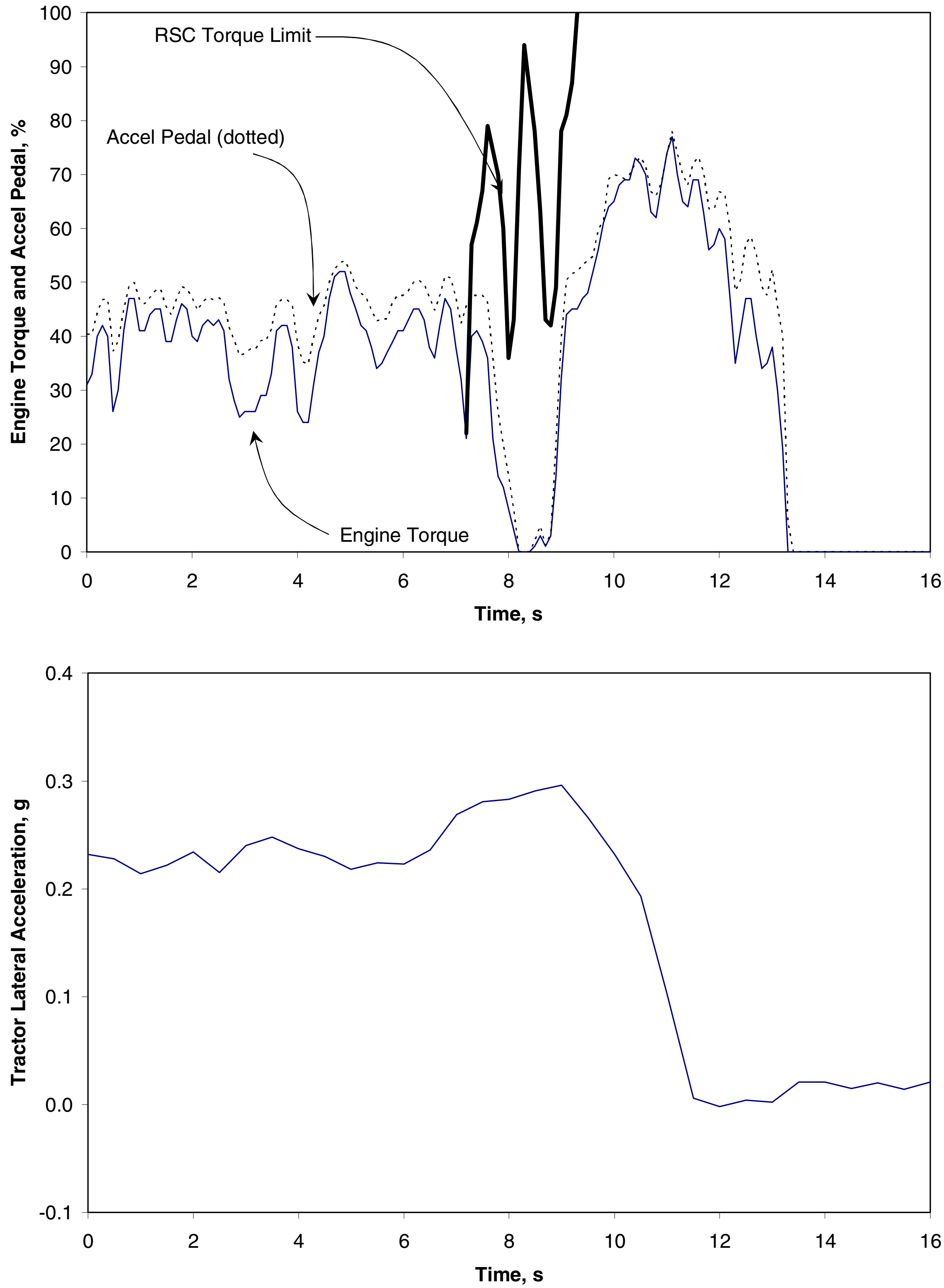

Figure 5-38. The Driver Reduced the Acceleration Pedal during the RSC Activation

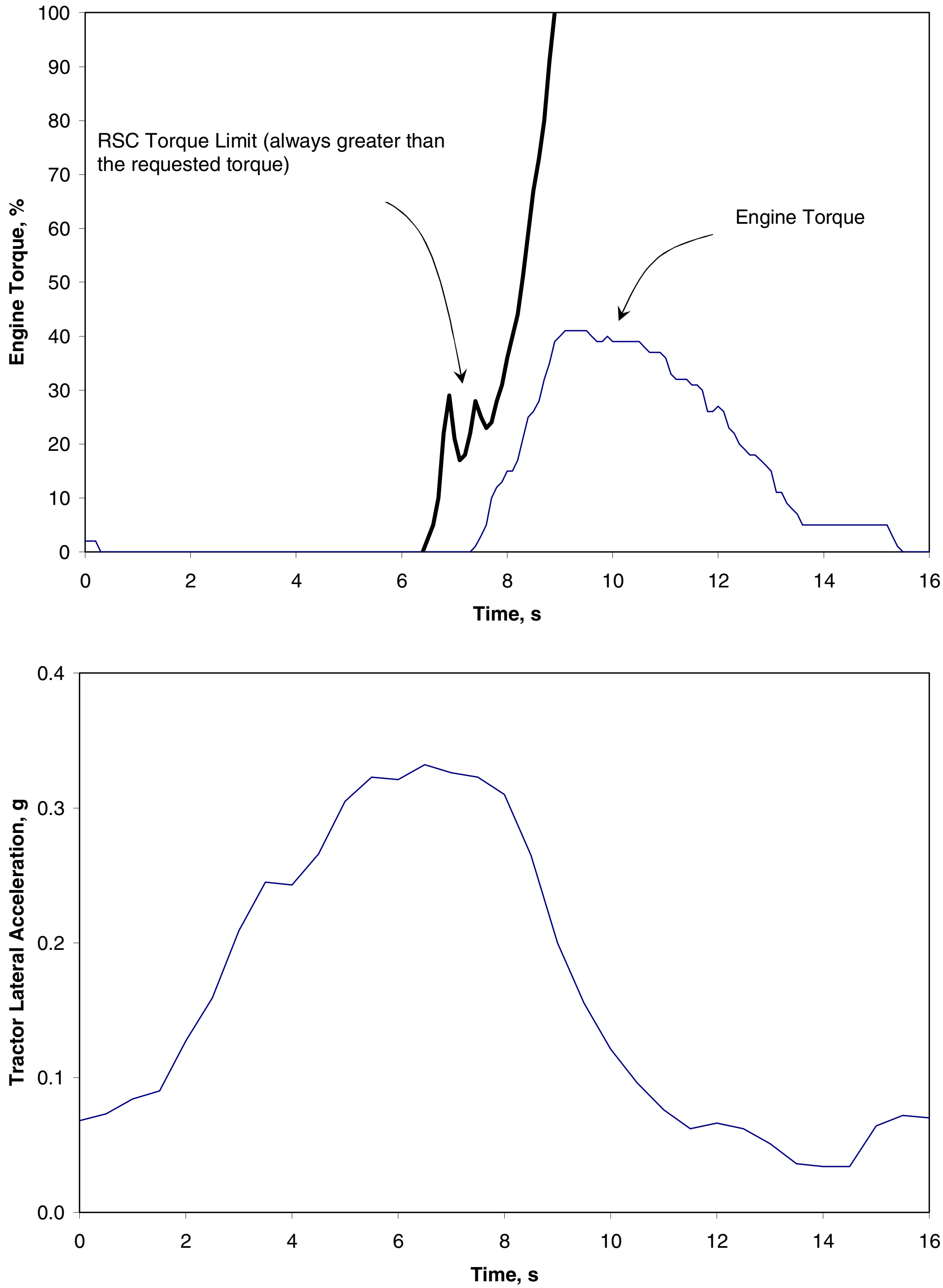

Figure 5-39. The RSC Activated when the Vehicle was Already Decelerating, and it did not Affect the Deceleration

lateral acceleration of the vehicle, as shown in the lower portion of Figure 5-c, remained above 0.3 g for three seconds. This would have been a hazardous maneuver had the tank been full, though, judged by the tilt table results in Figure 4-6, it probably would not have led to a rollover.

There were 25 unique instances where the RSC activated during the FOT. In most of them, the driver was trying to accelerate at the time of the activation, but there were six instances where the driver was already applying the brakes or at least reducing the throttle. The RSC has the authority to command the engine to limit its torque output, but in nine of the activation instances, the engine was already producing less torque than the commanded limit, so the RSC had no effect. In four cases, the RSC did limit the torque output but had no apparent effect on vehicle speed. There were six cases where the RSC prevented further acceleration of the vehicle, and only five where the RSC actually slowed the vehicle.

In every one of the cases where the RSC activated, the total weight of the vehicle, as calculated by UMTRI from the air spring pressure, was less than 20 tonnes; that is, the tank was empty. In all of these cases, the RSA had correctly measured the vehicle mass as being low. (The RSA-calculated mass was between 20 and 26 tonnes for all but one of the events. The RSA tended to estimate the mass high, but this range was the most common mass estimate for essentially empty trailers.) Many of the lateral accelerations at the time of activation were high, and some were in fact more than sufficient to roll a truck had it been full. However, since the trailers were all empty, the rollover danger was remote even in these cases. Therefore, in the 11 instances in the FOT where the RSC either prevented further acceleration or reduced the vehicle speed, no rollovers appear to have been avoided.

Not a single driver recalled during the exit interviews having received a notice that the RSC had activated. One driver, though, thought the traction control activated during an RSA event, but the recorded data showed this was an RSC. According to the data collected on the tractors, two drivers had triggered the RSC ten times each, and five had triggered it once each. One can speculate as to why the drivers did not recall the events – perhaps they mistook it for something else, or they were too busy at the time to notice the message. Unlike the RSA, no audible tone accompanies the RSC messages. With the lack of tone and minimal effect on vehicle motion, it is likely the drivers simply did not notice the RSC. In six of the 25 activations, there is no confirmation in the onboard data that the message was actually displayed to the driver. The RSC is presented as activating only when the vehicle is in imminent danger of rolling over, so it is imperative that such information be transmitted reliably and unambiguously to the driver.

One series of tests at the test track (Test 005 in Appendix D) was devoted to challenging the RSC in controlled conditions. The simplest test for demonstrating the RSC's capability is a constant-radius, increasing speed turn. A 200-ft-radius turn was executed several times, both with and without the RSC active. Without the RSC, the result was always the same—the speed increased until the outrigger touched the pavement. With the RSC present on the vehicle, the RSC triggered as the vehicle approached the limit of roll stability. In most, but not all, cases, the RSC prevented the outrigger from touching the pavement. Figure 5-40, reproduced from Test 006 in Appendix D, shows the speed of the truck as it accelerated around the 200-ft radius. In all cases, the driver attempted to increase the speed until the outrigger touched the pavement; but, with the

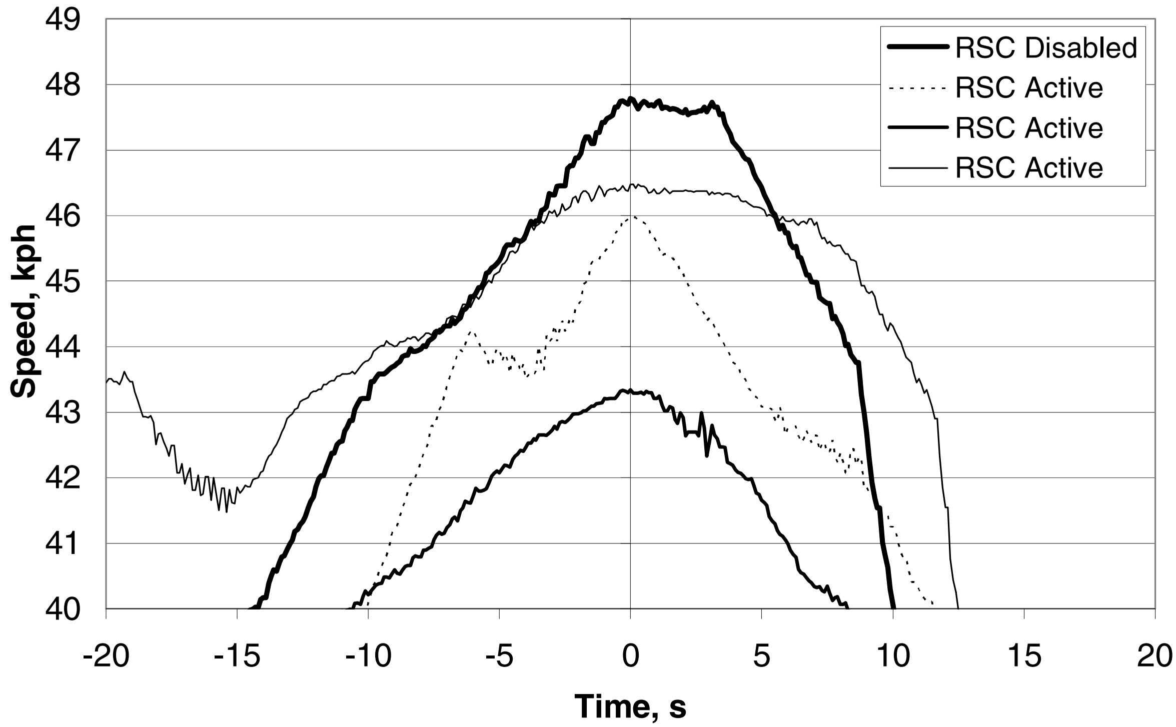

Figure 5-40. Speed Histories during RSC Testing at the Test Track

RSC, this was not possible. Personnel in the cab could hear and feel when the RSC used the engine brake. Personnel watching these maneuvers from outside the truck readily noticed the improved stability with the RSC. The RSC was clearly beneficial in this kind of maneuver.

There are maneuvers that occur too quickly for the RSC to intervene. This was demonstrated at the test track in a maneuver that began as a constant-radius turn at a constant speed. The driver suddenly turned inward. This might be typical of a freeway ramp or curved secondary highway with an unexpected sharpening at the end. As soon as the additional steering was applied in the experiments, the truck began to roll. Any slowing, by the RSC or otherwise, was too late to prevent rollover.

The evaluator ran a brief set of experiments in an effort to find a scenario where the RSC diminishes the stability of the vehicle. The vehicle was driven into a 200-ft-radius J-turn with the tank partially loaded. The thought was that excessive braking might cause the load to surge forward and upset the articulated vehicle. In the experiments, the vehicle was stable throughout the maneuver. The evaluator does note that UMTRI was able to demonstrate a limited but repeatable set of conditions where the RSC can cause a jackknife in low-friction surfaces. That work was done as part of the preparation for the human subjects review panel and was judged by UMTRI to be a remote possibility in service.

In summary, we found that the RSC activated a few times during the FOT, but never when the vehicle was in apparent danger of rolling over. On the other hand, while there are instances where the RSC can decrease the stability of a vehicle, the circumstances are quite limited. Therefore, we attribute no effect, beneficial or detrimental, to the Roll Stability Control.

Helping Drivers Identify Routes with Less Rollover Risk. When asked if there were specific locations where the RSA seemed to activate more often, most drivers said they had not noticed any. A few did mention one or two locations, and they were asked a follow-up question as to whether they already knew the location was risky or thought it was so. None thought the locations were risky.

These drivers, because of their limited delivery area and experience with the company, were intimately familiar with the routes before the FOT began. That the RSA did not reveal risky locations to the FOT drivers does not mean it is not useful for this purpose.

None of the locations identified in UMTRI's final report (Winkler et al. 2002, Appendix A-G) as having a high rate of RSA "episodes" during the FOT appeared on a list of high crash-rate locations provided by the Indiana Department of Transportation. The location with the highest number of episodes is the ramp shown in Figure 5-7. In the past four years, the state of Indiana has recorded no rollovers on this location and only two minor crashes of other types. The poor correlation of high advisory rate locations and high crash rate locations is likely due to the miscalculation of the weight and to the messages that were issued when the truck was empty.

5.1.3 Do Vehicles Equipped with RA&C Have Fewer SVRD Crashes?

The predominant driving conflict (high speed in turn) for rollover crashes can also lead to SVRD crashes. Notice that the "Rollover.1"conflict in Table 4-2, which leads to 55% of the tanker trailer rollovers, is also the "SVRD.5" conflict in Table 4-3. According to GES, this conflict accounts for approximately 9% of the tanker trailer SVRD crashes.

Because exposure is defined in terms of conflict type, the same Exposure Ratio derived for rollover crashes in the previous section is also used in the Benefits Equation to estimate a reduction in SVRD crashes attributable to the use of RA&C. Recall the benefits equation:

$$B = N_{wo}(S_1, C) \times [1 - PR_1 \times ER_1] \qquad (5\text{-}14)$$

where $N_{wo}(S_i, C)$ is the number of SVRD crashes preceded by the "high speed in turn" driving conflict (SVRD.5 in Table 4-3) encountered without the RA&C, and $[1 - PR_1 \times ER_1]$ measures the efficacy of the RA&C at preventing crashes of this type.

Due to the low availability of lane tracker data, especially in curves, it was not possible to identify driving conflicts characterized by lane excursions rather than excessive lateral acceleration. Therefore, we could not perform the appropriate analyses to calculate the Prevention Ratio for SVRD crashes. Thus, to complete the safety benefits analysis one could either use a default value of 1.0 for the Prevention Ratio or take a more conservative approach and use the Prevention Ratio calculated for the rollover crashes. As we observed in the analysis of rollover crashes, one might expect the Prevention Ratio for SVRDs to be greater than 1.0

because, even thought the driver is experiencing fewer conflicts, they are more severe, and thus, more likely to result in crashes. However, we do not have the required data to confirm that the Prevention Ratio for SVRD crashes is the same as the ratio calculated for rollover crashes.

Using the default Prevention Ratio of 1.0, the efficacy of the RA&C ($[1 - PR_1 \times ER_1]$) at preventing SVRD crashes due to high speeds in turns is estimated to be **0.33** with a standard error of 0.085. Thus, the safety analysis indicates that the RA&C can prevent 33% of SVRD crashes caused by taking a turn too fast. This result is statistically significant, but only because we used the default prevention ratio rather than an estimate which is subject to statistical uncertainty. Using the conservative approach, the efficacy of the RA&C for preventing SVRD crashes due to high speeds in turns is estimated to be 20%, the same as for the rollover crashes.

5.1.4 What Are the Decreases in Crashes, Injuries, and Fatalities if RA&C is Deployed Nationwide?

This section presents estimates of the potential safety benefits - in the form of reductions of crashes, injuries, and fatalities – under different deployment scenarios for the RA&C. The approach follows from the safety benefits estimation methodology for Objective 1A.3, which was summarized in Section 4.3.1.

Overview

The goal of this analysis is to extrapolate the estimated safety benefits of RA&C, determined from this FOT, to different populations of trucks for which the RA&C might be deployed. Freightliner and Meritor-Wabco believe the RA&C system can be beneficial for all large trucks (i.e., trucks with gross vehicle weight over 10,000 lbs.). Therefore, this group of over seven million trucks represents the largest population of interest for projecting safety benefits. However, given the large variation in truck sizes and configurations within this broad category, it is also useful to estimate safety benefits for other target populations. Two criteria were considered in selecting these target populations. First, we must be able to establish historical average numbers of vehicles involved in crashes as well as numbers of fatalities and injuries. GES and FARS provide the necessary data for this analysis. Secondly, it is important to consider the degree to which the findings obtained in this FOT are applicable to the target population. Although it is informative to perform the calculations to estimate the *potential* safety benefits of deploying RA&C 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 RA&C. In this section we calculate the potential safety benefits under various deployment scenarios and discuss how some of these factors might impact the benefits; however, we cannot quantify these impacts without performing additional studies.

