U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

DOT HS 811 205

October 2009

Safety Benefits of Stability Control Systems For Tractor-Semitrailers

Final Report

1. Report No. DOT HS 811 205	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Safety Benefits of Stability Control Systems for Tractor-Semitrailers	5. Report Date October 2009
	6. Performing Organization Code
7. Author(s) John Woodrooffe, Daniel Blower, Timothy Gordon, Paul E. Green, Brad Liu, Peter Sweatman	8. Performing Organization Report No. UMTRI-2008-xx
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, MI 48109-2150	10. Work Unit no. (TRAIS) 054256
	11. Contract or Grant No. DTNH22-06-H-00058
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration Office of Applied Vehicle Safety Research 1200 New Jersey Avenue SE. Washington, DC 20590	13. Type of Report and Period Covered September 2006-May 2008
	14. Sponsoring Agency Code NVS-322

15. Supplementary Notes

Contracting Officer's Technical Representative (COTR): Alrik L. Svenson

16. Abstract

This study was conducted by the University of Michigan Transportation Research Institute (UMTRI) under a Cooperative Agreement between NHTSA and Meritor WABCO to examine the performance of electronic stability control (ESC) systems, and roll stability control (RSC) systems for heavy-truck tractor-semitrailers. The study is based on the analysis of independent crash datasets using engineering and statistical techniques to estimate the probable safety benefits of stability control technologies for 5-axle tractor-semitrailer vehicles. The conventional approach for assessing the safety benefits of vehicle technologies is to analyze crash datasets containing data on the safety performance of vehicles equipped with the technology of interest. Because the deployment of the stability technologies for large trucks is in its infancy, national crash databases do not yet have a sufficient amount of factual data that can be directly linked to the performance of the technology. Therefore a novel method of examining the potential benefits of these systems was used. Crash scenarios that could likely benefit from the technologies were selected from national crash databases and the probable effectiveness of each technology was estimated. The analysis in this study did not have the advantage of examining representative crash datasets that contain identifiable data from vehicles equipped with the technology. Therefore, the analysis was based on probable outcome estimates derived from hardware-in-the-loop simulation, field test experience, expert panel assessment, and fleet crash data and these methods were used to estimate the safety benefits from the national crash data population.

17. Key Words ESC, RSC, stability control, heavy truck, safety benefit, roll stability, yaw stability		18. Distribution Statement Unlimited	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 160	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Executive Summary

This study was conducted by the University of Michigan Transportation Research Institute (UMTRI) under a Cooperative Agreement between NHTSA and Meritor WABCO to examine the performance of electronic stability control (ESC) systems, and roll stability control (RSC) systems for heavy-truck tractor-semitrailers. The study was based on the analysis of independent crash datasets using engineering and statistical techniques to estimate the probable safety benefits of stability control technologies for 5-axle tractor-semitrailer vehicles. The conventional approach for assessing the safety benefits of vehicle technologies is to analyze crash datasets containing data on the safety performance of vehicles equipped with the technology of interest. Because the deployment of the stability technologies for large trucks has only occurred recently, national crash databases do not yet have a sufficient amount of data that can be directly linked to the performance of the technology. Therefore a novel method of examining the potential benefits of these systems was used. Crash scenarios that could likely benefit from the technologies were selected from national crash databases and the probable effectiveness of each technology was estimated. The analysis in this study did not have the advantage of examining representative crash datasets that contain identifiable data from vehicles equipped with the technology. Therefore, the analysis was based on probable outcome estimates derived from hardware-in-the-loop simulation (HiL), field test experience, expert panel assessment, and fleet crash data and these methods were used to estimate the safety benefits from the national crash data population.

This research effort has produced an estimate of the anticipated benefits that would be achieved for specific crash types if electronic stability or roll control devices were deployed in the nation's 5-axle tractor-semitrailer fleet. Practical constraints limit the scope of this study to the evaluation of crashes involving first-event yaw instability and first-event roll instability. The subsets of crashes that constitute these two event categories are small in relation to all other crashes involving tractor-semitrailer vehicles. However, these crashes produce a substantial number of personal injuries and fatalities. The results presented in this report constitute the net benefit of the technology in relation to a potentially limited set of crash types where the benefits of the technology are most readily apparent and the results should be considered conservative. It is expected that there are events that may occur in other crash types that would benefit from the technologies, but these crashes cannot be identified effectively using coded data.

Tractor-semitrailer crashes tend to be complex events that involve factors not only in relation to crash cause, but also factors affecting post-crash yaw control that can result in secondary events that can increase the net severity of the crash sequence. Therefore it is anticipated that technologies that address vehicle yaw control (such as ESC) would have additional benefits across a broad range of crash types. The study team was not able to provide an estimate for these additional benefits, so true amount of benefits to be realized is likely higher.

Benefit Analysis and Study Results

Using the definitions of rollover and loss of control established in this study for tractor-semitrailers, baseline numbers of relevant rollover and loss-of-control crashes and injuries were derived. These were the numbers that may potentially benefit from the RSC and ESC technologies. A benefit equation was used to estimate benefits in terms of numbers of crashes, deaths, and injuries prevented that are attributable to the stability technologies. Two sources of information provided information for calculating effectiveness measures. One source was based on expert panel judgment of certain cases taken from the Large Truck Crash Causation Study (LTCCS) database. The other source is derived from HiL simulation.

For the HiL simulation portion of the analysis, data from a Roll Stability Adviser (RSA) field operational test (FOT) study conducted at UMTRI provided distributions of speeds at which heavy trucks enter curves of 68m radius and 227m radius. Data from the LTCCS supported the use of these curve radii. The FOT data were collected when the RSA feature was not active and are representative of normal driving. Since no vehicles rolled over at these speeds, the two distributions are shifted to the right to represent speeds of vehicles that rolled over, assuming a baseline case of ABS equipped vehicles. The amount of shift is determined by rollover cases in the LTCCS according to curve radius and point of rollover from the curve start. Results from the HiL simulation give critical speeds of rollover for ABS, RSC, and ESC that are used in the shifted distributions to calculate effectiveness measures.

The findings of the study indicate that stability control systems provide substantial safety benefits for tractor-semitrailers. Assuming that all existing 5-axle tractor-semitrailers operating on U.S. roads were fitted with RSC, the expected annual rollover relevant safety benefit is a reduction of 3,489 crashes, 106 fatalities, and 4,384 injuries. Alternatively, assuming that all existing 5-axle tractor-semitrailers operating on U.S. roads were fitted with ESC, the expected annual combined rollover and directional (yaw) instability relevant safety benefit is a reduction of 4,659 crashes, 126 fatalities, and 5,909 injuries. Because ESC addresses both rollover and yaw instability crashes and it is more effective in mitigating rollover crashes (through additional braking capabilities over RSC), the net annual expected benefit for an ESC system was found to be greater than for RSC.

The benefits are applied per victim injured according to economic estimates of costs of highway crashes involving large trucks (updated report by Zaloshnja & Miller, 2006). Since costs are reported in 2005 dollars, they are adjusted to 2007 dollars using the CPI Inflation factor of $1.06 as reported by the Bureau of Labor Statistics. The benefits relate specifically to tractors pulling one trailer.

Assuming ESC was fitted to all tractor-semitrailers, savings from rollovers prevented by ESC are estimated at $1.527 billion annually, and from LOC crashes prevented at $210 million annually, for a total of $1.738 billion annually. Assuming RSC was fitted to all tractor-semitrailers, savings from rollovers prevented at estimated at $1.409 billion annually, and from LOC crashes prevented at $47 million annually, for a total estimated benefit of $1.456 billion annually.

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1 Introduction

Although rollovers occur in only about 13 percent of heavy-truck fatal crash involvements, rollovers account for 50 percent of truck occupant fatalities.[1] Heavy-truck loss-of-control and rollover crashes are also a major cause of fatalities and traffic tie-ups, resulting in millions of dollars of lost productivity and excess energy consumption each year. Stability-enhancing technologies have been developed to sense when a loss of control or rollover is imminent and take corrective action without any input from the driver. This technology can be of benefit because by the time a driver senses that the vehicle is beginning to lose control, it is usually too late for a corrective action.[2] This study is specifically designed to estimate the potential benefit of two distinct safety systems, roll stability control (RSC) and electronic stability control (ESC). The RSC system senses vehicle lateral acceleration in a curve and intervenes to slow the vehicle in accordance with an algorithm. The deceleration interventions are graduated in the following order: de-throttling; engine brake; and foundation brake application. The ESC system contains all the attributes of the RSC system and has the added capability of sensing and controlling vehicle understeer and oversteer, which are directly related to loss of control. The loss-of-control intervention strategy uses selective braking of individual wheels on the tractor.

This study is based on the analysis of a number of independent crash datasets using engineering and statistical techniques to estimate the probable benefits of stability technologies for 5-axle tractor-semitrailer vehicles. Because these devices have only recently been introduced, none of the established crash sets have enough crashes to distinguish vehicles using the technology from those that do not.[3] Therefore a novel method of examining the potential benefits of these systems was used.

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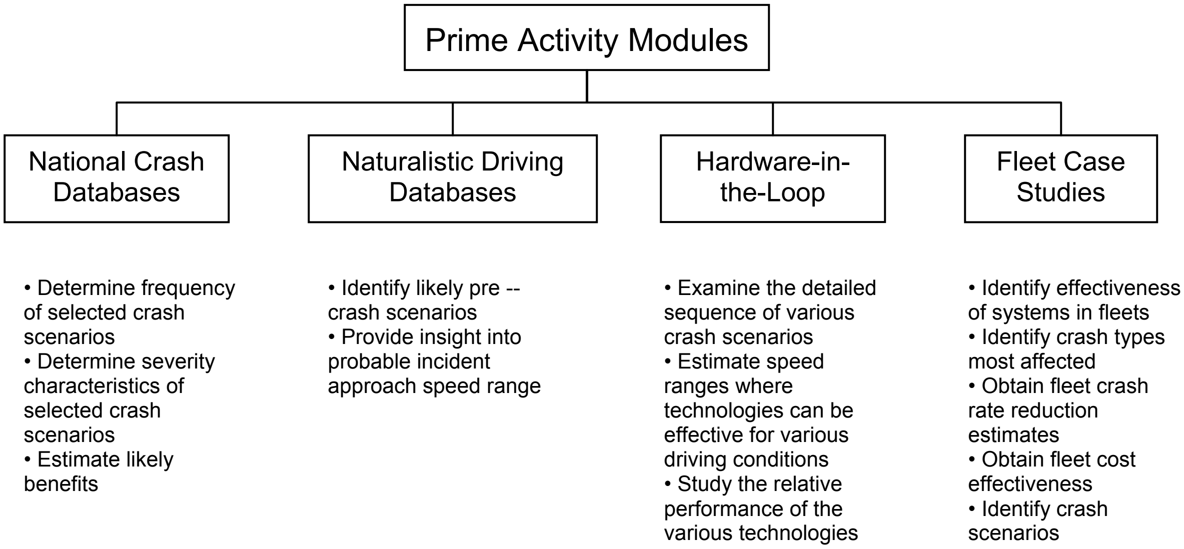
[1] Trucks Involved in Fatal Accidents, 1999-2005. Data file compiled by the University of Michigan Transportation Research Institute.

[2] See, for example, Winkler, C. B., & Ervin, R. D., "Rollover of Heavy Commercial Vehicles." The University of Michigan Transportation Research Institute, Ann Arbor, MI. 1999, page 3.

[3] UMTRI's Trucks Involved in Fatal Accidents file began tracking the presence of stability control technology in data year 2005.

2 Study Design and Approach

This study is organized in distinct modules, as shown in Figure 1, which have been arranged in a progressive order to allow for adjustment and change as the research developed. Most modules contain some redundancy with overlap based on separate data sources or, in the case of hardware-in-the-loop, data generators. The modular approach not only satisfied the requirement for redundancy in the event that certain modules produced inconclusive results, but it also provided a contingency option. Moreover, modular convergence towards particular findings provides assurance and added credence to the reliability of the study results.



- Determine frequency of selected crash scenarios
- Determine severity characteristics of selected crash scenarios
- Estimate likely benefits

- Identify likely pre -- crash scenarios
- Provide insight into probable incident approach speed range

- Examine the detailed sequence of various crash scenarios
- Estimate speed ranges where technologies can be effective for various driving conditions
- Study the relative performance of the various technologies

- Identify effectiveness of systems in fleets
- Identify crash types most affected
- Obtain fleet crash rate reduction estimates
- Obtain fleet cost effectiveness
- Identify crash scenarios

Figure 1. Modular Structure of Research Project

The conventional approach for assessing the safety benefits of vehicle technologies is to analyze crash datasets containing data on the safety performance of vehicles equipped with the technology of interest. Because the deployment of the stability technologies for large trucks is in its infancy, national crash databases do not yet have factual data that can be directly linked to the performance of the technology. In light of these limitations, this study used an indirect method of predicting the safety performance of stability technologies based on an understanding of the technical function of the technology relative to crash types that would likely benefit from the technology.

The technical function of the technology was determined through rigorous analysis based on knowledge of the performance attributes and control systems, vehicle intervention strategies, and vehicle corrective response. The knowledge was gained though independent study, field tests, and the development and use of hardware-in-the-loop simulation.

Linking the performance of the stability technologies to benefits based on estimates of national crash reduction was achieved by developing data selection algorithms compatible in the main crash data files used in this project: General Estimates System (GES), Trucks Involved in Fatal Accidents (TIFA), and Large Truck Crash Causation (LTCCS) databases. Probable effects of the stability technologies were then developed using the well-documented LTCCS cases. The LTCCS crash data formed the backbone for this study because of the high quality and consistent detail contained in the case files. Included in this resource are categorical data, comprehensive narrative descriptions of each crash, scene diagrams, and photographs of the vehicle and roadway from various angles. This information allowed the researchers to achieve a reasonable level of understanding of the crash mechanics for particular cases. The information was used to develop scenarios that either served as input to hardware-in-the-loop simulations or as necessary background for expert panel review and effectiveness estimation. Once the technology effectiveness estimates were completed for the LTCCS cases selected by the algorithm, scaling the benefits to the national population was achieved by applying the LTCCS effectiveness ratio to the corresponding cases identified by the algorithm from the GES database.

In the first part of the study, GES and TIFA were used as representative national crash data files to identify the population of tractor-semitrailer crashes to which the technologies would apply. The estimates were developed using an iterative process, in which tentative selection rules were developed using the coded data in the national crash files, and then specific examples from the LTCCS of the crashes selected were reviewed to determine whether the crashes in fact had the appropriate characteristics. This process identified a set of crashes in the national crash data for which the ESC or RSC technologies are most likely to be effective in reducing the number of crashes.

In the next part of the study, the effectiveness of the technologies in reducing the number of crashes was addressed through the use of HiL simulation and intensive review of specific crashes (from the LTCCS database) by an expert panel to supplement the results from the HiL testing. Data from a naturalistic driving field operational test were used to characterize important parameters such as the distribution of curve entry speeds for curves of different radii. The HiL simulation was unable to address all relevant crash types, particularly those related to loss of control, but the simulations were very helpful in revealing details of how the technologies function under different conditions of vehicle speed, roadway curvature and friction, load conditions, and driver input.

Crash data from a fleet that had deployed RSC were used in a parallel analysis. These data were from one fleet only (it was not possible to secure the cooperation of additional carriers in time for the report), but represented the experience of the use of the technology in the daily operations of a large carrier's fleet. The results, based on actual experience of the technology, provide an independent evaluation and thus bolster the results from the simulation and the expert panel. The results are not used directly in the estimate of safety benefits of the technologies. The results of the fleet data analysis are presented in Appendix C.

Simulation results and engineering judgment were used to estimate benefits in the national crash population. The crash selection algorithm in the national data was applied to the LTCCS data to produce a sample of the types of crashes identified in the national data by the algorithm. The effectiveness of the RSC and ESC technologies was estimated separately. The effectiveness was estimated for each crash, using HiL simulation where possible (primarily rollover on curves) and expert judgment informed by simulation and experience. Since the LTCCS cases were selected using the same algorithm developed in the national crash files, each crash could be linked to the national data to produce overall estimates of the effectiveness of the technologies in reducing crashes.

3 About the Technology

The technologies assessed in this study are tractor-based systems that can be broadly placed in two partially overlapping classes: roll stability control systems, which are designed to reduce the probability of vehicle rollover, and electronic stability control systems, which address vehicle loss of control. The overlapping characteristic of these technologies centers on the ability of ESC to manage LOC scenarios as well as to replicate the functionality of an RSC system.

RSC and ESC technologies are able to assess vehicle mass by monitoring engine torque and vehicle acceleration performance on a continuous basis. An onboard algorithm uses this data to set the lateral acceleration threshold and establish mass-related braking strategies for vehicle deceleration. The technology has the capability of overriding driver power commands to the engine and can activate the vehicle retarder/engine brake as well as the foundation brakes. The degree of intervention depends on the amount of lateral acceleration that the vehicle experiences. RSC and ESC technologies perform almost identically when controlling for excessive speed in a curve with the exception that ESC can apply the foundation brakes (all tractor axle and trailer axle brakes), including the tractor steer axle, while RSC can apply the foundation brakes, excluding the tractor steer axle.

The ESC system can also influence vehicle understeer and oversteer. Vehicle oversteer is associated with yaw-divergent loss of control (LOC), which often leads to vehicle jackknife. Understeer, at its limit, results in directional non-responsiveness to steer input often described as "plowing forward."

To control vehicle LOC, ESC monitors vehicle steering angle, speed, and yaw rate, calculates the vehicle state, and compares it to expected values resident in the technology to determine whether the vehicle is outside of the expected performance window. When vehicle performance exceeds the expected or normal performance range, the system intervenes by selectively braking certain wheels depending on whether the vehicle condition is related to oversteer or understeer.

4 Identification of Target Crash Types

This section describes the logic used in developing the algorithms that identify and select the sets of crashes that potentially may be addressed by the ESC and RSC technologies. The National Highway Traffic Safety Administration's General Estimates System (GES) file and UMTRI's Trucks Involved in Fatal Accidents (TIFA) file are used for this purpose. In addition, the NHTSA/Federal Motor Carrier Safety Administration's Large Truck Crash Causation Study (LTCCS) data file is used to test the logic and to validate the selection algorithms.

4.1 Crash Data Files

The GES crash file is part of NHTSA's National Automotive Sampling System (NASS). GES is a nationally representative sample of the estimated 6.4 million police-reported crashes that occur annually. GES covers all vehicles involved in a traffic accident, not just trucks. GES is the product of a sample survey with clustering, stratification, and weighting that allows calculation of national estimates. Police reports are sampled and the GES data are coded entirely from those police reports. The GES file includes vehicle information that allows tractor-semitrailers to be identified and variables that describe the crash that permit relevant rollover and LOC crashes to be identified. The GES file has been compiled since 1988. GES samples about 10,000 trucks per year. These 10,000 sampled trucks equate to a national estimate of about 440,000 trucks involved in a police-reported crash annually. [5]

The TIFA crash data file is produced by the Center for National Truck and Bus Statistics at the University of Michigan Transportation Research Institute. The TIFA file is a survey of all medium and heavy trucks (GVWR > 10,000 lb) involved in fatal crashes in the United States. Candidate truck cases are extracted from NHTSA's Fatality Analysis Reporting System (FARS) file, which is a census of all traffic accidents involving fatalities in the United States. To collect data for the TIFA survey, police reports are acquired for each crash, and UMTRI researchers contact drivers, owners, operators, and other knowledgeable parties about each truck involved in the crash. The TIFA survey collects a detailed description of each truck involved, as well as data on the truck operator and on the truck's role in the crash. The TIFA file is a census file, which means that every truck involved in a fatal crash is included in the file. TIFA includes about 5,200 trucks involved in fatal crashes each year. [6]

GES and TIFA are nationally representative crash data files, containing crashes of all severities and crashes involving a fatality, respectively. As such, they are used to estimate the size of the set of truck crash involvements that might be addressed by the technologies under consideration. In addition, they are used to identify and characterize the environmental and vehicle factors that are associated with the crashes.

LTCCS was undertaken jointly by FMCSA and NHTSA. LTCCS was based on a sample of 963 injury crashes or fatal crashes involving 1,123 large trucks that occurred between April 2001 and December 2003. The crash severity threshold for LTCCS was a fatality, an incapacitating injury (A-injury), or a non-incapacitating but evident injury (B-injury). The data collected provides a detailed description of the physical events of each crash, along with information about all vehicles and drivers, weather and roadway conditions, and trucking companies involved in the crashes. Because the goal of the study was to determine the reasons for crashes in order to develop countermeasures, the data collection was focused on pre-crash events. The data were collected by two-person teams: a crash investigator and a State truck inspector. [2, 3]

The LTCCS data shares many variables with GES and TIFA, so it is possible to identify crashes with the same types of events in all three files. While the GES and TIFA files provide coded data about the crashes, much additional information about the crashes is available for LTCCS. The datasets for LTCCS include the researcher's discussion of the crash, which is typically a lengthy and detailed description, often drawing conclusions about how and why the crash occurred. In addition, much of the supporting investigative detail is available for each crash at a website.[4] This additional detail includes scene photographs, photographs of the crashed vehicles, a scene diagram, and all of the coded information.

The LTCCS data were used for two purposes. First, the LTCCS data were used as a test bed to develop the selection algorithms to identify the set of crashes to which the ESC and RSC technologies might be relevant. While both TIFA and GES include information about crash events, the variables and code levels in those files were not developed to

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[4] The site may be accessed at http://www-nass.nhtsa.dot.gov/LTCCS_PUB/SearchForm.aspx.

identify the specific circumstances relevant to the technologies under consideration, but rather for more general purposes. Accordingly, when methods were developed to identify certain crash types, there is always a question as to whether the crashes actually identified include the characteristics sought.

The investigative detail available in LTCCS was used to test different selection algorithms. Case selection algorithms developed in GES and TIFA were applied to the LTCCS file. Cases that met the selection criteria in LTCCS were reviewed for applicability, using the researcher's narrative, scene diagram, and photographs, in some cases. This procedure either confirmed that the algorithm identified crashes relevant to the RSC or ESC technologies, or that the algorithm included cases that could not be addressed. In the latter event, the algorithm was adjusted accordingly. For example, the LOC crash type initially included cases in which the truck was coded as losing control due to excessive speed. However, when LTCCS cases coded as losing control due to excessive speed were reviewed by the expert panel in this study, the scene diagrams and scene photos indicated that almost all did not involve prior loss of control, but were simple rollovers.

The second use of LTCCS was as a source of detailed crash investigations, which would supply details of events and conditions to support the HiL simulations and the expert panel effectiveness evaluations. The descriptions of environments and events in GES and TIFA were not sufficiently detailed to support the HiL simulations or expert panel evaluations. For example, both data files include a roadway alignment variable to discriminate straight from curved roads, but the files do not include information about the radius of curvature or the point where the truck rolled over. Radius of curvature is typically on the scene diagram in LTCCS, or can be estimated from the scene diagram, while the roll point can usually be estimated from the diagram and scene photos. The researcher's discussion is also a rich source of information about the timing of events, including driver inputs. In this way, the LTCCS crashes served as very high-quality samples of crash investigations of the types of crashes identified by the selection algorithms developed in TIFA and GES.

TIFA, GES, and LTCCS are the most suitable datasets available for the present purpose. Only two other crash data files are national in scope (and thus could supply national estimates of the size of the crash problem): FMCSA's Motor Carrier Management Information System (MCMIS) crash file and the NASS Crashworthiness Data System (CDS) file. However, the CDS file has been targeted at passenger vehicles since 1987 and only includes trucks if they are involved with passenger vehicles that are sampled for the file. The MCMIS crash file is targeted at trucks and buses, but serves primarily as a census of the crash involvements that meet a specified severity threshold. The file includes only minimal detail about the vehicles, conditions, and events of the crash.

4.2 Selection Algorithms for Relevant Crash Types

It should be noted that TIFA, GES, and even LTCCS are essentially general-purpose crash data files, developed to provide a continuous monitor of traffic crashes that meet their respective thresholds. The files are designed to serve a variety of needs. They provide quite useful and even somewhat detailed descriptions of crash events and vehicles. But, the variables are structured to provide general descriptions that are generally useful. In the present context, selection algorithms were developed to capture events that could be addressed by specific technologies, using the information in the files. In the case of rollovers, which are addressed by both systems, it is straightforward to identify the set of crashes that contain the relevant rollovers. It is not difficult to determine whether the vehicle rolled over. There can be some ambiguity as to whether the rollover was a consequence of a collision, but generally the fact of rollover can be identified with great accuracy. However, crashes involving loss-of-control events that can be addressed by ESC systems are more difficult to identify in the available crash data. LOC involving yaw instability prior to a collision is not as obvious post-crash as is rollover. Good examples are the cases in LTCCS of trucks coded as losing control due to excessive speed. The review of scene photos by the expert panel indicated that the skid marks in the photos were consistent with simple rollovers, not a prior loss of yaw stability. It can be very difficult for non-experts to identify yaw instability.

The approach taken here was to develop tentative identifications of the relevant crash types in GES, apply the same algorithm to the LTCCS cases, and then examine the researcher's description and other information to see how well the algorithm captures the crashes expected.

Identification of the crashes relevant to the technologies under consideration focused on two general crash types with specific characteristics. For the ESC and RSC technologies, the attempt was to identify rollovers that could potentially be addressed by these devices. These systems sense vehicle speed and lateral acceleration to detect rollover risk. The control functions attempt to slow the vehicle through braking and the engine retarder. Within the context of this analysis, rollovers precipitated by collisions were considered not addressable by the devices. Thus, the rollovers that can be affected by ESC and RSC are basically first events, where the rollover is the first harmful event for the tractor-semitrailer in the crash.

A truck-tractor ESC system includes sensors for vehicle speed and lateral acceleration, along with steer angle and yaw rate sensors. When yaw instability is detected, for example when the power unit yaw response is at odds with that expected for a given steer angle, the unit attempts to point the vehicle in the direction the driver is trying to go, using selective wheel braking. Relevant crashes in the crash data are those in which the vehicles have lost control, specifically with excessive yaw (oversteer) or insufficient yaw (understeer) prior to the first harmful events.

Table 1 shows the primary variables available in the three files that this study used to identify the relevant crashes. Identification of relevant rollover and relevant LOC crashes is discussed separately.

Table 1. Primary Variables Available to Identify Target Crash Types in GES, TIFA, and LTCCS

Variable			Description
GES	TIFA	LTCCS	
ACC_TYPE	V1059	CRASHCODE	Captures the relative position and motion of the vehicle just prior to the first harmful event.
P_CRASH2	Not available	ACRCriticalEvent	Critical event, the event that made the crash imminent for the vehicle.
P_CRASH3	V143 (from FARS AVOID)	ACRAvoidance	Corrective action taken to avoid the collision.
P_CRASH4	Not available	ACRStability	Vehicle control after the corrective action.
EVENT1	V23 (from FARS HARM_EV)	See note	First harmful event in the crash (code 1 is rollover, 5 is jackknife).
JACKNIFE	V126 (from FARS J_KNIFE)	AJKType	Jackknife. The GES records whether the truck jackknifed; the TIFA variable (from FARS) distinguishes first event jackknifes from subsequent events. The LTCCS variable distinguishes tractor yaw from trailer swing.
ROLLOVER	V125 (from FARS ROLLOVER)	ROLLINITTYPE	Rollover. GES records whether the roll was tripped; the variable in TIFA (from FARS) distinguishes first-event from subsequent-event rollover; the LTCCS variable identifies the type of rollover.

Since each data file takes a different approach to the identification of rollover, it is necessary to harmonize the information as much as possible by relating the code levels available across data files. The next paragraphs describe that mapping.

A rollover relevant to the technologies is one that occurs prior to another event such as a collision with a vehicle or running off the road. Accordingly in the crash data, the initial goal is to identify first-event rollovers that occur on the roadway. In GES, all rollovers are identified using the ROLLOVER variable, which captures whether the rollover was tripped or untripped, and, if tripped, the source of tripping. Untripped rollovers (ROLLOVER=10) were viewed as RSC-relevant. Rollover is also identified as a first harmful event in the crash, so any rollover that was coded as the first harmful event in the crash was included.

Rollover is captured differently in TIFA (which incorporates the variable from FARS). Rollover is identified as either the first or subsequent event. All first-event rollovers are included. LTCCS captures rollover in a variable that codes the rollover initiation type (modeled after the variable in the NASS CDS dataset). Turn-over (the most common), fall-over, and other rollover types were classified as untripped rollovers, while trip-over, flip-over, climb-over, bounce-over, and collision with another vehicle all were classified as tripped rollovers and excluded.[5]

Relevant loss of control events are more difficult to identify in the crash data, in part because the event itself can be difficult to detect after a crash. In the GES data, there are two variables that are primarily used to identify pre-crash loss of control, ACC_TYPE and P_CRASH2. ACC_TYPE captures the role of the vehicle in the collision, and certain of the code levels cover crash types in which the vehicle lost control prior to the crash. Among single-vehicle crashes, it was determined to include as LOC events the codes that signify control/traction loss and roadway departure to the left or right, and the codes for avoidance maneuvers and roadway departure. For multiple-vehicle crashes, relevant LOC events included those where there was control/traction loss and a collision with another vehicle, either going in the same or opposite direction.[6] It should be noted that the codes for multiple-vehicle crashes preceded by LOC are very rarely used. Most of the cases identified as relevant LOC crashes were selected using the ACC_TYPE variable.

P_CRASH2 includes code levels that are apparently ideal for the purpose. P_CRASH2 identifies the precipitating event for the vehicle, the event that made the collision imminent. Within the variable, there is a set of codes for LOC due to various factors, including vehicle failures, road conditions (e.g., ice), excessive speed, and other conditions. LOC due to vehicle failure clearly does not meet the condition for relevant-LOC crashes, but those for road condition, excessive speed, and other or unknown reasons were included, initially. However, testing this identification in the LTCCS data resulted in dropping the code for LOC due to excessive speed. On examining a number of cases coded LOC due to excessive speed in the LTCCS, it was determined that almost all were rollovers. The evidence of LOC—skid and scuff marks in the road prior to the roll—actually was most likely just part of the rollover process. That is, LOC was not an independent event, followed by rollover. Rather, the evidence of LOC was created by the rollover sequence. Since GES uses the same P_CRASH2 variable as the LTCCS, it is

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[5] This definition of tripped as including "fall-over" and the "other rollover" type may include some rollovers that are not tripped. This definition only applies in the LTCCS data, and the available investigative materials for each case are extensively reviewed to determine the relevance of the technologies.

[6] As described above, the LTCCS data were used to test the result of using different variables and code levels. Cases coded with avoidance maneuvers and skidding were examined for possible inclusion, but in the great majority of such cases, the crash sequence was not relevant to the technologies.

assumed that cases coded as LOC due to excessive speed in GES are similar to those given that code in LTCCS. Accordingly, only LOC cases coded in GES as due to road conditions or other/unknown causes (i.e., not vehicle failure) were taken as relevant LOC cases.

Jackknife, at least first-event jackknife, is clearly a product of yaw-divergence and was therefore included. Jackknifes that occur after an event such as a collision are not included. The GES JACKNIFE variable indicates whether a combination vehicle jackknifed, but not whether the jackknife was a first event. However, the first harmful event variable (EVENT1) includes jackknife at the crash level, so crashes in which a tractor-semitrailer jackknifed and jackknife was the first harmful event in the crash were viewed as relevant-LOC crashes. Note that using jackknife at the crash level to identify first harmful event at the vehicle level runs some risk of misidentification, e.g., where two combinations were involved in the same crash and both jackknifed but only one as the first event. But this should be a very rare situation. Using the method described is the only way of identifying first-event jackknifes in the GES file. The TIFA file includes the FARS variable that distinguishes first event from subsequent event jackknife, so that can be used directly to identify yaw-divergence related LOC crashes. Similarly, the AJKType variable in LTCCS identifies first-event jackknifes.

Since most of the relevant LOC crashes were identified from the ACC_TYPE variable and were single-vehicle crashes, methods were sought to find other relevant LOC crashes that involved two or more vehicles. The codes in ACC_TYPE that include prior LOC describe events that very rarely occur, or at least are very rarely recorded. However, both GES and LTCCS include variables that record pre-crash stability as part of the sequence that describes crash events. P_CRASH3 (ACRAvoidance in LTCCS) identifies crash avoidance maneuvers and P_CRASH4 (ACRStability) captures the stability of the vehicle after the maneuver, but before the crash. A selection algorithm was developed using these variables to identify cases in which the tractor-semitrailer lost yaw stability prior to a collision with another vehicle. However, when tested using the LTCCS cases with the appropriate coding, almost none of the crashes identified fit the pattern sought. Each case was reviewed by a mechanical engineer experienced in crash reconstruction. In almost all cases, the lack of stability was determined to be longitudinal skidding immediately prior to the crash. In addition, in most cases, the collision took place immediately so there was no opportunity for a stability control system to intervene. Thus, the variables that record avoidance maneuver and resulting loss of stability were not used in the crash identification algorithms.

The complete and final algorithms in GES, TIFA, and LTCCS used to identify target crash types are provided in Appendix A. Crashes identified using all the variables listed in Table 1 in some sense capture the global population of crash involvements that include rollover at any point or loss of control at any point in the crash sequence. The final algorithms used to select rollovers and LOC crashes relevant to the technologies are a subset of the global population of rollover and crashes with loss of control. The study population of crashes identified by the final selection algorithm reflects an effort to capture as closely as possible, within the limits of the information coded in the crash data, those crashes that might be addressed by the technologies. In this sense, the selection algorithms are deliberately conservative, in that they are designed to exclude crashes that at face value would not be affected by the technologies.

It should be recalled that the level of detail available in the crash data files is uneven and not always well-suited to teasing out the types of events desired. Loss-of-control crashes are especially problematic. It is certainly possible, and even likely, that some LOC events occur as precursors to one or more of the other crash configurations. But these LOC events cannot be identified using the coded data, given how crash events are captured in existing data. Similarly, there may be other rollovers that could be addressed by the technologies, but which are, in a sense, buried in the set of rollovers that appear not addressable. An example might be a rollover that was initiated by a collision that could have been avoided if the truck had been able to maintain control. Given the variables and code levels available in existing files, it is not possible to identify such cases. It is really only possible to identify relevant LOC and rollovers that occur in relatively simple crash sequences.

5 General Scope of the Problem

Through an iterative process that involved examination of the data available in the LTCCS, GES, and TIFA databases, definitions of rollover and LOC crashes were developed that are believed to be addressable by the various stability enhancing technologies. These definitions tend to be more restrictive than global definitions that include all rollover and all loss-of-control crashes. Identification of rollover crashes is fairly straightforward in the GES and TIFA databases because rollover variables can be used to determine whether a tripped or untripped rollover occurred. Identification of loss-of-control crashes is much more difficult because even though some variables in the databases indicate the presence of loss of control, the definitions do not necessarily coincide with the usage needed to determine what effect stability-enhancing technologies would have on those particular crashes.