The reduction in the number of crashes (B) preceded by a particular type of conflict (S) is estimated using the equation

$$B = N_{wo} \times P(S|C) \times \mathrm{Eff}, \tag{5-15}$$

where Eff is efficacy of the RA&C at preventing crashes as calculated in Equation 5-13; N_{wo} is the average annual number of crashes of a specific type (rollover or SVRD) for trucks without the RA&C system, and $P(S|C)$ is the conditional probability that driving conflict S was the first harmful event given that crash type C occurred. The latter term is estimated in GES by the relative frequency of driving conflicts determined from actual crash investigations. Estimates of reduction in the number of fatalities and injuries are 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 the RA&C is on the driving conflict where the driver loses control of his vehicle because of excessive speed in a turn. As shown in Tables 4-2 and4-3, this type of conflict leads to 55% of the untripped rollovers and 9% of the SVRD crashes involving truck tractors pulling tanker trailers. The corresponding percentages for all large trucks, including tractor-trailer combinations, are 25% and 6% respectively.

In the remainder of this section we apply the benefits equation to five fleets of trucks. We begin with the Praxair national fleet, and then extrapolate our findings to other hazmat carriers using tanker trailers, all trucks pulling tanker trailers, tractor-trailer combinations, and finally all large commercial trucks.

Characteristics of the Praxair Fleet

The Praxair fleet that participated in the FOT carries compressed gas in bulk liquid tank trailers. Nationwide, Praxair operates approximately 650 power units that average nearly 100,000 vehicle miles traveled (VMT) per year. The LaPorte depot, which participated in the FOT, operates 13 power units. The drivers for Praxair are considered to be among the safest and most skilled in the industry. Examination of carrier information from the Safety and Fitness Electronic Record (SAFER) system confirms the impressive safety record of Praxair and its drivers. Over the past 24 months, 850 roadside inspections were performed on Praxair vehicles with only 61 vehicles (7.2 percent) placed out-of-service (OOS). The national average OOS rate for vehicle inspections is 23 percent. During this same period, only four of the 1,171 Praxair drivers inspected (0.3 percent) received OOS orders – compared to the national averages of six percent for HAZMAT drivers and eight percent for all drivers. Praxair's SafeStat Safety Evaluation Area (SAE) scores for vehicle and driver inspections are 13.66 and 5.37, respectively. The SAE score represents a percentile of the distribution of safety measures among motor carriers. For example, Praxair's driver SAE score of 5.37 means that their driver OOS rate is lower than almost 95% of the carriers in the country.

Praxair's accident SAE score is 9.16, which means that Praxair's recordable accident rate is among the lowest 10% within the motor carrier industry. According to Praxiar's own records, their fleet of 650 trucks average 5.8 rollovers per year.

Safety Benefits for the Praxair Fleet

In Sections 5.1.2 and 5.1.3 we determined the most probable estimates of the efficacy of the RA&C for preventing rollover and SVRD crashes to be 20% and 33%, respectively. That is, 20% of rollover crashes and 33% of the SVRD crashes caused by excessive speed in turns are expected to be prevented by the advisory function of the RSA. For SVRD crashes we used the default value of 1.0 for the Prevention Ratio to arrive at the efficacy estimate of 33%.

Praxair reports that it has historically experienced 5.8 rollovers per year (though the number has been less in recent years). However, Praxair does not track SVRD crashes. Therefore, we applyed the 1995 – 2000 GES/FARS data (that 8% of all tractor-trailer crashes are SVRDs) to Praxair's approximately 220 total crashes per year to arrive at an estimate of 18 SVRD crashes per year. Applying Equation 5-15 separately to Praxair's rollover crashes and their assumed SVRD crashes, and then we sum the results to calculate that the entire Praxair fleet would expect to prevent approximately one crash per year from the RSA:

$$B = N_{wo} \times P(S|C) \times Eff \qquad (5\text{-}15)$$

$$B_{rollover} = 5.8 \times 0.55 \times 0.20 = 0.64$$

$$B_{SVRD} = 18 \times 0.09 \times 0.33 = 0.53$$

$$B_{Total} = 0.64 + 0.53 = 1.17$$

Extrapolation of Safety Benefits to Other Fleets

Before we can determine the potential safety benefits of RA&C for other populations of trucks, we need to consider the effect of characteristic differences between the Praxair fleet and other target populations on the efficacy estimate obtained in this FOT. If the FOT was conducted in such a way that we could investigate 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 (tractors pulling tanker trailers). Although we can calculate the safety benefits for other populations of trucks using the efficacy estimates from this FOT, we do not know if the efficacy is the same for all truck types and carrier types. Nevertheless, we are able to obtain separate estimates of average annual numbers of crashes, injuries, and fatalities without the RA&C (i.e., N_{wo}) for each target population. Thus, the estimated safety benefits properly take these different rates into account.

Our 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 efficacy of RA&C is related to driver age, or equivalently, years of experience. The results of this analysis determined that a marginally statistically significant relationship exists between the driver's age and the effectiveness of the RA&C. However, the magnitude of this relationship and the limited range of ages for the FOT drivers are not sufficient to justify using an adjustment when applying the efficacy estimate to other populations. The Praxair drivers said during the final interview that they feel that less experienced drivers would see greater benefit from this system. This may reflect their feeling that younger drivers experience more conflicts and are more likely to be involved in rollover or SVRD crashes. However, we have no way of knowing whether the efficacy (percent of crashes involving high speed in turns that are avoided) is affected by the age and experience of the driver. Therefore, no adjustments are made to the efficacy estimate obtained in this FOT as the benefits are extrapolated to other populations of drivers.

Although engineering judgment cannot be used to make adjustments to the projected safety benefits for different fleets, it should be considered in assessing the confidence of any extrapolation that is performed. For example, we suggest that the findings from this FOT can be applied to other fleets of tractor trucks pulling tanker trailers. Although it might be necessary to recalibrate the RA&C itself for different trailer sizes, configurations (e.g., multiple compartments), and cargo types, the physical characteristics of the larger population of tanker trucks are reasonably similar to the FOT fleet. Therefore, no modification to the efficacy is required to extrapolate the safety benefits to all tanker trucks.

Although the extension of safety benefits to all truck-tractors pulling trailing units of any type is not intuitive, we still provide estimates of the potential safety benefits if the RA&C is deployed in this broader population of trucks. However, results should be interpreted with caution. Unless the RA&C is calibrated for each application, wide variations in the dimensions of the trailing unit or the distribution of cargo weight may result in miscalculations of the truck center of gravity. If the roll threshold, which is calculated from the weight and dimensions of the truck and various dynamic measures, produces more advisories than intended, driver acceptance and faith in the system would be adversely affected. Because most trucks have lower centers of gravity compared to tankers, this would be a common scenario if the RA&C were calibrated for tractors with tankers but used on tractors with all types of trailers. In other words, an RA&C calibrated for a tanker addresses the worst-case scenario. Of course, more serious consequences occur if the system fails to account for the higher rollover risk of a truck with a high center of gravity.

To illustrate the potential safety benefits under wider deployment of RA&C, we also calculate the potential crash reductions if the RA&C is used in all trucks with gross vehicle weight over 10,000 lbs. This is the population that Freightliner and Meritor-Wabco believe can benefit from the deployment of RA&C. Although we do not have evidence, nor are we claiming that the efficacy of the RA&C estimated in this FOT is applicable to this diverse population of trucks, we perform this calculation to obtain an upper bound on the potential benefits for truck applications.

Table 5-8 presents the untripped rollover and SVRD crash statistics for the four populations for which the safety benefits of the RA&C are calculated. The un-shaded rows of this table provide the statistics on the annual numbers of trucks in crashes, fatalities from truck crashes, and injuries from truck crashes estimated from 1995-2000 GES and FARS data. The shaded rows

Table 5-8. Annual Crash Statistics for Rollover and SVRD Crashes

		Crash Statistics[1]				
		Rollover	Rollover – Fast Turn	SVRD[2]	SVRD – Fast Turn	Potential Reduction[3]
Total Trucks in Crashes per Year	All Large Trucks[4]	3,150	787	33,394	2,004	2,791
	Truck-Tractor with Trailer[5]	1,884	471	20,602	1,236	1,707
	Truck-Tractor with Tanker Trailer[6]	84	46	848	76	123
	Truck-Tractor with Hazmat Tanker Trailer[7]	7.8	4.3	286	26	30
Total Injuries per Year	All Large Trucks	2,562	640	10,220	613	1,254
	Truck-Tractor with Trailer	1,293	323	5,576	335	658
	Truck-Tractor with Tanker Trailer	68	37	440	40	77
	Truck-Tractor with Hazmat Tanker Trailer	8.2	4.5	126	11	16
Total Fatalities per Year	All Large Trucks	90	23	455	27	50
	Truck-Tractor with Trailer	55	14	314	19	33
	Truck-Tractor with Tanker Trailer	11	6.0	45	4.0	10
	Truck-Tractor with Hazmat Tanker Trailer	4.8	2.7	20	1.8	4.5

1. Sources: Fatality Analysis Reporting System (FARS) and General Estimates System (GES), National Highway Traffic Safety Administration
2. SVRD = Single-vehicle roadway departure
3. Rows may not sum due to rounding
4. Class 3-8 trucks over 10,000 lbs. gross vehicle weight
5. Class 7 and 8 tractors with any trailing unit
6. Class 7 and 8 tractors with tanker trailer unit
7. Class 7 and 8 tractors with tanker trailer unit displaying hazmat placard

are the estimated proportion of these crashes that are from the driving conflict of interest - namely, turning or negotiating a curve at excessive speed and lose control. In other words, the shaded row is the product of the value presented in the row above and the conditional probability of the relevant conflict for each crash type. The bottom row has the sum of the two shaded rows in each column. It is the total number of crashes, fatalities, or injuries that could potentially be eliminated by the RA&C.

Table 5-9 shows the reduction in the numbers of trucks involved crashes, fatalities, and injuries for each of the target populations. The reductions are provided for only the driving conflict of interest (i.e., too fast in curve). They were calculated by applying the efficacy (0.20 for rollovers

Table 5-9. Estimated Annual Reduction in Crashes, Injuries and Fatalities for Four Target Populations

		Annual Reductions[1]		
		Rollover – Fast Turn	SVRD – Fast Turn	Potential Reduction[3]
Total Trucks in Crashes per Year	All Large Trucks[4]	157	661	819
	Truck-Tractor with Trailer[5]	94	408	502
	Truck-Tractor with Tanker Trailer[6]	9.3	25	34
	Truck-Tractor with Hazmat Tanker Trailer[7]	0.9	8.5	9.4
Total Injuries per Year	All Large Trucks	128	202	330
	Truck-Tractor with Trailer	65	110	175
	Truck-Tractor with Tanker Trailer	7.4	13	21
	Truck-Tractor with Hazmat Tanker Trailer	0.9	3.7	4.6
Total Fatalities per Year	All Large Trucks	4.5	9.0	13.5
	Truck-Tractor with Trailer	2.8	6.2	9.0
	Truck-Tractor with Tanker Trailer	1.2	1.3	2.5
	Truck-Tractor with Hazmat Tanker Trailer	0.5	0.6	1.1

1. Calculated using RA&C efficacy of 0.20 for rollover crashes and 0.33 for SVRD crashes caused by high speed in turns
2. SVRD = Single-vehicle roadway departure
3. Columns may not sum due to rounding
4. Class 3-8 trucks over 10,000 lbs. gross vehicle weight
5. Class 7 and 8 tractors with any trailing unit
6. Class 7 and 8 tractors with tanker trailer unit
7. Class 7 and 8 tractors with tanker trailer unit displaying hazmat placard

and 0.33 for SVRD crashes) to the set of applicable numbers of crashes, injuries, and fatalities shown in Table 5-9. These crash and injury reduction values were carried into the benefit-cost analysis in Section 5.9.

5.2 Achieve an In-Depth Understanding of Mobility Benefits

The mobility benefits of deploying RA&C are derived by combining crash reduction estimates with literature-derived estimates of the effect of crashes on mobility. These benefits, along with estimates of their value, are presented as part of the comprehensive benefit-cost analysis in Section 5.9. The main literature-based crash cost inputs are described in Orban et al. (2002) and Zaloshnja et al. (2000), as discussed in further detail below.

5.3 Achieve an In-Depth Understanding of Efficiency and Productivity Benefits

The impact of deploying RA&C on motor carrier efficiency and productivity is evaluated by determining both the costs to deploy and maintain the system and the cost savings that might be realized. Deployment costs and cost savings potentials are discussed in the following sections. Additional details are provided in the comprehensive benefit-cost analysis presented in Section 5.9.

5.3.1 Costs to Deploy and Maintain RA&C Technology

According to information obtained from Freightliner, the unit price for the RA&C alone will be approximately $385. If purchased, the RA&C system must be installed as an add-on to a Traction Control System (TCS), which itself costs $400, so the total combined price for the RA&C compared with a tractor equipped with neither TCS nor RA&C is approximately $785. Two scenarios based on these unit costs were used in the benefit-cost analysis: (a) assuming that 100% of tractors are already equipped with TCS, and (b) assuming that 10 percent of tractors are equipped with TCS already. These sensitivity analyses are described in Section 5.9.

Other potential cost elements affecting deployment were investigated, but none were found to be significant. There is no installation cost, because the system is not anticipated to be available in an after-market configuration. No software development costs, infrastructure investments, or consulting costs were incurred in the FOT. The manufacturer specifies no cost for annual maintenance, calibration, or consumable supplies.

The vendor warrants the RA&C for 3 years and the expected service life, based on comparisons with similar equipment, is 10 years. The BCA assumed that the RA&C would be replaced every 10 years.

One-time training costs would be on the order of 1 hour per driver, using industry survey data to derive an hourly wage and fringe benefit value, as detailed in Section 5.9.

Beyond the calculated reduction in the numbers of crashes, the system is not expected to have an effect on delivery times. It was hypothesized that the RA&C might cause drivers to operate more slowly on curves. Analysis showed that, because of the small fraction of time the trucks spend in curves, such an effect would be minuscule. This effect was disregarded for the BCA.

5.3.2 Cost Savings Potential

The cost savings from the RA&C result mainly from the reduced incidence of crashes. Such cost savings are presented in the benefit-cost analysis in Section 5.9. Sensitivity analyses were performed assuming a baseline level plus best- and worst-case levels of crash reduction efficacy, for comparison. It was hypothesized that additional cost savings might result from improved driver recruitment and retention, related to user satisfaction. However, as discussed in the human factors sections of this report, the drivers interviewed for this FOT said that their job satisfaction remained the same after deployment of the RA&C, so no effects from changes in driver recruitment or retention were included in the BCA.

5.4 Achieve an In-Depth Understanding of Environmental Quality Benefits

The benefits to environmental quality are considered as factors in the total benefit to society from deployment of the RA&C. Fewer truck crashes are expected to yield environmental benefits in the form of reduced fuel consumption and pollutant emissions because of traffic congestion. Also, hazardous material releases and their associated costs (e.g., cleanup, evacuation, fire, or explosion) will be avoided. These benefits and others related to the environment are detailed in the BCA (Section 5.9).

5.5 Assess Driver Acceptance and Human Factors

The driver acceptance and human factors assessment of the RA&C is organized around four evaluation objectives:

- Determine the Usability of the IVI Technologies
- Assess Driver Perceptions of Workload and Stress
- Determine Perceived Effects on Driver Risks and Vigilance
- Determine Perceptions of Product Quality and Maturity

The "Usability" objective focuses on how the RA&C system is used and understood by the drivers. Adequacy of training and ease of use are also addressed under this objective. The second objective addresses how the system affects driving workload, stress, and fatigue and attempts to assess driver confidence and concerns about nuisance factors. The third objective looks at the effects of RA&C on driver risks and vigilance from the drivers' perspective. Finally, drivers' perceptions of product quality and maturity are presented along with their recommendations for improving the system.

Background information on each driver was collected to determine relevant driving experience as well as experience with computers and other "high tech" truck control or information systems. The background information, originally presented Sections 4.2.3 and 4.3.5, is summarized in Section 5.5.1. The information from the four objectives summarized in Sections 5.5.2 through 5.5.5. Several appendixes supplement the information in this section. The interview outlines and survey forms are presented in Appendixes B and C, respectively. Responses to all of the human factors questions are tabulated in Appendix J.

In addition to addressing these four objectives, an on-board ergonomic assessment was performed by gathering information related to the interaction between the driver and the system. These results are presented in Section 5.5.6.

Key findings obtained concerning driver acceptance and human factors include:

- Before the start of the test, all of the drivers' expectations were that the RA&C would either greatly reduce or somewhat reduce their chances of a rollover. At the end of the FOT, all drivers thought their driving was either unchanged or "somewhat safer."
- The drivers approved of the message center design, indicating that the message center was a good way of delivering advisories. They could hear the advisories and distinguish them from other messages. Most drivers did not find them distracting.
- The training proved to be adequate for most drivers, but a few drivers continued with the misconception that the RSA was a warning for the present situation.
- The drivers did not believe that the system increased their workload or stress. A small number of drivers even indicated a slight reduction in perceived workload due to the systems.
- Opinions of the accuracy varied, but most drivers noted an inaccuracy at least occasionally.
- Most drivers preferred the RSA (advisor) function to the RSC (controller). Only a few preferred the RSA to a forward collision warning system or to a lane departure system.
- The RA&C system effectively applies human factors design principles in the design of the auditory signals and visual displays.

5.5.1 Background Information

Initially, 23 drivers at the LaPorte Terminal participated in the study. Eight of the drivers left employment at Praxair for various reasons during the study period and none resumed employment. No new drivers were assigned to the test trucks during the study period, so 15 of the original 23 drivers finished the entire study. As noted in Table 2-1, all of the drivers were at least 35 years old and most had at least 22 years of experience driving a truck and at least 8 years of experience with tankers.

Prior to system activation, a survey was administered to obtain some background information on how the drivers make decisions. The results show that most drivers:

- Think about their decisions,
- Enjoy making decisions,
- Plan ahead, and
- Take advice or consult others when making decisions.

The implication for this FOT is that, in general, the participating drivers are not prone to risky decision-making.

Additional background questions were included on the Initial Stage Survey, which was performed at the time the RA&C system was activated. The purpose of these questions was to gauge drivers' prior experience with technology as well as their experience and expectations of the IVI systems. Most of the Praxair drivers had some prior experience with computers and advanced in-vehicle electronic systems. About three-quarters of the drivers own a home computer and use it occasionally or frequently. The drivers were already familiar with the Eaton electronic log book system, which is in their trucks; some had used the CADEC data recorder before that. They indicated that "high tech" systems were either useful when driving a truck, or that such systems were neither useful nor problematic. The majority of the drivers were entering the FOT with either an optimistic or "wait and see" opinion of IVI systems.

5.5.2 Usability of the IVI Technologies

This objective focuses on how the RA&C was understood and used by the drivers. The objective is primarily interested in how well the drivers understood the system and how they learned to recognize and understand the signals.

Survey results collected when the system was activated found that the majority of the drivers thought the RSA was easy to learn and they understood its purpose.

Acceptance of the way the messages were delivered was good. The drivers were nearly unanimous in saying that the messages were easy to read and that there was sufficient time to read them. The audible signal was essential in calling the drivers' attention to the messages, but the volume and duration of the tone were acceptable. A significant minority of the drivers wished the sound were better distinguished from other sounds in the cab, such as the Eaton over-speed indicator.

Of course, the most important measure of the display's effectiveness is whether the drivers noticed and remembered the advisory messages. The drivers were asked during the debriefing interview how many advisories they received during the study. Responses ranged from zero to 30. Figure 5-41 compares the actual number of advisories determined from the engineering data with the numbers reported by the drivers. Clearly there is a strong trend. This is an encouraging finding. That the drivers recall fewer than the actual number is not troubling because they were neither asked nor expected to keep an exact count.

On the other hand, none of the drivers at the exit interview recalled receiving a message indicating that the RSC was activated. The engineering data recorded that seven drivers activated the RSC a total of 25 times during the FOT. Some of these were such minimal interventions that, without an audible signal, it is entirely understandable that the drivers did not notice them. Thus, it is recommended to include an audible message for the RSC component. If an audible signal during the RSC action is deemed to be an unnecessary distraction at an inconvenient moment, then a later tone or persistent visual message may be used. At least one driver mistook an RSC activation for the traction control. Interestingly, though none recalled an RSC at the exit interview, five made a positive statement on the long-form periodic survey at least once that the RSC had activated when they though it should not have.

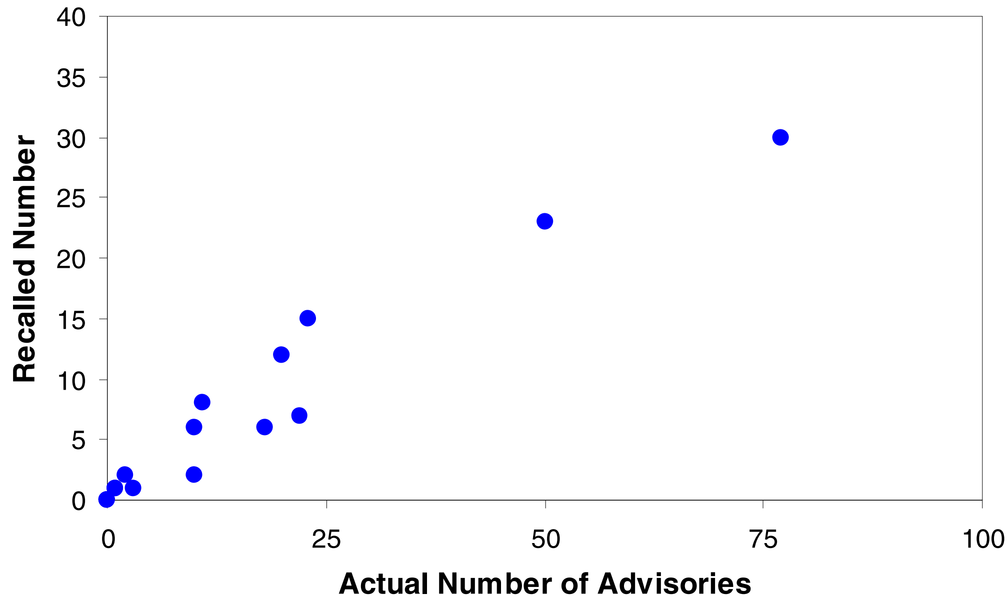

Figure 5-41. Recalled Number of Advisories versus Actual Advisories

Because the RSA acts exclusively through changes in drivers' behavior, it is essential that drivers not only notice or agree with the advisory messages but that they also trust the messages. While many of the drivers thought the system was fairly accurate, some drivers' level of trust was revealed by their response to the question of what they did when they saw an advisory:

- "I know the limitations way better than that."
- "Actually I ignored it. I thought I could go through the curve faster than it let me. I slowed down to keep it from beeping."
- "I thought, 'Huh?' "
- "Either I was accelerating so I could match traffic or I was already slowing, so I did not change what I was doing."

Their trust would likely have been better with a more mature system.

The research plan at one time included a task to evaluate "management feedback," where each driver would be told his own rate of advisory messages in relation to the others and those drivers with higher rates would be encouraged to modify their behavior. This plan was not carried out, but we can make comments about its possible implementation. When asked at the exit interview whether they would mind the management knowing their advisory message count, nearly all of the drivers had no objection. One driver, who had produced no RSA messages during the FOT, even went the next step and suggested that the counts be discussed with the drivers. The drivers were asked to estimate their own advisory message count with respect to the average. The responses are shown in Figure 5-42, where the actual number of advisories of each driver are plotted on the horizontal axis and the actual average is indicated by the vertical line.

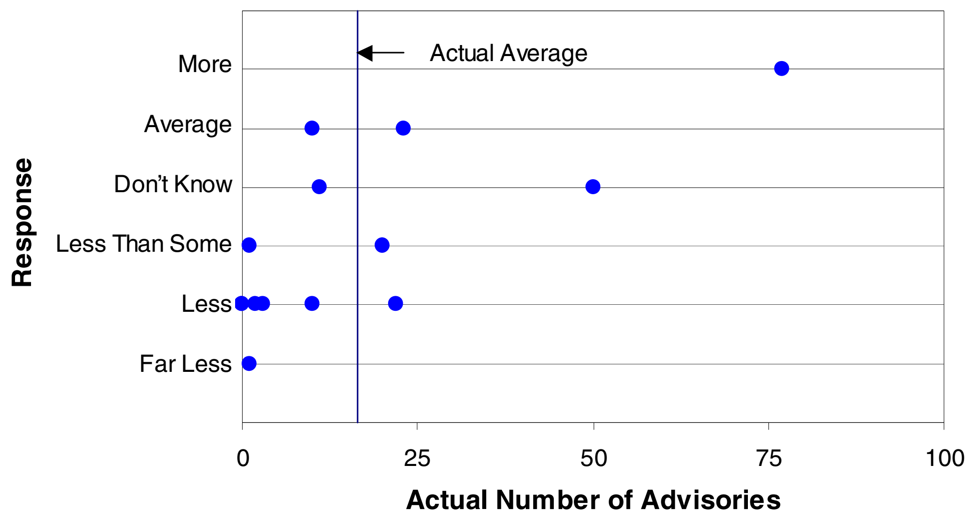

Figure 5-42. Drivers' Response to the Question, "Was your number of advisories more or less than the average?"

The drivers are aware of where they fall with respect to the others at the terminal. This study did not tell us whether speaking with the drivers would have led to a more significant behavior change. Perhaps a more mature, more accurate system would have led to more substantial behavior changes on its own.

At the exit interview, nearly all drivers thought the training had been adequate. In the survey given the week after the training, however, four of the 14 respondents had the misconception that an RSA message asked them to slow down right away rather than on the next curve. Also at the post-training interview, many drivers had to be prompted before they recalled the presence of the controller.

Figure 2-1 (Section 2) displays the RSA messages. There are three "levels" of advice. All messages include a recommended speed reduction. The RA&C calculates this reduction, which is independent of the advisory level, separately every time. Most or all of the drivers missed, either in training or in practice, that there are three levels. When they were asked during the exit interview the number of levels of message they had received, all reported the number of speed recommendations rather than the number of RSA levels. They remembered the fact that there was a speed reduction recommendation (which is good) and not the subtle differences in wording and tone duration. While the difference of the three levels is clear when they are presented together, as in Figure 2-1 or in the training session, the subtle differences in wording and tone duration are not noticed by drivers, who may go days or weeks between messages of different levels. It is good that the drivers remember that an RSA message was presented and the approximate speed recommendation; that is what is most important. The three levels seem to serve no purpose. They are not in themselves harmful, but the time spent on them in training may distract from other features of the system, notably the presence of the RSC.

5.5.3 Driver Perceptions of Workload and Stress

This objective focuses on how the RA&C affects the driving environment. Of particular interest are the perceptions of false positives and false negatives and the influence of the RA&C on the drivers' workload and job satisfaction.

Driver perceptions of the interference of the advisory was spread out. Depending on the wording of the question on the long survey, two to four of the drivers said it interfered with their driving or distracted them. Only one answered that the RSA was distracting at the exit interview, but that response was balanced by another who said it was, "helpful, actually." When asked to compare the interference of the RSA with other safety systems, drivers said the RSA was the same as or better than others. The sound was not distracting.

When asked to, "rate the accuracy of the system," at the exit interview, at least one driver selected each of the five answers offered. The distribution of the responses is shown in Figure 5-43, where each driver's actual number advisories is shown along with the accuracy opinion. There is no trend of high- or low-advisory drivers believing the system to be accurate or inaccurate.

Driver opinion was spread as to whether speed reduction recommendations from the RSA are accurate. However, most agreed or strongly agreed with the statement that they were surprised by some advisory messages that occur during what they thought was a safe maneuver. There were no significant changes over time in their responses. Similarly, during both the surveys and the exit interview, about half of the drivers reported they had received a message they thought was wrong. The vendors' recent work on the system is addressing these issues.

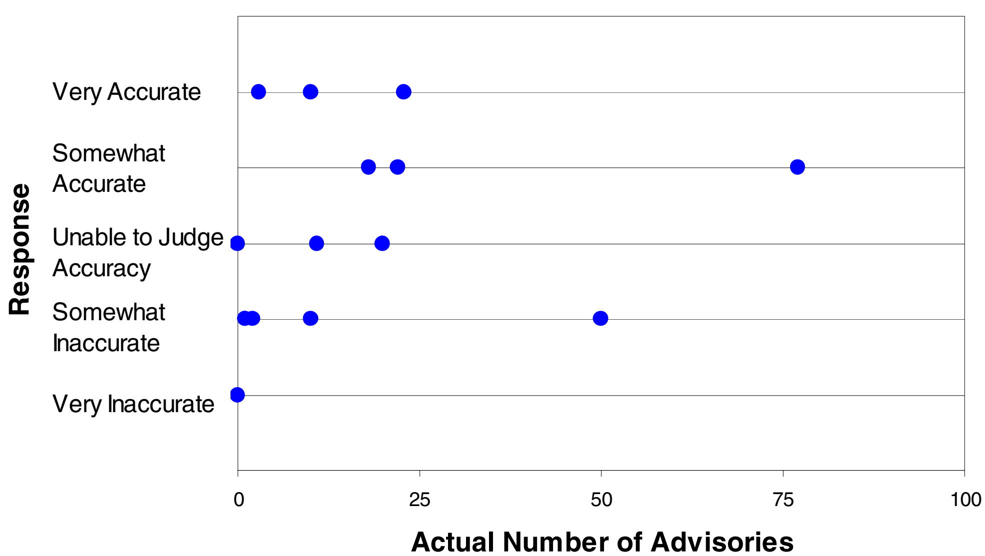

Figure 5-43. Drivers' Final Opinions on the Accuracy of the RA&C

The Debriefing Interview also contained the Mental Workload assessment using the Overall Workload scale (Vidulich and Tsang, 1987). This workload scale derives a rating of overall workload on a unidimensional scale of 0 to 100, with 0 representing very low workload and 100 representing very high workload. This workload scale was used because it has been shown to be highly sensitive and comparable to other multi-dimensional subjective workload measures, yet it is easy to administer and does not require much interview time. (Hill, et al., 1992). Using this scale, drivers provided ratings from 0 to 100 for four driving scenarios: going around a curve on a two-lane road, taking an off-ramp, making a fast lane change, and merging from an on-ramp. They also provided ratings for the "worst condition ordinarily faced." Drivers rated their mental workload at two points in time: when the system was activated, and at the end of the 5-month test period. The goal of this assessment is to determine if the activation of the system had a marked effect on the drivers' mental workload, either as a benefit to help reduce workload or as a hindrance resulting in increased workload. Only nine of the 15 drivers who participated in the exit interviews completed the mental workload assessment. In general, there was almost no difference between the ratings for the two time points. The only exception is that three of the eight drivers who responded to the question concerning workload while taking an off ramp gave lower mental workload ratings for System On period. The other drivers reported no difference in ratings. These data are not adequate to support any conclusions; however, they do suggest that the RA&C might be helpful in training drivers to be more careful on exit ramps, thereby reducing the stress and workload associated with that task.

The drivers said at the exit interview that the RA&C had no change on their level of fatigue, which is consistent with a long survey question, where two or three said it reduced their stress or fatigue.

5.5.4 Perceived Effects on Driver Risks and Vigilance

The very first set of objectives (Section 5.1) addressed whether drivers actually modify their behavior. This objective is concerned with learning whether they are aware that they are acting differently.

Immediately after the training, the drivers were evenly split between those who believed that the RA&C would change their driving behaviors and those who thought it would not.

The long-form survey contained the statement, "With the RSA I don't drive any differently that I would without it." The survey was given three times, and only one driver, the first time it was given, disagreed with the statement. Others either agreed or were neutral. Perhaps significantly, the level of agreement was least at the final time the survey was given. In response to a similar question at the exit interview, seven of the fifteen drivers said they do not drive differently than they did before. Three gave a qualified no (including one who said that learning never ends). Five said they do drive differently, using phrases such as, "more cautious," and "more aware." Again, another exit interview question asked if the drivers felt safer with the RA&C. Half said they did; half reported no change. None complained of feeling less safe.

While the average response may seem only moderately positive, and some of the drivers reporting a change may have simply said what they thought we were wanting to hear, it is encouraging that, among these experienced drivers, some of them admit to being more cautious in curves, which is the desired effect of the RSA. It is especially encouraging when considered in combination with the results presented in Section 5.1.2, where an objective effect was measured as well.

5.5.5 Perceptions of Product Quality and Maturity

This objective addressed the drivers' perceptions of the overall performance and value of the system, recommendations for improvements, and opinions on future deployment of the systems.

In the survey that followed the training, a number of drivers thought an experienced driver would not need such a system to prevent rollovers, though the drivers indicated that they were comfortable having both the RSA and RSC in their truck. In the surveys given as the FOT progressed, opinions on the usefulness to experienced drivers became less spread and more neutral. At the exit interviews, most said that the RSA was of "none" or "some" benefit to them, but only two were willing to go so far as to say that they were better off without it.

Several questions on the surveys given during the course of the FOT related to the usefulness of the information provided by the RSA. Nearly half of the drivers believed that the advice was helpful. Answers were quite spread on the question of whether the RSA was providing information the drivers had not already known.

Initial optimism of the drivers that the RA&C would help prevent rollovers diminished during the FOT. At the initial survey, all thought it would "somewhat" or "greatly" reduce their chances of a rollover. On the periodic surveys, in contrast, only a few thought the system had reduced their number of near-rollover situations or reduced their chances of a rollover.
When asked for their bottom-line assessment of the system, drivers were accepting, many without qualification. Several said they would accept it if advisory messages with an empty trailer could be avoided. (The vendors were working on this, but that was not mentioned during the interviews.) Others said they would accept it if the audible signal were better distinguished from other alerts in the cab.

Finally, the drivers were asked to rate their preference for six possible options in a hypothetical upcoming purchase of new tractors. Five of the options were safety devices, two of which were the RSA and RSC, and the sixth option was an interior upgrade, for comfort. The terminal had actually acquired new tractors during the FOT, which were equipped with the Eaton Vorad forward collision warning system. The drivers liked it, and two thirds of the drivers rated it as their first or second choice. Many drivers had heard of lane departure warning systems and were in favor of its capabilities; its overall rank was second. Support for the RSA was good but not as strong. It was clearly in the middle of the list with two thirds of the drivers rating it third or fourth among the six choices. The interior upgrade was rated in the top, middle, and bottom third by equal numbers of drivers. On average, it placed fourth. In the third tier, rated at the bottom of most drivers' lists, were the RSC and HBED. The average placing for the choices (with 1 being the highest preference and 6 being the lowest) was

1. Forward collision warning 2.8
2. Lane departure warning 3.0
3. RSA 3.3
4. Interior upgrade 3.5
5. RSC 4.2 (tie)
5. HBED 4.2 (tie)

5.5.6 Ergonomic Assessment

An in-cab ergonomic assessment was performed on a test Freightliner truck equipped with the RSC and RSA Systems and Driver Interface. The test was performed at the Transportation Research Center Inc. (TRC). It was a moderately sunny day with no traffic on a dry road surface. The specialized vehicle was driven by a TRC test driver. Because the RSA system acts as a learning tool and provides an alert after driving behavior that could potentially cause a rollover situation, the driver performed risky maneuvers to intentionally trigger the system so that the equipment could be evaluated. To prevent rollovers and to protect the safety of the evaluators, the vehicle was outfitted with outriggers and other safety equipment.

Judgments were recorded using the ergonomic checklist entitled "Descriptive Profile, Human Factors Assessment, and Operational Judgments of the Driver/System Interface," which was provided to Battelle by NHTSA (NHTSA, 2001) and is included as an attachment in Appendix B. Many of the questions pertained to warning systems, so they were not applicable to the assessment of an advisory system such as the RSA. Questions that were not applicable were marked as such in the checklist. The results of the assessment are as follows:

The System. The RSA in the Freightliner FOT is an advisory system meant to be a teaching tool that provides feedback *after* a risky driving maneuver. It is not a warning system intended to notify the driver *during* a hazardous maneuver. On the other hand, the RSC can slow the vehicle and apply engine brakes if a serious rollover threat is detected. While the RSA provides frequent interaction with the driver and is composed of both visual and auditory displays, the RSC produces only a visual advisory in the form of the message "Active Slowing" that is displayed on the same visual display as the RSA. The only control accessible to the drivers is a button which extinguishes the last message displayed. The system performs a functional test at power-up and continuously tests itself during operations. The driver is not able to turn the system off while the engine ignition is turned on.

No system documentation was provided and the installation was not observed by members of the evaluation team. Therefore, no judgments could be made on the adherence of the installation, operations, mounting, or maintenance to system specifications.

Visual Display. The RSA displays one of three possible, briefly worded messages after a maneuver, dependent on the severity of the potential risk. The RSC displays one possible message on the same display if a rollover was at risk. The visual display unit is mounted at zero degrees azimuth in front of the driver in the instrument panel. The driver has an unobstructed view from the forward driving position. Upon startup, the system displays a "system fault" message in the event of a failure. It remains displayed until the problem is remedied.

All messages are relayed on the same display, using the same size and type of font, with the same luminance, in the same green color. It is the content of the displayed message and the duration of the tone that differentiate the advisories. The increased severity of the situation is conveyed through the text message, which provides recommended speed reductions. Because advisories are presented in message form, there are no codes or a need for a legend. The displayed messages are easily readable from the driving position in a variety of light conditions. If the system determines safe operation, then no message is displayed. There is no adjustment for display brightness.

The visual displays cannot be read if attention is focused on the right side or left side mirrors, but is visible and readable when looking straight ahead. The visual display information is distinct from surrounding information and not easily confused with proximal information.

Visual display information from both the RSA and RSC is effective in conveying the necessary advisory information to the driver. The format the information is presented in is appropriate for the type of information being conveyed.

Auditory Alert. Upon startup, an alerting tone accompanies the system fault message in case of failure. Auditory tones are presented in conjunction with the visual text messages for the RSA. No tones are presented for the RSC, so all auditory tones from the system are from the RSA. No alert occurs if the system determines the maneuver was performed safely. There are three levels of alerts that can occur. The tone for each alert is the same, but the duration of the tone appropriately varies to convey the severity of the message. Tone and severity intuitively match in that the most severe risk of rollover is conveyed with the longest tone, while less risky driving advisories have successively shorter tone lengths. The tone itself is distinct from all other auditory signals in the vehicle. The differences in duration are distinguishable from one another when hear in succession, as during the ergonomic assessment. When the messages are presented in isolation, as during the FOT, they are not as easily distinguished.

Summary. The RSC and RSA effectively apply human factors design principles (Huey et al., 1996) in the design of the auditory signals and visual displays.

5.6 System Performance

The third goal deals with the ability of the RA&C to perform its functions according to the designer's intent with reasonable reliability. Drivers' opinions of accuracy were sought. The capability was assessed through analysis of the data collected during the FOT and from the test track.

Several inconsistencies in performance in the presence of RSA messages are noted in the following discussion. During the FOT, the partnership acknowledged that the weight estimate was not performing well. According to statements from Meritor-Wabco, the weight-estimating software has been significantly improved since it was deployed for the FOT. Not all inconsistencies, however, can be explained by an inadequate weight estimate.

5.6.1 Performance and Functionality

The repeatability of the RSA on the test track was good. In the uncontrolled conditions of the FOT, the repeatability was fair. Drivers' opinions of the accuracy were mixed but generally positive.

The consistency of the RSA was evaluated at the test track by running the same simple maneuvers at the beginning and end of every test day. The recommended speed reductions were noted, and the equivalent lateral accelerations were calculated from kinematic relations. The black diamonds in Figure 5-44 indicate the peak lateral acceleration (Ay) measured for left turns in all days' tests. The gray square markers show the speed recommended by the RSA for these same maneuvers. The gray boxes also indicate what the lateral acceleration would have been if the same maneuver were taken at the recommended speed.