Five years of GES and TIFA data (2000 to 2004) were combined to identify vehicles in crashes that were associated with loss-of-control or rollover outcomes. All vehicles involved in fatal crashes were removed from the GES database. Therefore, the GES database provides information for vehicles involved in nonfatal crashes. The TIFA database provides information for vehicles involved in fatal crashes. Figure 2 illustrates the combination of TIFA and GES data in the safety analysis.

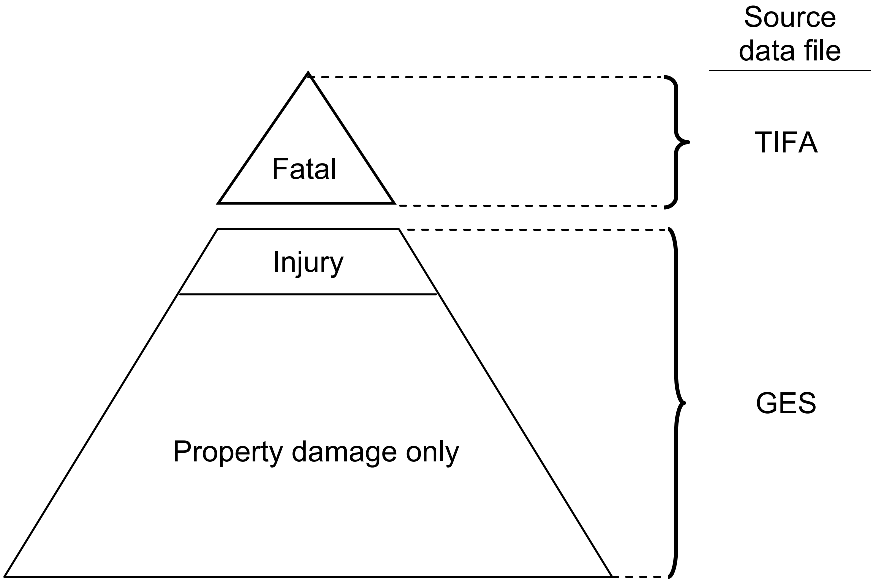

Figure 2. Combination of TIFA and GES Crash Data

This section focuses on the methods used to identify variables in the two crash databases and study definitions of rollover and loss of control. Results are presented that give an indication of the percentage of the truck population that may potentially benefit from RSC and ESC technologies in terms of the numbers of crashes and injuries. The role of antilock braking systems (ABS) and the possible effects of ABS on ESC and RSC are discussed. Finally, percentages of injury severity to people inside and outside the trucks are presented. The following definitions are applied to tractor-semitrailers.

Definitions of rollover:

1. **Rollover from untripped rollover**: In the GES database these vehicles are identified by rollover = 10. In the TIFA database, these vehicles are identified by v1059=97, accident type is untripped rollover.
2. **Rollover from first harmful event**: These vehicles include those that rolled over and rollover was coded as the first harmful event in the crash. In the GES database, these vehicles are identified by rollover > 0 and event1_i = 1. In the TIFA database, these vehicles are identified by V125=1, first event rollover.
3. **All other rollovers**: In the GES database these vehicles are identified by the rollover variable and include all rollovers not identified in 1 or 2 above. In the TIFA database, these vehicles are identified by V125=2, subsequent event rollover.

Definitions of loss of control:

1. **Loss of control from accident type**: The accident type variable (acc_type) describes control/traction loss or a maneuver to avoid collision with a vehicle, pedestrian, or animal. In the GES database, these vehicles are identified by acc_type =2, 3, 7, 8, 34, 36, 38, 40, 54, 56, 58, or 60. The TIFA database also has the accident type variable, and the same codes used in the GES database were applied in the TIFA database.
2. **Loss of control from critical event**: The critical event variable describes loss of control due to poor road conditions and other causes. In the GES database, these vehicles are identified by p_crash2 = 5, 8, or 9. In the TIFA database, these vehicles are identified by the first harmful event variable (v23=51, first harmful event jackknife).
3. **Loss of control from first event jackknife**: Vehicles in which jackknife was the first event in the crash are included. In the GES database, these vehicles are identified by jackknife=1 and event1_i = 5. In the TIFA database, these vehicles are identified by the jackknife variable (v126=2, first event jackknife).
4. **Loss of control from instability prior to the crash**: Vehicles that skidded either laterally or longitudinally, or where other loss of control was coded, are included. In the GES database, these vehicles are identified by pcrash4= 2-7. Not available in the TIFA database.
5. **Loss of control from single-vehicle run-off-the-road where the driver made an avoidance maneuver**: In the GES database, these vehicles are identified by acc_type=1, 6 and drman_av=1-5, 97 or p_crash1=17. Not available in the TIFA database.

The global definitions of rollover and loss of control include all definitions described above. Therefore, the global definition of rollover includes all rollovers. The study definition of rollover is limited to rollover definitions 1 and 2 above. The global definition of loss of control includes all five loss-of-control definitions, but the study definition is limited to definitions 1-3. The study definitions tend to revolve around first event rollover and loss-of-control crashes, while the global definitions do not make that distinction.

There has been considerable discussion about the effects that ABS has on loss-of-control crashes in addition to those provided by the stability-enhancing technologies. In an effort to adjust loss-of-control results to a standard baseline distribution of tractor-semitrailers equipped with ABS, trucks with power unit model years after 1997 were identified. (In the 2000-to-2004 crash databases, approximately half of the tractor-semitrailers have such power units.) All air-braked truck tractors built on or after March 1, 1997, were required to be equipped with ABS. To adjust the loss-of-control results to a baseline case of trucks equipped with ABS, distributions of trucks with model years after 1997 were found, and these distributions were adjusted to the population totals of all tractor-semitrailers identified in the GES and TIFA databases. Only loss-of-control results were adjusted; rollover results were not.

The estimates of LOC crash involvements adjusted for ABS reflect the best estimate of the distribution of crash types that would be observed if the whole crash population was equipped with ABS. These estimates are the target LOC crash population that may be reduced by the ESC or RSC technologies. Making this adjustment is both reasonable and desirable for two primary reasons. First, the population of tractors and trailers with stability-enhancing devices will also have ABS. All tractors manufactured since March 1997 and all semitrailers since 1998 have been equipped with ABS. Consequently, if ESC or RSC devices are added to a tractor-semitrailer, it will be to one equipped with ABS. It is thus reasonable to measure the effectiveness of the ESC or RSC technologies against the crash population experienced by ABS-equipped tractor-semitrailers. Second, the HiL simulations for estimating the effectiveness of the technologies assume a tractor equipped with ABS. There is no capability in the HiL simulations as configured to simulate a vehicle without ABS. For both of these reasons, adjusting the crash population for ABS provides the most reasonable baseline for estimates of effectiveness. It should be noted that the crash counts and distribution of rollover crash scenarios are not adjusted for ABS because ABS is not expected to affect the incidence of rollover.

Table 2 shows the distributions of crashes and injuries as a five-year annual average based on the global definitions of rollover and loss of control described above. A table of percentages is also shown. Annually, it is estimated that tractor-semitrailers are involved in 178,000 crashes resulting in 3,329 fatalities. According to the definitions described above, 90.1 percent of crashes are not associated with rollover or loss of control. The total percentage of loss-of-control crashes is 7.3 percent, but 2.0 percentage points of these also resulted in rollover. The total percentage of rollover crashes is 4.6 percent, and 2.6 percentage points of these are rollover crashes without loss of control.

Table 2. Global Definitions of Rollover and LOC – Annual Average of Crashes and People Injured Tractor-Semitrailers, LOC Adjusted for ABS (GES, TIFA 2000-2004)

LOC	ROLL	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Other
Yes	No	9,461.8	52.1	1,311.8	1,668.2	1,763.0	14,675.8	7.8
Yes	Yes	3,585.7	49.4	603.6	957.1	976.9	2,016.0	3.9
No	Yes	4,658.2	385.0	1,052.1	1,542.0	847.8	2,824.5	4.6
No	No	160,294.9	2,842.5	9,042.7	14,196.5	24,752.6	332,206.1	510.4
Total		178,000.6	3,329.0	12,010.3	18,363.8	28,340.4	351,722.4	526.7
Percent								
LOC	ROLL	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Other
Yes	No	5.3	1.6	10.9	9.1	6.2	4.2	1.5
Yes	Yes	2.0	1.5	5.0	5.2	3.4	0.6	0.7
No	Yes	2.6	11.6	8.8	8.4	3.0	0.8	0.9
No	No	90.1	85.4	75.3	77.3	87.3	94.5	96.9
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 3 shows the restricted definitions of rollover and loss of control used in this study. These are the definitions believed to be relevant to stability enhancing technologies. Based on the study definitions, 93.3 percent of crashes and 93.6 percent of fatalities are not associated with rollover or loss of control. The total percentage of relevant loss-of-control crashes is 4.5 percent, but 1.2 percent of these also resulted in rollover. The percentage of rollover crashes without loss of control is 2.2 percent. Injury severity can be compared between the two tables. It is clear that per crash, rollover crashes are the most severe.

Table 3. Study Definitions of Rollover and LOC – Annual Average of Crashes and People Injured Tractor Semitrailers, LOC Adjusted for ABS (GES, TIFA 2000-2004)

LOC	ROLL	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Other
Yes	No	5,857.1	80.5[7]	390.6	670.2	649.4	5,654.6	2.4
Yes	Yes	2,101.6	22.5	254.2	513.7	506.1	1,367.4	3.9
No	Yes	3,935.9	111.0	767.1	1,158.4	791.7	2,161.1	3.4
No	No	166,106.0	3,115.0	10,598.3	16,021.5	26,393.2	342,539.4	517.1
Total		178,000.6	3,329.0	12,010.3	18,363.8	28,340.4	351,722.4	526.7
LOC	ROLL	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Other
Yes	No	3.3	2.4	3.3	3.6	2.3	1.6	0.4
Yes	Yes	1.2	0.7	2.1	2.8	1.8	0.4	0.7
No	Yes	2.2	3.3	6.4	6.3	2.8	0.6	0.6
No	No	93.3	93.6	88.2	87.2	93.1	97.4	98.2
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

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[7] The number of fatal crashes in Table 3 in the cell LOC=Yes, Roll=No is higher than the same cell in Table 2 because some cases in the LOC=Yes, Roll=Yes moved to the LOC=Yes, Roll=No row. The definition of rollover is more restrictive in Table 3.

Based on the study definitions of rollover, Table 4 shows injury severity for people inside and outside the truck. The results apply for rollover only; that is, to the approximately 3,936 crashes shown in Table 3 where rollover is "yes" and loss of control is "no."[8] It can be seen that the majority of injuries are to truck occupants. This is particularly true for A-, B-, and C-injuries. It is likely that many of these rollover crashes are single-vehicle crashes.

Table 4. People Injured in Rollover Crashes, Inside and Outside the Truck (GES, TIFA 2000-2004)

Rollover	Fatal	A-injury	B-injury	C-injury	No injury	Other
In truck	87.6	713.7	1,146.6	699.1	2,021.5	3.6
Outside truck	21.0	53.0	9.0	90.6	137.2	0.6
Total	108.6	766.7	1,155.6	789.7	2,158.7	4.2
Percent						
Rollover	Fatal	A-injury	B-injury	C-injury	No injury	Other
In truck	80.7	93.1	99.2	88.5	93.6	85.7
Outside truck	19.3	6.9	0.8	11.5	6.4	14.3
Total	100.0	100.0	100.0	100.0	100.0	100.0

Table 5 shows injury severity to people inside and outside the truck based on the study definitions of loss of control. These results apply to the approximate 7,959 combined crashes shown in Table 3 where loss of control is "yes," regardless of rollover. In this case the numbers of fatalities inside and outside the truck are comparable, but, as in the rollover case, the vast majority of A, B, and C-injuries are to truck occupants.

Table 5. People Injured in Loss of Control Crashes, Inside and Outside the Truck, Adjusted for ABS (GES, TIFA 2000-2004)

LOC	Fatal	A-injury	B-injury	C-injury	No injury	Other
In truck	50.8	593.2	1,045.6	1,065.3	6,158.2	4.4
Outside truck	52.2	51.6	138.3	90.2	863.8	1.9
Total	103.0	644.8	1,183.9	1,155.5	7,022.0	6.3
Percent						
LOC	Fatal	A-injury	B-injury	C-injury	No injury	Other
In truck	49.3	92.0	88.3	92.2	87.7	69.1
Outside truck	50.7	8.0	11.7	7.8	12.3	30.9
Total	100.0	100.0	100.0	100.0	100.0	100.0

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[8] The numbers are slightly different from those shown in Table 3 because it was necessary to link TIFA data to the FARS Person file to break down occupants according to those inside and outside the truck, whereas results in Table 3 were derived from TIFA data alone. The differences are practically negligible. For example, Table 3 shows 111 fatalities, while Table 4 shows 108.6. Similarly, Table 3 shows 767.1 A-injuries while Table 4 shows 766.7, and so on.

5.1 Loss of Control, Rollover, and Certain Key Variables

This study focuses on the analysis of tractor-semitrailers involved in crashes that are potentially addressable by RSC and ESC technologies. Based on the study definitions described in the previous section, associations are assessed between loss of control and rollover, and seven variables. Five of the variables share common definitions in the TIFA and GES databases. Two of the variables are TIFA survey variables and are only recorded in the TIFA database. Results are limited to power units with model years after 1997 to capture associations that are representative of trucks equipped with ABS as baseline equipment. The following variables were investigated:

1. Roadway alignment (straight, curve);
2. Surface condition (dry, wet, other);
3. Trailer cargo weight in pounds (TIFA only. 0-5,000, 5,001-20,000, 20,001+);
4. Trailer body style (TIFA only. van, tank);
5. Crashes on ramps (yes, no);
6. Speed limit (0-35, 36-55, 56+); and
7. Light condition (day, dark, dusk or dawn or dark but lighted).

Associations in the following tables are assessed using odds ratios. These measures describe the odds or likelihood of rollover or loss of control based on the levels of the variable under investigation. For example, in Table 6, the variable under investigation is roadway alignment. Based on the study definition of rollover, the odds ratio is the cross-product ratio

$$\frac{5{,}255 \times 384{,}873}{3{,}744 \times 58{,}845} = 9.18$$

and indicates that the odds of rollover were about 9.2 times greater on curved roads than on straight roads. For a rare outcome such as rollover, an approximation of the odds ratio can be obtained by dividing the percentage of rollover in a curve by the percentage on straight roads. The percentages are shown in Table 6 and calculation leads to an estimate of 8.2/1.0, or 8.2. Although most of the vehicles were involved in crashes on straight roads (388,617 straight versus 64,100 curved), the odds ratio measures the likelihood of rollover according to the two levels of roadway alignment. In this case, rollover was much more likely on curved roads.

A similar calculation using the loss-of-control data shows that the odds of loss of control were about 4.7 times higher on curved roads than on straight roads. A quick approximation of the odds ratio can be made by taking the ratio of percentages12.8/3.0, which is about 4.3.

Table 6. Study Definitions of Rollover and Loss of Control by Roadway Alignment ABS-Equipped Tractors Only (GES, TIFA 2000-2004)

Rollover					
Roadway Alignment	Yes	%	No	%	Total
Curve	5,255	8.2	58,845	91.8	64,100
Straight	3,744	1.0	384,873	99.0	388,617
Total	8,998	2.0	443,718	98.0	452,716

Loss of Control					
Roadway Alignment	Yes	%	No	%	Total
Curve	8,674	12.8	58,845	87.2	67,519
Straight	12,006	3.0	384,873	97.0	396,879
Total	20,680	4.5	443,718	95.5	464,398

Table 7 shows the rollover and loss-of-control variables by surface condition. Surface condition is categorized into three levels: dry; wet; and snow, slush, or ice. Clearly, most tractor-semitrailer involvements occur on dry surfaces, but Table 7 demonstrates a clear distinction between rollover and loss-of-control involvements according to the definitions in this investigation. That is, rollover was more likely on dry surface conditions, while loss of control was more likely on wet surfaces or in road conditions with less friction. The odds of rollover on dry roads were about 1.8 times that on wet roads. Of the three surface conditions, the odds of rollover on snow, slush, or ice were smallest. In contrast, the percentage of loss of control increases steadily from dry to wet to snow, slush, or icy conditions. Compared to dry roads, the odds of loss of control were about 1.4 times greater on wet roads, and the odds were about 5.1 times greater on snow, slush, or ice.

Table 7. Study Definitions of Rollover and Loss of Control by Surface Condition ABS-Equipped Tractors Only (GES, TIFA 2000-2004)

Rollover					
Surface condition	Yes	%	No	%	Total
Dry	8,119	2.2	358,050	97.8	366,169
Wet	870	1.3	68,075	98.7	68,945
Snow, slush, ice	10	0.1	17,599	99.9	17,609
Total	8,998	2.0	443,724	98.0	452,722

Loss of Control					
Surface condition	Yes	%	No	%	Total
Dry	13,696	3.7	358,050	96.3	371,746
Wet	3,517	4.9	68,075	95.1	71,592
Snow, slush, ice	3,466	16.5	17,599	83.5	21,065
Total	20,679	4.5	443,724	95.5	464,403

Roll stability and yaw stability technologies address separate stability issues that are strongly influenced by vehicle mass. ESC systems address vehicle yaw instability manifested as understeer or oversteer. These conditions are more likely to occur when the vehicle is lightly loaded. RSC technologies address vehicle rollover that is correlated to center of mass height. Very lightly loaded vehicles will almost certainly have low center of mass height and therefore they are less likely to experience rollover. Low density loads can have high center of mass, and therefore, rollover propensity is not exclusively tied to high gross vehicle weight. Figure 3 contains a histogram of first trailer cargo weight for fatal crash frequency and was used to determine cut points for analysis. The cargo weight of 0 to 5,000 lb generates the highest number of fatal crashes and therefore was selected as the first cut point. The other cut points were determined to be 5,001 to 20,000 lb and greater than 20,000 lb. These categories are chosen to reflect light, medium, and heavy loads.

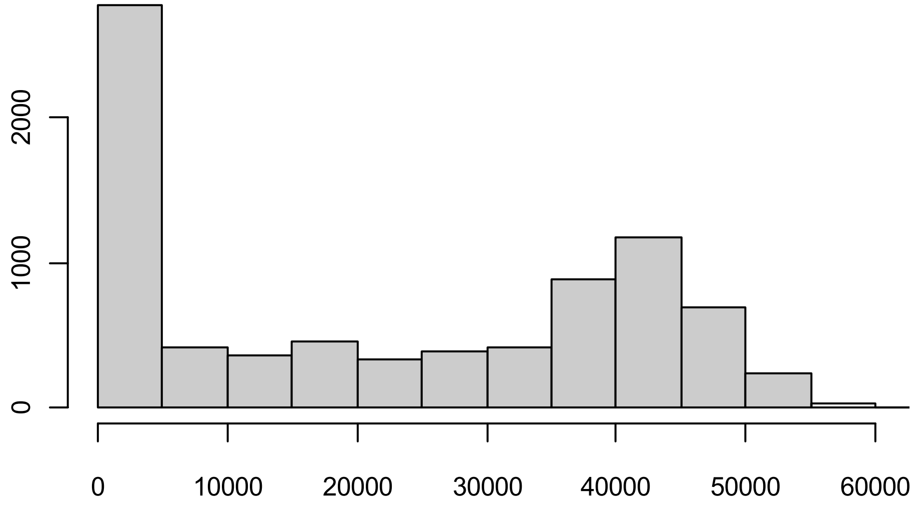

Figure 3. Histogram of First Trailer Cargo Weight (lb) (TIFA 2000-2004)

Table 8 shows rollover and loss of control according to trailer cargo weight. As expected, the odds of rollover increase as cargo weight increases. (Only fatal crash data from TIFA are included; the GES data does not capture cargo weight.) The odds of rollover were about 2.7 times greater for cargo weight in the 5,001-to-20,000-lb category compared to the 0-to-5,000 lb category. The ratio increases to 6.8 when comparing the heavy category to the light category. For loss of control, the comparative odds ratios were 1.3 and 1.5, respectively, suggesting much smaller associations between loss of control and trailer cargo weight.

Table 8. Study Definitions of Rollover and Loss of Control by Trailer Cargo Weight ABS-Equipped Tractors Only (TIFA 2000-2004)

Rollover					
Trailer cargo weight (lb)	Yes	%	No	%	Total
0-5,000	10	0.7	1,465	99.3	1,475
5,001-20,000	14	1.8	756	98.2	770
20,000+	126	4.5	2,697	95.5	2,823
Total	150	3.0	4,918	97.0	5,068

Loss of Control					
Trailer cargo weight (lb)	Yes	%	No	%	Total
0-5,000	36	2.4	1,465	97.6	1,501
5,001-20,000	24	3.1	756	96.9	780
20,000+	100	3.6	2,697	96.4	2,797
Total	160	3.2	4,918	96.8	5,078

Table 9 shows data for trailer body style. This variable is not recorded reliably in the GES database, but is recorded as one of the TIFA survey variables. The table shows that tank trailers were much more likely to roll over than van trailers. The odds ratio is approximately 4.4. For loss of control, the association is not as strong, but the odds of loss of control were 1.9 times greater for tanks compared to vans.

Table 9. Study Definitions of Rollover and Loss of Control by Trailer Body Style ABS-Equipped Tractors Only (TIFA 2000-2004)

Rollover					
Trailer	Yes	%	No	%	Total
Tank	65	8.5	699	91.5	764
Van	105	2.1	4,976	97.9	5,081
Total	170	2.9	5,675	97.1	5,845

Loss of Control					
Trailer	Yes	%	No	%	Total
Tank	37	5.0	699	95.0	736
Van	140	2.7	4,976	97.3	5,116
Total	177	3.0	5,675	97.0	5,852

The occurrence of rollover and loss of control were increased on ramps. Table 10 shows data taken from both GES and TIFA data files. The odds of rollover were 2.3 times greater on ramps than in other locations, and the odds of loss of control were 2.7 times greater.

Table 10. Study Definitions of Rollover and Loss of Control by Ramp ABS-Equipped Tractors Only (GES, TIFA 2000-2004)

Rollover					
Ramp	Yes	%	No	%	Total
Yes	1,135	4.1	26,538	95.9	27,673
No	7,864	1.9	417,191	98.1	425,055
Total	8,998	2.0	443,729	98.0	452,727

Loss of Control					
Ramp	Yes	%	No	%	Total
Yes	3,015	10.2	26,538	89.8	29,553
No	17,666	4.1	417,191	95.9	434,857
Total	20,681	4.5	443,729	95.5	464,410

Table 11 shows loss of control and rollover by speed limit. Speed limit is categorized into three levels: 0-35, 40-55, and 55+. For rollover, the effects were not great, but the percentages of rollover increase with speed limit group. The odds of rollover were 1.3 times greater in the 40-55 group compared to the 0-35 group, and 1.5 times greater in the 55+ group compared to the 0-35 group. For loss of control, the odds were greatest in the 40-55 range. The odds of loss of control were 1.6 times greater in the 40-55 range compared to the 0-35 range. The odds of loss of control were comparable between the 40-55 and 55+ ranges.

Table 11. Study Definitions of Rollover and Loss of Control by Speed Limit ABS-Equipped Tractors Only (GES, TIFA 2000-2004)

Rollover					
Speed limit (mph)	Yes	%	No	%	Total
0-35	1,815	1.6	113,592	98.4	115,407
40-55	4,235	2.0	204,994	98.0	209,229
55+	2,947	2.3	125,098	97.7	128,045
Total	8,996	2.0	443,684	98.0	452,680

Loss of Control					
Speed limit (mph)	Yes	%	No	%	Total
0-35	3,966	3.4	113,592	96.6	117,558
40-55	11,387	5.3	204,994	94.7	216,381
55+	5,326	4.1	125,098	95.9	130,424
Total	20,679	4.5	443,684	95.5	464,363

Likelihood of rollover and loss of control were both greatest during periods with dim lighting. Table 12 shows results according to light condition. The three categories considered are daylight; dark; and dusk, dawn, or dark but lighted. The odds of rollover were 2.6 times greater in dark conditions than in daylight and 6.0 times greater in dark compared to dusk, dawn, or lighted. For loss of control, the odds were about 1.7 times greater in dark than in daylight and about 2.9 times greater than in dusk, dawn, or lighted.

Table 12. Study Definitions of Rollover and Loss of Control by Light Condition ABS-Equipped Tractors Only (GES, TIFA 2000-2004)

Rollover					
Light condition	Yes	%	No	%	Total
Daylight	5,774	1.8	319,506	98.2	325,280
Dark	2,689	4.5	56,473	95.5	59,162
Dusk, dawn, lighted	536	0.8	67,746	99.2	68,282
Total	8,998	2.0	443,725	98.0	452,723

Loss of Control					
Light condition	Yes	%	No	%	Total
Daylight	14,488	4.3	319,506	95.7	333,994
Dark	4,378	7.2	56,473	92.8	60,851
Dusk, dawn, lighted	1,815	2.6	67,746	97.4	69,561
Total	20,680	4.5	443,725	95.5	464,405

5.2 Jackknife and ABS

All air-braked truck tractors sold in the United States built on or after March 1, 1997, are required to be equipped with antilock braking systems. The following tables are used to assess associations between the model year and jackknife. Jackknife is defined as a first-event jackknife. Results from the TIFA and GES databases are presented separately.

Table 13 shows first-event jackknife by the power unit model year for trucks involved in fatal crashes. Before 1998, the percentage of jackknife was 3 percent, while after that period the percentage reduced to 1.8 percent. The odds of jackknife were 1.6 times greater before 1998 with a 95 percent confidence interval of (1.3, 2.2).

Table 13. First Event Jackknife by Model Year (TIFA 2000-2004)

Power Unit Model Year	Jackknife	%	None	%	Total
Before 1998	104	3.0	3,405	97.0	3,509
1998 and Later	101	1.8	5,433	98.2	5,534
Total	205	2.3	8,838	97.7	9,043

For nonfatal crashes, the reduction in jackknife crashes since 1998 is even more pronounced. Table 14 shows that before 1998 the percentage of jackknife was 2 percent, while after that period the percentage reduced to 0.6 percent. The odds of jackknife in this case are 3.5 times greater before 1998 with a 95 percent confidence interval of (2.2, 5.7). The overall conclusion is that while ABS has reduced first-event jackknife, it has not eliminated it as a crash event.

Table 14. First Harmful Event Jackknife by Model Year (GES 2000-2004)

Model Year	Jackknife	%	None	%	Total
Before 1998	9,180	2.0	444,940.0	98.0	454,120
1998 and Later	2,754	0.6	469,779.0	99.4	472,533
Total	11,934	1.3	914,719.0	98.7	926,653

6 Engineering Evaluation of Relevant Crashes in LTCCS and TIFA

One of the most complex challenges of this study was establishing a reliable estimate of the proportion of crashes that could be addressed by these technologies. There is an inherent uncertainty in estimating how technologies will behave in real-world crashes. This is true of any analysis method open to the research team, since, however accurately the method is applied, key inputs, such as curve entry speed, vehicle loading conditions, and the line taken through the curve (driver input), have to be assumed. The vehicles involved in crashes were of course not instrumented, so the crash analyst was dependent on the evidence preserved by the crash investigators. Ultimately, a combination of methods was used to obtain estimates of the effectiveness of the technologies. Hardware-in-the-loop simulation was used for crash types and conditions that would support it. Some crash events could not be simulated, and an expert panel was employed, informed by the simulated behavior of the devices in various situations. A full explanation of the methods used to derive effectiveness estimates is in the next section. This section describes the LTCCS crash data used in preparing the estimates.

LTCCS data were used to provide specific examples of the types of crashes identified in the national crash data (TIFA and GES) as relevant to the ESC and RSC technologies. The LTCCS data contains high quality comprehensive narrative descriptions of crashes. The LTCCS cases provide details of the crashes to support the HiL simulation, including road surface condition, road curvature, cargo type, and weight to estimate center-of-gravity height, and some account of the driver's actions. These details also support engineering judgments on the likely effect of the relevant technologies in specific crashes. Case materials available include a detailed researcher's summary of the crash and crash diagrams. The researcher's narrative is particularly useful because it typically provides a summary of the salient events leading to the crash. The LTCCS effort was specifically designed to be a causation study for heavy trucks, rather than a crashworthiness or purely descriptive database. Accordingly, it includes many data elements that bear on the factors and events that have been found to be part of and contribute to truck crashes, such as cargo loading, jackknife, and rollover.

As described above, the LTCCS data files include data elements that are either identical with those in GES and TIFA or contain sufficient information to be reasonably mapped to GES or TIFA data elements. The crash selection algorithm, developed in an iterative process in GES and TIFA, and tested in LTCCS, was then exercised in LTCCS to select relevant LOC and rollover cases for a detailed evaluation.

Applying the crash selection algorithm developed in the iterative process among TIFA, GES, and LTCCS data, selected a set of 164 LTCCS cases. Eighty-one of the crash involvements were classified by the selection algorithm as rollovers and 83 as LOC. Each selected LTCCS crash was reviewed in detail to determine whether the crash characteristics were consistent with first event roll instability or first event yaw instability.

Note that this review resulted in a classification of each crash as roll or LOC that was independent of how the case was coded in the LTCCS data. In a substantial number of LOC cases, the review resulted in a different classification from the LTCCS coding. LOC, defined as yaw instability in the study population, is much more difficult to identify than rollover. As a result of the review of LTCCS cases, 37 of the 83 LOC cases did not show any evidence of identifiable yaw. Thirty-two of these included a roll, and so these cases were moved to the rollover group. Five of the 37 did not include roll, so they were dropped from the analysis. The estimates of the national crash totals from GES and TIFA were adjusted for this result when estimating the benefits of the technologies.

The following selection of LTCCS italicized case narratives illustrate the types of crashes identified by the selection algorithm, as well as the detail provided by the case narratives that are useful to the process. The specific examples were selected to show crash features that are particularly relevant to the technologies. The examples have been edited for brevity; complete versions are included in Appendix B.

Example 1 – Roll instability, no yaw instability

LTCSS Case 813005655 Vehicle # 1

The driver of the 1999 Freightliner tractor pulling one closed van semitrailer, a 39-year-old male, was traveling south on a 2-lane interstate in the first lane of travel approaching a one-lane exit ramp. The trailer was filled to 50 percent capacity with general freight. The driver of the truck intended to exit at the ramp and began decelerating from the interstate's posted speed of 113 km/h (70 mph) to the ramp's posted speed of 40 km/h (25 mph). The truck driver estimated his speed at between 40-56 km/h (25-35 mph) as he entered the sharp right curve of the ramp. As he got midway into the curve, the rig began to cant to the left and then rolled over one-quarter turn onto its left side. The truck came to final rest facing west on the roadway and left shoulder. The radius of curvature of the *ramp as measured was 57.25 meters and the superelevation was 5 percent. The Critical Reason for the Critical Event was coded as "too fast for curve," a driver decision error. This was chosen because it was believed that the driver of the truck was traveling in excess of the posted speed limit and that this speed, combined with the curve of the road and the truck's high center of gravity, caused the truck to roll over. It was believed that the truck driver was truthful when he stated that he was only traveling between 40-56 km/h (25-35 mph) as he entered the curve, because the curve just barely met the AASHTO standard for a posted speed limit of 40 km/h (25 mph). It was believed that due to the tight curve and the lack of "leeway" in terms of the posted speed limit, that the truck driver probably was only exceeding the speed limit by 10 mph. However, this extra speed was enough to cause the truck to roll over, given its higher center of gravity. … Although police cited a cargo shift as the cause of the crash, it was unlikely that a load of general freight (most of it on pallets) could shift on its own enough (en masse) to roll an entire truck…In summary, the crash occurred when the truck driver entered the exit ramp at a speed too great to safely negotiate the sharp curve. The speed of the truck, combined with the curve of the road and the truck's high center of gravity was the most likely reason for the rollover.*

The incident is an example of a roll instability crash to which ESC or RSC technologies would be applicable. There was no evidence of directional instability that would only be addressed by ESC functionality.

Example 2 – Roll instability, yaw instability

Case 815004312 Vehicle # 2

A single-vehicle crash occurred on an eight-lane urban interstate freeway. A concrete barrier divides the freeway with eight lanes in either direction. The crash occurred on the southbound lanes that curve to the right. This section of the roadway is level with no defects. The speed limit on the roadway is 55 mph (89 km/h). At the time of the crash, the road was wet from rain.

Vehicle two, a 2000 Freightliner tractor pulling a 1994 Great Dane van trailer was negotiating the right hand curve. As the Freightliner was negotiating the curve the trailer swung out to the left due to a cargo shift. The driver attempted to correct by steering left, right and then left again. The trailer rolled over onto its left side. The trailer rolled completely onto its left side, then the tractor rolled over onto its left side and both slid across the southbound lanes. After the trailer had rolled over the cargo broke through the top of the trailer and spilled onto the roadway. The tractor contacted the center Jersey barrier with its top, continued and the top of the trailer struck a light support pole. The Freightliner came to rest facing in a southerly direction on its left side. After the Freightliner had come to final rest and stabilized, a second vehicle came along and lost *control when it drove through the magazines and slid and impacted both the trailer, and the center median wall. This vehicle was not included in this case due to the stabilization of the first crash sequence and both crashes had the same KABCO reported level of a "B" (visible) injury. The Freightliner was towed due to damage.*

The incident is an example of a crash including yaw instability and roll instability, which may benefit from ESC or RSC devices.

Example 3 – Roll instability, possible yaw instability

Case 344007015 Vehicle # 1

*A single-vehicle crash occurred on an eight-lane concrete urban interstate in the dark at approximately 0430 hours. The roadway was lit with overhead streetlights. There were four southbound lanes and four northbound lanes divided by a concrete median barrier wall. To the right of the wall was a concrete shoulder without rumble strips with a solid painted yellow fog line separating it from lane four. Painted white dashed lines separated the travel lanes. To the right of lane one was a solid painted white fog line and a concrete shoulder without rumble strips. The road curved to the right and was level. An overpass is located in the crash area with concrete pillars supporting it. The speed limit on the roadway is 55 mph (89 km/h). A moderate rain was occurring at the time of the crash so the road was wet with light traffic density. The rain reduced the road friction and made the travel lanes slick. This was considered a roadway factor for vehicle one. The temperature was approximately 60 degrees. **Vehicle one**, a 1999 Kenworth conventional tractor with a sleeper berth, pulling an empty 1998 Kentucky moving van semitrailer was traveling southbound in the first lane. As the Kenworth was negotiating the right curve the trailer began to swing out left and the driver tried to correct but lost control. The vehicle slid across all travel lanes to the left and either the front plane or the front portion of the right plane struck the concrete barrier, before the bridge breaking a hole through the wall. The vehicle then went into a full jackknife... At the time of the crash, it was raining moderately and the police report indicated that the roads were wet with water on the road in places. It appears that this driver did not realize that he was driving too fast for conditions. As the driver was negotiating the curve, the trailer, which was nearly empty, swung to the left due to speed and the wet roads. It was then that the driver lost control. The pre-event movement for the Kenworth was coded as "(14) negotiating a curve..” The critical pre-crash event for the Kenworth was coded as "(06) this vehicle loss of control due to: traveling too fast for conditions.” The critical reason for the crash that was attributed to the Kenworth was coded as a driver decision factor: "(140) too fast for curve/turn. This driver was traveling too fast on the curve in the wet weather, with a nearly empty trailer.”*

The incident is an example of a yaw instability crash, without roll instability addressable by RSC. The loss of control was initiated by trailer swing followed by tractor lost control. Due to high speed and initial trailer swing leading to complete loss of control, it was concluded that ESC could possibly have been effective at preventing tractor loss of control.