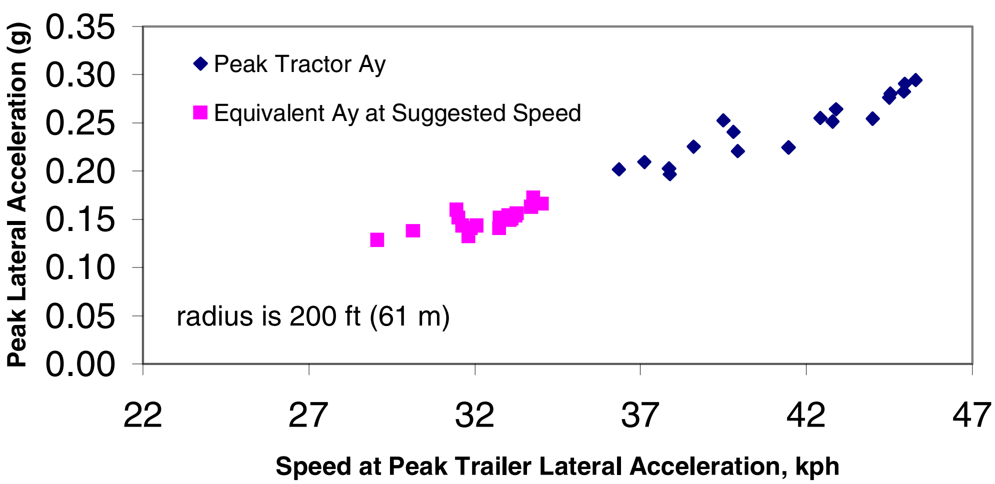

Figure 5-44. Results of the Daily Consistency Check at the Test Track

The equivalent recommended lateral acceleration was about 0.15 g in all cases, showing good day-to-day and run-to-run consistency. The maximum and minimum values were 0.17 g and 0.13 g. The lateral acceleration based on suggested speed appears to remain consistent across varied vehicle speeds and it does not vary from day to day. More details of this test procedure and its results are presented in the discussion of Test 001 in Appendix D.

The performance of the RSA in the FOT was studied in two ways:

- Noting the Rollover Index in all instances where the RSA issues an advisory, and
- Selecting two frequently traveled curves and observing the system's behavior in the repeated trips through these curves.

Figure 5-45a shows the relative number of RSA advisories and RSC interventions, as a function of peak Rollover Index during the event. This figure was produced by identifying all RA&C events during the System On period, calculating the peak Rollover Index during the event, and sorting the events according to peak Rollover Index. The different kinds of shading in the figure represent the distributions of Level 1, Level 2, and Level 3 advisories and RSC interventions. A significant number of RA&C actions were triggered by events with a high rollover index, but a significant number also came from events where the Rollover Index never got very high at all. The RA&C was triggered many times during maneuvers that produced a peak rollover index between 45% and 55%. This figure shows that there is no simple relation between the RA&C's internal assessment of the situation and the Rollover Index defined in Equation 4-1. (Actually, many of the low-index advisories were due to the RA&C's over-estimation of the vehicle weight.) This data led to the development of Test 003 (See Appendix D) at the test track to determine how close to rolling over the vehicle had come in events with a peak rollover index below 55%.

The Rollover Index is a rather simple measure by which to judge the severity of a near-rollover event, so a number of events with moderate peak Rollover Index were duplicated on the test track. In Test 003, which is described on pages D-11 through D-13 of the Appendix, five representative combinations of speed and curvature were selected from FOT maneuvers that had a peak Rollover Index in the range of 45 % to 55 % that resulted in an RSA advisory. The results of this test are shown in Figure 5-45b, where the peak trailer roll angle was in most cases between 1.5 and 3 degrees, which is well below the 8 degrees where the trailer tires begin to lift. The question of where a training system should sound is subjective and involves human factors. But many of the events with only a few degrees of trailer roll, especially those with a Rollover Index below 45 %, probably did not warrant an R&AC action.

The first of the two frequently traveled locations was a freeway exit ramp immediately north of the Praxair terminal. This curve is the exit from the eastbound Indiana Turnpike (Interstate 80-90) at Rt. 39, exit 49. It has a superelevation of 0.073 ft/ft (4.175 degree slope). A map of the path from GPS FOT data and an aerial photo from the USGS are in Figure 5-46. (The ?-shaped events in Test 004 at the test track were patterned after this location.)

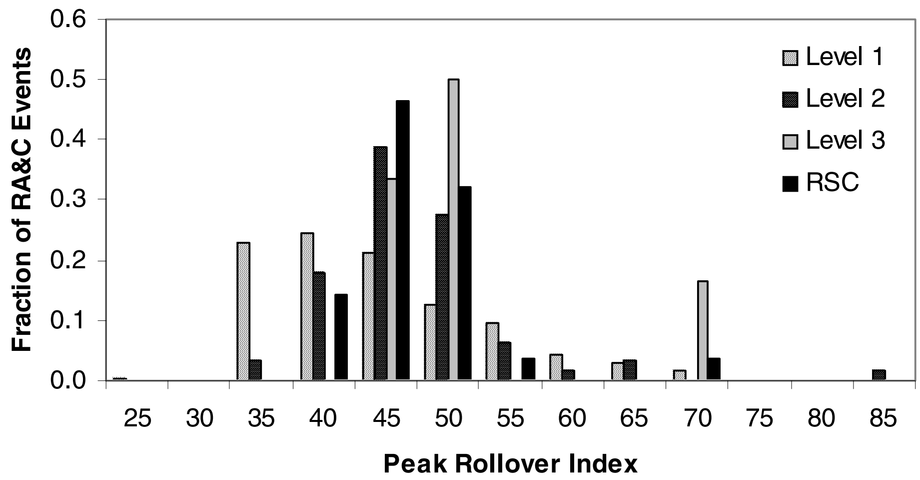

Figure 5-45a. Distribution of RA&C Events Over the Rollover Index Metric

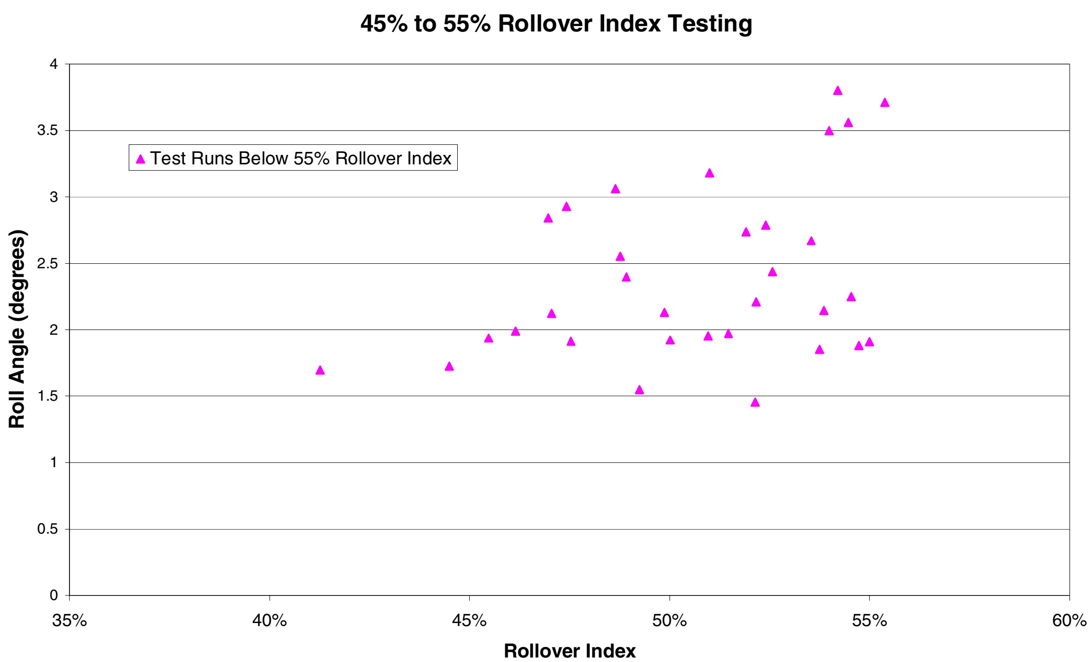

Figure 5-45b. Peak Roll Angles of the Tank Trailer on the Test Track for Maneuvers Where the Peak Rollover Index was Below 55%

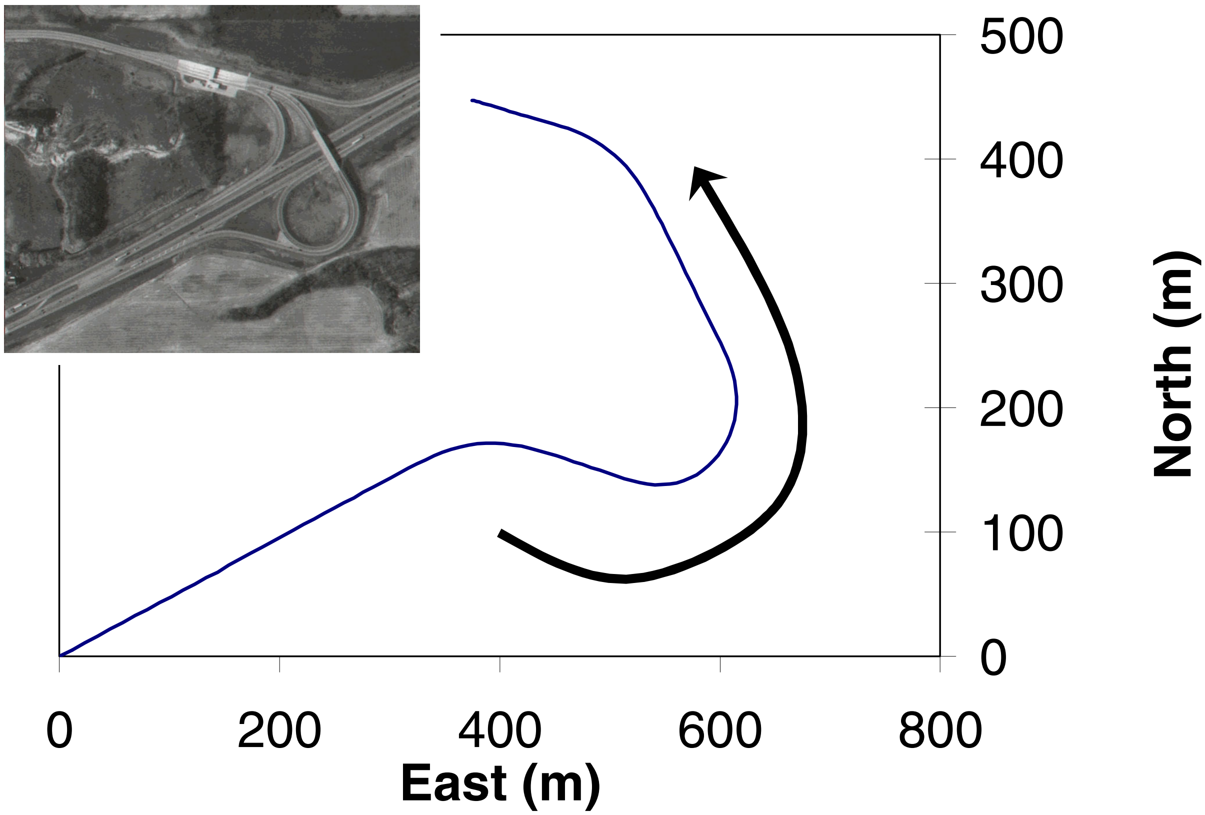

Figure 5-46. Plan View of the ?-shaped Turnpike Exit Ramp where RSA Consistency was Analyzed for Full Trailers

The advisories that occurred at this location were somewhat inconsistent. The advisories did take place on some of the fastest runs with high lateral accelerations, but there were many runs at similar and faster speeds that did not cause advisories, as shown in Figure 5-47a. In this figure, the many gray boxes represent all of the trips through this ramp that did not produce an advisory. The three open black diamonds are the speed and lateral acceleration of the three trips where the RSA issued an advisory. The three solid black diamonds are the speed and equivalent lateral acceleration suggested by the RSA. [The data in the figure are limited to cases where the trailer was full, i.e., the vehicle weight was more than 30 tonnes (i.e., metric tons). In all cases, the RSA's own estimate of the mass was at least 30 tonnes.] Whereas the limited number of trips recorded in the Daily Testing at the test track all showed an equivalent recommended lateral acceleration near 0.15 g, there is no such limit in this figure. To be fair, there is more to dynamic rollover propensity than simply peak lateral acceleration, so several of the trips through this ramp were analyzed with dynamic computer simulation. The three trips where an advisory was issued and seven other loaded trips with high peak lateral acceleration but with no advisory were simulated in a method similar to that used in the safety benefits analysis. The trips were reproduced at successively higher speeds until the simulated vehicle rolled over, to estimate how close the vehicles were to actually rolling over in the FOT trips. The results of this analysis are plotted in Figure 5-47b, where each simulated trip is represented by one marker. The horizontal axis is the speed increment required to roll the vehicle. Those trips with lower increments were those closer to rolling over. The vertical axis is the peak lateral acceleration, plotted for comparison with Figure 5-47a. The three trips where the RSA issued an advisory message are at the left side of the cluster; they were among the most severe of those simulated. However, there were other trips that were equally severe as estimated by the dynamic simulation but where no advisory was issued. A purely advisory system need not be absolutely consistent or accurate to raise drivers' awareness of rollover propensity, but inconsistencies such as those illustrated in this figure may cause experienced drivers to doubt the accuracy of the system or, at worst, confuse less experienced drivers.

As a cursory examination of the weather's possible influence on the system, the effects of temperature and wiper activity were considered with the trips on the ramp. There being only three trips having an advisory, firm conclusions are difficult to draw, but those trips are not outstanding in either respect.

The second location analyzed was significantly more consistent. This 270-degree ramp was the same location discussed with Figure 5-10. Figure 5-48 shows that advisories consistently occurred beyond certain speeds and lateral accelerations. There is considerable overlap between those trips with advisories and those without, but the most severe all resulted in an advisory.

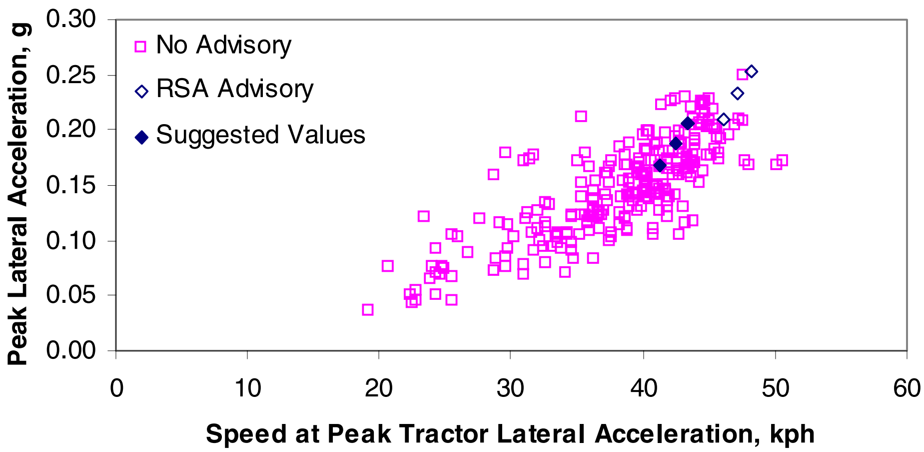

Figure 5-47a. Peak Lateral Acceleration of Trips through the ?-shaped Exit Ramp where the Total Vehicle Weight was at Least 30 Tonnes. The three events where the RSA issued an advisory message are diamond shaped. The filled-in diamonds indicate the speed suggested by the RSA and the equivalent lateral acceleration at that speed.

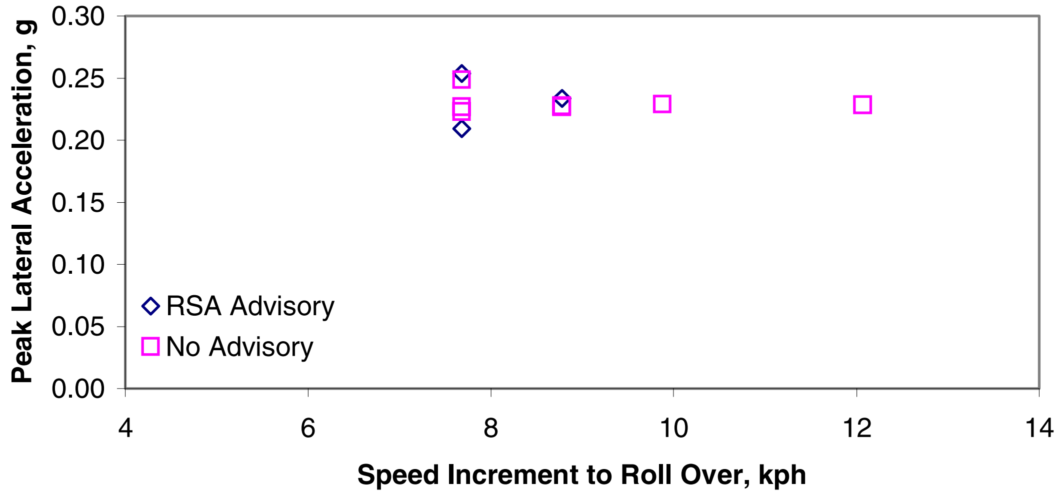

Figure 5-47b. Relative Severity of Trips through the ?-shaped Exit Ramp, as Estimated by the Dynamic Computer Simulation. Those requiring a lower increment to roll were more severe.

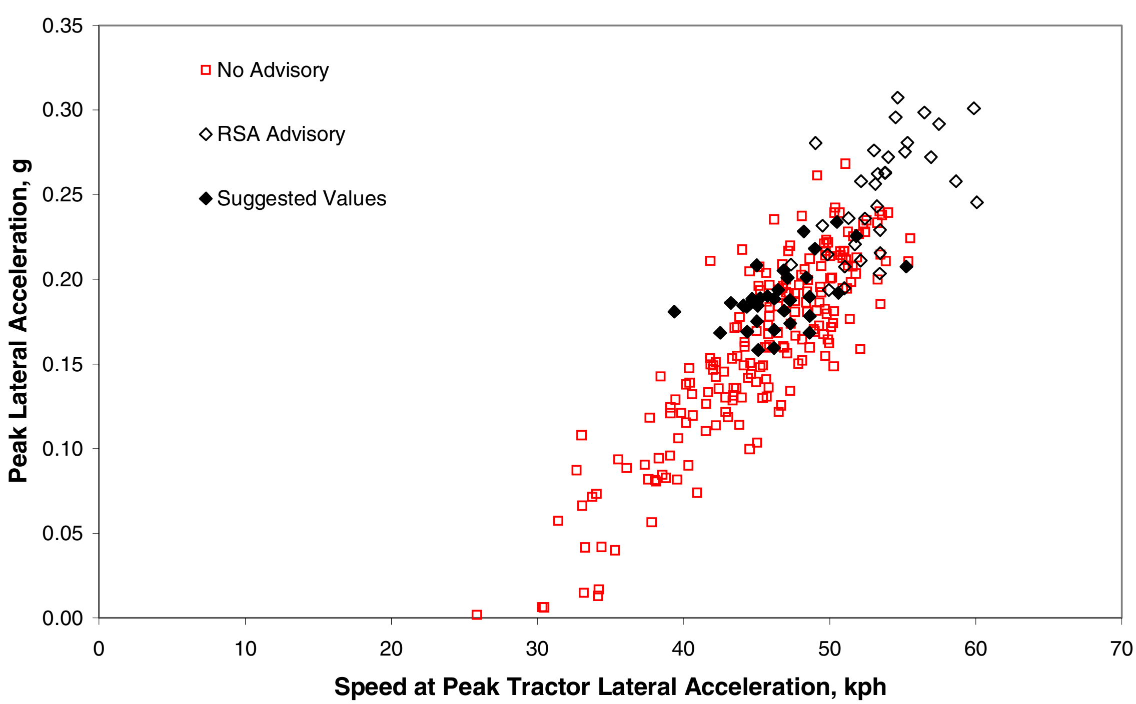

Figure 5-48. Peak Lateral Acceleration of All Trips through the 270-Degree Ramp of Figure 5-10

The vehicle was actually empty in nearly all of these events, as shown in Figure 5-49. The drivers, aware of their light load, were confident to take the curve faster than would be prudent with a full load, as evidenced by the number of points with a lateral acceleration above 0.25 g. Figure 5-50 plots the same events, but the horizontal axis is the RSA's estimate of the weight. The RSA's high estimate of the weight helps to explain the discrepancy of where the advisories were issued, as the black diamonds are generally at higher RSA-estimated weights.

Nearly equal numbers of drivers rated the system as "accurate" and "innacurate." Even among these experienced drivers, there are different senses of what is permissible. One driver who thought the RSA was too lenient said, "It allowed me to be aggressive before it went off." Later, when he was describing his only advisory, he said, "I intentionally did it, but it took quite a maneuver to do it." That maneuver was identifiable in the engineering data. It was a Level 2 advisory, and the RSC intervened. The lateral acceleration peaked at 0.25 g in the maneuver. That would have been a hazardous maneuver had the tank been full, but this trip was returning to LaPorte.

5.6.2 System Capability

To protect the proprietary interests of Freightliner and its partners in the RSA, the evaluator did not closely scrutinize the internal calculations of the system. Quantitative comments on the sufficiency of the accuracy or bandwidth of individual components could advise competitors of the minimum requirements. We believe that the above analysis on performance and functionality, which covers calibration, is sufficient to assess performance capability as well.

5.6.3 Reliability and Maintainability

The RA&C system appears to be reliable. None of the units required maintenance during the year-long FOT, and no self-diagnostic messages were recorded. With the qualification of the calibration issues mentioned above, the RA&C seems to have been functioning as it was intended throughout the FOT. This experience provides confidence that the system is reliable.

Should maintenance be required, the RA&C unit is small and easily accessible. It can be replaced by a skilled mechanic with standard tools.

5.7 Assess Product Maturity for Deployment

When the FOT began, the RA&C was in a developmental state that was nearing readiness for market. Of course, one of the requirements for the "Generation 0" Field Operational Tests was that development of the safety technology had already begun independently of the DOT's Intelligent Vehicle Initiative. The RA&C hardware that was deployed in the FOT was in a compact, rugged box suitable for the harsh environment of a tractor frame. The external signals of the unit were integrated with the communications bus on Freightliner's high-end model. Refinement of the RA&C, especially its software, continued as the FOT progressed. In fact,

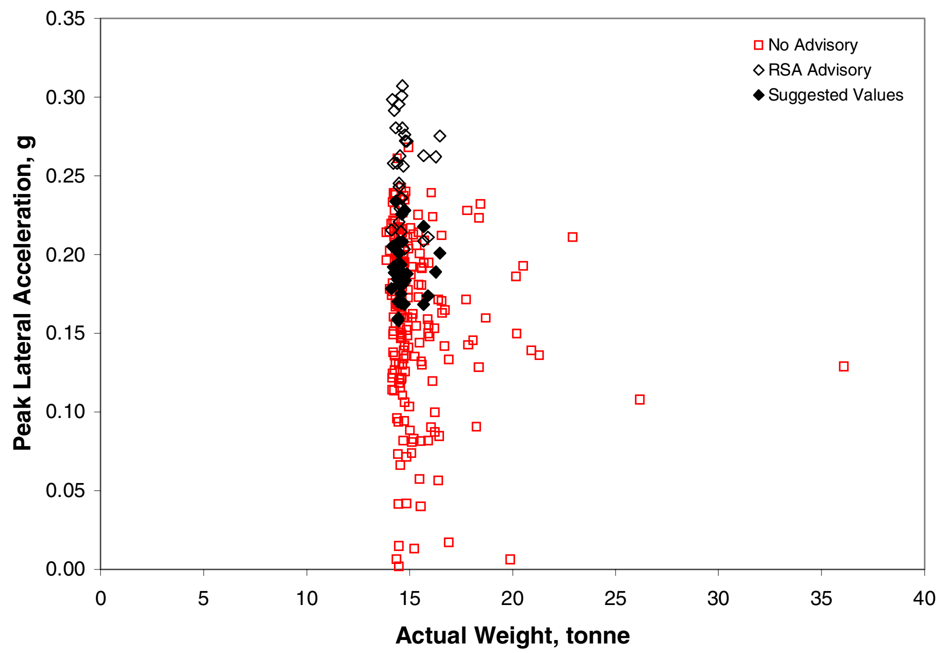

Figure 5-49. Peak Lateral Accelerations on the 270-Degree Ramp as a Function of Actual Vehicle Weight Calculated by UMTRI from the Air Bag Suspension Pressure

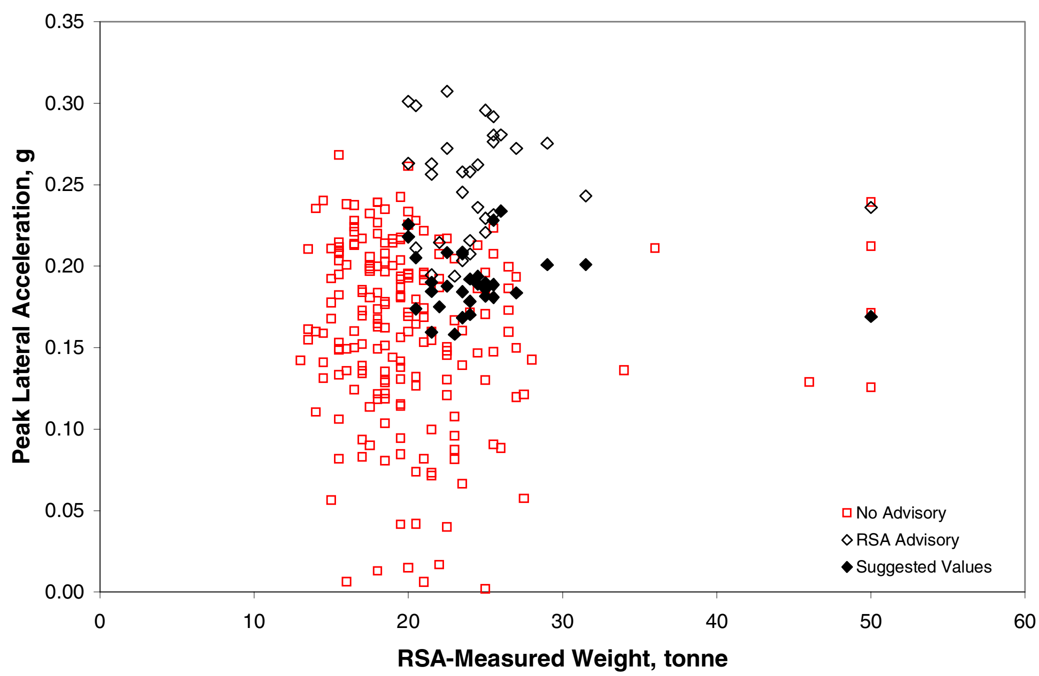

Figure 5-50. Peak Lateral Accelerations on the 270-Degree Ramp as a Function of Weight Measured by the RSA

several "tweaks" were made during the Baseline phase as the first substantial operational data became available. In addition, the mounting bracket was stiffened early in the FOT so the unit would not respond inappropriately to the vibration produced by driving continuously on shoulder rumble strips in a construction area. The vendor reports that further enhancements have been incorporated since the FOT's conclusion. The following discussion shows that the RA&C is quite mature. While the Implications of the Findings in Section 6 includes recommendations, the RA&C is sufficiently mature for the limited deployment it has seen since the FOT.

5.7.1 Estimated Production System Price, Installation Costs, and Maintenance Costs

Freightliner reported to the evaluator in the Summer of 2002 that the list price for the RA&C would be $385. However, the RA&C requires that the optional Traction Control System (TCS) also be installed since the two systems share components and functions. TCS was offered at $400, for a combined list price of $785. Pricing on trucks, as on other large capital items, is often negotiated between the buyer and seller, especially on large fleet purchases, so the actual price of the RA&C is difficult to isolate. Furthermore, Freightliner plans to offer the RA&C to its initial customers at substantial discounts to "seed" the market. At the same time, however, features on heavy trucks do not enjoy the economies of mass production common in consumer goods. The heavy truck business has a fairly limited volume output, approximately 180,000 tractor units a year in recent years, far less than the 17 million passenger cars and light trucks sold annually. Realizing that many factors influence the price but having only one number available, Battelle applied a purchase price of $785 for the RA&C, for those trucks assumed not to be already equipped with TCS, in the benefit-cost analysis. The benefit-cost analysis also presents scenarios assuming that all trucks would already be equipped with TCS.

The only direct indicator of maintenance costs is the history obtained during the FOT. No maintenance costs were incurred during operations of the FOT. Relying on their experience with similar systems, the vendor expects maintenance costs to be minimal. The Meritor-Wabco engineering target is to have no failures in five years of operation, and the commercial warranty is three years. This is consistent with information provided by the ATA Foundation for current ABS systems: the standard warranty is three years, and maintenance costs over the life of the vehicle are low.

The RA&C shares a number of components with the existing traction control option, and it uses the Driver Message Center, which is already available in Freightliner's Century Class model. The incremental cost of installing RA&C in this model is relatively low. Propagating the capability through the product line, however, will require engineering on every model, According to Freightliner, the RA&C will be extended to as many models as the market will support, but the process will be slow.

5.7.2 Infrastructure Investment Needs

There is no need for any modification to the infrastructure for the effective operation of the RA&C as it was deployed in the Freightliner FOT. Interviews indicated that dependency on communications between a vehicle and the roadside is unlikely to be initiated by the trucking industry, including OEMs, carriers, and trucking associations for reasons of protection of privacy. Communication with the roadside would be required for an advanced warning system, complementing the RA&C, that advises drivers to take precautions prior to entering high-rollover-risk geometries.

Freightliner is considering the longer-term possibility of advance curve warnings for drivers using existing GPS capability and improved roadway mapping. This approach would require little investment from highway maintenance authorities beyond perhaps cooperating with the entity that develops and maintains the database of curves.

5.7.3 Availability of State-of-the-Art, Low-Cost Manufacturing Capabilities

Meritor-Wabco's experience from ABS and other IVSS, including lane departure warning and collision avoidance radar systems, gives them confidence that their integrated design approach led to a near readiness for starting production of the RA&C. The RA&C equipment used in the FOT has the look and feel of a product that is ready for market.

Meritor-Wabco, a key supplier to Freightliner of IVSS components, has worked foremost with Freightliner to realize the earliest introduction of RSC in Freightliner's product line. Within one to two years, Meritor-Wabco intends to offer the RSC to other OEMs to fully utilize its manufacturing capabilities and capitalize on its investment. No issues were discovered in this research that would constrain needed production quantities.

5.7.4 Required Modifications to ITS Standards

The RA&C systems are integrated into the tractor systems and require no interfaces to outside systems. RA&C communications are based on SAE standards J1587 and J1939. Standard J1587 provides for electronic data interchange between microcomputer systems in heavy-duty vehicle applications. Standard J1939 provides recommends practices for truck and bus control communications network applications. The RA&C system is using appropriate communications standards. Neither involves any direct communications between tractor and trailer. While all system hardware components would be the same, communications needs eventually may vary when considering different trailer configurations than tankers.

Most of the *ITS standards* focus on the interfaces and exchange requirements between external systems and subsystems. Therefore for the current design implementation, no ITS standards are applicable. However, as more systems are integrated into the cab, the SAE standard J2366 and J2367 might become applicable. J2366 addresses the ITS data bus protocol for information flowing inside a commercial vehicle. J2367 standardizes a data gateway for interface to any kind of external system. As the system expands to new features, data exchange between the infrastructure and the vehicle may require this standard set.

The RA&C unit communicates with the Driver Message Center (DMC) through the vehicle's communication bus. Of the 282 recorded messages that the RA&C wanted to display during the

FOT, in 26 instances the RA&C failed to receive confirmation that the DMC actually displayed the message. There is no way to know why the confirmations were not received. One possible explanation is that the bus was momentarily too busy, although the request must have been placed on the bus, because that is how the DAS knew of it. While the vendor should continue to pursue the question of missed messages, the RA&C has demonstrated it is able to function within existing bus standards.

5.7.5 Suitability of the System for Widespread Deployment

Based on interviews, track testing, and engineering judgments, the RA&C device can be used with other types of truck operations and trailer loads.

Freightliner and Meritor-Wabco are both open about the fact that the RA&C has no instruments on the trailer and, therefore, does not know the height of the load's center of gravity. One of the tests at the TRC was intended to document the effect of the system's not having this information. The procedure and results for Test 005 (Flatbed Testing) are in Appendix D along with the other TRC tests. If the center of gravity is lower than assumed by the system, as in the case of steel plates, alarms will be issued prematurely to the driver. On the other hand, a center of gravity substantially higher than assumed might result in alarms not being issued to the driver in unsafe roll situations. The capability to estimate center of gravity height would be most important for drivers who carry loads with a different center of gravity height each day, such as bulky equipment or less than truckload.

5.8 Address Institutional and Legal Issues that Might Affect Deployment

Effectively meeting the established performance and benefit goals may not be sufficient to ensure successful implementation. Institutional and legal issues can adversely affect deployment, resulting in reduced benefits or outright failure. On the other hand, a well-organized and informed institutional and legal environment can lead to greater support for and benefits from system use. This section examines some of the institutional and legal issues that may have a bearing on the effective deployment of the RA&C technologies and actually IVSS technologies in general.

5.8.1 Institutional Issues

Institutional issues cover a range of so-called "non-technical issues" that may be faced. These include an understanding of the relevant organizations that can be considered stakeholders, their roles and responsibilities in the Freightliner program, and their perspectives on the kinds of institutional issues that are expected to be critical for program success. These organizations include the manufacturers as well as regulators, legislative bodies, unions, insurers, and organizations representing the carriers and the public interests.

Important questions arise as to whether all the organizations that should be actively engaged are in fact engaged in discussions about the current test program and considerations of deployment of these technologies. Then interest turns to the issues and concerns each of these players brings to the table, and the degree to which these issues are being aired and effectively addressed, recognizing that failure to address stakeholder issues early on can easily slow the deployment later on.

The kinds of institutional issues explored in this section include:

- How does each of the stakeholder organizations take account of institutional and legal issues that may be relevant from their point of view with regard to new safety technologies on trucks?
- What institutional involvement does each of the stakeholder organizations have with the RA&C technology?
- Are all the organizations that have an interest in being involved in this program properly included, and are they satisfied with their level of participation and ability to influence decisions?
- Are stakeholders who desire to be part of, or to influence, the decision processes satisfied with their roles and opportunity to play an appropriate role in the program?
- Are various institutional elements within the program functioning as they should? These might include oversight, regulation, staffing, training, procurement, maintenance, partnering agreements, data ownership and sharing.
- Where institutional issues have been identified, are they being adequately addressed and managed? Can any adverse consequences be effectively mitigated?

Telephone interviews were held with representatives of Freightliner, Praxair, the Commercial Vehicle Safety Alliance (CVSA), and the National Private Truck Council (NPTC) to explore these stakeholders' perspectives on the institutional and legal issues that pertain to this FOT.

Standards and Requirements. Freightliner takes a careful approach to the potential introduction of a new truck safety technology to ensure proper adherence to standards and compliance with applicable rules and laws. They continually monitor the relevant requirements and laws to be sure they are in compliance and aware of any changes in requirements. Freightliner's perspective is that you can't regulate safety; if carriers and drivers are proactive with regard to safety, they will adopt those technologies that make driving safer, not because they are regulated to do it.

The RSC as it was deployed in the FOT uses only the engine as a braking mechanism, not the foundation brakes, so it poses no issues with FMVSS 121.[3] The commercial version of RSC that is available at this writing does have the capability of applying the foundation brakes, but it does so through the pneumatic control system, so it, too, complies with FMVSS 121. Of course, the next logical step is electronically controlled braking systems (ECBS), and Meritor-Wabco is actively developing such systems for the North American market. ECBS is expected to provide faster and finer control of the brakes. How it will have to interact with redundant pneumatic controls depends on future amendments to FMVSS 121. As systems that offer enhanced control

[3] 49 CFR 571.121, Federal Motor Vehicle Safety Standard No. 121. Air Brake Systems.

of stability in one form or another come to market, as they are for both heavy and light vehicles, government and industry will need to cooperate so that the best systems can be offered and so that only those systems with proper testing and performance can be deployed.

CVSA represents the law enforcement community, and in that capacity they enforce regulations and promote highway safety. ITS technologies like the RA&C are in an early stage of development and not yet mandated, so enforcement is not an issue now, but to the extent that these new technologies can affect safety, CVSA is interested in supporting them. On matters of critical safety features, standardization is essential, for several reasons. First, it is important that the human factors aspects of the control layouts and driver interface be carefully considered early on. Some drivers are in the same truck every day and become very familiar with all the safety devices, controls, and alerts, while other drivers rotate frequently from one vehicle to another where equipment is likely to differ. Safety systems must be intuitive such that drivers don't have to consciously think about them, especially in emergency situations. CVSA believes that DOT can take a leadership role in ensuring that these safety devices are standardized across the industry, that their control systems are logical and intuitive, and that their operation and use are properly regulated.

A second reason for standardization is to provide for a smooth inspection procedure. The operator needs to be able to verify that the system has been inspected and maintained properly, both for driver safety and to protect against potential liability cases. The manufacturers of new safety technology devices, like the RA&C, will typically work closely with CVSA to establish proper inspection procedures. Should the system eventually be regulated, it will be beneficial to have inspection procedures ready to be used by enforcement personnel. CVSA's recommendation is that early in the technology development and deployment process the enforcement and regulatory communities should be involved and inspection procedures developed that are uniform, easily performed, and well understood, not only by those who use the systems but also by those who are charged with inspecting the systems. CVSA wants to take the safety regulations to a higher level, such that an identified hazard with consequential risk to the public results in the vehicle being taken out of service until the problem is resolved. Law enforcement needs to understand and be able to identify through the inspection process the level of risk to public safety based on clear safety performance indicators so that they can make appropriate decisions in this regard.

The NPTC represents private trucking companies, operated primarily by companies whose business is not trucking, but they operate trucks in support of their businesses. Their trucks operate as traveling advertisements for their companies' products, and the companies are highly attuned to attracting and retaining quality drivers and they highly value safe driving practices because they reflect directly on company image. Any new technologies that can help enhance this image of quality are desirable, and the role of the NPTC is to facilitate private truck company awareness and understanding of these technologies. These companies generally prefer not to be on technology's leading edge, but rather would like to evaluate technologies for their use that have been tried and proven by others.

The trucking industry generally supports voluntary compliance, as opposed to invoking regulations that mandate compliance, though there are differences of opinion on this across the stakeholder groups. There is an obvious reluctance to mandate a safety technology that may eventually be shown to be ineffective, or possibly even a hazard in its own right. The technologies must be developed and based on sound science and widely accepted in the industry. From a practical perspective, if government is going to mandate certain new technologies, then the rationale should be based on more than just safety criteria, and should proceed through a deliberate, participative rule-making process that takes account of the needs of and costs to the industry, and important differences in fleet operational types that influence return on investment (e.g., short haul versus long haul operations).

Stakeholder Involvement. Freightliner encourages a dialog among their drivers, supervisors, dealers, and customers in order to keep on top of any issues that might affect vehicle performance. This is important as a way to be sure that any institutional or technical issues are identified early and can be appropriately addressed. Freightliner relies on listening to its customers, through contact with the dealers' council, through membership on committees and task forces, and through direct interaction with customers.

Technology Acceptance. From Freightliner's perspective, there are several important steps in assuring acceptance of new safety technologies. The company wants to introduce appropriate and productive technologies that carriers and operators will use and that will not compromise safety. Freightliner holds quality reviews with its major customers that include representatives from engineering, product marketing, dealers, district and regional sales, and service and maintenance. They are also careful to conduct human factors analyses that address such issues as potential driver distraction, user interface, and the degree of control assumed by the technologies. This kind of interaction has been important in the introduction of the RA&C technology.

A potential issue with driver acceptance is the notion that "big brother" (i.e., their company) is watching over the drivers' shoulders looking for mistakes. New safety technologies offer comprehensive and immediate feedback to management on driver behavior and performance. There is a recognition that the possibility always exists that a driver can subvert the safety system to keep management from seeing what they are doing, but on balance, drivers accept technologies that enhance their safety and help protect good drivers from liability in crashes.