Example 4 – Roll instability, no yaw instability

Case 329006101 Vehicle # 1

Vehicle 1 was a 2000 Sterling tractor pulling a 1998 Great Dane refrigerated semitrailer on a two-lane north/south undivided rural road with a posted speed of 40 mph. The weather was clear, the roadway dry and it was daylight at the time of the crash. A one-lane pullover ramp that is used as a bus stop was located adjacent to the right side of the roadway. Driver 1 pulled into the bus stop ramp and completed the paperwork from his last delivery. When Driver 1 completed his paperwork, he attempted to turn right and return to the two-lane road. The left front corner of the trailer hooked a low telephone cable. The "1,200-pair" telephone cable, which was approximately 4 inches in diameter, formed swag between telephone poles. The mid-distance between two telephone poles was just off the center of the bus stop exit. As Vehicle #1 accelerated from the bus stop ramp the slack in the swag pulled tighter until it pulled the tractor and trailer onto their right sides.

The incident is an example of a crash without the yaw instability or roll instability addressable by the technologies. The rollover was the result of forces not associated with vehicle dynamics; therefore, ESC or RSC technologies could not have prevented the rollover.

6.1 LTCCS Cases for Effectiveness Estimates

The case selection algorithm developed to identify candidate roll and LOC events in the GES and TIFA data were applied to LTCCS to select cases to develop effectiveness estimates for each technology. The LTCCS cases are used as a sample of crashes that represent the types of crashes identified in the national data. A total of 83 LTCCS cases met the relevant yaw instability crash type criteria and 81 LTCCS cases met the relevant roll instability crash criteria, for a total of 164 cases selected for review. (The crash type criteria are defined to be mutually exclusive.) The review resulted in changes in the crash classification. Thirty-seven LOC cases did not show any evidence of LOC as defined here (yaw instability). Of these, 32 were simple rollovers and so were re-classified as roll; 5 were dropped, since they had no LOC relevant to the technologies, nor did they roll over. Removing the 5 miscoded LOC cases resulted in 159 LTCCS cases that contributed to the effectiveness estimates.

6.1.1 Scenario Development

Researchers developed scenarios for all relevant LTCCS crashes in the specific categories of rollover- and yaw-related crashes. Common crash factors found in the cases were identified and grouped into bins reflecting particular crash scenarios. In many cases, the crashes were individual enough to warrant single-case-only scenarios.

Each case was reviewed intensively for crash events and characteristics that might be addressable by both the ESC and RSC technologies. Though crashes were selected as roll or LOC crashes, at this stage the entire set of 159 crash involvements was considered for both technologies. The review identified cases coded as LOC that were simple rollovers. Similarly, we found cases in the group classified as roll-relevant by the coded data that included events that could be addressed by ESC.

Each case was reviewed and classified for consideration by the expert panel or for translation into simulation scenarios. The HiL simulations were run in the baseline ABS-only case, and then for each of the ESC and RSC technologies. The results of the simulations quantify the performance of the technology for a small number of grouped scenarios, and then were applied to a distribution of truck curve entry speeds to predict the probability of preventing each individual rollover crash event. Given the complex nature of truck crashes and the subtle but important variations that are impractical to categorize, the most reliable method to determine effectiveness for the scenarios not well covered by HiL was to use a panel consisting of two UMTRI scientists to evaluate each crash using the actual circumstances of each individual crash. Prevention ratios were determined by the panel for each crash and were used in the benefits equation.

The panel members were Peter Sweatman and John Woodrooffe. Both are mechanical engineers with over 25-year5-Years of direct experience in heavy-truck vehicle dynamics, simulation, accident reconstruction, and vehicle and component testing. The panel reviewed the LTCCS cases together in the same room at the same time following a prescribed method documented in section 6.6 of this report.

6.2 How HiL Was Used and Linked to the Crash Data

This section describes the method used to link the crash data to the hardware-in-the-loop simulation results. The method allows the HiL simulations to be mapped directly to the LTCCS target crash population, and through the LTCCS cases to the national population.

The majority of cases were found to be unsuitable for analysis using HiL because of the complexity of the crash event or because of limitations of the HiL system. For example, no loss of control cases could be modeled due to insufficient data on driver input, vehicle position, or because of limitations of the driver model in path follow maneuvers. During such maneuvers, the path follow driver model responded to the ESC intervention by grossly over–correcting, setting up an oscillatory steering response that was inconsistent with the typical driver response. Nevertheless the following analysis categorizes the factors that would be suitable for HiL simulation assuming the simulation was robust enough to successfully replicate the event.

A set of factors, and a set of levels within each factor, were defined based on four principal considerations:

1) The factors identify conditions, actions, or states that are tightly bound to the process of the two target crash types, rollover and LOC.
2) The factors can be identified in the LTCCS crash data, either in the coded data (e.g., vehicle descriptors, roadway surface condition, etc.) or in the narrative and scene diagram.
3) The factors can also be identified in the HiL simulation runs as vehicle conditions (e.g., trailer load, CG height, etc.), environmental conditions (roadway friction), or events (e.g., driver incapacitation, driver correction, lane deviation, rollover initiation point, etc.).
4) The factors and levels can be mapped back to the national crash data as captured in the TIFA and GES files.

The factors and levels are shown in Table 15. It should be noted that not all of the levels that can be coded from the LTCCS cases can also be identified in the GES/TIFA data. For example, GES and TIFA only distinguish straight and curved roads, not the radius of curvature. Rollover initiation point is also not identified with respect to roadway curvature. Therefore as with the safety analysis, the direct link between the HiL and the safety analysis were made through the LTCCS dataset to establish prevention ratios and then the prevention ratios were applied to the GES/TIFA subsets that were harvested using the original case selection algorithms. Benefits are aggregated over certain variables in the GES/TIFA databases to arrive at overall benefits.

Table 15. Factors and Levels for Target Rollover Crashes

Factor #	Descriptor	Levels
1	Curve radius	1. Radius ≤100m 2. Radius >100m 3. Straight
2	Curve radius change	1. Yes 2. No
3	Location of initial rollover (or surrogate in HiL)	1. On or near straight segment 2. Within 100 m of start of curve 3. Beyond 100 m of start of curve

Factor #	Descriptor	Levels
4	Driver makes a sudden correction	1. No sudden input from driver 2. Sudden correction (steer) 3. Sudden correction (brake) 4. Sudden correction (steer and brake)
5	Driver incapacitated	1. Yes 2. No
6	Maximum lane deviation prior to rollover – includes directionality, and typically associated with avoidance maneuver. Can include road departure.	1. Large deviation to outside of curve 2. Minor or no lane deviation 3. Large deviation to inside of curve 4. Off road
7	Friction	1. Low (rain, possibly mixed with ice or snow) 2. High (dry)
8	Trailer load	1. Unloaded 2. Fully loaded
9	CG Height	1. Medium 2. High

6.2.1 Evaluating Effectiveness

Simulations for rollover were run without RSC or ESC technology to determine where rollover initiation occurs on a tangent transitioning to a constant radius curve for curve radii of 68 m and 227 m; these radii represent the average curve radii in the broad categorization of LTCCS rollover curves with a radius less than or equal to 100 m and more than 100 m. (The specific values for radius of curvature, 68 m and 227 m, were computed as the mean radii of LTCCS cases classified as less than or equal to 100 m and greater than 100 m respectively.) This maneuver contains the essential curving elements of typical highway curve design. The simulations assume that the truck negotiates the prescribed curve without deviation at a constant speed. For both cases, the critical speed (V_c, the minimum speed that the vehicle can travel and roll over, i.e., if the vehicle travels any slower, rollover will not occur) of the vehicle is established by iterative simulation.

Figure 4 through Figure 7 show the results from exploratory simulations where V_c (critical curve speed) is established and then the vehicle speed is increased incrementally in successive runs to a terminal velocity of 120 km/h. As the vehicle curve entry speed increases, the point of rollover initiation occurs earlier in the curve sequence. From this we can conclude that any vehicle that enters a curve with a radius between 100 m and 200 m at or above its critical speed will initiate rollover within the 100 m of the start of curve. Similarly, any vehicle that can survive the first 100 m of the curve can be assumed to have entered the curve below the critical speed and has rolled over due to other factors such as acceleration in the curve, decreasing curve radius, or some dynamic steering input. It is also clear from these plots that rollovers occurring at or near the tangent curve interface strongly suggest either a failure of the vehicle to adequately follow the curve, or extremely high speed. It was concluded that "failure to follow curve" cases would not benefit from the technology, and that curve entry at extremely high speed would preclude assistance of the technology.

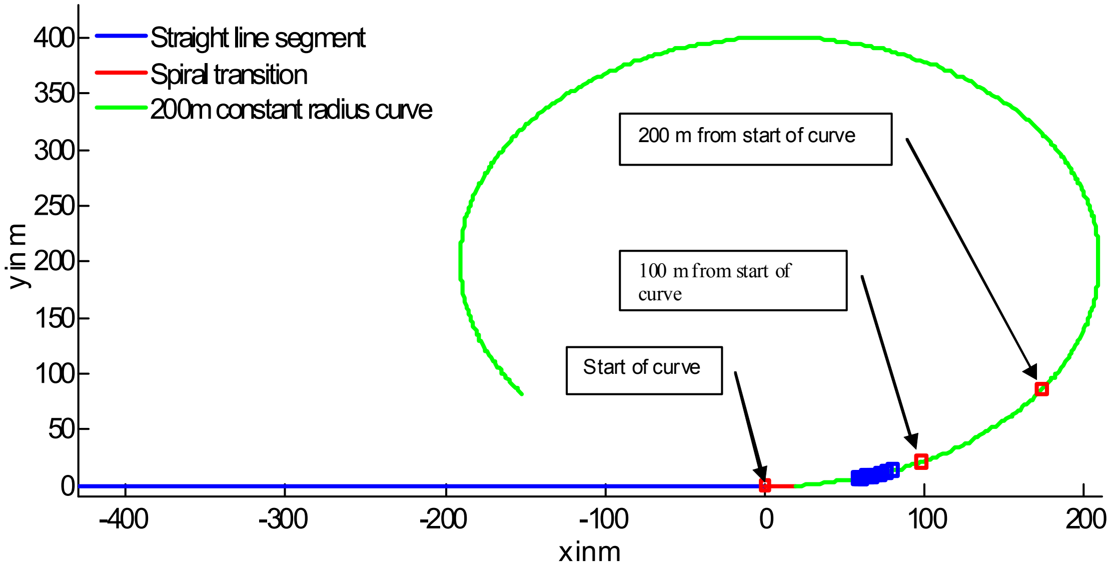

Figure 4. Points of Rollover on Transition Spiral to 200 m Radius (The constant radius curve portion is distorted in this figure)

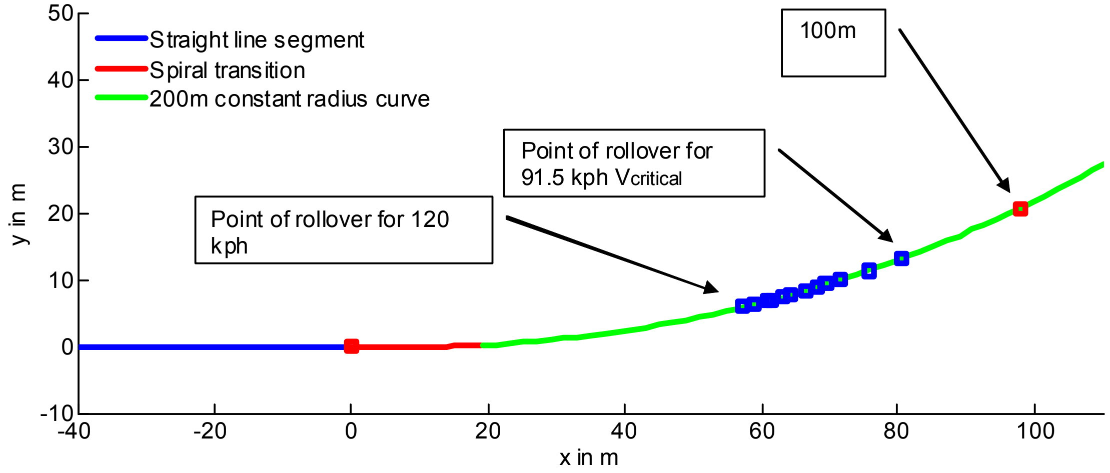

Figure 5. Zoomed-in View of Points of Rollover on Transition Spiral to 200 m Radius

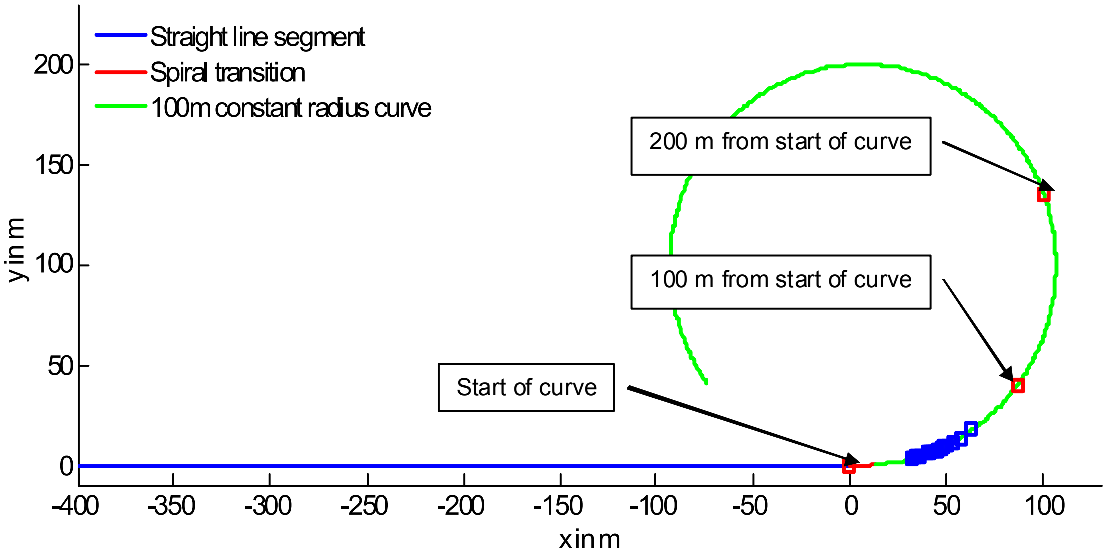

Figure 6. Points of Rollover on Transition Spiral to 100 m Radius

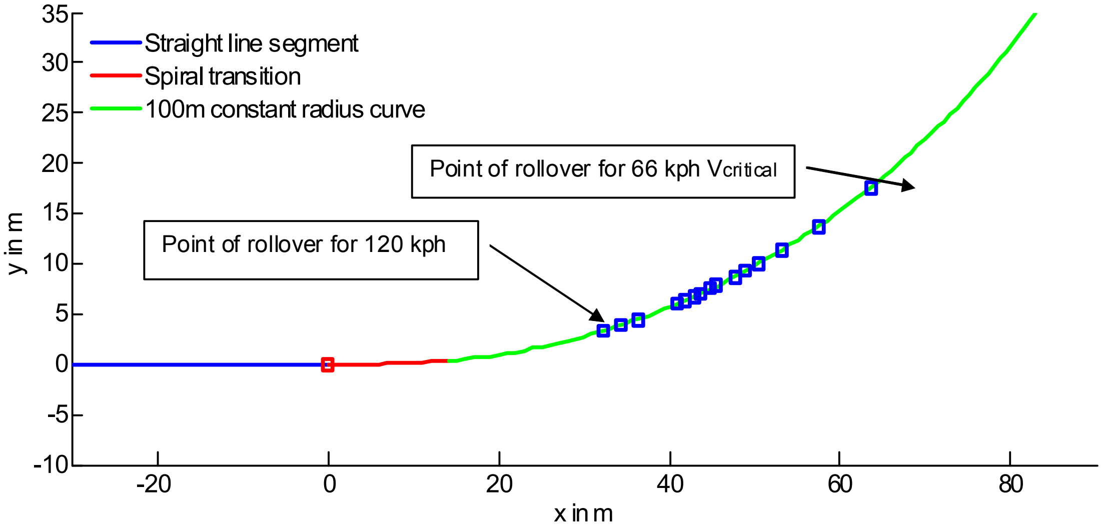

Figure 7. Zoomed-in View of Points of Rollover on Transition Spiral to 100 m Radius

Figure 8 shows how ESC and RSC modify vehicle speed upon entry into the curve. The technology significantly reduces vehicle speed within 3 seconds of curve entry. Given the conditions above and considering the manner in which the technology reduces speed in the early part of the curve, it can be assumed that any vehicle that survived the first 100 m did not enter the curve above the critical speed and that rollover events initiated after the first 100 m of a curve were most likely due to perturbing factors such as vehicle acceleration, diminishing curve radius, or some significant steering input. All of these factors would be manageable by the technology; therefore it is accepted that most rollover initiations occurring after the first 100 m of the curve onset would be prevented by both RSC and ESC. Field testing and sample HiL simulation confirmed this assumption. Rollovers initiated at or near the tangent curve interface (within 2 seconds of curve entry) could not be simulated, but each of these rollovers was assessed by an expert panel and assigned prevention ratios.

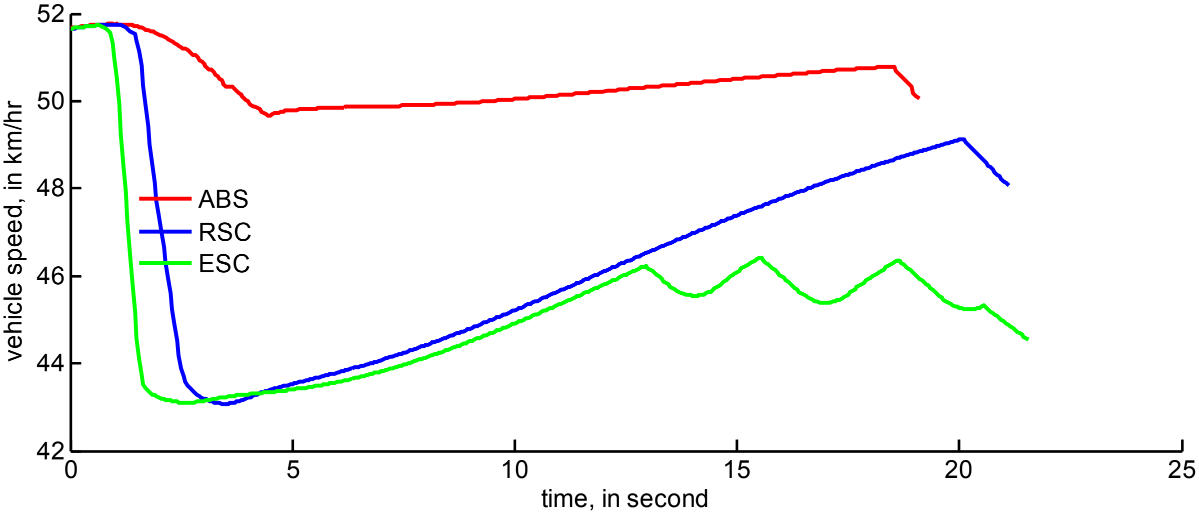

Figure 8. Speed Modulation Curves for RSC and ESC in Relation to ABS Base Case (Full payload, 2.0m CG height, 50 m radius curve)

Rollover initiations that occur after the tangent curve interface but within 100 m of the beginning of the curve require special study to resolve the prevention ratio. Table 16 contains data on rollovers identified from the subset of LTCCS cases used in this study. For the two curve radius conditions, there were 74 (46 + 28) cases, 3 occurred at the start of the curve, 30 within 100 m of the start of curve, and 41 after 100 m into the curve.

Table 16. Distribution of Rollovers on Curve: By Curve Radius and Roll Initiation Position

Radius	On/near straight	Within 100m of curve start	Past 100 of curve start	Grand Total
Straight	10	0	0	10
Less than 100m	3	23	20	46
More than 100m	0	7	21	28
Grand Total	13	30	41	84

6.3 Generating Rollover Scenarios

LTCCS cases relevant to roll control technologies were thoroughly reviewed to identify detailed conditions to support simulation. The factors identified include a classification of the radius of curvature (≤100m, >100m, or straight), roadway friction (high or low), a classification of the point along the curve where the roll initiated (on/near straight, within 100 m of curve start, or past 100 m of curve start), driver input (none, steer only, steer and brake, or brake only), trailer load (full, medium, or empty), center-of-gravity height (CG) (high, medium, or low), and whether the roll occurred at an intersection. Several other factors were also coded, including driver incapacitation, lane deviation, and radius change.

Table 17 shows the cross-classification of the factors and the number of cases that fall into each unique combination of factors and levels. As an example, 10 LTCCS cases fall into Scenario 1, which is a roll occurring on a curve with a radius 100 m and under, with high roadway friction (dry road), where the roll initiation point was 100 m past the curve start, the driver made no sudden input, the trailer load was medium, the CG height was medium, and the roll was not at an intersection. The 35 scenarios are listed in descending order of frequency. (The scenarios are not numbered because they underwent numerous revisions and it became impractical to renumber at each iteration.)

Table 17. Rollover-Relevant Scenarios

Scenario	Cases	Curve Radius	Road Friction	Roll Initiation Location	Correction	Trailer Load	CG Height	Intersection?
1	10	≤ 100m	High	Past 100M of curve start	No sudden input	Medium	Medium	No
2	6	≤ 100m	High	Past 100M of curve start	No sudden input	Fully loaded	Medium	No
3	6	≤ 100m	High	w/in 100M of curve start	No sudden input	Fully loaded	Medium	No
4	5	> 100m	High	Past 100M of curve start	No sudden input	Fully loaded	Medium	No
5	4	≤ 100m	High	w/in 100M of curve start	No sudden input	Medium	Medium	No
6	4	> 100m	High	Past 100M of curve start	No sudden input	Fully loaded	(High)	No
7	4	> 100m	High	w/in 100M of curve start	No sudden input	Medium	Medium	No
8	3	≤ 100m	High	Past 100M of curve start	No sudden input	Fully loaded	(High)	No
9	3	> 100m	Low	Past 100M of curve start	No sudden input	Medium	Medium	No
10	3	≤ 100m	High	On/near straight	No sudden input	Medium	Medium	No
11	2	≤ 100m	High	w/in 100M of curve start	No sudden input	Fully loaded	(High)	No
12	2	> 100m	High	Past 100M of curve start	No sudden input	Medium	(High)	No
13	2	> 100m	High	Past 100M of curve start	No sudden input	Medium	Medium	No
14	2	> 100m	High	w/in 100M of curve start	No sudden input	Fully loaded	(High)	No
15	3	Straight	High	On/near straight	Sudden steer input	Fully loaded	(High)	No
16	3	Straight	High	On/near straight	Sudden steer input	Fully loaded	Medium	No
18	1	≤ 100m	High	Past 100M of curve start	No sudden input	Medium	High	No
19	1	≤ 100m	High	w/in 100M of curve start	No sudden input	Fully loaded	(High)	Yes
20	3	≤ 100m	High	w/in 100M of curve start	No sudden input	Fully loaded	Medium	Yes
21	1	≤ 100m	High	w/in 100M of curve start	No sudden input	Medium	(High)	Yes
22	1	≤ 100m	High	w/in 100M of curve start	No sudden input	Medium	(High)	No
25	1	≤ 100m	Low	w/in 100M of curve start	No sudden input	Fully loaded	(High)	No
26	1	≤ 100m	Low	w/in 100M of curve start	No sudden input	Fully loaded	Medium	No
27[1]	1	≤ 100m	Low	w/in 100M of curve start	Sudden brake & steer	Fully loaded	Medium	No
28[2]	1	≤ 100m	Low	w/in 100M of curve start	Sudden brake input	Medium	Medium	No
29[2]	1	≤ 100m	Low	w/in 100M of curve start	Sudden steer input	Unloaded	Low	No
30	1	> 100m	High	Past 100M of curve start	Sudden steer input	Fully loaded	(High)	No
31	1	> 100m	High	Past 100M of curve start	Sudden steer input	Fully loaded	Medium	No
32	2	> 100m	High	Past 100M of curve start	Sudden steer input	Medium	Medium	No
33	1	> 100m	High	w/in 100M of curve start	No sudden input	Medium	(High)	No
34	1	> 100m	Low	Past 100M of curve start	No sudden input	Fully loaded	Medium	No
35[3]	1	Straight	High	On/near straight	Sudden brake & steer	Medium	Medium	No
36[3]	1	Straight	High	On/near straight	Sudden brake input	Unloaded	Low	No
37	1	Straight	High	On/near straight	Sudden steer input	Medium	(High)	No
38	1	Straight	High	On/near straight	Sudden steer input	Medium	Medium	No

Scenario 27[1]– Multiple opposite curves with vehicle rolling over on second curve, not to be simulated.
Scenario 28[2] and 29[2] – Trailer swing without tractor influence, not to be simulated
Scenario 35[3] and 36[3]– No ABS on vehicle – locking brakes resulted in loss of directional control, not to be simulated
(High) signifies that these will be treated as medium CG cases but we will perform a spot check to verify.

6.4 Establishing Prevention Ratios

Prevention ratios for rollover cases were evaluated through the combination of HiL simulation, field test information, and expert panel assessment. Rollovers that occurred at or near the start of the curve were evaluated on a case-by-case basis by the expert panel. Rollovers that occurred after 100 m into the curve were found to be highly addressable by RSC and ESC, so a generalized prevention ratio of 95 percent was applied to both technologies. The remaining rollover cases that occurred within the first 100 m into the curve were evaluated deterministically with HiL using the following logic.

Figure 9 through Figure 11 show points of rollover on transition spirals of 100 m and 200 m radii. The plots show the locations of rollover in the curve based on the entering speed of the vehicle. The plots also show the critical speed $V_{c,}$ such that rollover would not occur if a vehicle entered the curve at a speed less than V_c. Figure 10 is a reproduction of Figure 9, which shows a zoomed-in view of the points of rollover on a transition spiral of a 100 m radius for a vehicle equipped only with ABS. All points of rollover are within 100 m of the start of the curve (0,0). It can be seen that a vehicle entering the curve at a speed of less than 66 km/h will not roll over, unless other factors are present (such as acceleration in the curve, decreasing curve radius, or dynamic steering input).

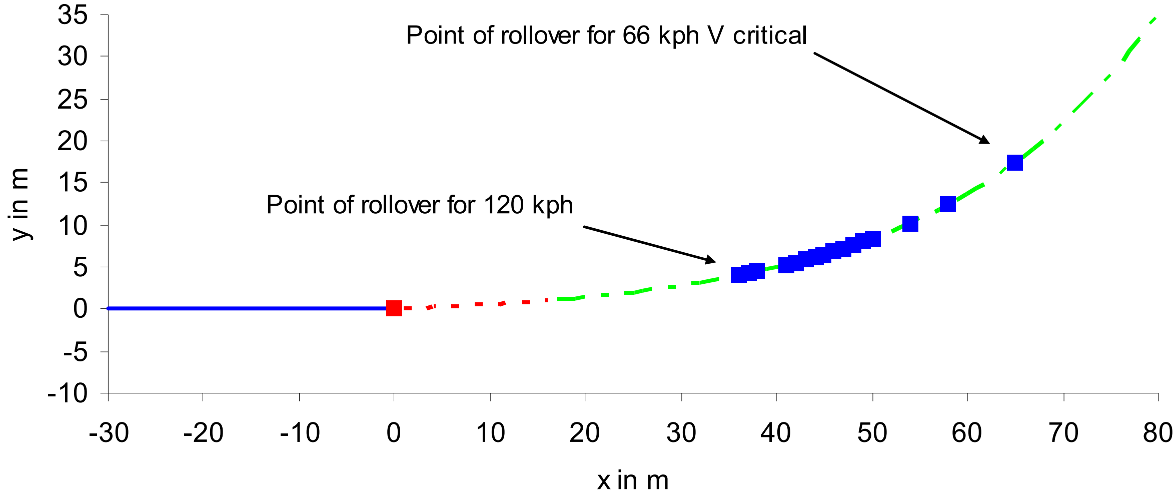

Figure 9. Zoomed-in View of Points of Rollover on Transition Spiral of 100 m Radius (ABS Case) by Varying Speed for a Single Case

If a vehicle is equipped with ESC or RSC, it is expected that the points of rollover in the plots will shift, due to the benefits that the technologies produce. For example, Figure 10 shows a hypothetical plot of a zoomed-in view of the points of rollover on a transition spiral of a 100 m radius for a vehicle equipped with ESC.[9] Note that the points are shifted to the right and that the critical speed is 76 km/h. Therefore, a vehicle entering the curve at less than 76 km/h will not roll over in the absence of other contributing factors, as discussed above.

Figure 11 is equivalent to Figure 9, except that the critical speed under ESC (76 km/h) is added to the plot. The points of rollover between 67 km/h and 76 km/h, which are highlighted in red, represent the benefit of the ESC technology relative to the baseline ABS case. The performance improvement of the technology can be expressed as the increase in critical speed (in this example, 76 – 67 = 9 km/h). To extend the performance improvements to effectiveness ratios, the performance improvement is translated to the likelihood of crash avoidance using a method discussed in Section 7 of this report.

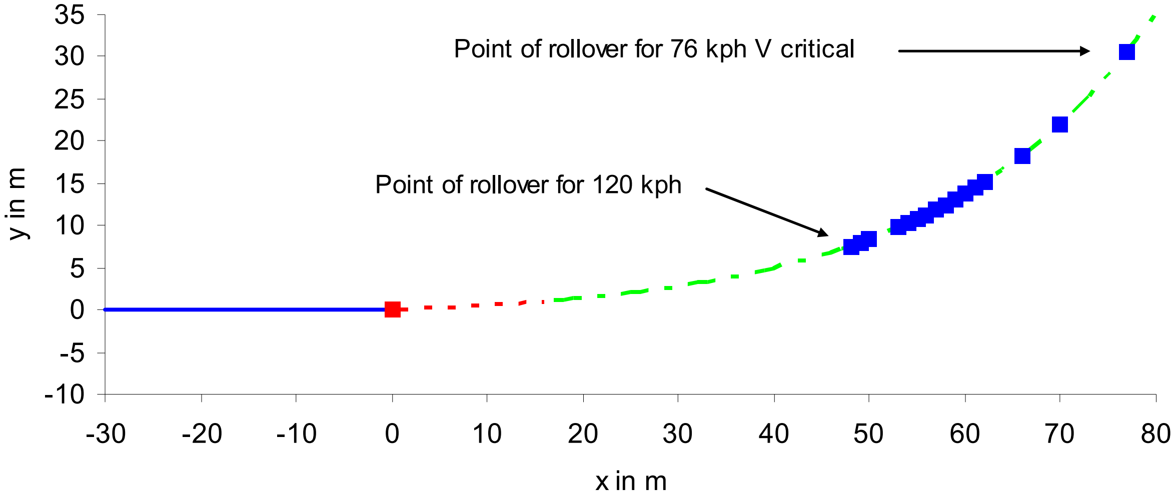

Figure 10. Zoomed-in View of Points of Rollover on Transition Spiral

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[9] HiL simulation was used to determine the actual values.

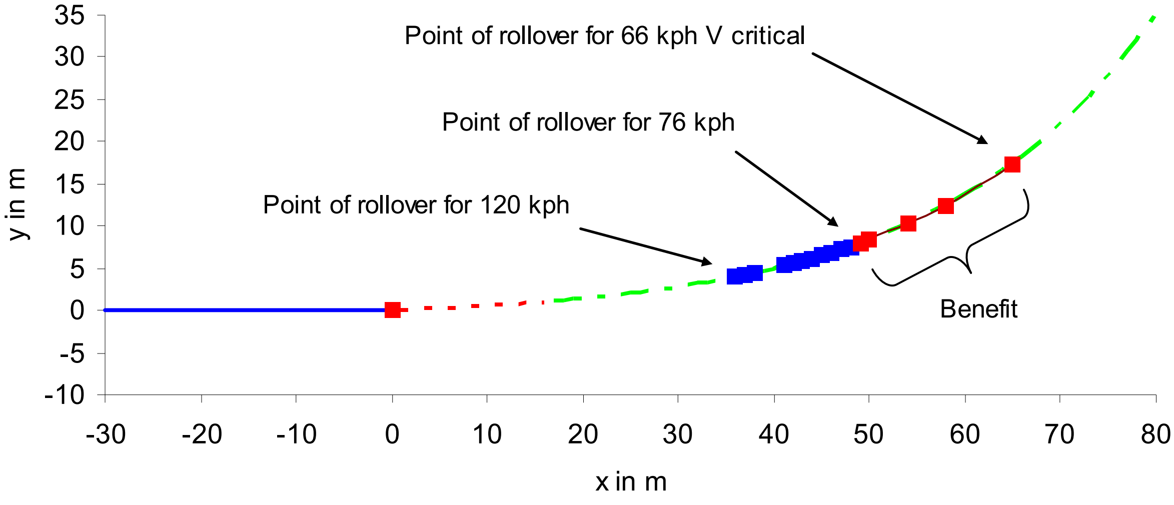


Figure 11. Zoomed-in View of Points of Rollover on Transition Spiral of 100 m Radius (ABS Case)

Table 18 shows the high-level crash scenarios for rollover that can be identified in the national crash data, using TIFA and GES. ("High-level scenarios" refer to the four crash scenarios identified in the TIFA/GES analysis. "Detailed scenarios" refer to the scenarios in the LTCCS data generated by the cross-classification of the factors coded to support the benefit analysis.) The data in Table 18 shows the cross-classification of study definition rollovers in Table 3. The level of detail that can be sustained in TIFA and GES splits roadway alignment between straight and curved roads, and road surface condition between dry and not dry. The table shows estimates of annual crashes and the percentage distribution of the high-level scenarios.