The NPTC's perspective on driver privacy is that, because of recently increased security awareness, companies consider it their right and duty to demand safe and secure performance, because now there is much more at stake. HazMat haulers, for example, are heavily investing in technologies that allow for real-time, continuous monitoring of driver performance, and the drivers themselves understand the reasons. Concerns about company use of technology for driver performance monitoring may be a lesser issue in private fleets where there is a culture that supports good driving behavior, and monitored performance offers a basis for driver rewards, good assignments, and safe driving bonuses. NPTC member companies are looking for ways to augment their current truck systems with new technologies where it makes sense to them.

Some communities ban engine brakes because of the noise they produce. The bans are often where marked highways coincide with city streets, so the likelihood of an RSC activation is small. It is conceivable a driver could be ticketed for unintentionally activating the RSC and violating the noise ordinance. Certainly the safety argument would be a defense. Should the problem become common, a federal regulation explicitly permitting noisy safety devices might be necessary to supersede the local ordinances.

Benefit/Cost Considerations. To be successful in the long run, new safety technologies have to pay for themselves. Freightliner's perspective is that the insurance companies have not offered the trucking industry adequate incentives for safety advances, as they have, for example, for passenger cars with airbags or ABS. Insurance companies were contacted by the Evaluator as part of a related effort on the deployment of IVI technologies. All reported that premiums would be reduced for IVI devices only after they have demonstrated that they reduce claims over a sustained period of years. Similarly, the industry has long noted that federal government applies the Federal Excise Tax (FET) on the entire vehicle, including the cost of safety devices, making it more difficult for carriers to recover costs.

Summary of Institutional Issues. Freightliner's strategy in dealing with these issues is to take a conservative approach from the start and to not allow problems to become so severe that the mitigation costs become a big challenge. Freightliner knows that management and driver perspectives are likely to be different, and that not every business in this industry functions the same way. With different owner/operators, drivers, and independent fleets, it is important to look at all sides of these institutional issues. Praxair will move ahead with anything that is believed to be beneficial from a safety perspective, affordable, and is acceptable to drivers. CVSA's perspective is that clear standards and performance indicators should be developed and accepted so there are unambiguous expectations for what is needed to keep vehicles maintained and operating in a safe manner, and that this can be accomplished by either or both the regulatory process and industry practices. CVSA contends that approach is directly applicable to a safety technology system like the RA&C. Implications include a need to standardize the technology across manufacturers and applications to make it relatively simple to inspect and evaluate, and make it easy for drivers to learn and intuitive to use.

5.8.2 Legal Issues

The legal issues deal primarily with regulatory matters and liability risks associated with project deployment and how they can best be anticipated and prevented or mitigated. Legal issues can arise in conjunction with such aspects as product failures, driver distractions, loss of vehicle control, property damage, and tort liability. There may also be concerns in employee relations pertaining to privacy or supervision.

The concern with legal liability risk is that the cost of defending against lawsuits and associated settlements will outweigh the benefit of the technology from the perspective of the manufacturer or the fleet operator. This concern may limit or delay deployment of safety-enhancing technology. Such an outcome would be unfortunate from a public policy perspective if the savings in lives, injuries, and property from deployment of the technology are substantially greater than the losses that may be suffered from its failure or misuse.

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

Scenarios of potential liability risk:

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

As safety-related technologies are developed, federal regulatory agencies may mandate their use. Manufacturers may be concerned that complying with such a mandate and associated standards, in the event of system failure or misuse, increases the exposure of the manufacturer to suit.

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

Intellectual Property. Collaboration with government agencies or within industries may be constrained by the desire of the manufacturer to protect intellectual property and/or secure a competitive advantage in the marketplace with its development and marketing of technology.

The rollover warning and avoidance technology is being developed to prevent such events. It also generates data regarding vehicle operations and stresses associated with rollover or near-rollover events. Collection and archiving of such data raises a number of questions, such as:

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

Mitigation Strategies. Actions that have been identified to address and reduce the risk associated with the issues discussed above include:

- Emphasis on human factors research to assess how the vehicle operator uses the technology and potential for misuse. Take potential for misuse into effect in design of user interface.
- Care in development of instructions for use and training procedures to ensure proper use and proper maintenance.
- Involvement with legal counsel responsible for defending products liability suits as technology is developed to ensure documentation of due diligence.
- Collaboration with insurance companies and regulating agencies as the device is developed and tested to demonstrate its effectiveness and to ensure that the process of deployment and regulatory oversight proceeds in a timely and effective way.
- Determination of policies regarding data collection, storage, and use in consultation with regulators, risk managers, and employee representatives.

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

Summary of Real World Experience to Date. Freightliner monitors legal requirements carefully and seeks to comply with all the laws pertaining to the use of safety technologies such as the RA&C. Their focus is on being responsive to their customers' and operators' needs and meeting the technical requirements. Their legal department provides oversight and guidance. They have not faced legal problems so far using this approach. The new safety technologies that automatically maintain vehicle logs actually serve to protect the carriers and their drivers in situations that receive close scrutiny, assuming the driver has not been negligent. The unions, who can be expected to be particularly sensitive to legal and privacy issues, have been generally accepting of industry's position with regard to the deployment of these technologies.

The NPTC recognizes that their member companies are walking a fine line between doing too little to ensure safe shipments, especially where hazardous materials are involved, leading to a court finding of negligence in the event of an accident, to investing excessively to the point where the financial viability of their business is at risk. Legal standards are evolving and likely to become increasingly proscriptive regarding standards. The upside of this according to the NPTC is that the high-risk and illegal activities of the minority of truck operations will be substantially curtailed.

5.9 Benefit-Cost Analysis

An important objective of this evaluation of the Freightliner IVI system is to conduct a thorough benefit-cost analysis (BCA) to determine the net economic benefits of deploying the IVSS technologies. This section describes the comprehensive BCA that has been carried out for this purpose.

5.9.1 Benefit-Cost Analysis Approach

The BCA, as applied to the Freightliner IVI FOT, is a public-sector evaluation tool that compares all of a project's benefits to society to all of the project's costs to society. 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, *Commercial* feasibility, the analogous private-sector criterion, is much narrower in the benefits and costs it compares. Benefits are restricted to commercial *revenue*, and costs are limited only to those paid directly by the project developer.

In a public-sector BCA, the specific hypothesis to be tested is that the total cost to society of developing, deploying, and maintaining the IVI system is less than the combined value of all the benefits. Therefore, 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, and
- Not a transfer.

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, even though they may appear to some not to be duplicative. And, finally, transfers between affected groups are not net charges to society and therefore cannot be included in a BCA.

Benefits and Costs Included in this Benefit-Cost Analysis

Tables 5-10 and 5-11 show all of the categories of benefits and costs included in this BCA, which are derived from the anticipated effects of the IVSS. For each benefit or cost, these tables present the measurable values that were sought, along with the sources of the information. More specific references to information sources are presented at the end of Section 5.9.

The IVSS are expected to alter the operation of trucks in various ways, but the net economic benefits cannot be assessed until the effects are translated into quantifiable measures. 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 values in the literature include a wide range of benefit elements. To the extent that such elements are available in the literature and have been monetized, the elements have been explicitly identified in order to avoid double counting or omitting a benefit.

Table 5-10. Benefit Measures and Information Sources for the Freightliner IVI FOT

Benefit	Measure	Sources
Safety	Reduced numbers of crashes	Crash avoidance analysis (statistical modeling)
	- Avoided fatalities, personal injury, vehicle damage, third party damage, and hazardous materials impacts per crash	Literature search (included in $ value of crash)
Productivity	- Avoided cargo damage	Literature search (included in $ value of crash)
Mobility	- Improved public mobility (reduced traffic congestion from crash)	Literature search (included in $ value of crash)
Improved Environmental Quality	- Dollar value of reduced numbers of HAZMAT incidents	Literature search (included in $ value of crash)

Table 5-11. Costs and Information Sources for the Freightliner IVI FOT

Cost	Measure	Sources[a]
One-Time Start-Up	Dollar value of capital equipment and installation	Interviews and site visits
	Dollar value of initial driver training	Interviews and site visits
Recurring	Dollar value of recurring equipment replacement	Interviews and site visits
	Expected service life (years) of capital equipment (used to determine recurring capital costs)	Interviews, site visits, and literature search
	Dollar value of ongoing driver/staff training	Interviews and site visits

a. Interviews were with Freightliner, Meritor-Wabco, and ATA.

A 20-year deployment period for this BCA allows the illustration of economic returns for the investment over a reasonable life cycle, which includes an original purchase and one replacement cycle for equipment.

The Freightliner FOT involved an on-board, self-contained safety system providing driver messages (RSA) and possible engine braking (RSC). The main benefit is increased safety in the form of reduced numbers of crashes involving trucks. Thus, the main evaluation tasks then are to estimate the crash rate reduction and the monetary values of the reduced number of truck crashes. However, because there were no activations of the RSC during safety-critical situations in this FOT, it was not possible to obtain a sufficiently reliable estimate of its safety benefits. Therefore, only the benefits attributable to changes in driver behavior—those due to the educational effect of the RSA—were included in this benefit-cost analysis. No benefits accruing from the RSC's direct intervention were included. While the RSC functioned well in some of the controlled test track conditions and it does promise some benefit in service, its performance in the realistic environment of the FOT was not sufficiently predictable to justify a numerical benefit.

Factors to be considered in valuing truck crashes in this BCA include the different kinds of crashes prevented by the RA&C. Accident rate reductions were estimated for two kinds of crashes (rollovers and single-vehicle roadway departures) and four categories of trucks. The two kinds of crashes were valued differently, but there were no gradations of severity within either kind. The only measure of crash severity used was a separate costing of crashes, injuries, and fatalities incurred and potentially avoided per year. The analysis required estimates of the distribution of fatalities, personal injuries, and property damage for the avoided crashes. The latter quantities are the bases for the unit costs used to value truck crashes. As shown below, crash costs also included factors for environmental damage and delays to other traffic. Cost factors beyond those listed below and in Appendix F were not included in the present BCA.

Discount Rates

To test the hypothesis that an IVSS has 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 occurring each year between 2000 and 2019 were discounted back to 2000 using both a 4 percent and 7 percent real discount rate to calculate the present values of the benefits and costs in 1999 dollars. The use of a 4 percent real discount rate in these kinds of benefit-cost calculations has been recommended by economists in both the public and private sector.[4] The use of a 7 percent real 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 (OMB 1992; 2000).

In the Freightliner IVI BCA, the 7 percent discount rate resulted in lower (less favorable) benefit-cost ratios. Across all of the scenarios modeled, the stricter 7 percent rate reduced the actual BCR by an average of approximately 0.13. Results in this section are presented using only the 4 percent discount rate. For reference, examples of annual and summary results using both the 4 and the 7 percent rates are shown in Appendices E and F.

Scenarios Evaluated in this BCA

Benefits and costs were calculated and compared for the deployment of RA&C systems to four increasingly large fleets of trucks. The four large truck fleets, with their estimated populations in the baseline year of the deployment, were:

- All tractors pulling tanker trailers and carrying hazardous materials (N=55,098)
- All tractors pulling tanker trailers (N=110,196)
- All tractors pulling trailers (N=1,474,664)
- All large trucks (N=7,392,583).

As discussed in Section 5.1.4, it is reasonable to conclude that the safety benefits estimated from this FOT can be projected to trucking operations that are similar to Praxair, specifically, to fleets of tractors pulling tanker trailers, especially those carrying hazardous materials. However, the results obtained by applying the findings from this FOT to larger fleets (all tractors pulling trailers and all large trucks) represent extrapolations presented to illustrate the potential benefits. Issues related to the applicability of these findings were discussed in Section 5.1.4.

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[4] E.g., U.S. EPA (2000), Chapter 6, recommends a real rate of 2 to 3 percent for some public projects.

Benefit-cost ratios are calculated for each of the four deployment scenarios under a baseline model in which we apply our best estimates of the efficacy and costs of the RA&C, as derived from this FOT. For the baseline case, the efficacy is based our best estimate that the RA&C would result in the avoidance of 20% of untripped rollovers and 33% of single-vehicle roadway departures (SVRDs), related to excessive speed in curves. Also, the baseline case uses Freightliner's list price of $385 as the purchase cost for the RA&C. Other cost factors, and their effects on the benefit-cost ratio, are discussed in the following section.

To test the sensitivity of changes in the benefit-cost factors to the overall benefit-cost analysis, selected efficacy and cost parameters were modified to create six different modeling assumptions for each of the four deployment scenarios. The six modeling assumptions were defined by different combinations of two cost models and three efficacy models.

The primary cost input to the BCA is the purchase price of the RA&C system, reported by Freightliner to list at $385 per vehicle. However, this price assumes that the vehicle already is equipped with a separate $400 traction control system (TCS), which is required for the RA&C, but which, according to Freightliner, is currently installed in only about 10 percent of its large trucks. Thus, for the baseline cost model, it was assumed that 100 percent of trucks would have traction control already installed; so, the total cost of the RA&C would be $385. For the second cost model, it was assumed that the purchasers of 90 percent of trucks would need to purchase TCS for an additional $400. Thus the weighted average purchase price of the RA&C for this half of the scenarios is $745 = $385 + $400x90%.

Although TCS is required for a fully operational RA&C, the cost of adding TCS is not included in the baseline cost model. The evaluation team did not attempt to measure any safety, economic, or other benefits of TCS per se, so the scenarios that include the TCS costs produce conservatively low benefit-cost ratios because they include only the costs for TCS without identifying and calculating the commensurate benefits of TCS. Also, the FOT evaluation concluded that the safety benefits of the RA&C stemmed only from the RSA function of the device. Because the TCS is required only for the RSC function, the TCS is in effect irrelevant to the safety benefits assumed to accrue from deployment of the RA&C and included in the benefit-cost analysis. For these reasons, the TCS costs were excluded from the baseline cost model, yet included, as part of the sensitivity analysis, to illustrate the worst-case costs.

We also looked at two alternatives to the baseline efficacy model. The two alternatives represent optimistic and pessimistic approaches to dealing with missing data or prevention ratio estimates that are not statistically significant. Under the *pessimistic* model, it was assumed that the efficacy of RA&C for avoiding SVRD crashes caused by high speeds in turns was 20%, which is the same as was estimated for rollover crashes. (Recall that we were not able to collect data to estimate the prevention ratio for SVRD crashes and, therefore, used a prevention ratio of 1.0.) The *optimistic* model uses an efficacy of 33% for both types of crashes, based on the premise that the estimated prevention ratio was not statistically different from 1.0 for either crash type.

By applying the six modeling assumptions to each of the four deployment scenarios we obtain benefit-cost findings for a total of 24 scenarios, as shown in Table 5-12.

Table 5-12. Definitions of the Scenarios Considered in the BCA

Scenario	Population	% Efficacy[a] of RA&C in Avoiding: Untripped Rollovers	SVRDs	Weighted Average Cost of IVSS, $/Vehicle[b]
1[c]	HazMat Tankers	20	33	$385
2[c]	All Tanker Trailers			
3[c]	All Tractor-Trailers			
4[c]	All Large Trucks			
5	HazMat Tankers	20	33	$745
6	All Tanker Trailers			
7	All Tractor-Trailers			
8	All Large Trucks			
9	HazMat Tankers	33	33	$385
10	All Tanker Trailers			
11	All Tractor-Trailers			
12	All Large Trucks			
13	HazMat Tankers	33	33	$745
14	All Tanker Trailers			
15	All Tractor-Trailers			
16	All Large Trucks			
17	HazMat Tankers	20	20	$385
18	All Tanker Trailers			
19	All Tractor-Trailers			
20	All Large Trucks			
21	HazMat Tankers	20	20	$745
22	All Tanker Trailers			
23	All Tractor-Trailers			
24	All Large Trucks			

a. Efficacy represents the percent of crashes (involving high speed in turns) that would be avoided by deployment of the RA&C technology.

b. The lower average cost (baseline) assumes that all trucks will have TCS already installed. The higher weighted average cost (alternative) assumes that 10 percent of trucks will have TCS already installed, and that the other 90 percent of truck purchasers will need to pay for the TCS system ($400) in addition to purchasing the RA&C ($385).

c. Baseline scenario using best estimates of cost and efficacy parameters.

The next section summarizes the results of the BCA. Examples of detailed year-by-year tables showing the discounted benefits and costs—and further information on the sources and procedures for their calculations—are given below and in Appendices E and F.

5.9.2 Benefit-Cost Analysis Results

The benefits were derived from the number of crashes avoided, along with the corresponding numbers of injuries and fatalities, and related savings involving productivity, mobility, and environmental quality. The primary input from this FOT to the calculation of benefits is the efficacy of the RA&C for avoiding rollover and SVRD crashes due to excessive speed in turns. The baseline efficacy was estimated to be 20% for untripped rollovers and 33% for single-vehicle roadway departures (SVRDs), as discussed in Section 5.1.4.

The major component of the baseline cost model is the $385 purchase price of the RA&C. Based on comparisons with similar heavy vehicle electronic systems, the replacement life for the RA&C was assumed to be 10 years, or equal to the expected life of the tractor. Discussions with the manufacturer and equipment supplier led to an assumption that maintenance and repair costs over the life of the RA&C would be negligible. One-time costs for driver training (1 hour paid per driver) were also included, along with literature-based projections for the training of new drivers and those who replace the drivers that leave the trucking industry.

Table 5-13 summarizes the results of the BCR calculations for the four baseline efficacy scenarios (20 percent efficacy for rollover crashes; 33 percent efficacy for SVRD crashes). The dollar values represent societal expenditures and accrued societal benefits over the 20-year life of the deployment. The benefit-cost ratios of scenarios that are greater than the break-even point of 1.0 (i.e., those with positive net present values) are shown in shaded cells.

Table 5-13. Benefit-Cost Comparisons for Four Deployment Scenarios under Baseline (Best Estimate) Cost and Efficacy Models ($Millions)

	Truck Fleet			
	HM Tankers	All Tankers	Tractor-Trailers	All Large Trucks
Scenario Number:	**1**	**2**	**3**	**4**
Benefits				
Crashes avoided	$83.8	$222.5	$1,247.7	$1,955.4
Total benefits	$83.8	$222.5	$1,247.7	$1,955.4
Costs				
Purchase cost	$40.2	$80.4	$1,076.4	$5,396.0
Training cost	$1.2	$2.4	$76.7	$384.4
Total costs	$41.4	$82.8	$1,153.1	$5,780.4
Total (Net Pres. Value)	$42.4	$139.7	$94.7	-$3825.0
Benefit/Cost Ratio	**2.02**	**2.69**	**1.08**	**0.34**

Similar cost, benefit, and BCR data for the best-case (optimistic) and worst-case (pessimistic) scenarios, and for the 7 percent discount rate models, are discussed below, and are included in Appendix F.

The total benefits and costs are charted in Figure 5-51. These values represent the dollar value of benefits and costs (in millions of U.S. dollars, discounted to 1999) over a 20-year analysis period and using a 4-percent discount rate. Because of the large differences in the size of the four truck fleets included in the 24 BCA scenarios, it is convenient to display the results on a log scale. This figure shows that for the HM tanker and tractor-trailer scenarios, the costs and benefits are relatively similar, while for most of the tractor-tanker scenarios the benefits exceed the costs, and for the "all large trucks" scenarios, all of the costs exceed the benefits, regardless of the assumptions used.