Table 18. National Estimates of High-Level Rollover Crash Scenarios (TIFA/GES, 2000-2004)

Roadway alignment	Road Surface condition	Crashes	%
Straight	Dry	1,541	39.1
	Not dry	207	5.2
Curve	Dry	1,903	48.3
	Not dry	285	7.3
Unknown		0	0.0
Total		3,936	100.0

Each of the crash scenarios identified in Table 17 can be mapped to one of the high-level crash scenarios in the national crash data shown in Table 18. For example, the cases in Table 17 that are marked with a curve radius of >100m or ≤100m and road friction marked "high" correspond to the cases in Table 18 where roadway alignment is "curve" and road surface condition is "dry." All the other cases in Table 17 can be mapped similarly. Table 19 shows the count of detailed scenarios for each combination of road alignment and road surface condition. In addition, the table shows the number of LTCCS crashes that map to each road alignment and surface condition. Twenty-two of the detailed LTCCS scenarios map to the curve-dry high-level scenario, representing 65 LTCCS crashes. Seven of the detailed scenarios map to the curve-not dry high-level scenario, representing nine LTCCS crashes. Six of the scenarios map to the straight-dry scenario, representing 10 LTCCS crashes.

Table 19. Detailed Scenarios From LTCCS Mapped to High-Level Crash Scenarios in National Crash Data

Roadway alignment	Road surface condition	Count of Applicable Scenarios	Count of Applicable LTCCS Crashes
Curve	Dry	22	65
	Not dry	7	9
Straight	Dry	6	10
	Not dry	0	0
Total For HiL Roll Scenarios		35	84

Table 20 shows the specific simulation scenarios that are mapped to each of the four high-level crash scenarios.

Table 20. Scenario Numbers From LTCCS for Each High-Level Crash Scenarios in National Crash Data

Roadway alignment	Road surface condition	Applicable Scenarios
Curve	Dry	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 18, 19, 20, 21, 22, 30, 31, 32, 33
	Not dry	9, 25, 26, 27, 28, 29, 34
Straight	Dry	15, 16, 35, 36, 37, 38
	Not dry	None

Table 21 provides the LTCCS case identifiers (CaseId and VehicleNumber) for each case assigned to a scenario. Note that scenarios were developed using all of the rollover relevant LTCCS cases in the study. This includes cases classified as rollover and also selected loss-of-control cases that were classified as both loss of control and rollover.

Table 21. Case Identification for Each Detailed Scenario from LTCCS

Scenario	CaseID	VehicleNumber
1	153006977	1
	335006545	1
	803004652	1
	808004226	1
	813004526	1
	813005655	1
	813006119	1
	815005814	2
	818004112	1
	884004325	1
2	338007582	1
	348006225	2
	620006525	1
	802005383	1
	816004261	1
	819004425	1
3	339006276	1
	816004201	1
	816006201	1
	819006125	1
	820004422	1
	884003927	1
4	339006451	1
	800004246	1
	817005908	1
	818005452	1
	884005168	1
5	332006696	1
	803004492	1
	811005442	1
	812004411	1
6	339006316	1
	348006445	1
	800003927	2
	813005190	1
7	332006697	1
	350006669	1
	810005647	1
	812006131	1
8	813006120	2
	815004252	1
	884005425	1
9	332006751	1
	814000361	1
	815004312	1
10	348006908	1
	819005325	1
	819005527	1
11	813003907	1
	819005865	1
12	332006211	1
	819005627	1
13	338007508	2
	339006771	1
14	811005582	1
	819004185	1
15	813005626	1
	819005808	1
	820003982	1
16	337006323	1
	340006826	1
	807005712	1
18	815004232	2
19	817004510	1
20	331006250	1
	818004792	3
	823005982	1
21	813004026	1
22	821005449	1
25	350006975	1
26	828004080	1
27	352006482	1
28	800006415	2
29	801003890	1
30	812004756	1
31	864004907	1
32	800004865	1
	803004276	1
33	333006294	1
34	813004966	1
35	811004362	1
36	803005076	6
37	813004046	1
38	808005621	2

Note: Dark shading indicates cases used in HiL analysis.

6.5 Developing Scenario Maneuvers

The scenario maneuvers for rollover are based on road geometries that reflect those found in the LTCCS rollover crashes. Many of the LTCCS rollover cases included data on the curve radius. These data were grouped into two subsets: curves with a radius less than 100 m and curves with radius greater than 100 m. The mean curve radius was calculated for each subset for use in the simulations. These curve radii were 68 m for curves less than or equal to 100 m and 227 m for curves greater than 100 m. The following maneuvers were identified as geometrically representative road alignments relating to the scenarios above.

M9 – Transient to Constant Curve

This maneuver approximates typical highway curves containing a spiral to a constant radius curve. It is representative of the entrance to a freeway exit ramp. The curve radii chosen for the simulations are 68 m and 227 m, and represent the mean values from LTCCS crashes on curved roads with a less than or equal to 100 m and greater than 100 m radius. The spiral transition rate of 1.3 m/s^3 is based on the AASHTO prescribed curve entry geometry corresponding to a steady-state lateral acceleration of 1.5 m/s^2.

V_c is evaluated separately for RSC, ESC, and ABS through an iterative process of increasing vehicle curve entry speed to the point of rollover. The criterion used to define V_c is absolute vehicle rollover.

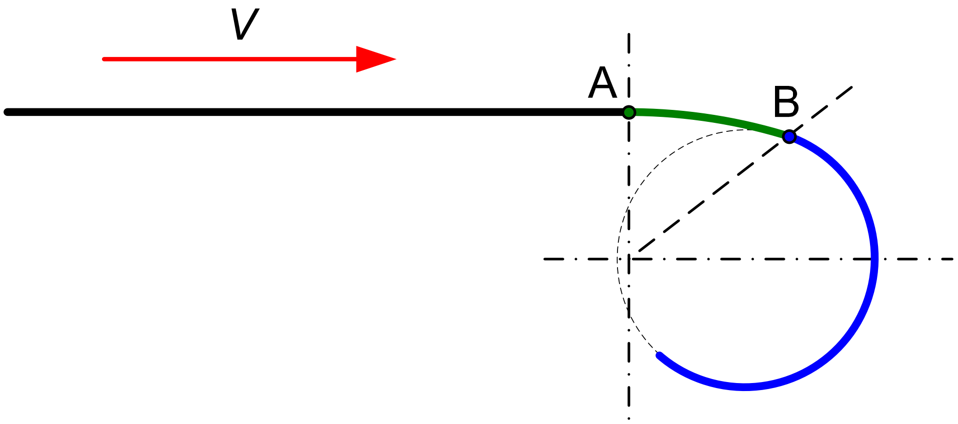


Figure 12. Schematic Trajectory of Maneuver M9 (Transient to Constant Curve)

MD – Constant Radius to Diminishing Curve

This maneuver represents a scenario where the vehicle enters the curve just below critical speed but then experiences roll instability due to a reduction in curve radius. It corresponds to rollovers that initiate beyond 100 m from start of curve. It uses the M9 maneuver as a building block, but at 90 degrees the curve radius diminishes at a rate of 0.4 m/s^3 to 0.9 m/s^3 based on the prescribed test speed curvature design speed, corresponding to a steady-state lateral acceleration of 1.5 m/s^2. In this maneuver, the vehicle enters the curve below V_c which allows it to survive the constant radius part of the curve and reach the start of the diminishing radius that begins at 90 degrees beyond the start of the constant radius curve.

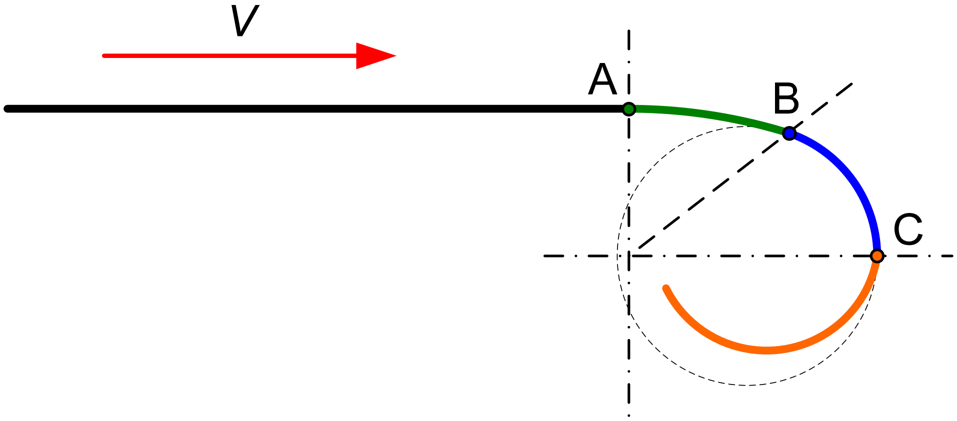


Figure 13. Schematic Trajectory of Maneuver MD (Constant Radius to Diminishing Curve)

MS – Single Lane Change (SLC) in Curve

The single lane change in a curve represents the scenario of a truck changing lanes during an overtaking maneuver on a roadway with two or three lanes in the direction of travel. The road alignment is based on maneuver M9, and the lane change occurs towards the outside of the curve. The vehicle enters the curve below V_c that will allow it to survive and stabilize in the curve. After traveling 90 degrees of turn, an ISO single-lane change is performed.

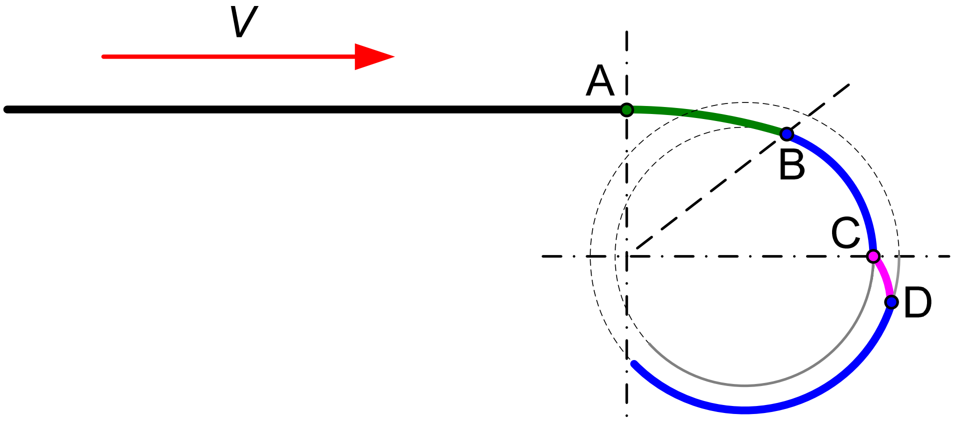


Figure 14. Schematic Trajectory of Maneuver MS (SLC on Curve)

<u>**MP** – Single-Lane Change on Straight 1</u>

From analysis of the LTCCS study, a single-lane change on a straight road is the maneuver most commonly associated with rollover on straight roads. It represents the scenario of the truck having to change lanes aggressively to avoid a slow or stopped vehicle or to correct errant road departure due to fatigue or inattention. This maneuver is performed at a medium level of severity (more severe than the ISO lane-change).

<u>**MQ** – Single-Lane Change on Straight 2</u>

This maneuver is a variation on MP, with the maneuver being performed at an incrementally higher level of severity.

<u>**MI** – Turn at Intersection</u>

There were several rollovers identified in LTCCS that occurred while turning at intersections. The radius selected for this maneuver is 20 m.

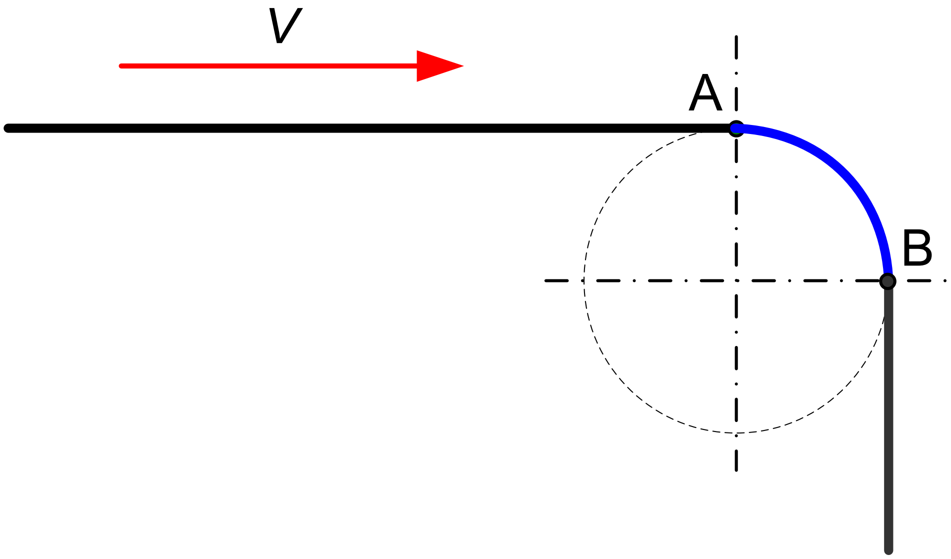


Figure 15. Schematic Trajectory of Maneuver MI (Turn at Intersection)

6.5.1 Loss of Control

The general classification of loss of control (LOC) in crash data covers a broad range of crash scenarios, many of which have no significance to this study. The term “loss of control” is general and is classified subjectively without reference to precise definition or engineering taxonomy. For example, many first-event rollovers in the LTCCS data are classified as LOC events because tire marks reflective of the typical rollover process are often assumed to be an indication of loss of control.

The definition of LOC pertinent to this study involves tractor yaw instability. Cases used to generate the LOC scenario list contain indicators that suggest tractor yaw instability. Some other types of LOC, including trailer swing, have been excluded because the vehicle dynamics are outside the sphere of influence of the subject technology. For expert panel effectiveness estimates, brake-related LOC cases where ABS was not present or functioning have been carefully examined to assess the potential for ABS to avoid the crash. In such cases, only the additional contribution of RSC or ESC was considered so as not to supersede the potential contribution of the ABS systems. While RSC and ESC may have been relevant to the vehicle dynamics involved, the instability would likely have been managed by a functioning ABS system.

6.5.1.1 Review of LTCCS LOC Cases

Using the variables coded in LTCCS for relevant roll and LOC, the selection algorithm identified 164 cases combined, and 83 as LOC. Researchers carefully reviewed each case as relevant to the ESC technology. For each case, the team made a yes/no decision with respect to the likelihood that the crash contained characteristics of yaw instability that would be relevant to the functional characteristics of the technology. The variables and code levels available in the LTCCS data for both LOC and rollover are imprecise tools to identify the specific characteristics of crashes that can be addressed by ESC and by RSC. The review identified cases that were coded as LOC, but that were simple rollovers. Similarly, some cases identified as roll-relevant in the coded data that included elements close to the LOC crash type sought. (The review resulted in the reassignment of some cases. The national estimates of the LOC and roll crash types relevant to the technologies are adjusted in the section in which the benefits of each are estimated.)

To best capture LOC crash involvements relevant to the ESC technologies, the results of all the individual LTCCS case reviews were used to identify crashes and crash scenarios for further analysis. Fifty of the LTCCS cases were classified initially as “likely” or “possible” to include elements that would make them a candidate to be addressed by ESC. These cases were individually evaluated by the expert panel and prevention values were assigned.

Generally speaking, LOC scenarios are more subtle and complex than rollover scenarios, and yet we had the same limited level of information on crash circumstances (from LTCCS). This means that we had insufficient information to meaningfully simulate LOC scenarios. In general, LOC cases can be categorized into five separate scenarios:

- Heavy brake and steer on straight road;
- Heavy brake only on straight road;
- Steer only on straight road;
- Sudden lane change in curve; and
- Loss of steering control in curve.

6.5.1.2 Limitations of LOC Analysis

Clinical review of the relevant LTCCS yaw-related LOC cases (including detailed study of the crash narrative, scene drawings, and photographs) can provide only limited insight into the details of the event. As found in the scenario analysis, the common precursor to LOC is severe braking or steering input in response to a threat. Examples of the most common events include heavy braking with or without lane change for crash avoidance, and rapid steering correction to prevent road departure due to inattention or fatigue.

In these events it is clear that driver reaction has influenced vehicle behavior through braking or steering input, but it is not clear whether LOC actually occurred. The driver may have run off the road while trying to direct the vehicle out of immediate danger or the driver may have over-corrected or simply froze after the initial braking or steering input. There is also the potential for tactical responses to unavoidable crashes, such as tractor-trailer drivers intentionally jackknifing the tractor as a mechanism for self preservation.

Each of the relevant LTCCS LOC cases was closely studied to extract the technical detail related to the crash. This effort exposed the fact that very little technical detail is available for LOC crashes. The analysis also showed that LOC crashes tend to be unique and complex events that are difficult to broadly categorize within generalized scenarios. This suggests that each crash would need to be analyzed separately to establish the likely effectiveness of technology. To do this using HiL simulation would require detailed technical knowledge about driver steering input (steer time history), brake application and forces generated, vehicle orientation, surface friction, and full knowledge of external factors that may have influenced pre-crash events. Understandably such information is not available in LTCCS or any other source. LTCCS contains general information based largely on driver interviews about steering and braking prior to collision and crash scene evidence of jackknife or trailer swing. Apart from these general conditions we do not have specific details for pre-crash vehicle state, steer rate and angle inputs, brake level, or timing and vehicle response. All of these details would be required in order to faithfully replicate the case using HiL simulation.

Assuming that LOC could be confirmed in a particular case, there is the added complication of not knowing the exact driver inputs and vehicle state variables that combined to generate a yaw-related LOC condition. The inability to confidently determine if a LOC condition actually existed and the lack of detailed information on driver input and vehicle state places great limitations on the ability to assess the potential of stability technologies to alter the outcome of a particular crash scenario. In contrast, for rollover crashes, it is clear and unequivocal that rollover occurred. Tire marks and road alignment provide solid evidence of the vehicle path and point of instability.

Considering the uncertainties surrounding LOC crashes, simulation of the LOC crashes was determined to be too complex for replication by HiL without modifications to address the limitations of the system.   It was decided that the effectiveness values could only be achieved through the use of an expert panel to meet the time constraints of the study.

6.6 Assigning LOC Effectiveness Ratios

As part of the early analysis process, all LTCCS LOC cases were reviewed and sorted as likely relevant or not relevant to the technology. As a first step, the cases found not to be relevant were assigned a technology effectiveness rating of zero. A total of 56 remaining relevant (yaw and also roll not simulated by HiL) cases were evaluated in detail by the expert panel.

Prior to the analysis task, the panel members participated in a full-scale track test where the technologies in question were exercised through a series of maneuvers. This provided insight into the behavior of the technologies. In addition, open loop and ramp steer runs were conducted using HiL. The intervention and subsequent vehicle response for each technology was studied and compared. Armed with this background knowledge about the technology, the expert panel reviewed each LOC case in detail using the case narrative, categorical data, scene diagrams, and photographs. The expert panel then used the evaluation form shown in Figure 16 to provide a systematic review of each case leading to an estimate of the effectiveness for each technology.

The step-by-step process used for clinical case review by the panel is described below. Each step of the evaluation process was recorded and copies were achieved in paper ballot form and in an electronic spreadsheet. Scores from the evaluation spreadsheet are presented in tabular form in groups of evaluation variables in Appendix E. In addition, an example case showing the analysis logic used by the expert panel can be found in Appendix G. All LOC cases were evaluated as well as all rollover crashes not addressed by the HiL analysis. Some general guidelines for the case review were:

1. The LTCCS case to be reviewed was selected from a specific set of cases from a crash scenario. The LTCCS case identification number was recorded.

2. The case narrative, scene diagrams and scene photographs were studied jointly by the panel members.

3. The panel members then discussed and summarized the relevant details of the crash ensuring that there was reasonable agreement about the facts, the probable sequence of events and relevance to the technology.

4. The evaluation form (see Figure 16) was completed by both members of the panel. For subjective evaluation variables, the individual scores were averaged.

The following is a detailed explanation of the step-by-step evaluation process. Evaluation categories contained on the evaluation form (Figure 16) are represented by variable names (boldface in brackets) that correspond to the individual case scores presented in tables in Appendix E.

1. *Was driver distracted or incapacitated?* **[dr_distract]** – (scored on a scale of 0 to 100%; yes=100%). This question attempts to generate an estimate of how active the driver was during the crash sequence and the likely level of distraction the driver may have experienced prior to the incident. For example, a driver who became incapacitated due to a heart attack would be assigned a score of 100% while a driver partially distracted by in cab activities may be assigned a value of 50%. A driver who was judged as being alert was given a score approaching 0%.

2. *Was the vehicle path faithful to driver input*? [**path_faithful**] – (scored on a scale of 0 to 100%; yes=100%). Evidence that the vehicle did not follow the intended path indicates that ESC may be relevant. The uncertainty in the assessment warrants a sliding scale.

3. *Was there an indication of oversteer (%) understeer(%)?* **[oversteer, understeer]** – (scored on a scale of 0 to 100%; yes=100%). Oversteer occurs when the yaw rate of the vehicle exceed that which the steer input would generate if the vehicle were in the neutral steer condition. Early stages of tractor jackknife is a good example of oversteer. Understeer is the opposite effect where the directional response of the vehicle becomes sluggish in response to steer input as would occur on an icy road. ESC is capable of responding to either of these two conditions but the intervention strategies are different. The sliding scale provides an estimate of the amount of understeer and oversteer that likely occurred.

4. *Excessive brake; steer; brake and steer* **[brake_steer]** – (scored categorically – yes/no). Excessive driver intervention of this type can result in understeer or oversteer including jackknife. Many of the LTCCS case narratives, scene diagrams, and photographs provide insight into such driver input.

5. *Excessive speed* **[ex_speed]** – (scored on a scale of 0 to 100%; yes=100%). From case reviews, the expert panel made a judgment as to the likelihood that excessive truck speed for the conditions was a factor in the crash. The ability for ESC and RSC to reliably function is highly dependent on vehicle speed for a given scenario.

6. *Was there first event jackknife?* **[jackknife]** – (scored categorically – yes/no/unknown). An attempt was made to evaluate the crash sequence to determine if there was a first event jackknife that would be an indicator of loss of yaw control. Jackknife is a common occurrence in truck crashes but it often occurs as a subsequent event (i.e., after initial vehicle collision).

7. *Was there first event trailer swing?* **[trlr_swing] –** (scored categorically – yes/no/unknown). Trailer swing was cited as a first event occurrence in the LTCCS narratives more frequently than the panel had expected. This is a form of LOC that the technology can neither detect nor correct.

8. *Likely algorithm trigger–* (scored as rapid steer, yaw rate, lateral acceleration, and wheel slip) **[rapid_steer, yaw_rate, lat_accel, wheel_slip]**. Rapid steer and yaw rate are triggers associated with ESC technology. RSC cannot be triggered by these parameters; however, RSC and ESC are both triggered in a similar manner by lateral acceleration.

9. *Travel speed* **[travel_spd]** – (estimated as greater than 60 mph, between 40 and 60 mph, less than 40 mph). There was very little information available on vehicle speed just prior to the crash. Using posted speed limit and case details, the pre-crash speed was estimated within a fairly broad range.

10. *Surface condition* **[surface]** – (scored as dry, wet ice). There was excellent data available on surface condition. Surface condition is of particular interest to LOC cases.

11. *ABS likely?* **[abs_likely_trac, abs_likely_trlr]** – (Tractor, trailer scored on a scale of 0 to 100%; yes=100%). If the tractor build date was after the date when tractor ABS systems became mandatory on new vehicles, it was assumed that ABS was functioning unless the LTCCS data field stated otherwise. For tractors manufactured prior to this date, it was assumed that it did not have the technology unless the LTCCS data field stated otherwise.

12. Using the above pre-crash information, the estimated technology response (by ABS, RSC, and ESC technologies) was determined independently by each panel member by formulating responses and assigning a percentage crash avoidance

contribution to the following questions 17, 18 and 19. Note: Since ABS resides with both RSC and ESC systems, for vehicles equipped with functioning ABS systems, the contribution of ABS was taken as zero, reflecting the fact that it could provide no *additional* benefit to the particular case. Where ABS was not present or not functioning, the panel attempted to estimate the likely contribution of ABS to the likelihood of crash avoidance. In some cases it was determined that RSC or ESC may have provided additional benefit; however, the sum of the ABS plus ESC or RSC benefits could not exceed 100%. The intent of this accounting was to ensure to the extent possible that the benefit of the ABS technology was not double-counted by either ESC or RSC.

13. *Would the event likely trigger the algorithm?* **[c1 variables]** – (scored on a scale of 0 to 100%; yes=100%). Knowing the functional characteristics of the technology and considering the pre-crash information, a judgment was made by the panel members as to whether conditions were sufficient for the technology to intervene.

14. *Would the technology have time to respond?* **[c2 variables] –** If it were judged that the conditions were sufficient for the technology to intervene, then the panel evaluated the particular pre-crash history to provide an opinion as to whether there was sufficient time within the pre-crash sequence for the technology to influence the crash outcome.

15. *Would the crash likely have been avoided?* **[c3 variables] –** Finally, in full consideration of all the information generated by the evaluation process up to this point, an overall effectiveness score was assigned by each panel member reflecting the likelihood that each technology, acting independently, would avoid the crash. These scores were averaged and recorded as the effectiveness rating for each technology. The effectiveness values for RSC and ESC are presented in Table 22.

Case number: ____________________________

Estimated Driver Related Factors

Was driver distracted or incapacitated: (Yes =100%)	**Was vehicle path faithful to driver input:** (Yes =100%)	**Was there an indication of:** Oversteer % Understeer %	**Excessive:** Brake ☐ Steer ☐ Brake and steer ☐	**Excessive speed**: (Yes =100%)

Estimated Algorithm/Technology Factors

Was there a first event jackknife yes ☐ No ☐ Unknown ☐ %	**Was there a first event trailer swing** yes ☐ No ☐ Unknown ☐	**Likely algorithm trigger** Rapid steer ☐ Yaw rate ☐ Lateral acceleration ☐ Wheel slip ☐	**Travel speed** >60mph ☐ >40<60mph ☐ <40 mph ☐	**Surface:** Dry ☐ Wet ☐ Ice ☐ %	**ABS Likely:** (Yes=100%) Tractor % Trailer %

%

Estimated Technology Response (%)

Condition	**ABS Tractor**	**ABS Trailer**	**RSC**	**ESC**	**Comments**
Would the event likely trigger the algorithm?					
Would it have time to intervene?					
Would the crash likely be avoided? (Overall Score)					

Effectiveness Score
Crash avoidance (100%)

ABS Tractor	
ABS Trailer	
RSC	
ESC	

Event Type

Rollover	**LOC**	
	no	☐
no	yes	☐
Yes	Yes	☐

Maneuver #_________

Figure 16. Review Form for LOC/Roll Over/Yaw Relevant Crashes in LTCCS Database

yes

ABS Consideration

In the assessment, the expert panel assigned effectiveness ratings to ABS technology for vehicles not equipped with ABS. The effectiveness ratings of the RSC and ESC technologies were adjusted so as not to supersede the benefits of ABS and the two stability technologies. In cases where ABS was considered a factor, the sum of the benefit estimate assigned to ABS and the benefit assigned to either RSC or ESC could not exceed 100%. The effectiveness ratings for each case are shown in Table 22.

Table 22. ESC and RSC Effectiveness Ratings for LTCCS Cases

CaseID	Vehicle-Number	RSC	ESC
153006977	1	95	95
207004905	1	0	15
222004325	3	0	70
329006101	1	0	0
331005867	1	0	0
331006249	1	0	0
331006250	1	90	90
331006312	1	0	0
332006211	1	95	95
332006696	1	97	99
332006697	1	48	96
332006751	1	5	25
333006294	1	62	62
333006958	1	0	80
335006545	1	95	95
337006323	1	0	35
337006565	2	0	0
338007508	2	95	95
338007582	1	95	95
339006276	1	97	99
339006316	1	95	95
339006411	2	0	0
339006451	1	30	40
339006771	1	80	95
339006915	8	0	10
339006971	2	0	20
340006566	3	0	20
340006826	1	5	15
340007050	1	0	0
344007015	1	50	70
348006225	2	95	95
348006445	1	95	95
348006908	1	0	10
350006669	1	48	96
350006975	1	96	99
350007220	3	0	90
813004191	1	95	95
813004406	2	5	25
813004526	1	95	95
813004546	1	0	0
813004667	1	0	0
813004966	1	95	95
813005190	1	95	95
813005511	1	0	0
813005530	2	0	0
813005626	1	5	20
813005655	1	95	95
813006119	1	95	95
813006120	2	95	95
813006166	6	0	0
814000341	2	0	20
814000361	1	95	95
815004232	2	95	95
815004252	1	95	95
815004312	1	60	70
815005814	2	95	95
816004041	1	0	0
816004201	1	97	99
816004261	1	95	95
816005042	1	10	50
816005321	3	0	0
816006201	1	97	99
817003933	1	0	0
817004510	1	80	80
817005748	1	20	90
817005908	1	95	95
817006028	2	0	0
817006509	1	0	0
818004012	1	0	0
818004112	1	95	95
818004792	3	100	100
818004912	1	95	95

CaseID	Vehicle-Number	RSC	ESC
352006482	1	80	95
495005661	1	0	50
620006525	1	95	95
620006805	1	10	40
800003927	2	95	95
800004246	1	95	95
800004865	1	95	95
800006415	2	0	0
801003890	1	10	30
801005488	2	0	35
801005488	4	0	75
802005383	1	95	95
803004276	1	10	35
803004433	3	0	0
803004492	1	97	99
803004652	1	95	95
803004794	2	10	35
803005076	6	0	0
805005055	1	0	0
807004925	2	0	0
807005712	1	30	70
807005713	1	20	45
808004226	1	95	95
808005621	2	30	50
808006003	1	0	0
808006301	2	0	0
808006705	1	97	99
810005468	2	0	20
810005522	3	10	30
810005647	1	48	96
811004362	1	5	15
811005442	1	97	99
811005582	1	62	62
811006302	3	0	20
812004351	1	0	20
812004411	1	97	99
812004756	1	95	95
812004892	2	0	0
812005915	3	0	0
812005951	1	0	0
812006131	1	48	96
813003907	1	96	99
813004026	1	60	60
813004046	1	10	20

CaseID	Vehicle-Number	RSC	ESC
818005452	1	95	95
818005992	1	80	80
819004045	1	0	0
819004185	1	62	62
819004425	1	95	95
819005086	1	95	95
819005325	1	20	30
819005527	1	10	15
819005585	1	0	0
819005627	1	95	95
819005808	1	10	30
819005865	1	96	99
819006125	1	97	99
820003962	1	0	0
820003982	1	5	10
820004422	1	97	99
820004643	1	0	10
820004783	1	0	0
821003867	2	0	10
821005449	1	96	99
821005450	2	0	0
821005589	3	0	10
821005752	29	0	0
821005769	1	0	0
821006149	2	5	25
823005424	1	0	0
823005982	1	90	90
828004080	1	95	95
864004267	1	0	0
864004487	3	0	0
864004488	1	0	0
864004729	1	0	10
864004907	1	95	95
870004688	1	0	0
870004733	1	0	30
870004748	1	0	30
884003927	1	97	99
884004325	1	95	95
884004485	5	0	20
884005168	1	95	95
884005169	2	0	0
884005425	1	95	95
884005486	2	0	0

Note: Light shading indicates an assigned value (rollovers that occurred after 100 m into the curve: refer to section 6.4). Dark shading indicates HiL, and non-shaded indicates panel case review was used for determination of effectiveness.

7 Hardware-in-the-Loop System

The HiL system described below was designed to represent the dynamics of a loaded truck in safety critical situations appropriate to the crash types and technologies considered in this project. HiL is a hybrid of hardware and software components designed to represent, with as much fidelity as necessary, the interacting dynamic sub-systems that are crucial to making high fidelity performance evaluations:

a) Truck dynamics: including sprung and unsprung masses, suspension and steering characteristics, tire mechanics for road-tire contact, powertrain and transmission.

b) Braking system: the mechanical operation of the pneumatic braking system including air pressure propagation, transient response of valves, S-cam brake actuator, and friction material performance.

c) Electronic control system: sensing, control algorithms and actuation mechanisms for ABS, ESC and RSC

d) Driver decision making and control: for throttle, manual braking and steering

e) Environment: road geometry and surface characteristics. (Traffic environment and off-highway conditions are also potentially relevant, but for this project these aspects were not to be directly considered.)

HiL sits within a spectrum of options for simulation of crash scenarios, where at one end the full pre-crash conditions would be carried out on a test track, and all components use physical hardware; at the other end there is the option for pure computer simulation with all sub-systems represented in software. HiL provides an intermediate option capable of synthesizing the “best of both worlds.” In computer simulation there is excellent scope for running large numbers of tests with a high level of test replicability – the same conditions can be re-run with differing options for technology intervention, allowing detailed comparisons to be made between these options. In physical simulation (test track experiments were considered a form of simulation) much of the physical hardware operates as it would in the real crash situation. For this study, these are the preferred and viable options for physical/computer simulation:

a) Truck dynamics: established multibody simulation (MBS) software is commonly used by industry to represent vehicle dynamics, including the dynamics of tractor-trailer combinations. Modeling for computer simulation typically involves some simplification to the real-world dynamics. On the other hand, physical test track work requires some modification to the vehicle (e.g., outriggers for rollover prevention, idealized trailer loads) so neither approach is going to be100-percent faithful to the real world crash situation. For reasons of cost, time and repeatability the clear advantage appears to be with computer simulation based on established MBS for truck dynamics.

b) Braking system: the mechanical braking system is complex and nonlinear; for the air flow, the model needs to account for wave propagation within compressible hoses, valve dynamics and nonlinear friction material properties. A high fidelity simulation model requires a lengthy period of development, including validation with detailed measurements taken from the physical system. Since a laboratory rig needs to be set up in any case, there is a clear advantage to setting this up as physical hardware in the laboratory. With 5 axles and 10 brake actuators on the target vehicle, a large number of brake dynamometers would be required to physically represent wheel rotational dynamics and clearly this is not feasible for a study of this type. Therefore, wheel rotational dynamics were to be represented in software, with brake torque values obtained from lookup tables of experimental data.

c) Electronic control system: the core algorithms for the electronic control unit (ECUs) are complex and have major proprietary commercial value to the brake system supplier, and therefore it was not reasonable to expect these algorithms to be released directly to the project. Running the electronic control units as "black boxes," operating in real-time within the simulation therefore offers a very significant advantage over what is possible in a pure software-based simulation. Therefore, the physical ECUs were included in hardware.

d) Driver decision making and control: whether physical or computer-based simulation is used, reproducing actual human behavior in crash situations is immensely difficult. For this project, an early decision was made to reduce emphasis on the human component, and concentrate instead on the engineering performance of the systems in the pre-crash situations represented. Thus, a simple path-follower model was applied to the directional control, and a pre-defined speed profile (typically a constant speed) was assumed for longitudinal control of the truck.

e) Environment: since tests can hardly be carried out on public highways, road geometry and surface characteristics are going to be highly idealized in either track or computer simulation. Once it is decided to perform computer simulations for the truck dynamics, the environment must also be represented in the same way. The essential component is to define lane boundaries and surface friction levels.

Based on the above considerations, the HiL system comprised:

- Software-based:
    - overall truck dynamics (including wheel rotational dynamics);
    - environmental model;
    - driver model;
- Hardware-based:
    - full mechanical brake system;
    - electronic control system.

The brake system hardware included all pneumatic components (except the air compressor and drier) relative to the selected heavy-truck configuration- a heavy truck with a 3-axle power unit (tractor) and a 2-axle semitrailer. The entire pneumatic system, from air reservoirs to treadle and other system valves to brake actuation chambers, was set up in the laboratory. Appropriate fittings and proper length tubing and hose were used. The brake chambers were installed on real S-cam brakes with appropriate pressure/deflection properties. The electronic control system components were essentially commercial off-the-shelf units, though some modifications to hardware and firmware were necessary for laboratory operation.

Figure 17 shows a schematic drawing of the main components and their interaction in the HiL simulation setup. Figure 18 is a photograph of the physical system in the laboratory. The MBS truck dynamics simulation is carried out using Mechanical Simulation Corporation's Real-Time TruckSim (TruckSim RT), an established commercially available system for simulating a variety of unit and combination heavy commercial vehicles. In the real-time system, TruckSim is used to define the truck system dynamics and provides an executable model that is co-simulated with MathWorks' Simulink (general nonlinear simulation) software. This provides flexibility in defining external routines (e.g., a customized driver model for speed control) and also to define interfaces with the real-time hardware. At run-time, both the Simulink and TruckSim executable code is exported to a pair of real-time computers (PC machines running OPAL-RT software on a QNX operating system) that contain the necessary A/D, D/A, and CAN cards. Two computers, connected using a Firewire link, were used to run the dynamic system model in real time.

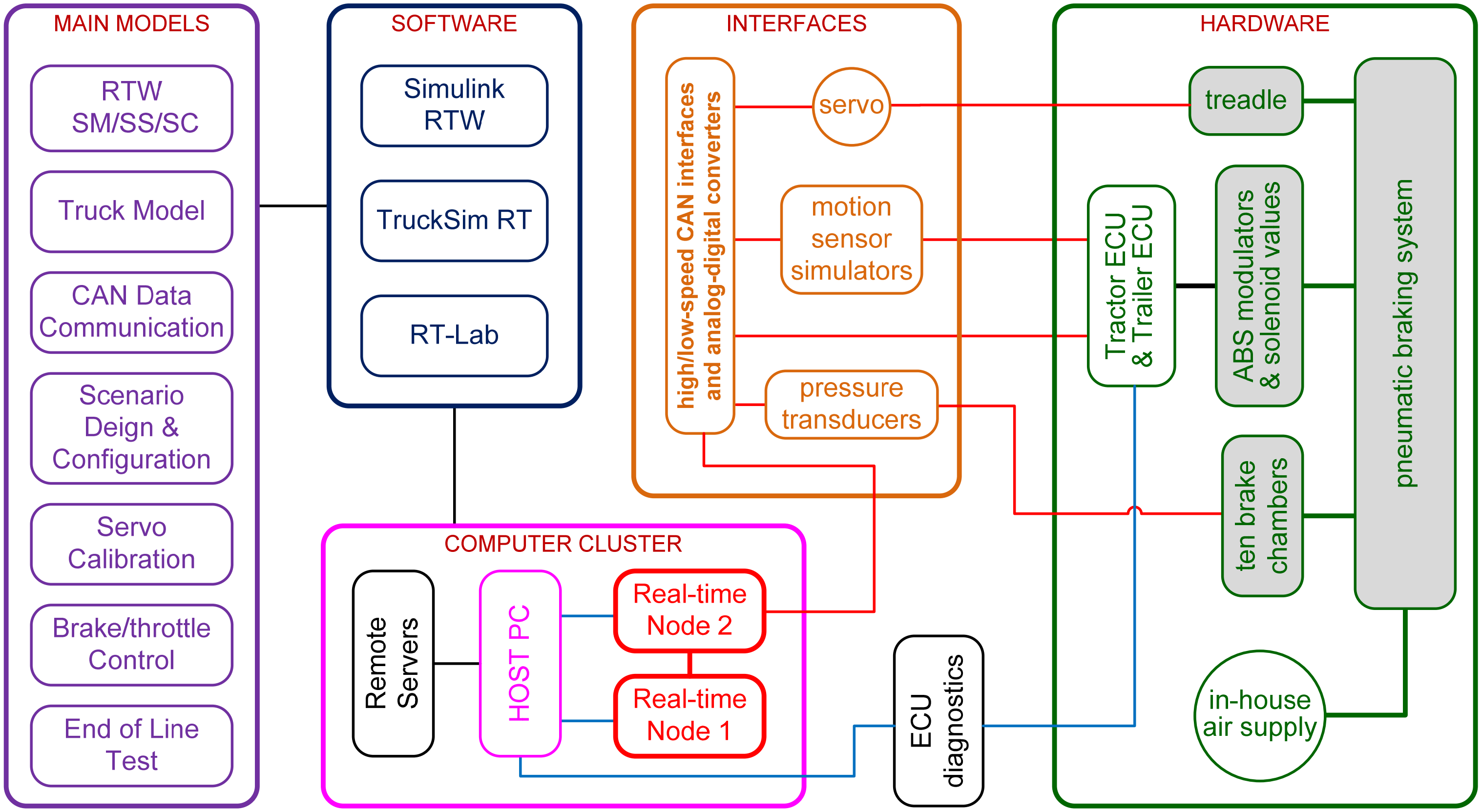


Figure 17. Components and Schematic Interaction of HiL Simulation System

Figure 18. Physical Pneumatic Brake System With 10 Brake Actuation Chambers

The TruckSim and driver models provide all necessary signals to the brake system hardware. The simulation outputs the following to the hardware system, via the appropriate interface devices:

- **Motion variables**: speed, yaw rates and lateral accelerations at the locations of system sensors.
- **Control variables**: steering wheel angle and treadle valve displacement. Treadle displacement requested by the simulation is converted to actual displacement via an electro-mechanical servo.
- **Wheel speeds**: wheel speeds are calculated in the simulation and converted to an appropriate form to be inserted into the hardware system via transformers that replace the standard wheel-speed magnetic pickups.

With these inputs provided to the electro-pneumatic air-brake system, the hardware responds by providing throttle and/or engine brake control commands and/or actuation of the air brakes (in unison or individually). Hence, the inputs to the simulation from the hardware elements are:

- brake-chamber air pressure - air pressures at each wheel chamber is measured through an installed pressure transducer and sent to the simulation via A/D interfaces;
- throttle and engine brake commands from the tractor ECU are input via an appropriate CAN interface.

Also shown in Figure 17, the components of the HiL simulation system consist of hardware, computer cluster, software, simulation models, and the interfaces, which connect the hardware with the real-time computer Node 2.

The next section describes the integration of the various subsystems within the overall HiL simulation.

7.1 Truck Modeling

Figure 19 shows the general layout of the 3-axle tractor and 2-axle semitrailer configuration for the heavy-truck modeling in TruckSim. In this report, all five axles and 10 wheels are listed in a standardized order (see Table 23 and Table 24 for the ID conventions). The basic truck modeling data collected are shown in Figure 20.

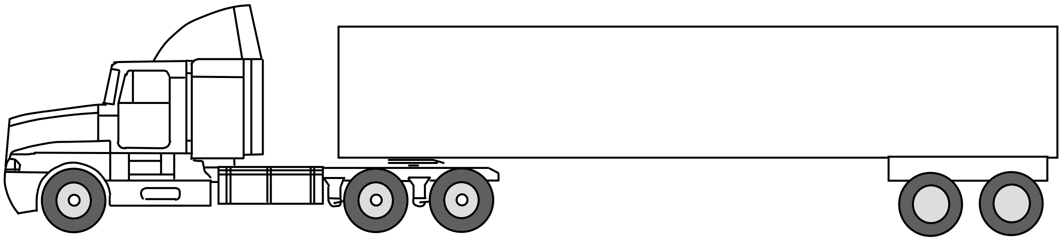


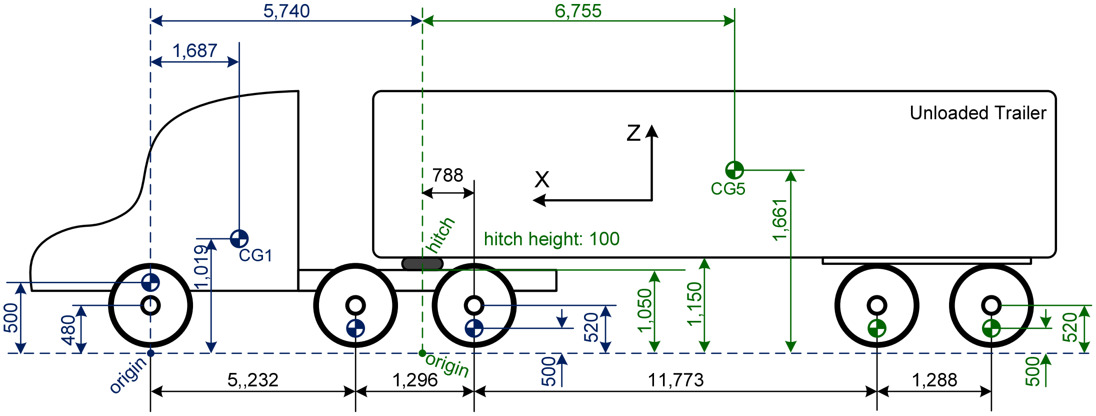
Figure 19. Heavy-Truck Configuration: 3-axle Tractor and 2-axle Semitrailer

Table 23. Axle ID Convention

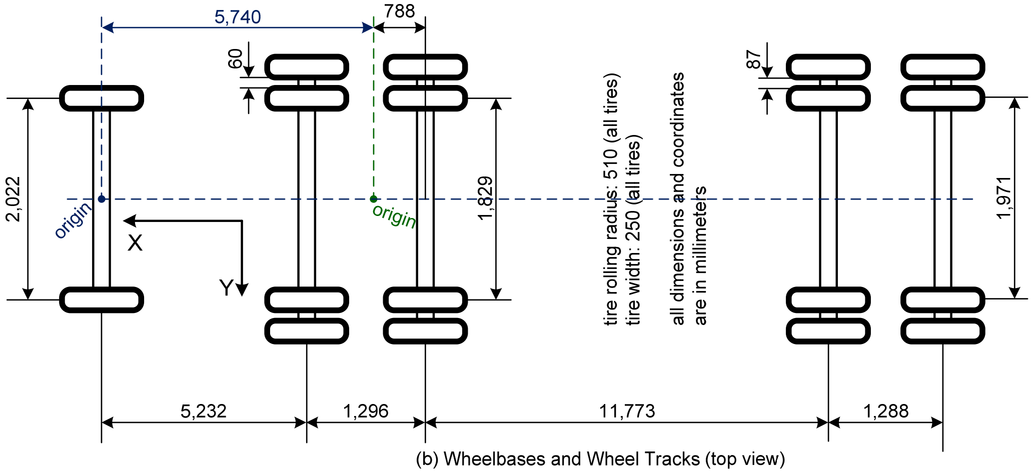
Heavy truck	Number of axles	Axle ID	Axle name	Number of wheels
Tractor	3	axle 1	steer axle (or front axle)	2
		axle 2	front drive axle (or first drive axle)	4 (dual wheel)
		axle 3	rear drive axle (or second drive axle)	4 (dual wheel)
Semitrailer	2	axle 4	front trailer axle (or first trailer axle)	4 (dual wheel)
		axle 5	rear trailer axle (or second trailer axle)	4 (dual wheel)

Table 24. Wheel ID Convention

Left wheel			Right wheel			Dual wheel	Located axle
Wheel No.	Wheel ID	Wheel name	Wheel no.	Wheel ID	Wheel name		
1	LW1	left wheel 1	6	RW1	right wheel 1	N/A	steer axle
2	LW2	left wheel 2	7	RW2	right wheel 2	Yes	front drive axle
3	LW3	left wheel 3	8	RW3	right wheel 3	Yes	rear drive axle
4	LW4	left wheel 4	9	RW4	right wheel 4	Yes	front trailer axle
5	LW5	left wheel 5	10	RW5	right wheel 5	Yes	rear trailer axle



(a) CG Location of Tractor and Trailer (side view)



(b) Wheelbases and Wheel Tracks (top view)

Figure 20. Truck Geometry Configuration

7.2 Driver Model

The driver model consists of two parts, speed control and steering control. The steering control is supplied by the TruckSim internal model based on the work of MacAdam [12]. This model is based on optimal control theory and determines the steering behavior of the driver based on a simplified internal model of the truck dynamics. The controller performs appropriately in quasi steady-state conditions, following the intended path with high accuracy and without making unnecessary corrections. There is however a tendency of the steering control model to attempt to correct for vehicle instability as the handling limits are reached, and one problem encountered in this study was the occasional highly transient steering inputs generated by the driver model when for example an oversteer condition was encountered; in this case the driver model could become quite aggressive in attempting to damp down the yaw response of the tractor, providing confusing inputs to the ESC (when fitted). The driver model parameters – particularly the preview time – were adjusted to minimize these effects, but on occasions a simulation was rejected as invalid when such transient effects were encountered.

This happened for one particular set of tests, when the truck model was driven on a tangent to a 227m circle, with fully loaded trailer and high mass center (2.3m.). In this case the entry speeds were relatively high and roll instability caused the driver model to attempt aggressive steer interventions. In the case of ESC, the resulting interactions between driver and the brake system actually degraded performance relative to RSC only; because such interactions are unlikely (though not impossible) to happen based on a human driver response these tests were not considered valid. Replacing these tests with an approximating open loop steering input overcame the problem, but in this case it was not possible to fully control the steady-state turning radius. Given more time to execute further simulations this secondary problem could have been resolved, but the clear conclusion here is that, once truck and road conditions have been set, path following stability and performance depends on the *combination* of driver steering control algorithm and active safety system, not just the latter. The preference for testing is for the driver to operate via a smooth transition from straight-ahead to steady-state steering, and not attempt to intervene too much to control lateral or roll stability.

The issue is not simple, since the quality of path following is also tied up with the transient behavior of the driver model. The MacAdam model, based on an optimal control model, almost certainly provided better path following than a human driver would be capable of. But should a less capable but less aggressive model be used? If so what control model is "best for purpose"? In the long term the options are (i) emulate the range of human driver responses (ii) focus almost exclusively on open-loop tests (iii) perform optimal steering inputs subject to path following constraints. In (i) the driver model is to be based on real driver performance under critical conditions and is perhaps preferred. For (ii) and (iii) the driver input is reduced to an objective action by external means so that the need for a steering control model is essentially removed. For the present study, it is noted that while the particular choice of steering controller did undoubtedly affect the absolute critical speed results obtained, since all systems were subject to the same type of control, the critical speed *differentials* were likely to be largely independent of the particular steering controller. This assumes that the driver model behavior was not having an undue effect on one or more of the systems, and again it noted that simulations were screened to exclude such interactions.

By comparison the speed control model was very simple and easily implemented. In order to have full control over speed demand, and provide options for driver brake interventions at particular instances of time, the model was implemented in Simulink, external to the TruckSim simulation. It was also important to set the vehicle speed with certain time sequence so that ECU can pass the self-diagnostics check during the start-up and the stopping sequences. Figure 201 shows the longitudinal speed control model components, which interfaces to the brake or throttle activation as necessary. Figure 212 shows an example of how the speed controller performs – here the desired (or reference) speed is pre-set and triggers a sequence of throttle and brake events: accelerate to speed, perform emergency braking, release brakes and perform a controlled acceleration to a lower speed, and finally perform controlled deceleration.

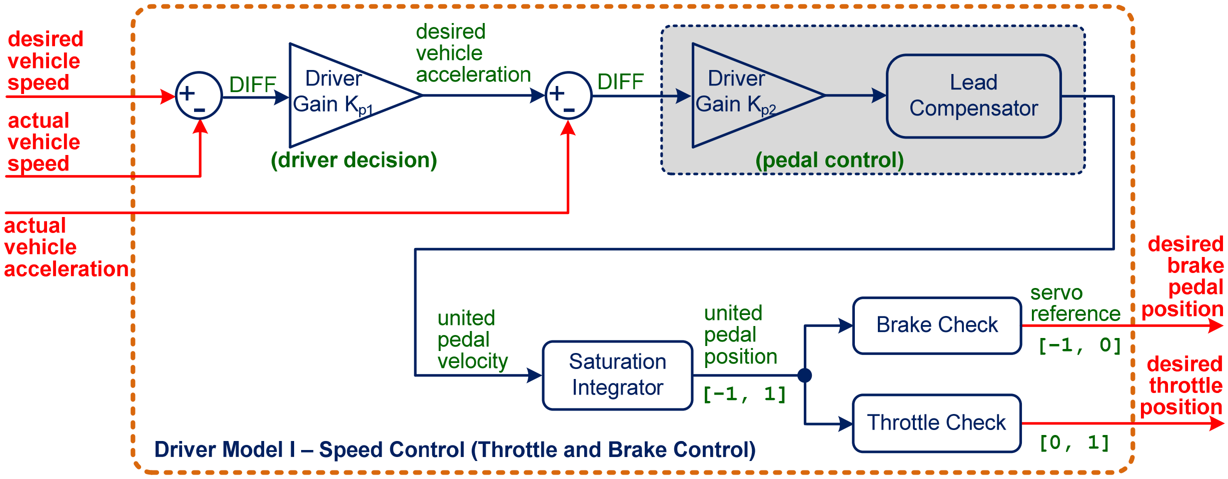


Figure 21. Longitudinal speed control (throttle/brake controls) model

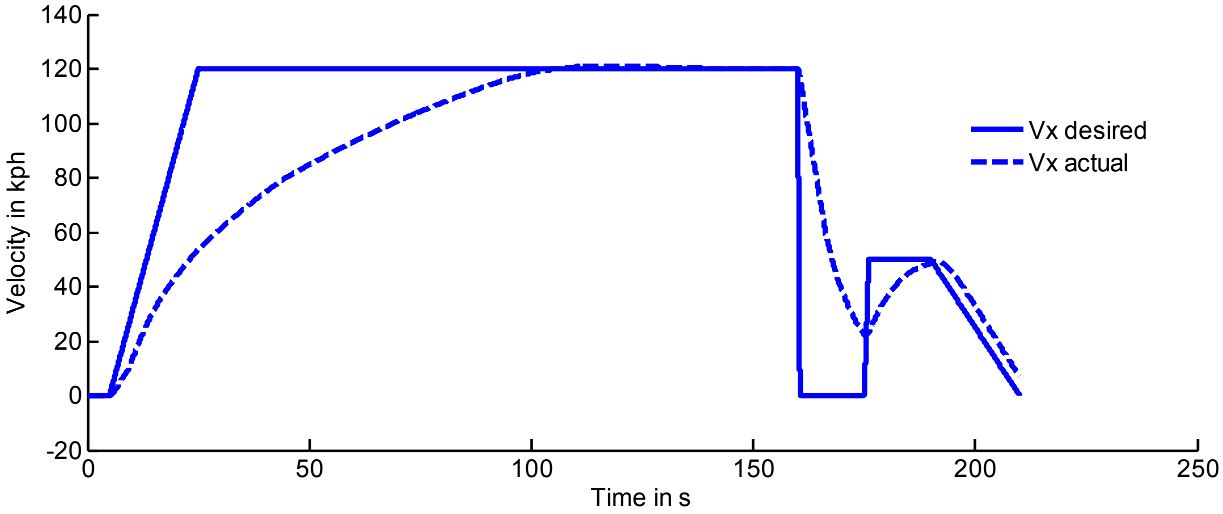


Figure 22. Longitudinal Speed Control Example.

7.3 Validation Procedures

No formal experimental program of test and measurement was set up on the test track during this project, so for this reason it was not possible to conduct a traditional parameter calibration and model validation procedure. Some level of confidence in the truck simulation model is that the underlying TruckSim code has been used and tested in the industry for some time, and it was not expected to find basic errors in the simulation code.

To build confidence in the overall HiL predictions a number of basic validation checks were carried out in conjunction with technical specialists at the NHTSA Vehicle Research and Test Center (VRTC) in East Liberty, Ohio and Meritor WABCO:

(a) Parameter values for vehicle geometries (e.g., track and wheelbase), inertias, suspension properties, tire properties, brake friction coefficient, etc. were developed within the team using test measurements previously obtained from UMTRI, VRTC and Meritor WABCO

(b) Standard tests were performed on the pneumatic system to assess the rise and decay time of the brake pressures – these results were confirmed with Meritor WABCO.

(c) A series of ramp steer tests were conducted and sent to VRTC to check reasonable behavior in comparison to previous tests conducted there

(d) Repeatability of these tests was used as a startup procedure to confirm that hardware was performing as previously tested.

(e) Initial "end of line testing" was performed to calibrate the ESC system, and simultaneously validate that the system was seeing a consistent set of signals from the simulated truck

(f) Diagnostic tests were performed during each simulation to confirm that the system (ABS, RSC or ESC) did not show any fault condition. In case such a fault condition was present (a rare occurrence once a number of calibration adjustments had been made) the simulation was discarded and repeated. In the case of ESC there was also a check made that the ECU did not consider the steer angle sensor had moved from its reference position.

(g) As mentioned above, the steer angle control input was monitored to exclude simulations where excursions in the steering angle could trigger or interact with the ESC system. When this was noticed in the early stages of testing, the parameters of the steering control model were re-tuned to reduce these excursions and avoid the false triggering or clear interactions. As also mentioned, in one particular set of tests this behavior could not be tuned out, and the results were deemed useless.

While it is always desirable to conduct formalized validations, practical limitations did not permit the inclusion of a full validation exercise, but for the purpose of this study there is significant data to confirm that both trends and absolute values are highly typical of the physical truck, and that HiL is indeed representative of the real-world conditions simulated.

7.4 Simulation Results

The following set of simulation results show the relative performance of RSC and ESC with respect to ABS control condition. The M9 tangent transition to constant curve maneuver was used for all cases. This maneuver approximates typical highway curves containing a spiral to a constant radius curve. It is representative of the entrance to a freeway exit ramp. The curve radii chosen for the simulations are 68 m and 227 m, and represent the mean values from LTCCS crashes on curved roads with a less than 100 m and greater than 100 m radius. The spiral transition rate of 1.3 m/s^3 is based on the AASHTO prescribed curve entry geometry corresponding to a steady-state lateral acceleration of 1.5 m/s^2. All results shown are for a fully loaded 36,400 kg (80,000 lb) GVW 5-axle tractor semitrailer.

The critical speed V_c is evaluated separately for RSC, ESC, and ABS through an iterative process of increasing vehicle curve entry speed to the point of rollover (critical speed is the highest speed for which no rollover occurs). The criterion used to define V_c is absolute vehicle rollover. In some cases although the vehicle did not rollover, wheel lift did occur as indicated by a small circle overlaid on the time history plot.

Lower Speed Performance
Figure 23 shows the maximum curve entry speed that could be achieved by each technology without the vehicle rolling over for a relatively low speed curve (68m radius) with typical entry speeds of less than 55 km/h (35 mph). The maximum curve entry speed for ABS system was 63km/h (39 mph), 71 km/h (44mph) for the RSC system and 80 km/h (50 mph) for the ESC system. Relative to the ABS case, the RSC system was able to manage a curve entry over-speed of 8 km/h (5 mph) and the ESC system could manage 17 km/h (11 mph) over-speed. The superior performance of the ESC is attributed to earlier detection and reaction of the system and increased braking performance shown in Figure 24 due to the addition of steer axle braking that is not used with the RSC system.

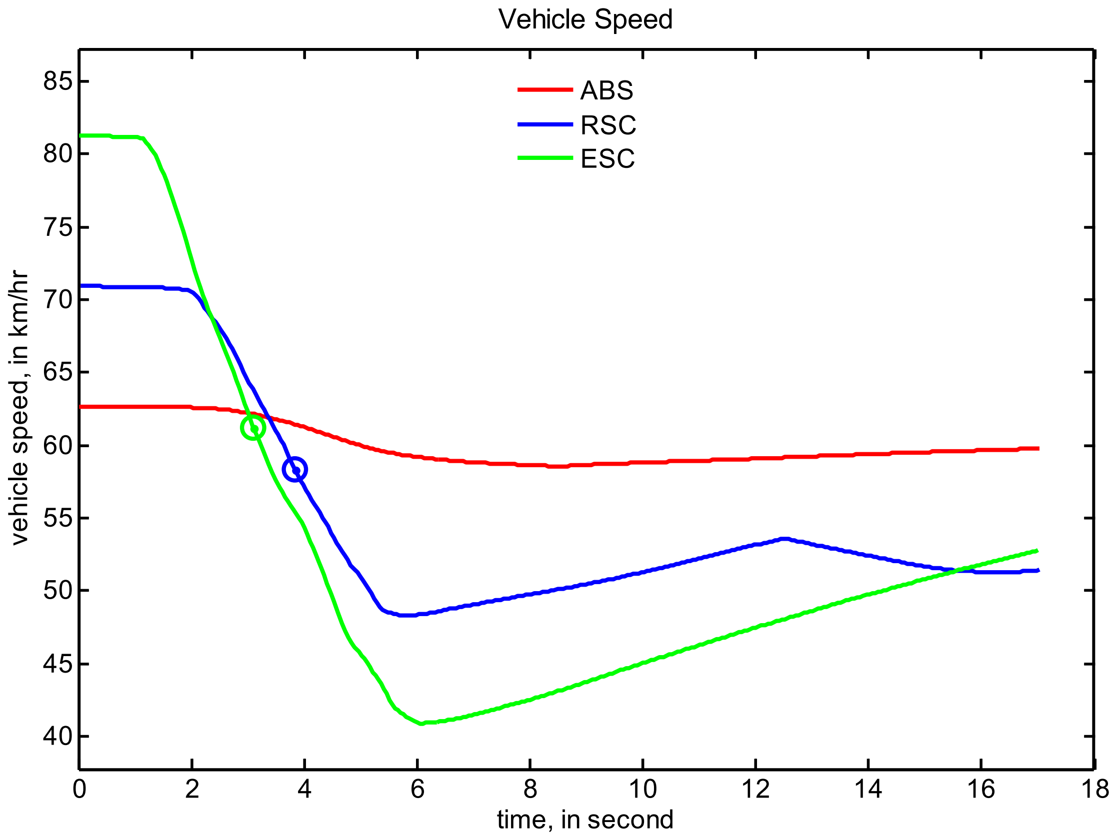


Figure 23. Vehicle Speed Time History for ABS, RSC And ESC Technologies Vehicle Mass 36,400 kg, Trailer CG 2.0m, Maneuver M9 at 68m Radius Curve Entry Speed Is the Maximum Achievable for Each Technology

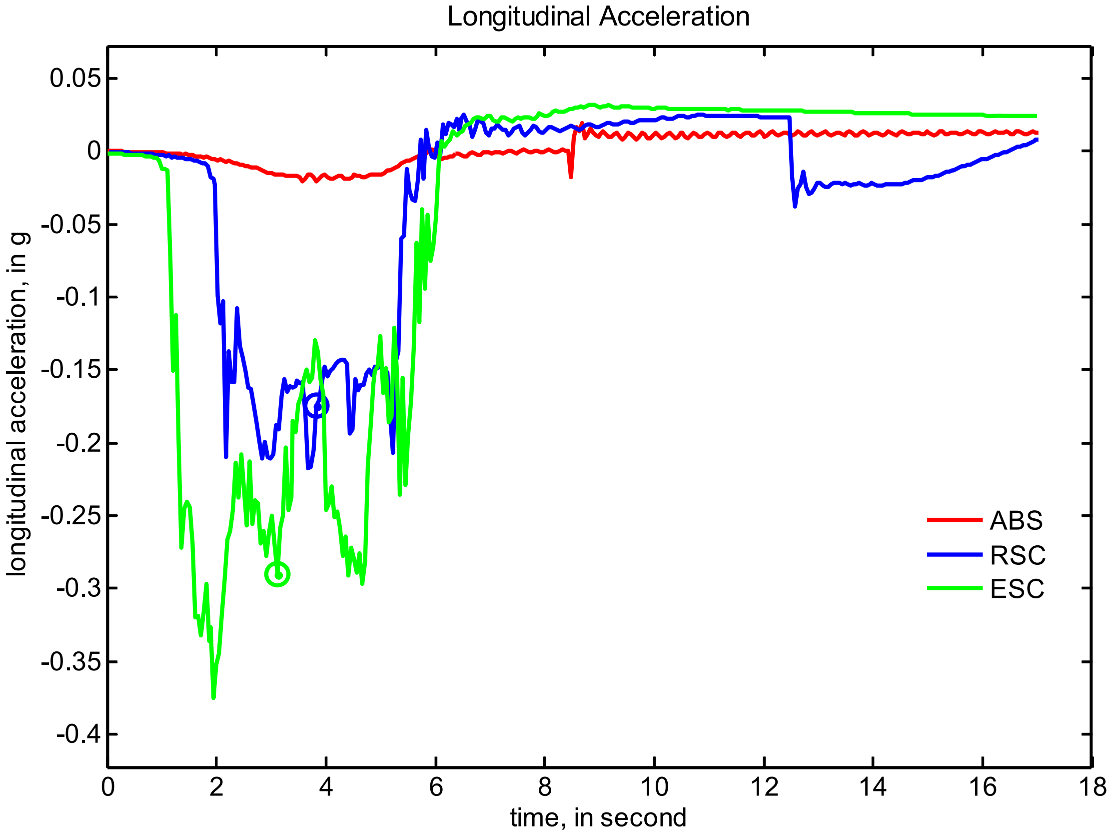


Figure 24. Longitudinal Acceleration Time History for ABS, RSC and ESC Technologies Vehicle Mass 36,400 kg, Trailer CG 2.0m, Maneuver M9 at 68m Radius

Higher Speed Performance

Figure 25 shows the maximum curve entry speed that could be achieved for a relatively high speed curve (227m radius) with typical entry speeds of less than 90 km/h (55 mph). The maximum curve entry speed for ABS system was 109km/h (68 mph), 113 km/h (70mph) for the RSC system and 121km/h (75 mph) for the ESC system. Relative to the ABS case, the RSC system was able to manage a curve entry over-speed of 4 km/h (2 mph) and the ESC system could manage 12 km/h (7 mph) over-speed. The amount of over-speed that the systems can manage at higher speeds is significantly less due in part to the increased kinetic energy of the vehicle that must be managed by the brake systems. Kinetic energy varies as the square of the vehicle velocity meaning that the amount of energy that the brake system is required to dissipate is disproportionally greater than at the slower speed. Figure 26 shows the deceleration performance for the technologies at the higher speed.

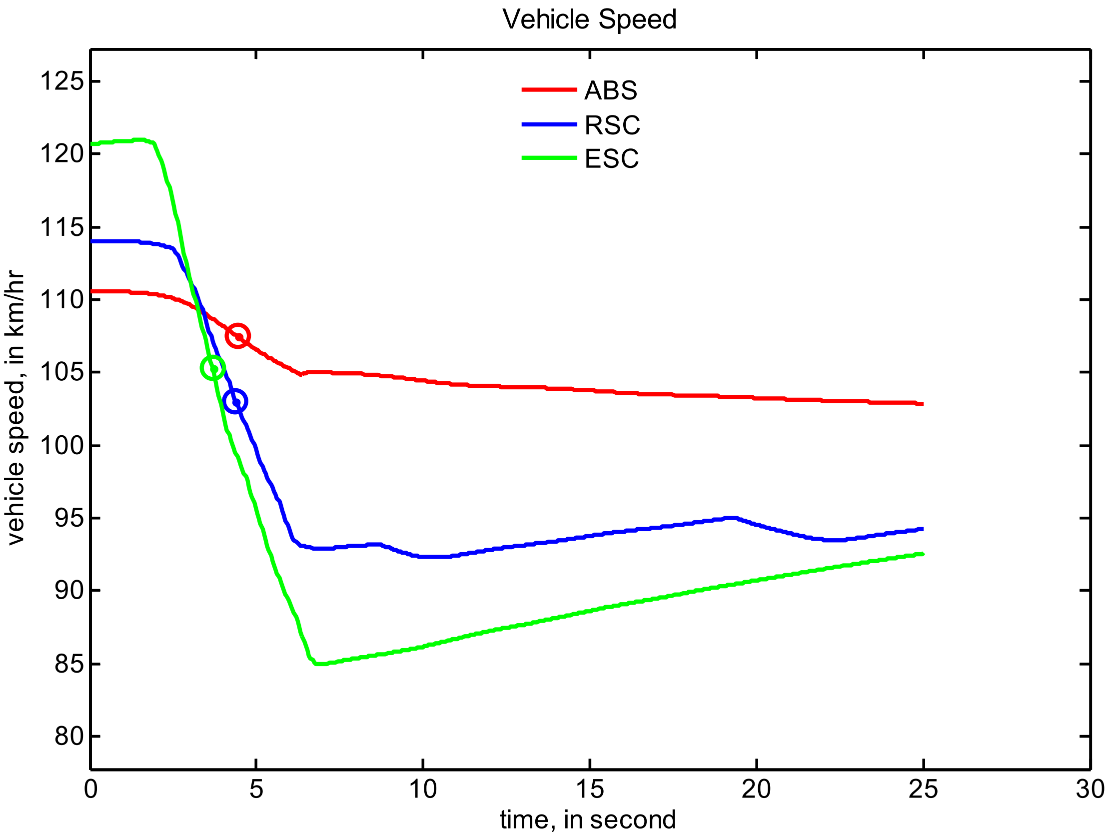


Figure 25. Vehicle Speed Time History for ABS, RSC and ESC Technologies Vehicle Mass 36,400 kg, Trailer CG 2.0m, Maneuver M9 at 227m Radius Curve Entry Speed Is the Maximum Achievable for Each Technology

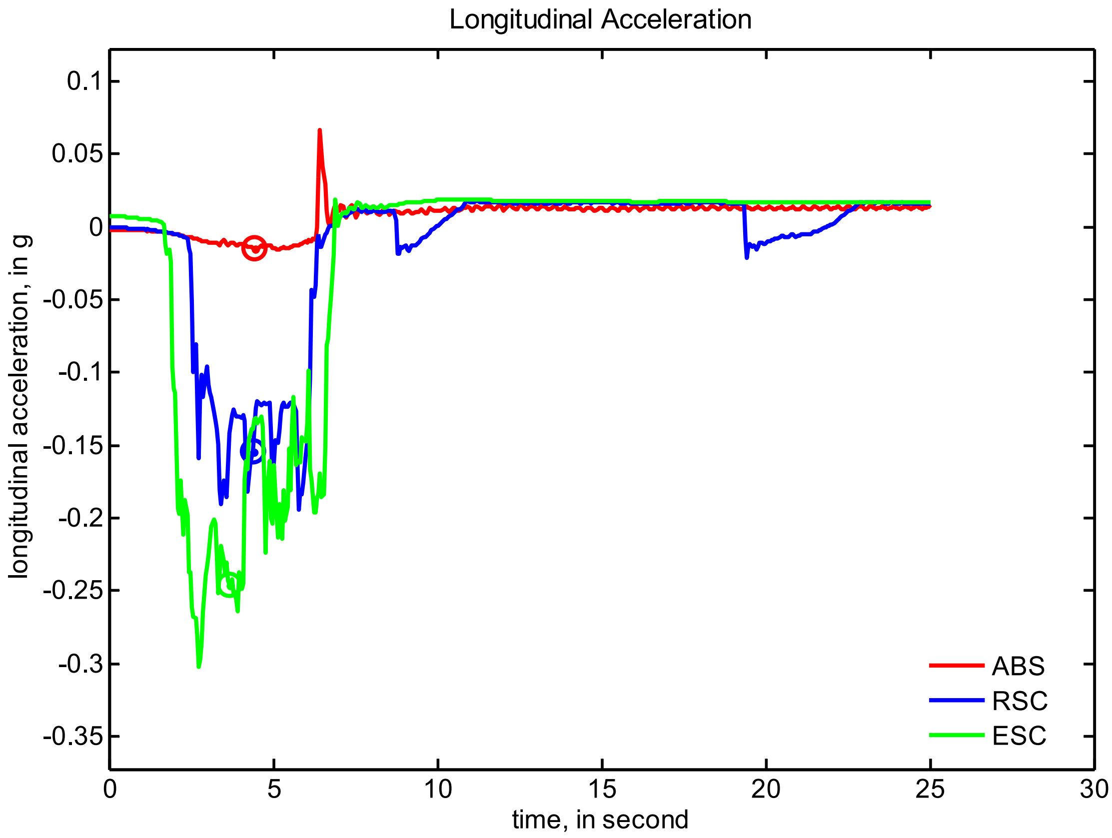


Figure 26. Longitudinal Acceleration Time History for ABS, RSC and ESC Technologies Vehicle Mass 36,400 kg, Trailer CG 2.0m, Maneuver M9 at 227m Radius

8 Estimated Benefit Derived from an Active Safety Technology

Methods are presented for estimating the benefits derived from the stability enhancing technologies. A benefit equation is introduced that can be used to estimate the reduced number of crashes attributable to the introduction of active safety technologies. A baseline of relevant rollover and loss-of-control crashes is derived from GES and TIFA databases.