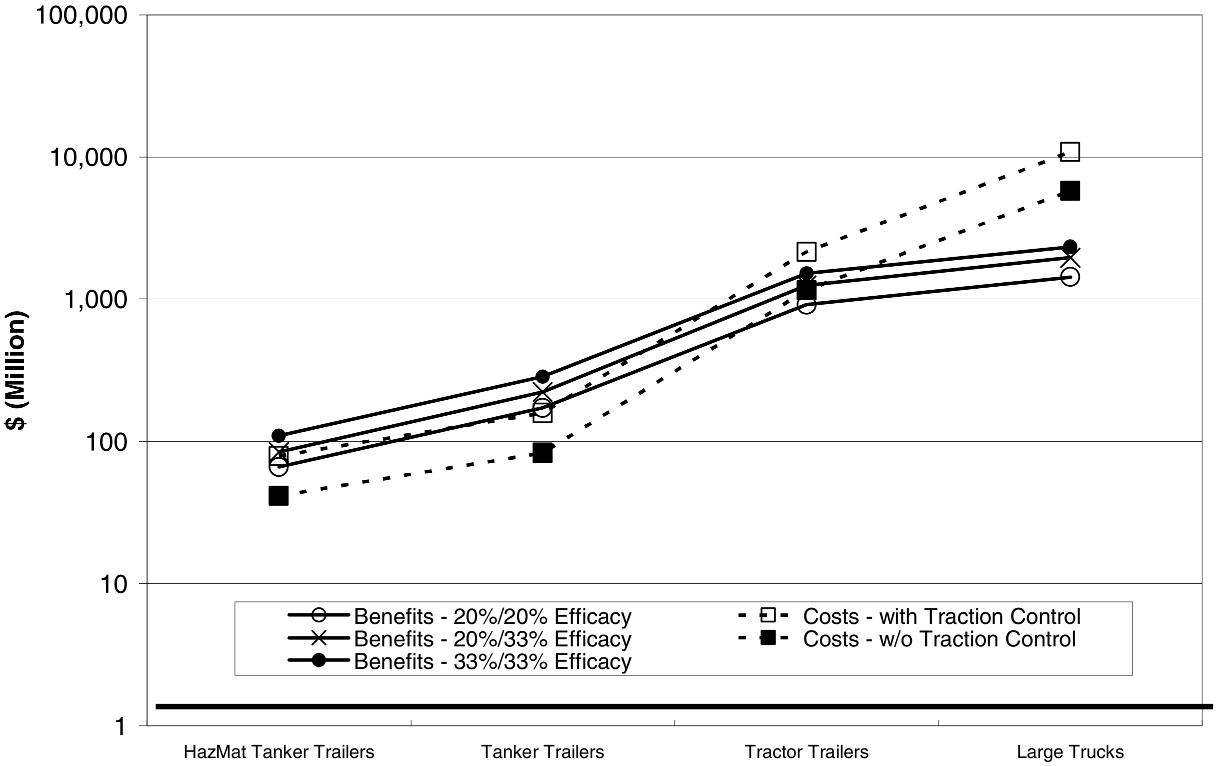

Figure 5-51. Dollar Values (in Millions) across All Scenarios with Different Governing Assumptions

Table 5-14 summarizes the benefit-cost ratio (BCR) findings across all 24 combinations of truck types, crash avoidance efficacy assumptions, and TCS cost assumptions. A BCR of 1.0 represents an exact balance of societal costs and benefits over the life of the deployment. Ratios greater than 1.0 (shaded cells) indicate that the deployment saves more than it costs. Looking across all 24 scenarios, 13 of the scenarios applying the RA&C system to the various total U.S. national fleets appear to be economically justified at the 4 percent discount rate, while 11 do not. With the more stringent 7 percent discount rate, 10 of the 24 scenarios are economically justified, and 14 are not. The deployment scenarios for all tractors pulling tankers offer the most promising BCRs, ranging from 1.09 to 3.43. Hazardous materials tankers are the next best candidates for deployment. None of the scenarios involving deployment of the IVSS to all large trucks is projected to offer a positive economic result.

The table also shows that the inclusion or exclusion of the separate TCS has a marked effect on the BCRs. In five of the 24 scenarios, the inclusion of TCS costs in the model brought the BCR from being greater than 1 to being less than 1.

Table 5-14. Benefit-Cost Ratios across All Scenarios (4% Discount Rate)

	Baseline Efficacy: 20% and 33%		Worst-Case (Pessimistic) Efficacy 20% and 20%		Best-Case (Optimistic) Efficacy 33% and 33%	
TCS Costs:[1]	Excluded[2]	Included	Excluded	Included	Excluded	Included
HazMat Tankers	2.02	1.06	1.59	0.83	2.64	1.39
All Tankers	2.69	1.41	2.08	1.09	3.43	1.8
Tractor Trailers	1.08	0.58	0.79	0.42	1.32	0.7
Large Trucks	0.34	0.18	0.25	0.13	0.4	0.22

Note: Shaded cells indicate ratios >1 (positive net benefit to society).

1. TCS: Traction control system. When costs are excluded, the models assumed that all trucks would already have the TCS paid for at the time of purchasing the RA&C. When TCS costs are included, the models assumed that 10% of trucks would have TCS already paid for, and that 90% of truck purchasers would need to buy TCS in order to obtain the benefits of the RA&C technology.

2. Baseline scenario (i.e., best estimates of cost and efficacy parameters).

Figure 5-52 depicts the benefit-cost ratios graphically for the 24 BCA scenarios. As would be expected, the best-case efficacy assumption coupled with the exclusion of TCS costs results in the most favorable BCRs. The figure also shows that the baseline efficacy assumption offers a net benefit to society in three of the four truck fleets modeled.

5.9.3 Implications of BCA Results

In summary, the RA&C technology may be economically justified when deployed nationally on tanker trucks, HM tanker trucks, and tractor-trailer configurations. The economic payback after a 20-year deployment period depends on the assumptions used for crash reduction efficacy and the accounting for traction control system costs.

Other applications of the RA&C that might be economically justified—but that were not evaluated specifically in this FOT—include trucking companies that may be experiencing higher rates of rollovers and SVRDs than industry averages for reasons specific to their operation (e.g., roads used, truck fleet composition).

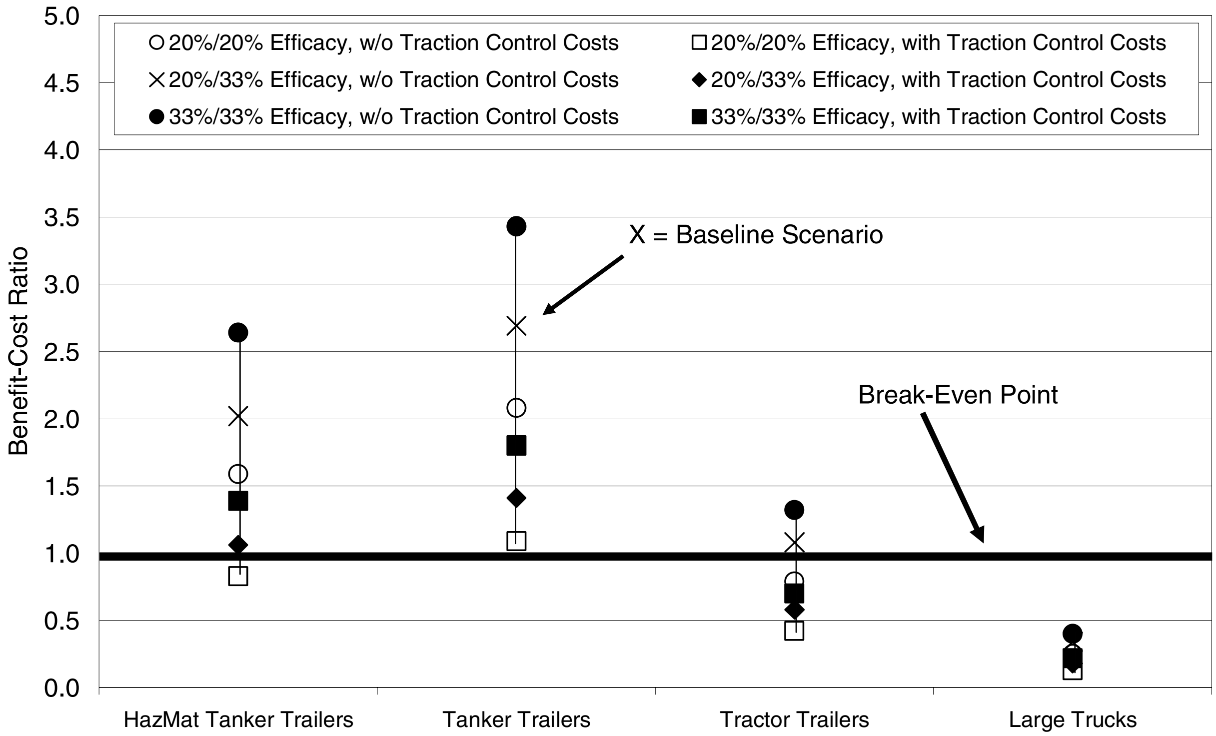

Figure 5-52. Benefit-Cost Ratios across All Scenarios with Different Governing Assumptions

5.9.4 Unit Costs and Calculation of BCRs

This section itemizes the benefit and cost inputs and other numerical elements used in the BCA, and the methods used to combine, weight, and sum the dollar values. Examples of annual analysis tables and further summaries and details are presented in Appendices E and F. Tables 5-10 and 5-11 above listed the benefits and costs, and the general information sources for valuing these benefits and costs of this IVI FOT. This section provides the general approach and methods used to derive the BCRs, the unit values of each benefit and cost used in the analysis, and the other information used in combining and calculating the total benefits and costs.

Figure 5-53 depicts the flow of dollar cost values and population counts that were combined in the BCA. The benefits, in terms of crash cost avoidance, are shown on the left, and the costs, in terms of equipment purchases and driver training, are shown on the right. In general, unit costs were summed with similar per-crash, per-truck, or per-driver cost elements, and then multiplied by population numbers (e.g., trucks, crashes, injuries, drivers, hours) to provide total annual costs, which were summed and discounted over a 20-year deployment life cycle.

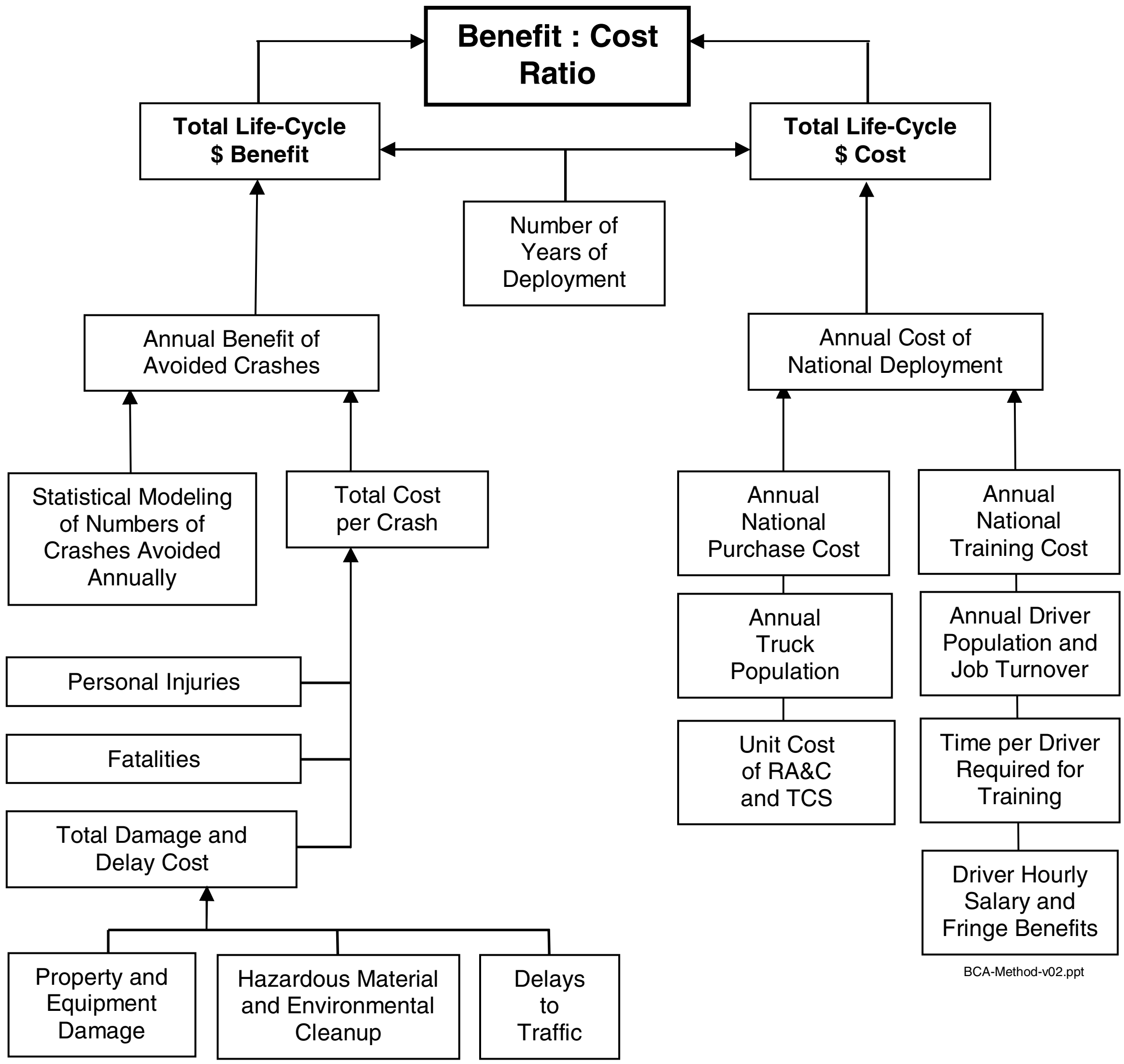

Figure 5-53. Combining Data Elements to Determine the Benefit-Cost Ratio

Benefits (Crash Costs Avoided)

Table 5-15 provides the estimated reductions in crashes by type for the entire U.S., as used for the baseline efficacy scenarios. The statistical modeling that was done as part of the Freightliner evaluation, based on GES and related federal data sources, provided counts of crashes, injuries, and fatalities, presuming deployment of the RA&C nationwide to the specified truck fleets. An FMCSA-sponsored report prepared by the Pacific Institute for Research and Evaluation (Zaloshnja et al. 2000) and a report for the ITS Joint Program Office (Orban et al. 2002) were key literature sources for many of the truck crash data and related cost values. The counts from the Freightliner safety benefits estimation were then applied to the crash and cost data in the literature to yield proportions of incapacitating and non-incapacitating injuries, along with the

Table 5-15. Estimated Reductions in Crashes, Injuries, and Fatalities for Baseline Scenarios Modeled (20% Efficacy for Rollovers; 33% Efficacy for SVRDs)

	Crash Type	National Annual Reduction In				
Truck Type	(All Scenarios Assume High Speed in a Turn)	Crashes of All Severities	Persons Injured in Crashes - Incap.	Persons Injured in Crashes - Non Incap.	Persons Injured in Crashes - Total	Persons Killed in Crashes
Hazardous materials tankers	Untripped Rollovers	0.9	0.36	0.54	0.9	0.5
	SVRDs	8.5	1.49	2.21	3.7	0.6
	Untripped Rollovers and SVRDs	9.4	1.86	2.74	4.6	1.1
Tankers	Untripped Rollovers	9.3	2.99	4.41	7.4	1.2
	SVRDs	25	5.25	7.75	13	1.3
	Untripped Rollovers and SVRDs	34	8.48	12.52	21	2.5
Truck tractors with trailing units	Untripped Rollovers	94	26.25	38.75	65	2.8
	SVRDs	408	44.42	65.58	110	6.2
	Untripped Rollovers and SVRDs	502	70.67	104.33	175	9
All large trucks	Untripped Rollovers	157	48.60	79.40	128	4.5
	SVRDs	661	76.70	125.30	202	9
	Untripped Rollovers and SVRDs	819	125.30	204.70	330	14

SVRD = Single Vehicle Roadway Departure   Incap = Incapacitating
Source: Section 5.1

dollar values of each type of consequence. For example, as shown in Table 5-15, the safety benefits estimation process of the Freightliner FOT evaluation provided an estimate of 330 fewer total persons injured per year in rollover and SVRD crashes combined, when considering all large trucks.

Injury, Fatality, and Property Damage Costs. Table 5-16 provides the unit values per personal injury and fatality. The FMCSA report indicated that, of all injuries in truck crashes, 38 percent would be incapacitating and 62 percent of them would be non-incapacitating. Using the example of 330 injuries given above (Table 5-15), these proportions were then used to give the counts of 125.30 and 204.70 in the respective injury subcategories. As shown in Table 5-16, the FMCSA report also gave a value of $69,407 per non-incapacitating injury, $298,927 per incapacitating injury, and $3,358,240 per fatality. Factors such as these were used to generate monetary values for the personal injury and fatality portions of the crash reductions, across all scenarios, that resulted from the safety benefits estimation.

Table 5-16. Unit Cost of Fatalities and Injuries from Truck Crashes ($1999)

Type of Cost	Unit Cost
Fatality[2]	$3,358,240
Incapacitation injury[2]	$298,927
Non-incapacitating injury[2]	$69,407

Source: Zaloshnja et al. (2000), with calculations by Charles River Associates.

Property damage cost estimates (shown in Table 5-18, below) were provided by the American Transportation Research Institute (ATRI), an independent research affiliate of the American Trucking Associations (ATA). The property damage cost values were aggregated from information gleaned in interviews conducted in late 2002 with six motor carriers, three large insurance companies, and two environmental cleanup companies. The costs include direct damage to the vehicles (tractor and trailer) plus extraneous costs, towing, cargo loss, and damage to third-party property. Extreme cases, because of their rarity, were excluded from the aggregation of costs.

Environmental Damages (Hazardous Materials Crash Costs). According to the U.S. Census Bureau Vehicle Inventory and Use Survey, approximately 50 percent of large tanker trailers carry hazardous materials (54,202 out of 108,400 tanker trucks) (VIUS 1997). (The corresponding national population of tanker trailers used in the safety benefits estimation is slightly higher at 110,196.) The VIUS figure for HM tanker trailers includes both liquid (52,383) and dry bulk (1,819) tankers; liquid carriers represent a great majority of the HM tankers. It is noted that the National Tank Truck Carriers (NTTC, Alexandria, Virginia) estimated that approximately 70 percent of large tanker trailers carry hazardous materials (HM). Battelle elected to use the VIUS figure of 50 percent HM tankers in the Freightliner BCA, because the underlying total number of tankers in the VIUS data more closely matched the population of all tanker trailers used in other aspects of the Freightliner FOT truck fleet population modeling.

Because of the large proportion of HM tankers, Battelle evaluated the cost impacts of HM crashes in comparison with non-HM crashes, and developed a benefit-cost model that assumed deployment of the RA&C technology to only those tanker trailers that are carrying HM. The 50 percent factor from NTTC was applied to the known population of large tractors pulling tanker trailers (110,196) and Battelle's HM scenario was thus based on a starting population of 55,098 HM tankers. To include the costs for crashes involving HM, data were drawn from an FMCSA report (2001) that presented comparative risks and dollar cost impacts of HM and non-HM truck shipment accidents and incidents.

The 2001 FMCSA report on HM crash costs covered all large trucks (greater than 10,000 lbs GVW, excluding pickup trucks and vans), and did not distinguish among various trailer body types or tractor-trailer-single unit configurations. The report also examined 12 classes or divisions of HM cargo separately. To attempt to model the types of HM most likely to be carried in large bulk tanker trailers, Battelle selected three of the HM categories, namely Division 2.1 (flammable gases), Class 3 (flammable liquids), and Class 8 (corrosive materials). The report also broke down the crash cost elements as follows: Cleanup, Product loss, Carrier damage, Property damage, Environmental damage, Injury, Fatality, Evacuation, and Incident delay.

Many of these same cost elements had already been determined in the Freightliner FOT benefit-cost analysis. Therefore only the three cost elements that set HM crashes apart from the non-HM crashes were selected from the FMCSA report: Cleanup Costs, Environmental Damage, and Evacuation Costs. The crash types from which data were drawn were Enroute Accident (Total Releases) and Enroute Accident (Non-Release). Thus the HM crash costs from these two crash types and from these three cost elements were added to the non-HM crash costs determined in the FOT. Likelihood estimates (numbers of crashes per year) as given in the FMCSA report were used for all of the crash types to prepare weighted average cost estimates per crash, as shown in Table 5-17.