The estimated crash totals from GES and TIFA are adjusted to take into account the results of the LTCCS review, which showed that a substantial number of cases identified in the coded data as yaw-relevant LOC actually did not include LOC but were simple rollovers. In addition, some of the cases did not include either relevant LOC events or rollover, and the estimates of national crashes relevant to the devices are reduced to reflect this result. The LTCCS cases were used as a sample of the types of crashes that are identified by the selection algorithms developed in the national crash data files. Since the review of LTCCS cases showed that many LOC cases in which the vehicle subsequently rolled were actually simple rollovers, the national estimates were adjusted to reflect that fact. The final adjusted estimate of crashes, presented as a 5-Year annual average, represent the numbers of crashes that may potentially benefit from the introduction of RSC and ESC technologies.

Table 25 shows the adjusted estimates of the annual average number of crashes relevant to the technologies from Table 3, reflecting the reallocation of cases based on the results of the LTCCS review.

Table 25. Adjusted Annual Average Estimates of Relevant Roll and LOC Crashes (GES, TIFA 2000-2004; LTCCS)

Road alignment	Road Surface condition	Roll	LOC
Straight	Dry	2480.2	1207.7
	Not dry	206.5	1801.5
Curve	Dry	3783.4	572.4
	Not dry	403.4	767.3
Unknown		0.4	0.8
Total		6874.0	4349.6

Of the 159 cases presented in Table 22, 22 of the effectiveness ratings were calculated based on results from the HiL simulation (dark shaded cases in Table 21 and Table 22). The remaining cases were evaluated based on expert panel judgment of certain rollover and loss-of-control crashes taken from the LTCCS database. Derivation of benefits for technology effectiveness derived from both HiL simulation and expert panel judgment will be explained using concrete examples in the following sections.

Estimated benefits adjusted to 2007 dollars are presented using published reports on the costs of highway crashes involving large trucks and the CPI inflation factor as reported by the Bureau of Labor Statistics. The benefits are applied specifically to tractors pulling one trailer. The standard value of a statistical life (VSL) of $6.1 million is applied when assessing the benefit of preventing fatalities.

8.1 The Benefit Equation

A benefit equation is introduced that is used to estimate the reduction (increase) in the number of crashes attributable to the intervention of an active safety technology. Variants of this equation have been used in other studies to estimate safety benefits due to deployment of intelligent vehicle safety systems, for example. [9, 10]. The following procedure is a method to calculate B, the benefit derived from an active safety technology such as ESC, RSC, or the combination of both. The benefit is expressed as the reduction (or increase for disbenefits) in the number of crashes attributable to the intervention.

- Identify safety technology (ESC, RSC)

- Identify pre-crash scenario (S) (high speed in a turn, double lane change)
- Identify a particular crash outcome (C) (rollover, loss of control)
- Use benefit equation to calculate B

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

Terms in the equation are defined below:

N_{wo}: The number of truck crashes without the technology from historical data.

$P_{wo}(S \mid C)$: Given a rollover or loss-of-control crash (C), this is the probability (without the technology) of scenario (S). This can be estimated from historical data by the proportion of crashes (C) that were preceded by the scenario (S).

$\dfrac{P_w(C \mid S)}{P_{wo}(C \mid S)}$: Given scenario (S), this is the ratio of the probability of a rollover or loss-of-control crash (C) with and without the technology. These probabilities can be estimated in several ways. In some cases they are estimated from panel judgment resulting from review of the LTCCS database. In other cases they are estimated through HiL simulation by simulating scenarios at different speeds and determining where rollover or loss of control occurs with and without the technology. Based on the distribution of the speeds, rollover and loss of control will occur at some point with high probability. When the technology is beneficial in reducing the probability of a rollover or loss-of-control crash given the pre-crash event, the ratio should be less than one. This ratio is usually called the *prevention ratio*.

$\dfrac{P_w(S)}{P_{wo}(S)}$: This is the ratio of the probability of scenario (S) with and without the technology. This can be estimated by fleet or FOT data by counting the number of scenario events and dividing by VMT, each with and without the technology. This ratio measures the exposure or the opportunity to encounter the pre-crash event (S) with and without the technology. When the technology reduces the opportunity of encountering the pre-crash event, this ratio should be less than one. This ratio is often called the *exposure ratio*. In practice, estimation of this ratio may be difficult since fleet or FOT data may not capture the information needed to measure scenario events. With respect to stability-enhancing technologies, it may be reasonable to assume the exposure ratio is one.

8.2 Relevant Rollover and Loss-of-Control Crashes and Injuries

In order to begin the benefits analysis, a baseline for determining the number of crashes that potentially may benefit from the RSC and ESC technologies is provided. Table 26 shows relevant rollover crashes and injuries by roadway alignment and surface condition. The data are presented as a 5-year annual average collected from TIFA and GES databases, and are adjusted to reflect the results of the LTCCS case review (as shown in Table 25). All fatal results were derived from the TIFA database, while nonfatal results were derived from the GES database. In total, there were approximately 6,874 crashes involving 197 fatalities. The bottom half of the table shows percentages. The great majority of rollover crashes occurred on dry surface conditions. The combined percentage of rollover relevant crashes on dry surface conditions was 91.1 and the percentage of fatalities was 90.5.

Table 26. Adjusted Rollover Crashes and Injuries by Roadway Alignment and Surface Condition 5-Year Annual Average (TIFA, GES, 2000-2004; LTCCS)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	2,480.2	53.8	358.1	667.5	616.6	1,354.3	0.0
	Not dry	206.5	6.2	24.5	32.4	7.5	172.7	0.0
Curve	Dry	3,783.4	124.1	935.6	1,252.7	782.8	1,751.4	5.5
	Not dry	403.4	12.2	70.1	114.9	10.6	376.1	0.0
Unknown		0.4	0.4	0.0	0.0	0.0	0.0	0.0
Total		6,873.9	196.6	1,388.3	2,067.5	1,417.6	3,654.5	5.5
Percentages								
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	36.1	27.3	25.8	32.3	43.5	37.1	0.0
	Not dry	3.0	3.2	1.8	1.6	0.5	4.7	0.0
Curve	Dry	55.0	63.1	67.4	60.6	55.2	47.9	100.0
	Not dry	5.9	6.2	5.0	5.6	0.7	10.3	0.0
Unknown		0.0	0.2	0.0	0.0	0.0	0.0	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 27 shows relevant loss-of-control crashes and injuries according to roadway alignment and surface condition, adjusted to be representative of ABS-only tractor-semitrailers, and also to reflect the results of the LTCCS review. The ABS adjustment was made by assuming that truck tractors with power unit model years after 1997 were equipped with ABS, and then applying those distributions of crashes and injuries to the population of all tractor-semitrailers. In comparison to rollover results in Table 26, loss of control was much more likely on surface conditions that were not dry. The total number of crashes was approximately 4,350 and the total number of fatalities was about

58. Inspection of the two tables gives evidence that rollover crashes were more severe with respect to numbers of fatalities and injuries per crash.

Table 27. Adjusted LOC Crashes and Injuries by Roadway Alignment and Surface Condition 5-Year Annual Average, Adjusted for ABS (and LTCCS Review) (TIFA, GES, 2000-2004; LTCCS)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	1,207.7	15.7	125.4	156.2	181.1	1,049.5	0.9
	Not dry	1,801.5	21.7	22.7	314.3	195.5	1,916.7	0.0
Curve	Dry	572.4	6.7	56.1	73.8	58.5	458.8	0.4
	Not dry	767.3	12.7	76.2	163.6	248.7	597.5	2.0
Unknown		0.8	1.1	1.2	0.0	0.0	0.8	0.0
Total		4,349.7	58.0	281.6	707.9	683.8	4,023.3	3.3
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	27.8	27.1	44.5	22.1	26.5	26.1	26.0
	Not dry	41.4	37.5	8.1	44.4	28.6	47.6	0.0
Curve	Dry	13.2	11.6	19.9	10.4	8.6	11.4	12.8
	Not dry	17.6	21.8	27.1	23.1	36.4	14.9	61.2
Unknown		0.0	1.9	0.4	0.0	0.0	0.0	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Since Table 26 and Table 27 provide baseline data for assessing the number of crashes that potentially may benefit from the stability technologies, the numbers in these tables correspond to certain quantities in the benefit equation. For example, in Table 26, the number of crashes for straight roadway alignment and dry surface condition is 2,480.2. For this scenario, this number corresponds to the quantity in the benefit equation designated by:

$$N_{wo} \times P_{wo}(S \mid C) = 2{,}480.2\ .$$

The remaining part of the benefit equation, which consists of the prevention ratio, is derived from the results of the hardware-in-the-loop simulation and expert panel judgment.

8.3 Calculation of Prevention Ratios From HiL Simulation

In total, prevention ratios are assigned to the 159 LTCCS cases shown in Table 22. Two sources of information were used to assign prevention ratios: expert panel judgment of certain cases taken from the LTCCS database (as explained earlier) and HiL simulation. This section describes the method for calculating prevention ratios for the 22 LTCCS cases based on results from the HiL simulation.

In a Roll Stability Adviser (RSA) FOT study conducted at UMTRI, 3,460 measurements of peak lateral acceleration (Ay) of heavy trucks were made through 42 curves. [11] The data was analyzed from the RSA-not-active period so that naturalistic driving was represented. A histogram of the 3,460 measurements is shown in Figure 27. The distribution looks close to normal with a mean of 0.179.

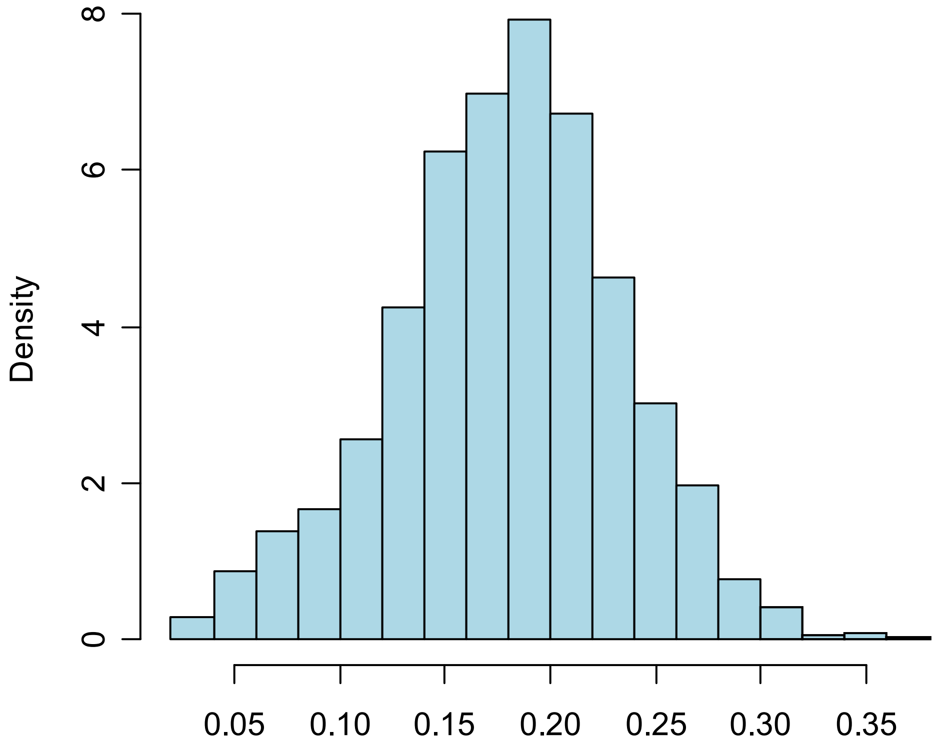


Figure 27. Distribution of FOT Peak Lateral Acceleration

Two curve radii were considered during the HiL simulation, so the peak lateral acceleration was converted to kilometers per hour (km/h) for both cases. The curve radii were 68 m and 227 m. The conversion formulas are shown in Table 28 below.

Table 28. Conversion of Lateral Acceleration (Ay) to Kilometers per Hour

Curve Radius	Kilometers per Hour (km/h)
68 m	$\sqrt{Ay \times 9.80665 \times 68} \times 3.6$
227 m	$\sqrt{Ay \times 9.80665 \times 227} \times 3.6$

The 68 m radius was the mean radius for all relevant LTCCS crashes that occurred on curves below a 100 m radius and the 227 m radius is the mean for crashes that occurred on curves greater than 100 m. The histograms in Figure 28 show distributions of curve entry speed in km/h for the two curves. Since the 68 m curve is a more severe curve, vehicles tended to enter the curve at a slower speed. The average speed on the 68 m curve was 38.8 km/h, while the average speed on the 227 m curve was 70.9 km/h. These histograms give the general shapes of the distributions and can be used in conjunction with results produced from the HiL simulations to calculate estimated benefits of RSC and ESC relative to the baseline ABS case. Note that the shapes of the distributions tend to be skewed to the left with clusters of observations at the slower speeds.

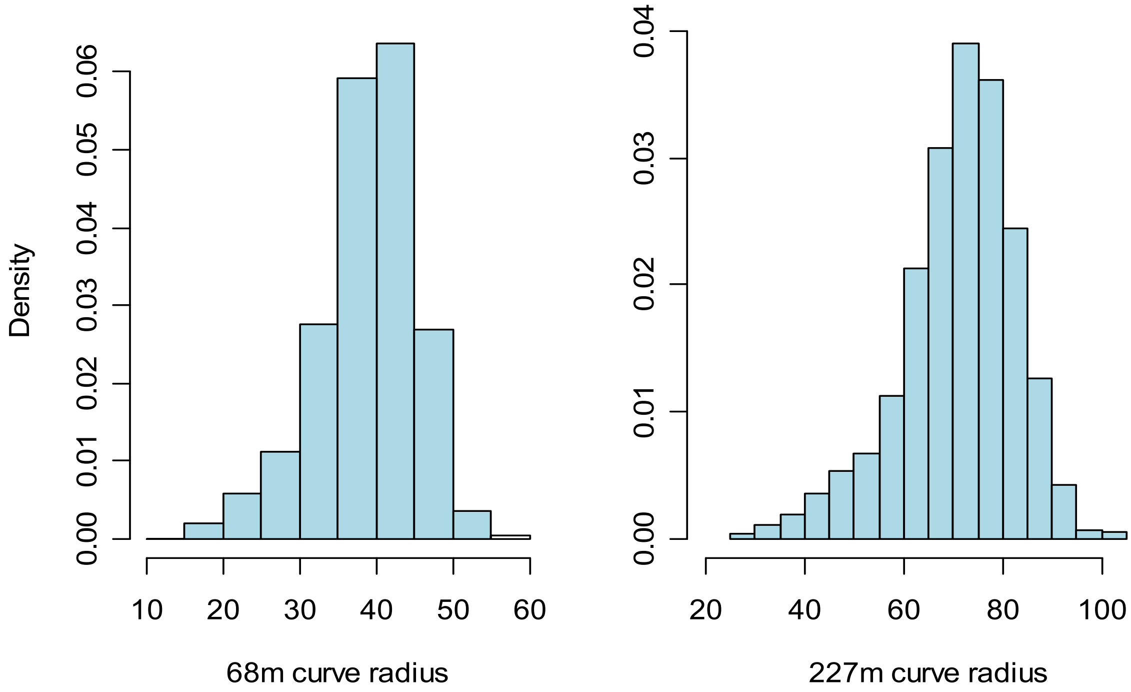


Figure 28. FOT Data Curve Entry Speed (km/h)

The displayed distributions represent curve speeds during normal driving in which the RSA feature was not active. No vehicles rolled over at these speeds. Therefore, for this portion of the analysis, the distributions needed to be shifted to the right to represent the speeds of vehicles that rolled over assuming the baseline case of ABS equipped vehicles. Table 29 shows the distribution of rollovers on curves by curve radius and roll position taken from the LTCCS data. Simulations of vehicles entering curves below100 m and above 100 m showed that vehicles entering the curve above critical speed initiated rollover within 100 m of curve entry. Vehicles that rolled over after 100 m of curve entry likely entered the curve below critical speed, but rolled due to changes in road geometry or from some vehicle action. Of all trucks that rolled over, 20/43=0.465 entered the curve below V_c (radius<100 m) since those vehicles made it past 100 m of the curve start. In addition, 21/28=0.75 entered the curve below V_c (radius>100 m) since those vehicles also made it past 100 m of the curve start. These values can represent the percentiles of ABS V_c in the shifted distributions.

Table 29. Distribution of Rollovers on Curve by Curve Radius and Roll Position

Radius	Within 100m of curve start	Past 100m of curve start	Total
<100 m	23	20	43
>100 m	7	21	28

Figure 29 shows an example of a fit to a shifted distribution and the method for calculating the estimated effectiveness of the relevant technology. The example is only illustrative and does not represent actual results from the HiL simulation. The example shows hypothetical critical speeds of 66 km/h for ABS and 80 km/h for ESC to be determined from the HiL simulation. The method applies equally well to RSC. The percentile (area to the left) of ABS V_c=66 was chosen to be 0.465 in the shifted distribution for the 68 m curve radius, and 0.75 in the shifted distribution for the 227 m curve radius.

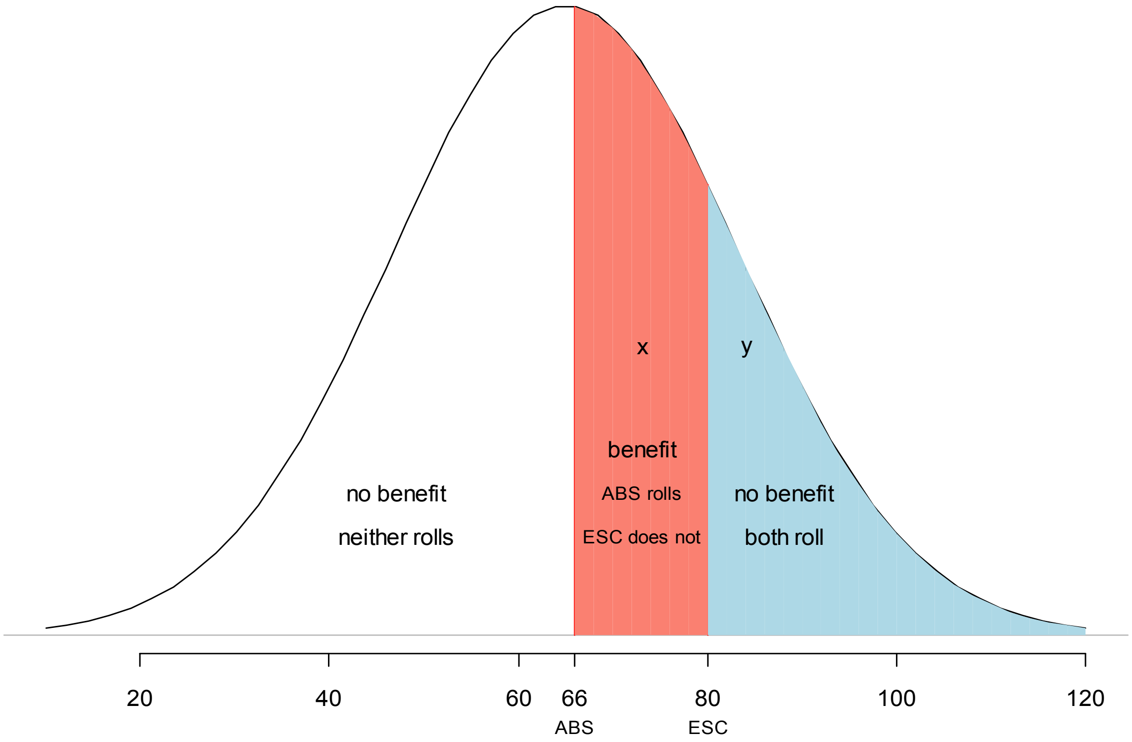


Figure 29. Estimation of Technology Effectiveness

In reference to Figure 29, the effectiveness of the technology is calculated using the equation:

$$E = \frac{x}{x+y}$$

that represents the ratio of the proportion of the distribution where ABS-equipped vehicles roll over, but ESC-equipped vehicles do not, to the proportion of the distribution where ABS-equipped vehicles roll over. Note that for the 68 m curve radius x + y = 1-0.465=0.535, while x + y = 1-0.75=0.25 for the 227 m curve radius. In terms of the benefit equation, the quantity *E* is equivalent to

$$1-\frac{P_w(C\,|\,S)}{P_{wo}(C\,|\,S)}$$

In the actual analysis, the distributions of curve entry speeds are converted back to the peak lateral acceleration scale, since this distribution is close to the normal distribution and not skewed to the left. This simplifies calculation of E since standard software can be used to calculate areas under the normal distribution.

During the HiL simulation, two curve radii of 68 m and 227 m were used. In addition, two CG heights of 2.0 m and 2.3 m were used. In all cases the gross vehicle weight was fixed at 36,360 kg (80,000 lb), which represents the worst case. Table 30 shows the critical speeds according to curve radius and CG height. These are the speeds that were used in the shifted distributions to calculate the effectiveness of the RSC and ESC technologies.

Table 30. Critical Speeds Used in HiL Simulation by Curve Radius and CG Height

		Critical speed (km/h)		
Curve Radius	CG Height	ABS	RSC	ESC
68m	2.0m	62.8	70.8	80.5
	2.3m	57.9	66.0	70.8
227m	2.0m	109.4	112.7	120.7
	2.3m	101.4	106.2.8	106.2

Effectiveness measures (E) were calculated for each of the 22 cases (8 cases of the 30 could not be simulated) from the HiL simulation according to curve radius and CG height. Table 31 shows the effectiveness measures for RSC and ESC technologies relative to the baseline ABS equipped vehicle. Critical speeds in kilometers per hour for ABS, RSC, and ESC are shown, along with the corresponding conversions to lateral acceleration that can be calculated by inverting the formulas in Table 28. Conversion to lateral accelerations allows effectiveness measures to be derived with reference to normal distributions since the distribution of lateral acceleration is close to normal. The normal means and standard deviation (SD) in the shifted distributions are shown. The SD is constant since the distribution is only shifted to the right.

Table 31. Effectiveness Measures Calculated for 22 LTCCS Cases Based on HiL Simulation According to Curve Radius and CG Height

				Critical Speeds (km/h)			Lateral Accelerations								
CaseID	Veh. Num	Curve Radius	CG Height	ABS	RSC	ESC	ABS	RSC	ESC	Normal Mean	Normal SD	RSC_x	ESC_x	RSC effect	ESC effect
332006696	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
332006697	1	227m	2.0m	109.4	112.7	120.7	0.4151	0.4399	0.5050	0.3781	0.0549	0.1199	0.2396	47.9	95.8
333006294	1	227m	2.3m	101.4	106.2	106.2	0.3563	0.3911	0.3911	0.3193	0.0549	0.1544	0.1544	61.8	61.8
339006276	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
350006669	1	227m	2.0m	109.4	112.7	120.7	0.4151	0.4399	0.5050	0.3781	0.0549	0.1199	0.2396	47.9	95.8
350006975	1	68m	2.3m	57.9	66.0	70.8	0.3884	0.5038	0.5802	0.3932	0.0549	0.5130	0.5347	95.9	99.9
803004492	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
808006705	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
810005647	1	227m	2.0m	109.4	112.7	120.7	0.4151	0.4399	0.5050	0.3781	0.0549	0.1199	0.2396	47.9	95.8
811005442	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
811005582	1	227m	2.3m	101.4	106.2	106.2	0.3563	0.3911	0.3911	0.3193	0.0549	0.1544	0.1544	61.8	61.8
812004411	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
812006131	1	227m	2.0m	109.4	112.7	120.7	0.4151	0.4399	0.5050	0.3781	0.0549	0.1199	0.2396	47.9	95.8
813003907	1	68m	2.3m	57.9	66.0	70.8	0.3884	0.5038	0.5802	0.3932	0.0549	0.5130	0.5347	95.9	99.9
816004201	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
816006201	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
819004185	1	227m	2.3m	101.4	106.2	106.2	0.3563	0.3911	0.3911	0.3193	0.0549	0.1544	0.1544	61.8	61.8
819005865	1	68m	2.3m	57.9	66.0	70.8	0.3884	0.5038	0.5802	0.3932	0.0549	0.5130	0.5347	95.9	99.9
819006125	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
820004422	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9
821005449	1	68m	2.3m	57.9	66.0	70.8	0.3884	0.5038	0.5802	0.3932	0.0549	0.5130	0.5347	95.9	99.9
884003927	1	68m	2.0m	62.8	70.8	80.5	0.4558	0.5802	0.7492	0.4606	0.0549	0.5203	0.5350	97.2	99.9

RSC_x and ESC_x represent the numerators in the effectiveness measures, respectively

Summary of Effectiveness by Curve Radius

Curve Radius	CG Height	RSC	ESC
68m	2.0m	97.2	99.9
	2.3m	95.9	99.9
227m	2.0m	47.9	95.8
	2.3m	61.8	61.8

The RSC_x and ESC_x columns are the numerators in the effectiveness measures, respectively. Statistical software is used to calculate these numbers since they represent areas under the normal curve, corresponding to “x” in Figure 29. (Calculation of these quantities by hand is intractable, but can be accomplished using statistical software.) Effectiveness measures can be calculated by dividing these numbers by 0.535 or 0.25, depending on whether curve radius is 68 m or 227 m. For example, the effectiveness measure for RSC in the first row of Table 31 (CaseID=332006696) equals 0.5203/0.535 = 97.2%. As another example in the second row of Table 31 (CaseID=332006697), the effectiveness measure for RSC is 0.1199/0.25 = 47.9%. The effectiveness measures based on these results are inserted in Table 22.

8.4 Estimated Benefit in Relevant Rollover and Yaw Crashes

The effectiveness measures for all 159 LTCCS cases are shown in Table 22. Of those cases, 22 effectiveness measures were calculated using results from HiL simulation as described in the previous subsection. The remaining 137 effectiveness measures are the result of the combined scores obtained from expert panel judgment as described in Section 6. Based on the expert panel judgment of LTCCS cases and HiL simulation, Table 32 shows the overall effectiveness measures for the 113 LTCCS rollover cases. Table 33 shows the effectiveness measures for the 46 LTCCS LOC cases. The results are averaged by roadway alignment and surface condition so that they can be applied to the baseline cases that may potentially benefit from RSC and ESC as presented in Table 26 and Table 27. For example, the estimate of 21.14 for ESC is derived by averaging the 22 ESC effectiveness measures in Table 22 that correspond to conditions in which roadway alignment is straight and surface condition is dry (see Appendix F for effectiveness measures grouped by roadway alignment and surface condition). The estimate of 16.36 for RSC is derived similarly. The largest measures correspond to curved roads especially when surface condition is dry.

Table 32. ESC/RSC Effectiveness for Relevant LTCCS Roll Crashes

Road alignment	Surface condition	LTCCS cases	ESC	RSC
Straight	Dry	22	21.14	16.36
	Not dry	3	0.00	0.00
Curve	Dry	79	75.05	71.15
	Not dry	9	55.56	45.56
Grand Total		113		

Table 33. ESC/RSC Effectiveness for Relevant LTCCS LOC Crashes

Road alignment	Surface condition	LTCCS cases	ESC	RSC
Straight	Dry	9	17.78	0.56
	Not dry	17	20.59	1.76
Curve	Dry	7	31.57	14.00
	Not dry	13	39.62	11.54
Total LTCCS LOC crashes		46		

These aggregated effectiveness measures for RSC and for ESC are then applied to the baseline cases in Table 26 and Table 27 to arrive at the results shown in Table 34 through Table 37 that show the estimated benefits in terms of reduced crashes and injuries attributable to each stability technology. The bottom portions of the tables show percentages. Table 34 shows RSC benefits in terms of relevant rollover crashes and injuries reduced, and Table 35 shows ESC benefits for rollover crashes and injuries reduced. As an example to show how the calculations proceeded, Table 32 shows that the average estimate effectiveness of RSC for rollover crashes in the straight, dry condition is 16.36. Table 26 shows 2,480.2 crashes in that circumstance. 0.1636 × 2480.2 ≈ 405.9 crashes reduced. As described above, in rollover-relevant crashes, most of the benefits were derived when roadway alignment was curved and surface condition was dry. Note that ESC provides a somewhat greater reduction of roll crashes than does RSC.

Table 34. RSC Benefit From Reduction of Relevant Rollover Crashes (Counts and Percentages)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	405.9	8.8	58.6	109.2	100.9	221.6	0.0
	Not dry	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Curve	Dry	2,692.0	88.3	665.7	891.3	557.0	1,246.2	3.9
	Not dry	183.8	5.5	31.9	52.3	4.8	171.3	0.0
Unknown		0.2	0.2	0.0	0.0	0.0	0.0	0.0
Total		3,281.8	102.8	756.2	1,052.9	662.7	1,639.1	3.9
Percentages								
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	12.4	8.6	7.7	10.4	15.2	13.5	0.0
	Not dry	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Curve	Dry	82.0	85.9	88.0	84.7	84.0	76.0	100.0
	Not dry	5.6	5.4	4.2	5.0	0.7	10.5	0.0
Unknown		0.0	0.2	0.0	0.0	0.0	0.0	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 35. ESC Benefit From Reduction of Relevant Rollover Crashes (Counts and Percentages)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	524.2	11.4	75.7	141.1	130.3	286.2	0.0
	Not dry	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Curve	Dry	2,839.5	93.1	702.1	940.2	587.5	1,314.4	4.1
	Not dry	224.1	6.8	38.9	63.8	5.9	209.0	0.0
Unknown		0.2	0.2	0.0	0.0	0.0	0.0	0.0
Total		3,588.0	111.4	816.8	1,145.1	723.8	1,809.7	4.1
Percentages								
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	14.6	10.2	9.3	12.3	18.0	15.8	0.0
	Not dry	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Curve	Dry	79.1	83.6	86.0	82.1	81.2	72.6	100.0
	Not dry	6.2	6.1	4.8	5.6	0.8	11.5	0.0
Unknown		0.0	0.2	0.0	0.0	0.0	0.0	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

For relevant LOC crashes, note that ESC provides over five times the benefit in terms of crashes reduced, compared with RSC. Crash reduction from RSC primarily occurred on curved roads, as expected, and relatively equally in the dry and not dry condition. A somewhat higher percentage of the ESC benefits in LOC crashes was associated with straight roads than curved, but for both roadway alignments, substantially more of the benefit is realized in the not-dry roadway surface condition, compared with dry roads.

Table 36. RSC Benefit From Reduction of Relevant LOC Crashes (Counts and Percentages)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	6.7	0.1	0.7	0.9	1.0	5.8	0.0
	Not dry	31.8	0.4	0.4	5.5	3.5	33.8	0.0
Curve	Dry	80.1	0.9	7.9	10.3	8.2	64.2	0.1
	Not dry	88.5	1.5	8.8	18.9	28.7	68.9	0.2
Unknown		0.4	0.6	0.6	0.0	0.0	0.4	0.0
Total		207.6	3.4	18.3	35.6	41.3	173.2	0.3
Percentages								
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	3.2	2.5	3.8	2.4	2.4	3.4	1.6
	Not dry	15.3	11.2	2.2	15.6	8.3	19.5	0.0
Curve	Dry	38.6	27.4	42.8	29.0	19.8	37.1	19.9
	Not dry	42.7	42.5	48.0	53.0	69.4	39.8	78.5
Unknown		0.2	16.4	3.2	0.0	0.0	0.2	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 37. ESC Benefit From Reduction of Relevant LOC Crashes (Counts and Percentages)

Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	214.7	2.8	22.3	27.8	32.2	186.6	0.2
	Not dry	370.9	4.5	4.7	64.7	40.3	394.6	0.0
Curve	Dry	180.7	2.1	17.7	23.3	18.5	144.8	0.1
	Not dry	304.0	5.0	30.2	64.8	98.5	236.7	0.8
Unknown		0.4	0.6	0.6	0.0	0.0	0.4	0.0
Total		1,070.7	15.0	75.5	180.6	189.4	963.1	1.1
Percentages								
Roadway Alignment	Surface condition	Crashes	Fatal	A-injury	B-injury	C-injury	No injury	Injury unknown
Straight	Dry	20.1	18.7	29.5	15.4	17.0	19.4	14.0
	Not dry	34.6	29.9	6.2	35.8	21.3	41.0	0.0
Curve	Dry	16.9	14.2	23.5	12.9	9.7	15.0	12.3
	Not dry	28.4	33.5	40.0	35.9	52.0	24.6	73.7
Unknown		0.0	3.8	0.8	0.0	0.0	0.0	0.0
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0

8.5 Estimated Cost Benefit Adjusted to 2007 Dollars

Benefits were applied per victim injured according to economic estimates of costs of highway crashes involving large trucks (updated report by Zaloshnja & Miller, 2006). [8] Since costs were reported in 2005 dollars, they were adjusted to 2007 dollars using the CPI inflation factor of $1.06 as reported by the Bureau of Labor Statistics. [1] The benefits were applied specifically to tractors pulling one trailer. Table 38 shows the applicable data reproduced from Zaloshnja and Miller.

Table 38. Costs per Medium/Heavy-Truck Crash Victim Involved in Police-Reported Injury Severity, 2001-2003 (in 2005 dollars) [10]

	Injury severity	Annual number victims	Medical costs	Emergency services	Property damage	Lost prod. from delays	Total lost productivity	Monetized QALYs based on VSL $6.1 million	Total cost per victim
Truck-tractor, 1 trailer	O	215,614	485	43	2,313	1,794	2,828	1,990	7,659
	C	29,283	8,831	187	6,274	4,109	23,473	83,891	122,656
	B	27,240	13,347	150	7,708	4,477	46,655	135,420	203,280
	A	14,529	33,931	264	9,314	4,740	104,494	344,015	492,018
	K	3,296	30,916	989	23,509	6,143	916,141	5,339,640	6,311,195
	U – inj sev	1,172	3,741	85	4,601	3,036	8,178	12,033	28,638
	Unknown	13,843	2,122	92	3,381	1,891	12,303	29,423	47,321

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[10] Reproduced from Zaloshnja & Miller, 2006, using VSL $6.1 million value of 306,172 QALY instead of the VSL $3 million value published in the report.

Table 39 and Table 40 show rollover cost benefits for RSC and for ESC, respectively, adjusted to 2007 dollars. As shown by the last row in the two tables, the total benefits are greater for ESC than for RSC for the rollover crash type.

Table 39. Estimated RSC Cost Benefit for Rollover (in 2007 dollars)

Roadway alignment	Surface condition	Fatal	A-Injury	B-Injury	C-Injury	No Injury	Injury Unknown
Straight	Dry	58,851,292	30,563,912	23,535,673	13,118,944	1,799,171	0
	Not dry	0	0	0	0	0	0
Curve	Dry	590,609,583	347,172,182	192,061,140	72,419,999	10,117,045	195,316
	Not dry	37,045,818	16,656,809	11,280,136	627,884	1,391,061	0
Unknown		1,337,973	0	0	0	0	0
Total		687,844,666	394,392,903	226,876,949	86,166,827	13,307,277	195,316

Table 40. Estimated ESC Cost Benefit for Rollover (in 2007 dollars)

Roadway alignment	Surface condition	Fatal	A-Injury	B-Injury	C-Injury	No Injury	Injury Unknown
Straight	Dry	76,016,252	39,478,386	30,400,244	16,945,303	2,323,930	0
	Not dry	0	0	0	0	0	0
Curve	Dry	622,971,752	366,195,316	202,585,038	76,388,218	10,671,403	206,018
	Not dry	45,177,827	20,313,182	13,756,263	765,712	1,696,415	0
Unknown		1,337,973	0	0	0	0	0
Total		745,503,803	425,986,884	246,741,546	94,099,232	14,691,749	206,018

Table 41 and Table 42 show LOC cost benefits for RSC and for ESC, respectively, adjusted to 2007 dollars. As shown by the last row in the two tables, the total benefits are significantly greater for ESC than for RSC for the LOC crash type.

Table 41. Estimated RSC Cost Benefit for LOC (in 2007 dollars)

Roadway alignment	Surface condition	Fatal	A-Injury	B-Injury	C-Injury	No Injury	Injury Unknown
Straight	Dry	584,666	363,291	187,044	130,777	47,338	242
	Not dry	2,564,604	208,672	1,195,083	448,624	274,603	0
Curve	Dry	6,302,698	4,097,162	2,226,623	1,064,128	521,451	3,006
	Not dry	9,772,403	4,587,660	4,066,592	3,731,093	559,695	11,825
Unknown		3,758,534	308,439	0	0	3,057	0
Total		22,982,905	9,565,224	7,675,342	5,374,623	1,406,144	15,073

Table 42. Estimated ESC Cost Benefit for LOC (in 2007 dollars)

Roadway alignment	Surface condition	Fatal	A-Injury	B-Injury	C-Injury	No Injury	Injury Unknown
Straight	Dry	18,709,304	11,625,326	5,985,421	4,184,873	1,514,803	7,743
	Not dry	29,920,376	2,434,505	13,942,637	5,233,951	3,203,706	0
Curve	Dry	14,213,035	9,239,393	5,021,193	2,399,686	1,175,910	6,778
	Not dry	33,551,918	15,750,965	13,961,964	12,810,085	1,921,618	40,600
Unknown		3,758,534	308,439	0	0	3,057	0
Total		100,153,166	39,358,628	38,911,215	24,628,595	7,819,093	55,121

Table 43 shows the total estimated cost benefits aggregated from the previous four tables above. ESC shows greater benefits for both the roll crash type and for the LOC crash type. The difference between ESC and RSC is only about eight percent in the case of rollover. The greater benefit from ESC in the roll case is probably due to the earlier engagement of ESC in the crash sequence. Substantially more benefits accrue from reduction in rollovers than reduction in LOC crashes, both because of the greater number of roll crashes and because of the higher severity of rollover crashes. In the case of RSC, almost 97 percent of the benefits are related to the prevention of rollover. For ESC, which is effective against LOC, almost 88 percent of the benefit is related to reducing the number of rollover crashes.

Table 43. Estimated Total Cost Benefits From RSC and From ESC (in 2007 dollars)

	Benefit	
Crash type	ESC	RSC
Roll	1,527,229,232	1,408,783,937
LOC	210,925,819	47,019,310
Total	1,738,155,051	1,455,803,247

Overall results in terms of crashes, fatalities, and injuries (including property damage only) prevented are presented in Table 44. The first column shows the estimated annual study population of tractor-semitrailer crashes, deaths, and injuries. These are the crashes, deaths, and injuries that occur in crashes relevant to the technologies. Also shown are those estimated to be prevented by each of the two technologies.

Table 44. Adjusted Annual Study Population Crashes, Deaths, and Injuries, and Estimated Crashes, Deaths, and Injuries Prevented by RSC and ESC

	Annual total study population	Prevented by	
		RSC	ESC
Crashes	11,224	3,489	4,659
Deaths	255	106	126
Injuries	14,233	4,384	5,909

9 Summary and Discussion

This research effort has produced an estimate of the anticipated benefits that would be achieved for specific crash types if electronic stability or roll control devices were deployed in the nation's 5-axle tractor-semitrailer fleet. Practical constraints limit the scope of this study to the evaluation of crashes involving first-event yaw instability and first-event roll instability. The subsets of crashes that constitute these two event categories are small in relation to all other crashes involving tractor-semitrailer vehicles. However, these crashes produce a substantial number of personal injuries and fatalities. The results presented in this report constitute the net benefit of the technology in relation to a potentially limited set of crash types where the benefits of the technology are most readily apparent and the results should be considered conservative. It is expected that there are events that may occur in other crash types that would benefit from the technologies, but these crashes cannot be identified effectively using coded data.

Tractor-semitrailer crashes tend to be complex events that involve factors not only in relation to crash cause, but also factors affecting post-crash yaw control that can result in secondary events that can increase the net severity of the crash sequence. Therefore it is anticipated that technologies that address vehicle yaw control (ESC) would have additional benefits across a broad range of crash types. The study team was not able to provide an estimate for these additional benefits, so true amount of benefits to be realized is likely higher.

The following summary addresses the principal findings of this research effort.

9.1 Problem Definition

Based on the global definitions of rollover and loss of control, it was estimated that tractor semitrailers are involved in 178,000 crashes annually, resulting in 3,329 fatalities. Results for injury and property damage indicated that 88.5 percent of crashes are not associated with rollover or loss of control. The odds of rollover increase as cargo weight increases, but loss of control and cargo weight appear independent. The odds of rollover were about 2.6 times greater for cargo weight in the 5,001 to 20,000 lb category compared to the 0 to 5,000 lb category. The ratio increases to 7.4 when comparing the heavy category to the light category. For loss of control, the comparative odds ratios were 0.9 and 1.0, respectively, suggesting no association between loss of control and trailer cargo weight.

The odds of rollover were 2.6 times greater on ramps than in other locations, and the odds of loss of control were 2.2 times greater. Tank trailers were much more likely to roll over than van trailers. The odds ratio is approximately 3.5. For loss of control, the association was not as strong, but the odds of loss of control were 1.8 times greater for tanks compared to vans.

9.2 Influence of ABS

All air-braked truck tractors sold in the United States built on or after March 1, 1997, were required to be equipped with antilock braking systems. Antilock brakes prevent drive axle wheel lockup, which is a major cause of first-event tractor jackknife. Results from the TIFA and GES databases indicate that the odds of first-event jackknife in fatal crashes are 1.64 times greater for tractors built prior to 1998 than for those built after. For nonfatal crashes, first-event jackknife is 3.52 times greater for tractors built prior to 1998. These results support the argument that tractor-mounted ABS brake systems reduce the likelihood of tractor jackknife.

9.3 LTCCS Analysis Using HiL and Expert Panel to Estimate Effectiveness Ratios

The case selection algorithm developed in the national crash data was applied to the LTCCS data file to select a set of crashes that meet the criteria for crashes potentially addressable by ESC or RSC technologies. A total of 83 LTCCS cases were identified as meeting the yaw-unstable criteria and 81 LTCCS cases met the roll-unstable criteria. Review of these cases showed that a substantial number of cases that were coded as relevant LOC were actually simple rollovers, and some met neither the LOC nor the roll criteria. The LOC cases determined to be simple rollovers were re-assigned to the roll group and the cases miscoded as LOC and that did not roll were dropped. (This reassignment was primarily significant in estimating benefits for the two technologies by crash types.)

Each case was exhaustively reviewed and crash factors coded for relevance to RSC or ESC technologies. Common crash factors allowed cases to be grouped into bins reflecting specific crash scenarios. In many cases, however, the crashes were sufficiently individual to warrant single-case only scenarios.

Crash scenarios involving rollover on curves were selected for HiL simulation. Case detail in the LTCCS data was sufficient to support simulation. The HiL simulations were run in the baseline ABS-only case, and then for each of the ESC and RSC technologies. The results of the simulations quantified the performance of the technology for a small number of grouped scenarios, by determining how much the technology increased the critical speed—at which the truck would rollover—for the curve. Using the shape of a distribution of curve entry speeds derived from naturalistic data, it was possible to estimate the probability of preventing each individual rollover. However, given the complex nature of rollover events, it was determined that certain rollover scenarios could not be covered by HiL. For rollovers not simulated, an expert panel of UMTRI scientists was used to estimate technology effectiveness.

Estimates of the effectiveness of ESC and of RSC to prevent the LOC events identified in the LTCCS data were produced by the expert panel. LOC events are typically more complex than rollover events, and the LTCCS data did not supply enough information to support simulation. It was determined that effectiveness estimates could only be achieved through the use of an expert panel. Each of the relevant LTCCS LOC cases was carefully studied to extract as much technical detail as possible. In addition, panel members observed a full-scale track test where the technologies were exercised in a series of maneuvers. This provided considerable insight into the behavior of the technologies. Using this background knowledge about the technology and the detail available in the LTCCS, the panel provided a systematic review of each case and an estimate of the effectiveness of each technology.

9.4 Analysis of Fleet Data

An analysis of crash data from a large for-hire carrier was conducted to assess the influence of technology on crash rates. The results are presented in Appendix C. The company began adding tractors with a roll stability control (RSC) device in 2004. The carrier provided a well-documented set of data that allowed identification of the crash types of interest, crash severity in a form that can be mapped to the definitions in the GES and TIFA files, as well as whether the involved vehicle was equipped RSC. The data covered the years 2001 to 2007 and included 112,060 records.

Changes in rollover rates for the fleet were found to be consistent with the introduction of RSC in the fleet. Rates of rollover per 100 million vehicle miles traveled (VMT) fluctuated within a narrow band from 2001 to 2005, and then declined in each of the next two years. Over the period from 2001 to 2005, rollover rates ranged from 4.64 per 100 million VMT in 2003 to 5.33 in 2001. But the rate declined in 2006 to 4.39 and 2.98 in 2007, a drop of about 40 percent in two years. This drop occurred at the same time that the penetration of RSC in the company’s fleet increased from 39 percent in 2004, to 59 percent in 2005 and 78 percent in 2006.

9.4.1 Jackknife Anomaly

Rates of jackknife also varied significantly over the same period, though the pattern was different from that observed for rollover. Jackknife rates remained relatively stable from 2001 to 2004, ranging from 5.61 to 6.54. But in 2005, the rate dropped almost in half to 3.66, with 2.88 in 2006 and 3.14 in 2007. In contrast to the rollover rate, which showed a linear decline from 2005, jackknife rates showed a step change that started the year before the decline in the rollover rate. This is an unexpected observation since the introduction of RSC by itself should not have affected jackknife risk. Moreover, information supplied by the company indicated that virtually all the power units were equipped with ABS three years prior to the drop in the jackknife rate. A logistic regression model was fitted to the data to attempt to determine the effect of RSC in light of all the other factors shown to affect jackknife. The modeling showed some apparent association with RSC and with ABS. However, the most important factor in jackknife was road surface condition. Slick roads (wet, snowy, or icy) were associated with an increase in the conditional odds of jackknife by 34 times. None of the factors in the model could explain the reduction in jackknife. It is most likely that the change was related to some exogenous factor, such as changes in driver training and supervision.

9.4.2 RSC Fleet Effectiveness

Logistic regression was used to estimate the effect of the factors on first event rollover. RSC was found to reduce the odds of rollover, given a crash, by about 25 percent, relative to a vehicle without RSC, even taking into account the other factors, most of which had a larger effect. In the rollover model, roadway curvature had the largest effect, increasing the odds of rollover by 7.3 times over that on a straight road. Cargo weight also had a large effect: trucks with cargoes weighing 5,000 or more pounds increased the odds of rollover by 2.3 times over more lightly loaded vehicles. Driver tenure, age, the type of driver team, and the division of the company also had statistically significant effects.

9.5 Benefit Analysis

Using the definitions of rollover and loss of control established in this report for tractor-semitrailers, baseline numbers of relevant rollover and loss-of-control crashes and injuries are derived. These are the numbers that may potentially benefit from the RSC and ESC technologies. A benefit equation is used to estimate benefits in terms of numbers of crashes, deaths, and injuries prevented that are attributable to the stability technologies. Two sources of information provided information for calculating effectiveness measures. One source is based on expert panel judgment of certain cases taken from the LTCCS database. The other source is derived from HiL simulation.

For the HiL simulation portion of the analysis, data from a Roll Stability Adviser FOT study conducted at UMTRI provided distributions of speeds at which heavy trucks enter curves of 68m radius and 227m radius. Data from the LTCCS support the use of these curve radii. The FOT data were collected when the RSA feature was not active and are representative of normal driving. Since no vehicles rolled over at these speeds, the two distributions are shifted to the right to represent speeds of vehicles that rolled over, assuming a baseline case of ABS equipped vehicles. The amount of shift is determined by rollover cases in the LTCCS according to curve radius and point of rollover from the curve start. Results from the HiL simulation give critical speeds of rollover for ABS, RSC, and ESC that are used in the shifted distributions to calculate effectiveness measures.

Overall results from the expert panel judgment of LTCCS cases and the HiL simulation are presented in Table 45. The first column shows the estimated annual number of tractor semitrailer crashes, deaths, and injuries in crashes relevant to the technologies. Also shown are those estimated to be prevented by the two technologies.

Table 45. Total Crashes, Deaths, Injuries, and Estimated Crashes, Deaths, and Injuries Prevented by RSC and ESC

	Annual total study population	Prevented by	
		RSC	ESC
Crashes	11,224	3,489	4,659
Deaths	255	106	126
Injuries	14,233	4,384	5,909

The benefits are applied per victim injured according to economic estimates of costs of highway crashes involving large trucks (updated report by Zaloshnja & Miller, 2006). Since costs are reported in 2005 dollars, they are adjusted to 2007 dollars using the CPI Inflation factor of $1.06 as reported by the Bureau of Labor Statistics. The benefits relate specifically to tractors pulling one trailer.

Estimated benefits are greater for ESC than RSC, for each of the crash types considered. Assuming ESC was fitted to all tractor-semitrailers, savings from rollovers prevented by ESC are estimated at $1.527 billion annually, and from LOC crashes prevented at $210 million annually, for a total of $1.738 billion annually. Assuming RSC was fitted to all tractor-semitrailers, savings from rollovers prevented at estimated at $1.409 billion annually, and from LOC crashes prevented at $47 million annually, for a total estimated benefit of $1.456 billion annually.

10 Conclusions

This research project calculated benefits of roll stability control and electronic stability control systems. These systems have different sensing and vehicle control strategies, and the purpose of the research project was to evaluate the probable benefits and the relative performance of each technology. Crash scenarios that could likely benefit from the technology were selected from national crash databases and the probable effectiveness of the technology was estimated. Because these technologies are not yet widely used, the analysis did not have the benefit of examining representative crash datasets that contain identifiable data from vehicles equipped with the technology. Therefore the analysis was based on probable outcome estimates derived from hardware-in-the-loop simulation, field test experience, expert panel assessment, and fleet crash data. Because the study only considered 5-axle tractor-semitrailers, the estimated benefits apply only to this particular vehicle configuration operating within the United States. The research project resulted in the following conclusions:

1. Electronic stability systems were found to provide substantial safety benefits. Assuming that all existing 5-axle tractor semitrailers operating on U.S. roads were fitted with the technologies as they address rollover-relevant crashes, the expected annual reductions are 106 fatal injuries and 4,384 injuries. For the technologies as they address yaw relevant crashes, the expected annual reductions are (126 fatalities, 5,909 injuries). The annual

economic benefit expressed in 2007 dollars from these prevented crashes is estimated at $1,455,803,000 for RSC and $1,738,155,000 for ESC. Because ESC addresses both rollover and yaw crashes and it mitigates more rollover crashes (through additional braking capabilities over RSC), the net annual expected benefit for ESC systems is greater than for RSC.

2. The study found that ESC provided more overall safety benefit than RSC. The difference between the estimated effectiveness of RSC and ESC varied among crash scenarios.
3. The analysis of crash datasets proved challenging. Identifying relevant loss-of-control (LOC) and rollover crashes within the national datasets proved a formidable task because the databases are developed for general use and this project required very precise definitions of LOC and rollover. Relying on the general LOC or rollover categories captures a wide range of crashes, many of which have no relevance to the technology. LTCCS proved highly valuable in providing a certain level of detail concerning rollover and LOC crashes. This information was used to construct a number of relevant crash scenarios in such a way that the technical potential of the candidate RSC and LSC technologies could be estimated systematically. Assessment of the technical potential of the respective technologies was based on hardware-in-the-loop simulation.
4. There were certain technical limitations of the HiL simulation, notably for driver actions (simple path follower) and trucks (rigid frame model), especially for loss-of-control crashes. These can both be addressed in future work.
5. The benefit estimates are limited to 5-axle tractor-semitrailers operating within the United States. The analysis focused on a select subset of crash categories with notional relevance to the intent of the technology. The study was not able to assess benefits attributable to less obvious crash types that may nevertheless have an unforeseen connection to the technology. Similarly, the study did not include benefit estimates for other types of tractor-semitrailers.
6. The study could not account for secondary benefits such as driver awareness benefits from intervention experience, directed driver performance modification from company initiatives derived from technology intervention records, or any post-crash benefits attributable to the technologies.
7. HiL simulation was employed mainly to assess technology-related critical speeds for rollover analysis on curves, and to a very limited extent for LOC crashes. Based on the available crash information, even in LTCCS, it is difficult to sufficiently define LOC scenarios for HiL simulation; factors that restrict HiL usefulness in LOC analysis include the inability to define driver input and vehicle parameters prior to a LOC event. Beyond this issue of defining LOC scenarios for HiL simulation, typical LOC scenarios also place much greater demands on the simulation model and its parameters. For example, yaw instability places greater demands on the tire model used in HiL, relative to more

straightforward rollover scenarios. Some LOC scenarios also involve driver steering intervention after the activation of the technology, and this is difficult to model in a realistic or consistent manner.

11 References

1. Bureau of Labor Statistics, U.S. Department of Labor, Inflation Calculator, accessed at http://www.bls.gov/home.htm.

2. Large-Truck Crash Causation Study Codebook. FMCSA, NHTSA, U.S. Department of Transportation, June 2006.

3. Large-Truck Crash Causation Study Analytical User’s Manual. FMCSA, NHTSA, U.S. Department of Transportation, June 2006.

4. Large-Truck Crash Causation Survey search interface, NHTSA, accessed at http://www-nass.nhtsa.dot.gov/LTCCS_PUB/SearchForm.aspx

5. National Automotive Sampling System General Estimates System Analytical User’s Manual, 1988-2005. National Highway Traffic Safety Administration, US. Department of Transportation, National Center for Statistics and Analysis, Washington, DC. n.d.

6. 2004 Trucks Involved in Fatal Accidents Codebook (Version March 23, 2007). Anne Matteson, Leslie Pettis, Paul E. Green, John Woodrooffe. 2007.

7. Winkler, C. B., & Ervin, R. D., “Rollover of Heavy Commercial Vehicles.” The University of Michigan Transportation Research Institute, Ann Arbor, MI. 1999.

8. Zaloshnja, E., and Miller, T. (2006). Unit Costs of Medium/Heavy-Truck Crashes, Pacific Institute.

9. McMillan, N. J., Christiaen, A. C., & Stark, G. V. “Estimating the Safety Benefits for the IVI Generation 0 Field Operational Tests.” Society of Automotive Engineers, 01TB-59, 2001.

10. Najm,W. G., daSilva, M., & Wiacek, C. J. “Estimation of Crash Injury Severity Reduction for Intelligent Vehicle Safety Systems.” SAE Technical Paper Series, 2000-01-1354.

11. Winkler, C., Sullivan, J., Bogard, S., Goodsell, R., & Hagan, M. “Field Operational Test of the Freightliner/Meritor WABCO Roll Stability Advisor & Control at Praxair,” UMTRI report UMTRI-2002-24.

12. MacAdam, C. C.: Application of an Optimal Preview Control for Simulation of Closed-Loop Automobile Driving. *IEEE Transactions on Systems, Man, and Cybernetics*, Vol 11, No. 6, June, 1981, pp.393-399.

Appendix A

Code used to identify relevant LOC and rollover events in GES:

```
 /* loss of control from accident type (34-56,60 are empty)*/
  if acc_type in(2,3,7,8,34,36,38,40,54,56,58,60) then loc_acc=1;
  else loc_acc=0;

  /* loss of control from critical event */
  if p_crash2 in (5,8,9) then loc_cr=1;
  else loc_cr=0;

  /* loss of control from first harmful event jackknife */
  if jacknife=1 and event1_i=5 then loc_jack=1;
  else loc_jack=0;

  /* rollover from untripped rollover
  (unfortunately 2% unknown tripped untripped) */
  if rollover=10 then rol_untrip=1;
  else rol_untrip=0;

  /* first harmful event rollover (noncollision) */
  if rollover>0 and event1_i=1 then rol_first=1;
  else rol_first=0;

  /* create loss of control and rollover variables */
  if loc_acc=1 or loc_cr=1 or loc_jack=1 then loc=1;
  else loc=0;

  if rol_untrip=1 or rol_first=1 then roll=1;
  else roll=0;
```

Code used to identify relevant LOC and rollover events in TIFA:

```
/*Accident type, 1st event jackknife, or first harmful event */
 if v1059 in(2,3,7,8,34,36,54,56) or v126=2 or v23=51 then loc=1;
 else loc=0;

/* First event rollover or untripped roll accident type
 if v125=1 or v1059=97 then roll=1;
 else roll=0;
```

Code used to identify relevant LOC and rollover events in LTCCS:

```
/* loss of control from accident type */
 if crashcode in(2,3,7,8,34,36,38,40,54,56,58,60) then loc_acc=1;
 else loc_acc=0;

 /* loss of control from critical event
 ltccs includes jacknife [sic] as code 7
 */
 if acrcriticalevent in(5,7,8,9) then loc_cr=1;
 else loc_cr=0;

 /* loss of control from pre-crash jackknife
 ajktype is explicitly pre-crash.
 */
 if ajktype in(1,2,9) then loc_jack=1;
 else loc_jack=0;


/* rollover from untripped rollover */
 if rollinittype in(3,5,8) then rol_untrip=1;
 else if rollinittype in(1,2,4,6,7,98,99) then rol_untrip=0;
 else rol_untrip=.;

 /* first harmful event rollover (noncollision) */
 if rollinittype>0 and first_harm=31 then rol_first=1;
 else rol_first=0;

 /* create loss of control and rollover variables
 NOTE that loc related to stability or pre-crash
 maneuver is not used */
 if loc_acc=1 or loc_cr=1 or loc_jack=1 then loc=1;
 else loc=0;

 if rol_untrip=1 or rol_first=1 then roll=1;
 else roll=0;
```

Appendix B

Example 1 – Roll instability likely, yaw instability unlikely

Case 813005655 Vehicle # 1 Roll flag 1, LOC flag 1 (Filter 140)

The driver of the 1999 Freightliner tractor pulling one closed-van semitrailer, a 39-year-old male, was traveling south on a two-lane interstate in the first lane of travel approaching a one-lane exit ramp. The trailer was filled to 50 percent capacity with general freight. The driver of the truck intended to exit at the ramp and began decelerating from the interstate's posted speed of 113 km/h (70 mph) to the ramp's posted speed of 40 km/h (25 mph). The truck driver estimated his speed at between 40-56 km/h (25-35 mph) as he entered the sharp right curve of the ramp. As he got midway into the curve, the rig began to cant to the left and then rolled over one-quarter turn onto its left side. The truck came to final rest facing west on the roadway and left shoulder. The truck driver was transported to a local hospital where he was treated for a facial laceration and abrasions to his left hand. He was released the same day. The crash occurred in the early evening hours on a clear night. The ramp was illuminated by streetlamps. The radius of curvature of the ramp as measured was 57.25 meters and the superlevelation was 5 percent. The ramp itself was an uphill grade of 2 percent. The curve of the ramp just barely conformed to the AASHTO standard for a posted speed limit of 40 km/h (25 mph). The critical pre-crash event for the driver of the truck was when he lost control of his vehicle due to his traveling too fast for conditions. The critical reason for the critical event was coded as "too fast for curve," a driver decision error. This was chosen because it was believed that the driver of the truck was traveling in excess of the posted speed limit and that this speed, combined with the curve of the road and the truck's high center of gravity, caused the truck to roll over. It was believed that the truck driver was truthful when he stated that he was only traveling between 40-56 km/h (25-35 mph) as he entered the curve, because the curve just barely met the AASHTO standard for a posted speed limit of 40 km/h (25 mph). It was believed that due to the tight curve and the lack of "leeway" in terms of the posted speed limit, that the truck driver probably was only exceeding the speed limit by 10 mph. However, this extra speed was enough to cause the truck to roll over, given its higher center of gravity. The truck driver claimed that the load in the trailer must have shifted and that he had checked on the load before starting out. He stated that all he could see was pallets of bottled water, stacked halfway up. He did not know what was in front of the water, but suggested that the load in front of the pallets of water was not blocked or braced correctly. Although police cited a cargo shift as the cause of the crash, it was unlikely that a load of general freight (most of it on pallets) could shift on its own enough (en masse) to roll an entire truck. The driver of the truck reported that he was not fatigued and was familiar with both his vehicle and the roadway. He reported that he drove on this road on a weekly basis. He said that he took a medication to control his blood pressure, but did not know its name. Police did not consider either alcohol or illegal drugs to be involved and ordered no tests; however, the motor carrier ordered both tests. Both the drug and alcohol screen were negative. In summary, the crash occurred when the truck driver entered the exit ramp at a speed too great to safely negotiate the sharp curve. The speed of the truck, combined with the curve of the road and the truck's high center of gravity was the most likely reason for the rollover.

Example 2 – Roll instability likely, yaw instability likely

Case 815004312 Vehicle # 2 Roll flag 1, LOC flag 1

A single-vehicle crash occurred on an eight-lane urban interstate freeway. A concrete barrier divides the freeway with eight lanes in each direction. The crash occurred on the southbound lanes that curve to the right. This section of the roadway is level with no defects. The speed limit on the roadway is 55 mph (89 km/h). At the time of the crash, the road was wet from rain.

Vehicle two, a 2000 Freightliner tractor pulling a 1994 Great Dane van trailer was negotiating the right hand curve. As the Freightliner was negotiating the curve the trailer swung out to the left due to a cargo shift. The driver attempted to correct by steering left, right, and then left again. The trailer rolled over onto its left side. The trailer rolled completely onto its left side, then the tractor rolled over onto its left side and both slid across the southbound lanes. After the trailer had rolled over the cargo broke through the top of the trailer and spilled onto the roadway. The tractor contacted the center Jersey barrier with its top, continued and the top of the trailer struck a light support pole. The Freightliner came to rest facing in a southerly direction on its left side. After the Freightliner had come to final rest and stabilized, a second vehicle came along and lost control when it drove through the magazines and slid and impacted both the trailer, and the center median wall. This vehicle was not included in this case due to the stabilization of the first crash sequence and both crashes had the same KABCO reported level of a "B" (visible) injury. The Freightliner was towed due to damage.

Example 3 – Roll instability unlikely, yaw instability possible

Case 344007015 Vehicle # 1 Roll flag 0, LOC flag 1 (Filter 35)

A single-vehicle crash occurred on an eight-lane concrete urban interstate in the dark at approximately 0430 hours. The roadway was lit with overhead streetlights. There were four southbound lanes and four northbound lanes divided by a concrete median barrier wall. To the right of the wall was a concrete shoulder without rumble strips with a solid painted yellow fog line separating it from lane four. Painted white dashed lines separated the travel lanes. To the right of lane one was a solid painted white fog line and a concrete shoulder without rumble strips. The road curved to the right and was level. An overpass is located in the crash area with concrete pillars supporting it. The speed limit on the roadway is 55 mph (89 km/h). A moderate rain was occurring at the time of the crash so the road was wet with light traffic density. The rain reduced the road friction and made the travel lanes slick. This was considered a roadway factor for vehicle one. The temperature was approximately sixty degrees. Vehicle one, a 1999 Kenworth conventional tractor with a sleeper berth, pulling an empty 1998 Kentucky moving van semitrailer was traveling southbound in the first lane. As the Kenworth was negotiating the right curve the trailer began to swing out left and the driver tried to correct but lost control. The vehicle slid across all travel lanes to the left and either the front plane or the front portion of the right plane struck the concrete barrier, before the bridge breaking a hole through the wall. The vehicle then went into a full jack knife. Several large pieces of the wall fell into the northbound *travel lanes. The force of the impact was so great that the engine, grill and front bumper components were thrown into the opposing lanes. The cab disintegrated and all the three occupants were completely ejected onto the left shoulder as the truck skidded along the wall moving south. The front axle became dislodged from the frame and was found on the left shoulder and in the fourth lane, as well as the hood, roof and other pieces of the truck. The frame of the tractor, with the second and third axles still attached, and the trailer was deflected to the right and crossed all the southbound travel lanes. The Kenworth came to final rest with the trailer still attached blocking all the lanes facing southeast. The Kenworth and its trailer were towed due to damage. The unrestrained driver of the Kenworth, a41-year-old male, was dead on arrival at the trauma center where he was transported with a neck fracture and multiple brain injuries. It is unclear from the PAR the seating positions of the two passengers. The unrestrained second passenger, a 37-year-old male was hospitalized with skull and facial fractures, brain hemorrhages, and multiple open ankle fractures. He was later transferred to a rehabilitation facility. The unrestrained third passenger, a46-year-old male, died with a cervical spinal cord transection and flail chest. The Kenworth was inspected post crash by CMV enforcement inspectors. No violations were discovered during the inspection but not much was left of the tractor to inspect. They were unable to check the second axle brakes due to damage: all the other brakes were adjusted within the allowable tolerances. The entire Kenworth weighed 31,438 lb (14,260 kg). This weight includes the approximate 100 lb (45 kg) of miscellaneous cargo. No citations were issued for the driver. The driving record for the driver of the Kenworth showed one citation for improper lane use and one speeding ticket in the last five years prior to the crash. The driver had a medical card and his examination record showed him to be in good health. An alcohol-and-drug test was performed during the autopsy and both results were negative. It is unknown if this driver was taking any prescription or over the counter medications at the time of the crash. The logbook showed that the driver was not over his hours and had been off work for two days prior to the crash. The company he worked for was a moving company that moved household goods. Most of his time at work was not spent driving but packing, loading and unloading. They had only been on the road for a half an hour that morning. There is no known sleep data. Due to his being off the previous two days, fatigue is not considered a factor for this driver. At the time of the crash, it was raining moderately and the police report indicated that the roads were wet with water on the road in places. It appears that this driver did not realize that he was driving too fast for conditions. As the driver was negotiating the curve, the trailer, which was nearly empty, swung to the left due to speed and the wet roads. It was then that the driver lost control. The pre-event movement for the Kenworth was coded as "(14) negotiating a curve." The critical pre-crash event for the Kenworth was coded as "(06) this vehicle loss of control due to: traveling too fast for conditions." The critical reason for the crash that was attributed to the Kenworth was coded as a driver decision factor: "(140) too fast for curve/turn. This driver was traveling too fast on the curve in the wet weather, with a nearly empty trailer."*

Example 4 – Roll instability unlikely, yaw instability unlikely

Case 329006101 Vehicle # 1 Roll flag 1, LOC flag 1 (Filter27)

Vehicle 1 was a 2000 Sterling tractor pulling a 1998 Great Dane refrigerated semitrailer on a two-lane north/south undivided rural road with a posted speed of 40mph. The weather was clear, the roadway dry, and it was daylight at the time of the crash. A one-lane pullover ramp that is used as a bus stop was located adjacent to the right side of the roadway. Driver 1 pulled into the *bus stop ramp and completed the paperwork from his last delivery. When Driver 1 completed his paperwork, he attempted to turn right and return to the two-lane road. The left front corner of the trailer hooked a low telephone cable. The "1,200-pair" telephone cable, which was approximately 4 inches in diameter, formed a swag between telephone poles. The mid-distance between two telephone poles was just off the center of the bus stop exit. As Vehicle #1 accelerated from the bus stop ramp the slack in the swag pulled tighter until it pulled the tractor and trailer onto its right side. The cable never broke and remained resting on the trailer. Prior to the crash, Driver 1 had his window open and the refrigeration unit on the trailer was running. The trailer had an approximate cargo weight of 1,000 pounds. The center of the swag formed between the next two telephone poles north of the swag Vehicle 1 hooked onto was measured and found to be 8'4" above the ground. Vehicle 1's measured trailer height was 12' 6." Vehicle 1 was towed from the scene due to damage sustained during the rollover. Driver 1 sustained minor severity injuries, but refused medical treatment. The investigating officer did not believe that alcohol or illegal drugs were involved in the crash and did not request associated screening tests for these substances. Driver 1 reported that he had normal vision, that he was not fatigued, that he was taking a prescription blood pressure medication that had no commonly reported side effects, and that he was taking an over-the-counter sinus medication that again had no commonly reported side effects. He further reported that he was familiar with both his vehicle and the roadway. The pre-event movement for Vehicle 1 was coded "Turning right," the critical pre-crash event was coded "Other-trailer snagged by low hanging utility cable," and the critical reason was coded as "inadequate surveillance" because the driver did not see low hanging utility cable. An "other" roadway related factor was assigned for the low hanging cable. Driver 1 reported that he stopped at this location every week to complete paper work and that he had not had any problems with the cable in the past.*

Appendix C: Analysis of Fleet Data

The main thrust of this study was to develop a means of predicting the expected effect of ESC and RSC technologies deployed throughout the trucking fleet. This is accomplished primarily through estimating the effectiveness of the total number of crashes in which the technologies might be effective and then simulating the activity of the technologies in situations as close to those real-world crashes as possible. However, some trucking companies have begun to adopt and deploy the technologies in their fleets. The crash experience of these companies provides an opportunity to study the effect of the technologies in a real-world context, in the actual experience of continuing trucking activities, with the same complexity that would be experienced if the technologies were actually commonly deployed. It should be noted that the results of the fleet data analysis were not used in estimating the overall effect of the technologies in reducing crashes. The results did show the beneficial influence of RSC, for this fleet. However, these data are based on one company's experience with RSC and broad generalizations can not be made on RSC effectiveness for other fleets.