Table 5-17. Additional Costs per Crash for Hazardous Materials Tanker Truck Crashes

HM Categ.	HM Release?	No. of Crashes per Year	Cleanup $	Environmental Damage $	Evacuation $	TOTAL $
2.1	No	229	0	0	2,135	
2.1	Yes	47	1,443	2,742	4,251	
		276				
		Weighted Avg. $/Crash:	246	467	2,495	**3,208**
3.0	No	889	0	0	28	
3.0	Yes	490	31,877	3,672	135	
		1,379				
		Weighted Avg. $/Crash:	11,327	1,305	66	**12,698**
8.0	No	184	0	0	1,877	
8.0	Yes	73	15,584	726	12,100	
		257				
		Weighted Avg. $/Crash:	4,427	206	4,781	**9,414**
Total Number of Crashes in Model:		**1,912**				
					Weighted Average in 1996 Dollars:	$10,886
					Grand Weighted Average in 1999 Dollars, Assuming a 4% Discount Rate:	**$12,246**

Hazardous Materials Categories/Divisions:
2.1 = Flammable Gases 3.0 = Flammable Liquids 8.0 = Corrosive Materials

Source: FMCSA (2001), Tables 30, 33, and 38

Combining the cost data from across all three HM categories and both HM crash types, an additional average cost per crash of $12,246 was determined to account for the presence of HM in a tanker, whether or not the HM itself was released in the crash. Category 3.0, Flammable Liquids, was the most likely HM cargo to be involved in a crash, and was also the most costly on a per-crash basis. Because the FMCSA report presented cost values in constant 1996 dollars, a discount rate of 4 percent per year was applied to convert the costs to constant 1999 dollars, as had been used in the other aspects of the Freightliner FOT benefit-cost analysis.

It is recognized that other categories and divisions of HM may be carried in tanker trailers, and that some HM in the three categories that were chosen may be carried in trucks other than tankers (e.g., acetylene cylinders carried on a small flatbed straight truck), but the approach described here was intended to approximate as closely as possible—given the available data—the differences in costs between the most typical HM tanker trailer and non-HM tanker trailer truck crashes.

Delay Costs. Lost productivity and delays were combined in a single "Delay" cost element, factored into the crash avoidance benefit side of the analysis. Delay cost values were obtained from Tables 6, 7, and 10 of the FMCSA report previously cited (2000). Weighted average values of delays were calculated by applying the distribution of occupants involved in crashes by category (no injury, possible injury, fatality, unknown severity, etc.) to the costs of delays.

Per-Crash Cost Totals. The property damage, hazmat/environmental damage, and delay costs were then totaled for each fleet and crash type, as shown in Table 5-18.

Table 5-18. Cost of Damages and Delays per Truck Crash ($1999)

Type of Cost	Truck Type	Rollover	SVRD
Property damage[a]	Hazardous materials tankers	$25,223	$13,854
	All tankers	$25,223	$13,854
	Tractors with trailing units	$25,223	$13,854
	All large trucks	$6,350	$6,350
Hazardous Materials Impacts[b]	Hazardous materials tankers	$12,246	$12,246
	All tankers	$0	$0
	Tractors with trailing units	$0	$0
	All large trucks	$0	$0
Delays to other traffic[c]	Hazardous materials tankers	$9,064	$9,064
	All tankers	$9,064	$9,064
	Tractors with trailing units	$9,064	$9,064
	All large trucks	$9,355	$9,355
Total damage and delay cost	Hazardous materials tankers	$46,532	$35,163
	All tankers	$34,541	$23,172
	Tractors with trailing units	$34,287	$22,172
	All large trucks	$15,705	$15,705

Note: property damage includes vehicle, cargo and third party costs.

Sources:

a. American Transportation Research Institute (ATRI), 2002.
b. Federal Motor Carrier Safety Administration, 2001.
c. Zaloshnja et al. (2000), with calculations by Charles River Associates

Direct Costs (Equipment Purchase and Driver Training)

Table 5-19 provides the unit costs and other factors for calculating the equipment costs for the RA&C. The costs in Table 5-19 represent the assumption that trucks would already have TCS installed, so that no buyers of trucks to be equipped the RA&C with would be required to pay for both the TCS and the RA&C. For the scenarios assuming that the buyers of only 10 percent of trucks would already have paid for the TCS (results presented in Appendix F), the 100 percent value shown in row D was changed to 10 percent, so the average cost per truck (row E) increased

Table 5-19. Unit Costs of Equipment ($1999)

	Cost Element	Cost per Vehicle	Source
A	Purchase Cost for Onboard IVSS	$385.00	Freightliner
B	Cost of traction control (required for IVSS)	$400.00	Freightliner
C	Total cost for vehicles without traction control	$785.00	A + B
D	Current percent of vehicles with traction control	100%	Assumed[a]
E	Weighted average purchase cost for onboard IVSS	$385.00	A X D + C X (1-D)
F	Maintenance and calibration cost	$0	Freightliner[b]
G	Expected service life of IVSS	10 years	Assumed[b]

Note: Equipment costs recur every 10 years.

a. Line D (percent of vehicles with TCS already paid for) was varied between 100% and 10%, depending on the scenario. The 10% value for the number of vehicles already having TCS was based on interviews with Freightliner.

b. Lines F and G: Absence of maintenance cost was based on interviews with Freightliner. Expected service life of 10 years was assumed, based on comparisons with similar vehicle technologies.

Source: Freightliner, with calculations by Charles River Associates.

from $385 to $745. As discussed above, this change in the cost assumption has a substantial effect on the ultimate benefit-cost ratios.

Table 5-20 provides the number of trucks included in the analysis at the beginning of each scenario. The truck populations were used for two purposes: (a) to calculate the cost of equipping all trucks in each fleet across the U.S. with the RA&C, and (b) the cost of initial and ongoing driver training for all drivers of such trucks in the U.S. Table 5-21 provides the information needed to calculate the costs of driver training.

A constant growth rate of 2.98% per year was used, based on the ATA's "U.S. Freight Transportation Forecast to 2008" forecast for Class 8 trucks.

Table 5-20. Number of Trucks (1999)

Truck Type	Population Description	Number of Trucks
Haz Mat Tankers[a]	Truck-tractors pulling tanker trailers containing hazardous materials	55,098
Tankers[b]	Truck-tractors pulling tanker trailers	110,196
Truck-Tractors[c]	Truck-tractors with at least one trailing unit	1,474,664
All Heavy Trucks[d]	Large trucks, GVWR >10,000 lbs.	7,392,583

Sources:

a. The proportion of hazardous materials-carrying tankers (50% of all tankers, or 0.5 * 110,196 = 55,098) was provided by the 1997 Census of Transportation; Vehicle Inventory and Use Survey.

b. 1997 Census of Transportation; Vehicle Inventory and Use Survey.

c. FHWA Highway Statistics Series Table MV9: Average for 1995-2000 (Example of 2000 data http://www.fhwa.dot.gov/ohim/hs00/mv9.htm)

d. FHWA Highway Statistics Series Table VM1 "Single-Unit 2-Axle 6-Tire or More and Combination trucks" Column: Average for 1995-2000 (example of 2000 data http://www.fhwa.dot.gov/ohim/hs00/vm1.htm).

Table 5-21. Cost of Driver Training ($1999)

	Cost Element	Cost or Other Factor	Source
F	Annual wage	$40,800	ATA 2000 Driver Compensation study
G	Hourly wage	$19.62	F / 2080 hours
H	Assumed markup for fringe benefits	41.9%	U.S. Bureau of Labor Statistics (BLS) National Compensation Survey
I	Assumed hourly wage with fringe benefits	$27.84	G X (1+ H)
J	Assumed hours required for training	1	Experience with Praxair in the FOT
K	Assumed driver turnover (industry) - tankers	5%	ATRI
L	Assumed driver turnover (industry) - all trucks	20%	ATRI
M	Total trucks	7,392,582	Population of all heavy trucks
N	Total drivers	3,136,170	BLS National Occupational Employment and Wage Estimates
O	Ratio of drivers to trucks	0.42	N / M

Initial Training cost = total drivers x cost per driver

where:

drivers = total trucks in each scenario x driver/truck ratio

cost per driver = 1 hour at hourly wage rate with fringe benefits

Recurring training cost = new drivers x cost per driver

where:

new drivers = total trucks in each scenario x driver/truck ratio x turnover rate

cost per new driver = 1 hour at hourly wage rate with fringe benefits

6.0 Implications of Findings

The RA&C was still in a developmental stage when it was deployed in the Field Operational Test. The drivers participating in the test were skilled and experienced. That the advisory function had any effect at all in improving drivers' practices bodes well for its larger deployment. Even in this study of 12 months, 15 drivers, and only six tractors, a statistically significant reduction in risky driving behavior was observed. All parties, including Battelle (the independent evaluator) and the drivers themselves, believe its benefit will be greater when it is deployed more widely, particularly with less experienced drivers.

The FOT raised a number of questions, and suggestions for addressing them are presented in this section. Meritor-Wabco has continued to work on the RA&C since it was deployed in June 2001, so some of the points noted below, particularly those concerning improvements to the device, may already have been addressed.

Just as the technology of the RA&C has developed during the past three years, Freightliner and Meritor-Wabco's plans for the device have evolved since the application for a cooperative agreement was submitted. The most prominent change has been the shift in focus from the purely advisory function of the RSA to the intervention function of the RSC. The larger portion of the safety analysis in the present report concerns the RSA's effect on driving behavior. The safety benefits estimate and the benefit-cost analysis are both based entirely on changes in driver behavior. Freightliner is currently indicating that it expects the larger benefit to come from the RSC rather than the RSA, so the remarks specific to the RSC are given below.

6.1 Device Functionality

While the RSA performed well in simple maneuvers on the test track, its consistency in actual use on open highway seems to be less than optimum. The discussion in Section 5.6, particularly Figures 5-47a and 5-47b, shows that the RSA did alert drivers to some of the highest risk maneuvers in a frequently traveled exit ramp. However the simulations showed that there were a few other passes through the ramp of equally high risk where the driver was not alerted. The existing data for this and other frequently traveled curves provides a good opportunity to reexamine the decision algorithm. Objective benchmark indicators of roll propensity, such as a multibody dynamic model, should be compared with the current RSA score algorithm on many passes through diverse curves. The actual grade and cross slope of the FOT road segments needs to be included in the model. The goal of this work should be first to learn whether the algorithm was performing as expected. If necessary, the algorithm should be refined so that it consistently provides advisory messages on the most risky maneuvers and not on the less risky maneuvers. The modified algorithm should then be tested on additional trips through the same curves and on trips through other FOT curves.

The RA&C includes a means for estimating the vehicle mass, which is essential for ascertaining rollover potential. Battelle understands that the estimation method has been improved since it was installed in the FOT trucks. Compensation for the grade of the roadway would greatly expand the range of application. One can imagine a logging operation where trailers are stacked high with uncut timber and they are driven down tortuous mountain roads toward a mill. The rollover potential of the load will be about as high as possible, and the many curves will provide opportunity for rollover. In this situation the downgrade will cause the RA&C to underestimate the load. It will assess the rollover potential to be substantially less than what it is.

The drivers in the final interview recalled the numbers of messages much better than they recalled levels of messages. Therefore, the mere fact of providing an advisory message is more important than selecting an advisory level or quantitative speed reduction recommendation. When the RA&C's decisions are more consistent and the nuisance alarms at low vehicle weight are less frequent, drivers should begin to trust it more and adjust their behavior accordingly.

6.2 Recommendations on the Controller Function

The limited scope of the FOT did not allow the RSC, which is intended to operate only in extreme circumstances, an adequate opportunity to demonstrate itself. The conservative cadre of drivers in the FOT did not produce a situation that was truly dangerous enough to warrant an RSC intervention. Some information can be gleaned from the 25 occasions where the RSC did intervene. In all of them the vehicle was empty, so it was not truly in danger of rolling over, but its performance was studied. In only a few of its interventions did the RSC actually slow the vehicle. A small number of the maneuvers were severe enough that they could have nearly rolled the vehicle had it been fully loaded. Just as the algorithm for the advisory function can be tested with "real-world" data from the FOT, so should the RSC's formulas.

The deceleration authority of the RSC in the FOT was confined to engine torque reduction and engine braking. Meritor-Wabco said at the outset that engine braking was limited in effectiveness. At this writing, RSC with the authority to apply service brakes is being sold. This version has not been tested by Battelle.

Development of a more prominent message to be displayed when the controller intervenes is essential. Though seven of the drivers in the FOT triggered an RSC intervention, some of them more than once, not a single driver recalled having an intervention at the final interview. Drivers whose lives are spared by the RSC and do not know of its actions will become reliant on the technology. These drivers may not understand the function of the RSC or might not even know of its presence in the vehicle. A driver who takes an identical load on the same road at the same speed with an unequipped tractor will roll the vehicle. Perhaps a mandatory use of the acknowledge button would draw the drivers' attention to the RSC message. Freightliner has indicated that it may deploy the RSC, without the RSA, on a tractor without the Driver Message Center. If the market goes in that direction, it will be especially important to provide a foolproof method of communicating to the driver when and why the RSC has intervened.

The RSA, being merely an educational tool, leaves direct vehicle control to a qualified driver, so it probably does not warrant regulation. The RSC, on the other hand, does take partial control of the vehicle in safety-critical situations. The DOT may wish to consider regulations, possibly in the form of amendments to FMVSS 121, to address issues posed by the RSC. One issue would be a series of performance tests to ensure that safety devices with authority to apply the service brakes will "do no harm." That is, they will not diminish the stability of the vehicle when they activate. Another portion of the regulations should address the driver notification issue. Drivers who execute a maneuver that activates the RSC should be given a clear notification of what has happened. The notification should be clearly understood by drivers, even those that have had no training on the RSC. The treatment of ABS in FMVSS 121 could serve as models for these regulations.

6.3 Training Revisions

The training for the RSA should emphasize better that the message results from the maneuver just completed and that the recommendation applies to the future. At the June survey the week after the drivers were oriented to the system, one fifth of the drivers thought that the messages called for an immediate reduction in speed. Thought most drivers at the exit interview understood the purpose of the RSA, the comments of some drivers showed they still thought the recommendation applied to the current situation.

The training manuals should also highlight the RSC function better. At the interviews conducted the week after the orientation, the drivers were asked an open-ended question on the device's function to see what they had internalized. The information that they would be getting advice for their speed on curves had clearly been heard, but many drivers had to be asked a leading question before they remembered that the a controller was present as well. The organization of the training materials seems to emphasize the RSA over the RSC. There are six slides on the RSA, followed by seven on the HBED including the summary of the two. There are only two slides on the RSC, nearly at the end of the materials. There were two nearly identical slides, one of which was the final slide, that listed all of the new functions, clearly including the RSC. Evidently, however, the late placement of the brief RSC explanation is after the drivers have already formulated an impression that the new systems were purely advisory in nature.

6.4 Institutional and Legal Issues

As Freightliner is proceeding with taking the RA&C to market, it will be important that it continue to communicate with voluntary and mandatory standards bodies to ensure its smooth assimilation into the "high tech" cab. Battelle has found no immediate obstacles to deployment; contacts that were interviewed suggested ways to ease the product's widespread adoption.

Freightliner should cooperate with SAE committees on the driver interface. The drivers in the study indicated that the messages were distinguishable from others in the cab, but only with the audible tone. As other audible tones come in the cab, particularly other safety devices such as the Vorad, it will be important that each have its own characteristics that are universally recognized by trained professional drivers. In fact, to the extent possible, the messages should be intuitively recognized even by drivers who have not had thorough training.

Some drivers may object if their tally of RA&C activations is reported to fleet management. There is precedent for review of unusual, potentially hazardous driving events. Monitoring instances of overspeed and hard braking at Praxair is a condition of employment, and the drivers accept it. A few drivers in the study did not want RA&C information known to management, in part because they were concerned that the RSA was inaccurate. Other drivers, though, thought discussions between management and drivers on RA&C counts would be beneficial. Certainly, as RA&C becomes more popular, if fleets choose to implement a form of management review, drivers will raise objections of "big brother" and "privacy." However, judging by the Praxair interviews, the better drivers will welcome the dialogue if they are convinced of the system's accuracy and will appreciate the improvements to safety. If training materials include test results, possibly in the form of photographs or videos that can be readily understood by drivers, that will help the drivers to trust it more readily.

Legal issues with the RA&C, as with similar systems, can be mitigated by establishing and following procedures for training all users, for storing and protecting any data generated from its use, and by documenting due diligence in doing so.

The vendor should begin plans for regulatory compliance even before regulations require performance. As a minimum, calibration or status check procedures to ensure operation should be established. The system's self-test feature may already meet this objective.

7.0 Recommendations for Future FOTs

This Field Operational Test was efficient and effective. Communication between Battelle, the independent evaluator, and its primary contact in the partnership, UMTRI, was excellent. Staff at the DOT were willing to provide guidance or assistance when necessary.

An important factor contributing to the success of this FOT was the existence of a sound experimental design and data acquisition plan at the early stages of the project. Measures of safety were considered at the outset, and the data were rich enough to allow other questions to be answered as analysis progressed. The Partnership's plan to collect 100 percent of the driving data, rather than triggering data collection based on prespecified driving events, made it possible for the independent evaluator to adjust threshold values and perform special queries as the analysis progressed. This approach ensured that the data analysis and findings would not be adversely affected by the data collection process. The ability to raise and answer new questions proved invaluable. There were many parts of this report where an analysis could be conducted only by studying all trips through a given road segment, not just those trips where a pre-defined trigger condition was met. Continuously recording helped to improve the quality of the data itself, too. The drift in the drive axle accelerometer needed to be corrected more often than UMTRI anticipated. Because data were recorded on long, straight stretches, the signal could be zeroed according to the known cross slope of several straight highway segments.

The use of a single terminal kept logistics to a manageable level. There were two occasions when a Battelle staff member interviewed the drivers. In both instances, nearly all of them were seen in a single trip of only a couple days. A benefit of the limited delivery area was that there were many road segments through which each driver passed many times. There were, however, disadvantages to the selection of a single terminal. Only six tractors, driven for six months each in the control and treatment phases, produced a fairly small number of serious events to analyze. By the nature of statistics, confidently estimating small changes, as were expected and observed in this FOT, requires large numbers of near-rollover incidents, which were simply not available. In this sense, the compact size of the FOT fleet was largely responsible for the lack of statistical significance in the final safety benefits estimate. Also, while the convenience of the terminal's proximity to both UMTRI and Battelle had its benefits, the RA&C was tested exclusively in the Great Lakes region of the country, which is fairly free of hills and curves. As with many experiments, there is an inherent trade-off: a larger experiment provides richer data but a smaller one is easier to conduct.

Data collection was largely automatic. UMTRI reviewed the data to make sure all was working well. On ordinary days it took no help from Praxair personnel. In the cases where valid data were missing or the data collected were invalid, the partnership could readily trace the path through the server at the terminal to diagnose and fix the problem.

There were two ways that the experimental design limited the strength of the conclusions. The FOT was conducted essentially within a one-year period, with one phase conducted as the weather was warming and the other phase conducted as the days shortened. Separating the seasonal effects from the RA&C's effects could not be done with absolute certainty. Secondly, the demographics of the drivers was uniform. All were experienced, and all were within a twenty-year age span. A better test of the educational benefits of the RSA would have been to study two similar groups of novice drivers, one with the system and one without. Battelle understands, of course, that any experiment must be planned within constraints, and the partnership worked around these constraints as well as possible.

Personal interviews with the drivers allowed a much greater understanding than would have been possible had all the human factors been collected with pencil surveys. Even during the final interview, which was quite structured, the extra comments of the drivers revealed insights on how they interacted with the system, what they thought of its behavior, and even how they drive their trucks.

The conclusions of this report were strengthened by Battelle's ability to test hypotheses and run experiments on the test track. This was possible only through the cooperation of all four members of the partnership. Praxair donated a trailer to the project and provided valuable information on its operations. Meritor-Wabco allowed Battelle to use its flatbed trailer and ballast for one of the tests, and it provided two RA&C units, one configured with RSC and one without. UMTRI allowed Battelle to use a DAS and several instruments for the experiments, so the test track data would be readily comparable to the FOT data. Freightliner leased a tractor to Battelle for the tests. Much of the delay in performing the evaluation was due to difficulties obtaining the tractor for the test track experiments. All parties were understandably reluctant to reveal sensitive corporate information, and, of course, not everything that Battelle requested was granted. The success of the project was possible only with the cooperation and open communication and the sense that all were working toward a common goal.

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