Crash data from a large for-hire carrier were made available for analysis. The company adopted RSC in 2004, so its crash data permit the effect of that technology to be studied. The RSC system was from a single supplier. The company did not adopt ESC, so the experience of ESC in real-world operations and crashes cannot be evaluated. Despite efforts to acquire crash data from a number of companies, only one was able to provide data in the time available.

The firm is a large and well-managed carrier, with a history of continuous improvement in the safety culture. Adding RSC to its fleet is in itself indicative of an effort to improve safety. Other things that occurred over the period covered by the crash data included increases in driver compensation, several changes in the training program including simulation-based training and "virtual skid-pad" training, and changes to the system for monitoring hours-of-service compliance. In discussions with the company, it was clear that the company continually modifies its efforts to improve safety and that the addition of RSC to the fleet was part of its ongoing safety program.

The crash data was provided under an agreement to preserve the anonymity of the fleet and the confidentiality of the data. This fleet began purchasing tractors with RSC devices in 2004, and provided crash data from 2001 through 2007. The crash data includes enough detail to identify some of the crash types of interest, to select crashes comparable in severity to those in TIFA and GES, and to determine whether the vehicle involved was equipped with RSC. The purpose of the analysis was to determine the effect of RSC on the probability of first-event rollover and jackknife (jackknife is the only relevant LOC event that could be reliably identified), as well as to identify other factors related to rollover and to jackknife.

The data included 112,060 records of events involving some type of loss, either property or due to an injury. All types of loss events were included in the file, not just traffic crashes, since the data are used to manage events that occur to the vehicles that involve some sort of harm. For example, the file included records of vandalism and other property damage. In addition, the data included events that occurred in locations other than on public roads (such as backing into a load dock at the fleet terminal). Accordingly, a procedure was developed to identify events that occurred on public roads and that were identifiable as traffic crashes. Thus, events described as "vandalism" or "stuck, needed tow" were omitted. A total of 46,838 crash involvements were used in the analysis dataset.

The company indicated that all tractors with a manufacture date after February 1, 2004, were equipped with RSC, and the manufacture date was available for all company-owned tractors in the dataset. The presence of ABS was also determined from the manufacture date as the company advised that company trucks with a manufacture date after January 1, 1996, were equipped with ABS.

The company data did not include the full set of crash descriptors in GES and TIFA, so it was necessary to develop other means of identifying the crashes of interest. All of the crash types defined in the GES and TIFA data could not be identified in the company data. Rollover could be identified and was available in a way that matched the GES and TIFA target rollover type, i.e., first-event rollovers. Almost all rollovers identified in the company data were first events. When rollover followed a collision, the collision was captured, not the rollover. Loss-of-control crashes were more difficult to identify. Of the different modes of LOC identified in the national crash databases, only jackknife could be identified reliably.

Rollover and jackknife were identified using a principle event description variable, which identified the main event in the crash. Rollovers were coded as "overturn," while jackknifes were identified by one of five codes: "jackknifed," "jackknifed, hit #2," "jackknifed, hit by #2," "jackknifed, hit object," and "jackknifed – rollover." Note that all categories imply that the jackknife was the first event in the crash. The carrier confirmed that using the principle event description variable was the only way to identify rollover and jackknife, and that the variable describes the first event in the crash. There was one involvement in which a rollover followed a collision with another vehicle and this case was excluded from the analysis.

1 Factors Associated with Rollover and Jackknife

Changes in fleet rollover rates were consistent with the introduction of RSC. Rates of rollover per 100 million VMT fluctuated within a narrow band from 2001 to 2005, and then declined in each of the next two years (Figure 30). Rollover rates ranged from 5.33 per 100 million VMT in 2001 to 4.64 in 2003. The rate further declined in 2006 to 4.39 and in 2007 to 2.98, a drop of about 40 percent in two years. This drop occurred at the same time that the penetration of RSC in the company's fleet increased from 39 percent in 2004 to 59 percent in 2005 and to 78 percent in 2006. Variations in rollover rate from 2001 through 2005 are not statistically significant, while the difference between the 2005 and 2007 rates is statistically significant. Figure 31 shows the overall crash rate per million miles of travel for comparison.

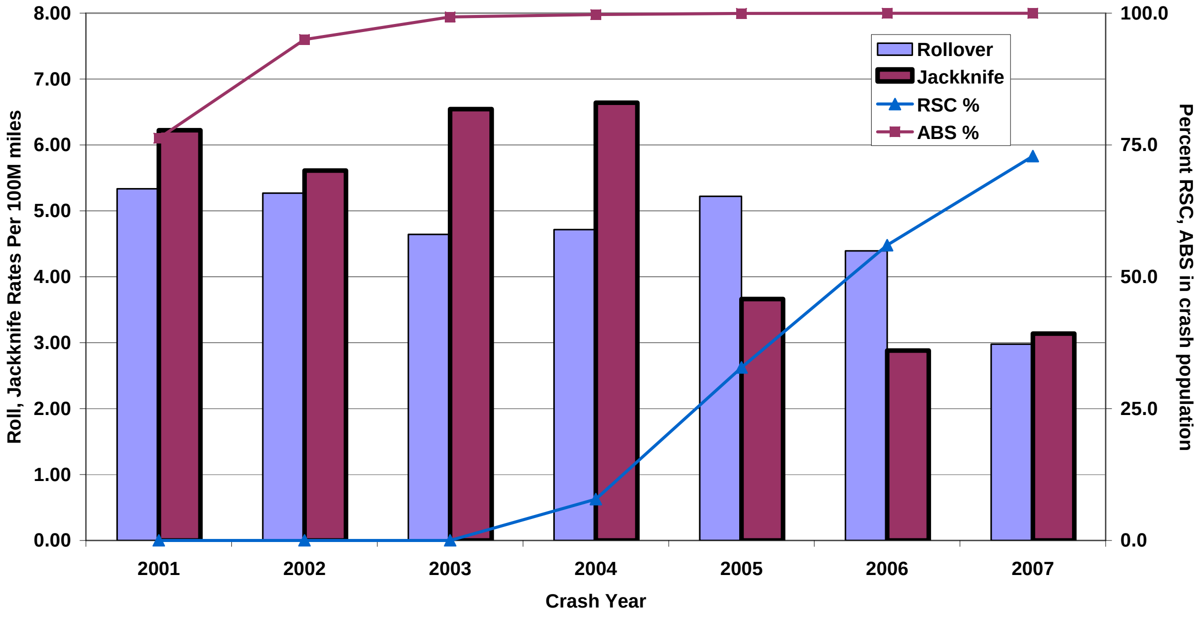

Figure 30. Rollover, Jackknife Rates per 100 Million Miles per Year Penetration of RSC and ABS in Crash Population

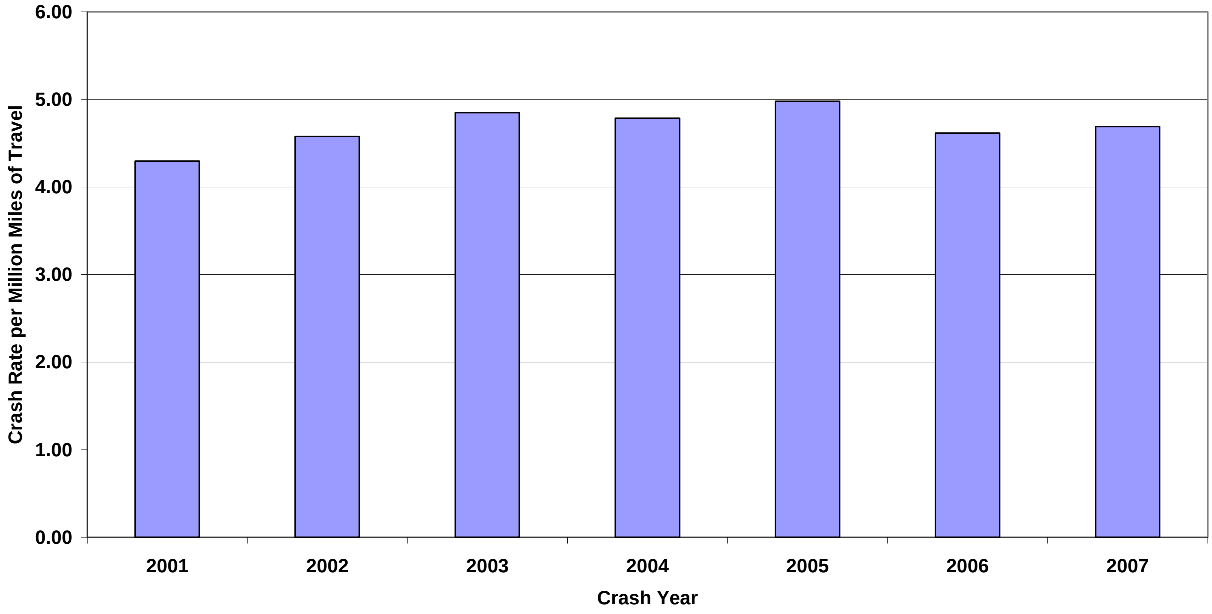

Figure 31. Crash Rate per Million Miles of Travel

Rates of jackknife also varied significantly across the same period, though the pattern differed from that observed for rollover. Jackknife rates remained relatively stable from 2001 to 2004, ranging from 5.61 to 6.54. This variation is not statistically significant. In 2005, the rate dropped almost in half to 3.66, with 2.88 in 2006 and 3.14 in 2007. In contrast to the rollover rate, which showed a linear decline from 2005, jackknife rates showed a step change that started the year before the decline in the rollover rate. Confidence intervals for the jackknife rates showed that the step change was a statistically significant drop.

Figure 30 also shows the proportion of crash-involved tractors with RSC or ABS for each year of crash data (lines, right scale). By 2003, virtually all trucks had ABS installed, while prior to 2003, no trucks had an RSC system. In 2004, 7.8 percent of the crash-involved vehicles had an RSC system, which increased to 32.8 percent in 2005, 56.0 percent in 2006, and 72.9 percent in 2007, the last data year.

Table 46 shows the penetration of RSC in the carrier's fleet, not just the crash population. RSC was first introduced in 2004 and grew substantially in 2005 and 2006. The RSC proportion for 2007 could not be obtained from the carrier, but is likely higher still. Similar data were not available for ABS, though it appears from the proportion of the crash population that it was close to 100 percent in 2002.

Table 46. Penetration of RSC in Company Fleet

Year	Percentage of fleet equipped with RSC
2001	0%
2002	0%
2003	0%
2004	31%
2005	59%
2006	78%
2007	Not available

The remainder of this section identifies factors in the fleet data associated with rollover and with jackknife. Then, statistical models of rollover and jackknife probability are presented to measure the effect of RSC and other factors on rollover and jackknife. The factors include driver age, tenure with the fleet, cargo loading, fleet division, whether the driver was solo or part of a team, road surface condition at the time of the crash, and whether the tractor was equipped with ABS. For this analysis, only trucks owned or leased by the company are included, not those of independent contractors to the fleet, since the presence of RSC could only be determined for company trucks. The number crash involvements for company-owned or –leased available in the crash file is 35,055, and this is the number of crash involvements used in the analysis.

The tractors in the company's fleet equipped with RSC had proportionally fewer rollovers in crashes than their other tractors.[11] Only 0.8 percent of vehicles equipped with RSC rolled over, compared with 1.2 percent of trucks not equipped. (The top half of Table 47 shows the frequency counts of rollover, jackknife, and all other crash involvements, by whether the truck was equipped with RSC. The bottom half shows the proportion of rollover, jackknife, and other crash types by whether the vehicle had RSC. The following tables use the same structure.) Thus, RSC was associated with a reduction of about 40 percent in the probability of rollover, given involvement in a crash. Note also that the probability of jackknife was also cut about in half with the presence of RSC.

Table 47. Rollover and Jackknife by Roll Stability Control Fleet Data

RSC	Rollover	Jackknife	Other	Total
No	314	362	26,104	26,780
Yes	65	59	8,151	8,275
Total	379	421	34,255	35,055
Row Percentages				
No	1.2	1.4	97.5	100.0
Yes	0.8	0.7	98.5	100.0
Total	1.1	1.2	97.7	100.0

The amount of cargo also affects the probability of rollover and jackknife, though inversely. The probability of rollover, given crash involvement, for truck combinations with cargo weights up to and including 5,000 pounds was 0.7 percent, compared with 1.5 percent for trucks with more than 5,000 pounds of cargo (see Table 48). As would be expected, lightly loaded trucks jackknifed at a much higher rate than more heavily loaded vehicles. About 1.5 percent of trucks with up to 5,000 pounds of cargo jackknifed in the crash, compared with only 0.9 percent of trucks with more than 5,000 pounds.

Table 48. Rollover and Jackknife by Cargo Weight Fleet Data

Cargo weight	Rollover	Jackknife	Other	Total
<=5000	114	264	16,793	17,057
>5000	265	157	17,462	17,884
Total	379	421	34,255	35,055
Row Percentages				
<=5000	0.7	1.5	98.5	100.0
>5000	1.5	0.9	97.6	100.0
Total	1.1	1.2	97.7	100.0

---

[11] The proportion of rollovers is not comparable to that in the other crash databases used in this project, because it is not feasible to determine that crashes are defined in precisely the same way. The important point is how the presence of RSC and other factors affect the relative probability of rollover and jackknife, not the absolute rollover or jackknife rates.

Driver age is also associated with the probability of rollover or jackknife in a crash. Figure 32 shows the distribution of rollover probabilities by driver age, in 5-year increments. (The numbers shown on the x-axis are the lower bound of the age range; 20 includes ages 20-24, 25 includes 25-29, and so on.) Younger drivers have a somewhat higher probability of rolling over, given crash involvement, which declines after about age 30, but then rises again at the oldest age category, 65 and older. Other than the youngest group of drivers (<25 years old) who were more likely to be in tractors equipped with RSC, there was no association between driver age and RSC-equipped vehicles.

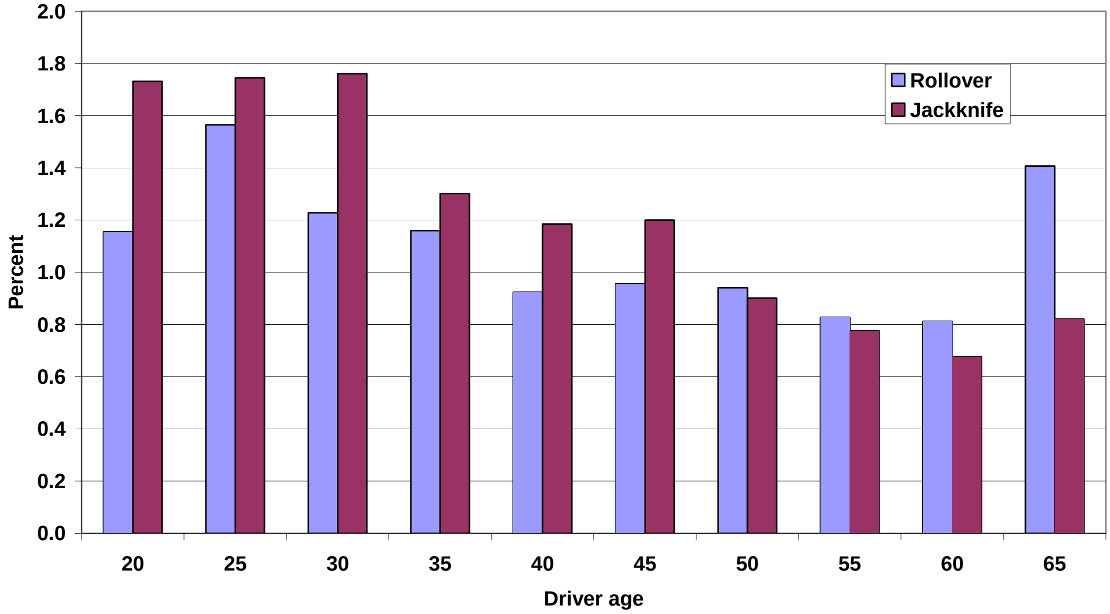

Figure 32. Rollover, Jackknife Probability by Driver Age, Fleet Data

Similarly, the probability of jackknife given crash involvement varies by driver age, with younger drivers having a higher jackknife probability—in fact, a consistent rate of around 1.7 percent of crash involvements—to age 30, and then an almost linear decline to age 60, followed by a slight increase for the driver population (in this fleet, 65 and older). Figure 30 shows the pattern.

Driver age may be regarded as related to truck driving experience, though clearly there are variations, e.g., a driver entering the trucking industry in middle age might be an experienced light-vehicle driver but a novice truck driver. The fleet data also included information on the driver's tenure with the company. Table 49 shows driver experience at the company, aggregated into different spans, with the different duration spans defined by the company. Both rollover and jackknife show the same pattern. The probability of rollover is low for the drivers who most recently joined the company, with a roll probability of 0.9 percent for drivers who had been with the company for fewer than 90 days. The rate increases to 1.2 percent for those with 91 to 180 days tenure, and then peaks at 1.5 percent for those in the second half of their first year with the company. Drivers with two or more years at the company have the lowest rate, at 0.8 percent. Jackknife shows the same pattern, though the peak probability is for drivers with 31 to 180 days of tenure. It is likely that there is some selection here, in that drivers with excessive crash involvements would not be retained by the company, so that the longer-serving drivers would tend to have a better safety record.

Table 49. Rollover and Jackknife by Driver Tenure
Fleet Data

Driver tenure	Rollover	Jackknife	Other	Total
0-90 Days	62	81	7,140	7,283
91-180 Days	60	91	4,833	4,984
181-365 Days	82	89	5,418	5,589
1-2 Years	61	56	4,570	4,687
>2 Year	96	96	11,536	11,728
Unknown	18	8	758	784
Total	379	421	34,255	35,055
Row Percentages				
0-90 Days	0.9	1.1	98.0	100.0
91-180 Days	1.2	1.8	97.0	100.0
181-365 Days	1.5	1.6	96.9	100.0
1-2 Years	1.3	1.2	97.5	100.0
>2 Year	0.8	0.8	98.4	100.0
Unknown	2.3	1.0	96.7	100.0
Total	1.1	1.2	97.7	100.0

The fleet operates both solo and team drivers, and records the type of team in the crash data. The solo driver situation is associated with higher rates of both rollover and jackknife, given crash involvement. About 1.1 percent of solo drivers involved in a crash rolled over, compared with 0.4 percent of team drivers (Table 50). In other words, solo drivers experience rollover almost three times as much as team drivers. The contrast was less dramatic for jackknife, with jackknifes accounting for about 1.1 percent of the crash involvements of solo drivers, but only 0.8 percent of team driver crashes. (The other and unknown category includes drivers in training.)

Table 50. Rollover and Jackknife by Driver Team
Fleet Data

Drivers	Rollover	Jackknife	Other	Total
Solo	345	383	29,418	30,146
Team	16	31	3,686	3,733
Other & unknown	18	7	1,151	1,176
Total	379	421	34,255	35,055
Row Percentages				
Solo	1.1	1.3	97.6	100.0
Team	0.4	0.8	98.7	100.0
Other & unknown	1.5	0.6	97.9	100.0
Total	1.1	1.2	97.7	100.0

The type of operations also was found to be related to the probability of rollover and jackknife. The fleet crash data classified the trip by the division operating the vehicle. Divisions were aggregated into a smaller number of types to reflect different operations. The bulk division typically operates tankers in hauling bulk commodities. The other categories include dedicated trucks that haul for a particular customer, intermodal, and van truckload operations. The bulk division experienced the highest probability of rollover, at 1.6 percent, compared with 0.9 percent for the dedicated operation, 1.0 percent for intermodal, and 1.1 percent for the van division. In contrast, intermodal had the highest jackknife rate at 1.5 percent and dedicated was the next highest at 1.4 percent. Both the bulk and the van divisions had the lowest rate at 1.1 percent. However, it should be noted that penetration of RSC into the fleet by division is not known, and could not be obtained from the carrier.

Table 51. Rollover and Jackknife by Fleet Division
Fleet Data

Division	Rollover	Jackknife	Other	Total
Bulk	25	17	1,551	1,593
Dedicated	118	173	12,271	12,562
Intermodal	13	19	1,242	1,274
Van	209	211	18,316	18,736
Other	14	1	875	890
Total	379	421	34,255	35,055
Row Percentages				
Bulk	1.6	1.1	97.4	100.0
Dedicated	0.9	1.4	97.7	100.0
Intermodal	1.0	1.5	97.5	100.0
Van	1.1	1.1	97.8	100.0
Other	1.6	0.1	98.3	100.0
Total	1.1	1.2	97.7	100.0

Two environmental factors were also associated with rollover and jackknife, though in different ways. Roadway alignment was found to be associated with the probability of both rollover and jackknife. The fleet data included a field that captures roadway alignment as straight, curved, downhill, or uphill. About 5.4 percent of crash involvements on curves included a rollover, compared with 0.8 percent of involvements on straight road segments, 1.1 percent on downhill segments, and 1.4 percent on uphill segments. Jackknife was also overrepresented on curved road segments. About 3.5 percent of crash involvements on curves included jackknife, compared with 1.1 percent on straight road segments. Interestingly, jackknife was also associated with downhill road segments, where about 4.4 percent of involvements included a jackknife, compared with 1.7 percent of involvements on uphill segments.

Table 52. Rollover and Jackknife by Roadway Alignment
Fleet Data

Alignment	Rollover	Jackknife	Other	Total
Straight	181	253	22,924	23,358
Curve	121	78	2,046	2,245
Downhill	10	41	891	942
Uphill	13	16	915	944
Unknown	54	33	7,479	7,566
Total	379	421	34,255	35,055
Row percentages				
Straight	0.8	1.1	98.1	100.0
Curve	5.4	3.5	91.1	100.0
Downhill	1.1	4.4	94.6	100.0
Uphill	1.4	1.7	96.9	100.0
Unknown	0.7	0.4	98.9	100.0
Total	1.1	1.2	97.7	100.0

Road condition also affected rollover and jackknife probabilities, though the effect was stronger for jackknife. The probability of rollover was higher when the road surface was coded as wet or icy (Table 53). About 1.7 percent of involvements on wet roads included rollover, compared with 1.0 percent on dry roads. The effect of different road conditions on the probability of jackknife was much stronger. On dry roads, only 0.2 percent of involvements included jackknife, but on wet roads the percentage increased to 3.3 percent, and on icy roads the percentage was 15.0 percent. Note that the probability of jackknife increased 30 times between dry and icy road conditions. The effect is much smaller for rollover.

Table 53. Rollover and Jackknife by Road Surface Condition
Fleet Data

Road condition	Rollover	Jackknife	Other	Total
Dry	241	46	24,023	24,310
Wet	69	132	3,835	4,036
Icy	26	133	726	885
Snowy	9	96	899	1,004
Unknown	34	14	4,772	4,820
Total	379	421	34,255	35,055
Row Percentages				
Dry	1.0	0.2	98.8	100.0
Wet	1.7	3.3	95.0	100.0
Icy	2.9	15.0	82.0	100.0
Snowy	0.9	9.6	89.5	100.0
Unknown	0.7	0.3	99.0	100.0
Total	1.1	1.2	97.7	100.0

2 Statistical Modeling of Factors Associated With Rollover and Jackknife

The previous section identified a number of factors associated with the probability of rollover and jackknife, in addition to whether the vehicle was equipped with RSC. The factors ranged from environmental (road condition and alignment) to characteristics of the driver (age, driver tenure with the company), operations (team or solo drivers and division of the company), and the vehicle (cargo load). Given the large number of factors that are apparently associated with differences in rollover probability, statistical models were fitted to the data to estimate the effect of each factor, holding the other factors constant.

Logistic regression was the modeling technique used. The models estimated the effect on the probability of an event (in this case, rollover) from factors relative to a baseline case. For the purposes of the model, some of the levels of the variables were combined. Cargo weight was aggregated as <=5,000 pounds or more than 5,000 pounds. Driving team was either a solo driver or a team of drivers. Three levels of driver tenure were specified: 0 to 90 days, 91 days to two years, and more than two years. Driver age was split into two groups: 21 to 29 and 30 or older. Company divisions were aggregated into three groups: bulk, van, and other, which consisted of dedicated service and intermodal. Finally, roadway alignment was aggregated as straight (straight plus downhill and uphill) and curved.

In this model, the parameters for each factor were estimated relative to baseline cases. The parameters estimated the increase (or decrease) in rollover probability when the particular factor varied from the baseline case. The following list shows the baseline cases for the rollover model:

Cargo weight: <5001
Team type: Solo
Tenure: 0-90 days
Age: 21-29 years
Road alignment: Straight
Division: Bulk

Table 54 shows the parameter estimates, standard errors of the parameters, and the statistical significance of the parameters. Almost all the parameters are significant at least at the 0.1 level, except for tenure level >2 years, which is retained because tenure is used as a three-level variable and the second level (90 days to two years) is strongly significant. Recall also that the pattern for tenure was that the top and bottom levels were about the same, with the middle categories showing higher rates of rollover. The parameter estimates here reflect that pattern. Interactions between all the parameters were tested and none were significant. In the table, a parameter of zero would mean no effect. Negative parameters indicate that the factor reduces the probability of rollover relative to the baseline, and positive parameters indicate that the factor increases the probability of rollover relative to the baseline.

Table 54. Rollover Logistic Regression Model

Parameter	Level	Estimate	Standard error	p value
Intercept		-4.438	0.3144	<.0001
RSC	yes	-0.2916	0.1552	0.0603
Cargo weight	>5000	0.8526	0.1348	<.0001
Team type	team	-1.0762	0.2795	0.0001
Tenure	90-2yr	0.3958	0.1592	0.0129
Tenure	>2 yr	0.1044	0.1866	0.5759
Driver age	30+	-0.4381	0.151	0.0037
Road alignment	curve	1.9897	0.1206	<.0001
Division	van	-0.6755	0.2872	0.0187
Division	other	-0.692	0.2821	0.0142

Table 55 shows the odds ratios for each parameter, i.e., the change in the odds of rollover given the parameter. In this model, the effect of RSC is lower than other parameters and the p-value is 0.06. The p-value implies that the estimated effect is different from zero (no effect) with 94 percent confidence, somewhat lower than the usual standard of 95 percent. RSC was associated with a reduction in the odds of rollover by about 25 percent. Several of the other factors in the model had greater effect on the probability of rollover. Cargo weights in the heavier category increased the odds of rollover by 2.35 times, while the odds of rollover increased by 7.31 times on curved roads in comparison with straight. On the other hand, team drivers, drivers in the older age group, and operations in the van or other division groups all reduced the odds of rollover. Note that ABS was not significantly related to the probability of rollover and as such did not appear in the model.

Table 55. Odds Ratio for Rollover Model

Effect	Ratio	Odds ratio estimate	95% confidence limits
RSC	yes vs. no	0.75	0.55 to 1.01
Cargo weight	>5000 vs. <5000	2.35	1.80 to 3.06
Team type	team vs. solo	0.34	0.20 to 0.59
Tenure	90 days -2yr vs. <90 days	1.49	1.90 to 2.03
Tenure	>2 yr vs. <90 days	1.11	0.77 to 1.60
Driver age	30+ vs. 21-29	0.65	0.48 to 0.87
Road alignment	curve vs. straight	7.31	5.77 to 9.26
Division	van vs. bulk	0.51	0.29 to 0.89
Division	other vs. bulk	0.50	0.29 to 0.87

It is may be surprising to see that factors other than RSC had a larger impact on rollover than RSC alone did. However, many factors can contribute to the events of a truck crash, and those factors continue to operate with RSC installed. The model shows that even in light of the other factors affecting roll probabilities, the odds of rollover with RSC are about 75 percent of the odds of rollover otherwise, in these data. Another way of putting it is that the odds of rollover are about 1.3 times greater without RSC.

Jackknife rates also were noted above to vary with RSC (see Figure 30 and Table 47). This was unexpected. However, it was noted that jackknife rates for the fleet decreased in a step change, and that the change was initiated one year prior to the reduction in rollover rates. Again, a logistic regression model was fitted to the data to attempt to determine the effect of RSC in light of all the other factors shown to affect jackknife.

The same modeling procedure as for rollover was followed, except the dependent variable was the probability of jackknife. In addition, a variable flagging whether a truck was equipped with ABS was used. The company advised that all trucks with a manufacture date after January 1, 1996, were equipped with ABS, and those with prior manufacture dates did not have ABS.[12] The baseline case was largely the same as for the rollover model, adding only that the baseline case does not have ABS. Road condition (split between dry and not dry) was also substituted for roadway alignment because road condition was shown to be so strongly related to jackknife.

The modeling showed that RSC is associated with lower rates of jackknife, as is ABS. In the model, the parameter estimate for RSC was about the same size as for ABS, and both were highly significant (Table 56). Moreover, the parameter for ABS was -0.58, estimating an odds

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[12] ABS is only known for tractors. The rule requiring ABS on trailers went into effect a year after that for tractors, though operators were free to install ABS on trailers prior to the rule, just as they were for tractors and as this carrier did. However, trailer manufacture date is not know, so trailer ABS could not be taken into account.

ratio of 0.56, and the parameter was significant at a p-value of 0.004. All of the tractors with RSC also had ABS functionality, of course.

Table 56. Jackknife Logistic Regression Model

Parameter	Level	Parameter estimate	Standard error	Pr > ChiSq
Intercept		-5.1139	0.2832	<.0001
RSC	Yes	-0.4668	0.1475	0.0016
ABS	Yes	-0.5818	0.2037	0.0043
Cargo	<= 5,000	-0.5894	0.1066	<.0001
Tenure	90 days -2 years	0.304	0.1376	0.0272
Tenure	>2 years	-0.2233	0.163	0.1707
Driver age	30+	-0.3973	0.144	0.0058
Road condition	Not dry	3.5303	0.1592	<.0001

Table 57 shows the odds ratios for each parameter in the jackknife model, along with 95 percent confidence intervals. Road condition is clearly the dominant factor in the model, with an odds ratio of over 34, meaning slick roads (primarily icy) increase the odds of jackknife in a crash by over 34 times. ABS, cargo weights over 5,000 pounds, and older drivers all reduce the odds of jackknife, while drivers with tenure between 90 days and two years increase the odds of jackknife by 1.36 times.

Table 57. Odds Ratios for Jackknife Model

Parameter	Ratio	Odds ratio	95% confidence limits
RSC	Yes vs. no	0.63	0.47 to 0.84
ABS	Yes vs. no	0.56	0.38 to 0.83
Cargo	>5,000 vs. <=5,000	0.56	0.45 to 0.68
Tenure	90-2yr vs. <90	1.36	1.04 to 1.78
Tenure	>2 yr vs. <90	0.80	0.58 to 1.1
Driver age	30+ vs. 21-29	0.67	0.51 to 0.89
Road condition	slick vs. dry	34.14	24.99 to 46.63

The primary purpose of the jackknife model was to sort out the effect of RSC from the other vehicle (ABS and cargo), driver (tenure and age), and environmental (roadway surface condition) factors associated with jackknife. It appears that RSC is associated with lower rates of jackknife, even accounting for ABS, driver, loading factors, and the roadway. However, the model does not explain the step change in jackknife rates shown in Figure 30. Nor can ABS, since penetration of ABS in the crash population was essentially 100 percent three years prior to the change. The purpose of the model, of course, was not to identify the factors associated with the rate change over time, but to evaluate the overall effect of RSC and ABS. Nevertheless, the step change in jackknife rates from 2004 to 2005 is intriguing.

The change in jackknife rates observed in the period is likely the result of other factors and programs. The company implemented training changes and enhancements over the period, including the use of skid pad training. In addition, changes to the Federal hours-of-service (HOS) rules were implemented in January, 2004, and modified in October 2005, though the overall crash rate for the company remained consistent over this period. However, it seems unlikely that the HOS rules change was a major factor, since it is not clear how that change could have affected jackknife but not the overall crash rate.

3 Summary of Analysis of Fleet Data

The fleet data provided by the carrier documented the real-world experience of RSC in normal operation. The data supplied appeared to be quite well-maintained, and had good documentation, variables in formats comparable to public crash databases, low rates of “wild” (undocumented) codes, and reasonably low rates of missing data. The data allowed trucks with RSC installed to be clearly identified. In addition, it was also possible to identify crashes of interest, particularly rollovers, but also jackknife, which is one aspect of the target loss-of-control crash type as defined in the national crash databases. Finally, the data included useful information on a range of factors associated with rollover and jackknife, so it was possible to control for those factors in attempting to measure the effect of RSC on rollover and jackknife.

Overall, it appears that RSC is associated with a reduction in the number and rate of rollovers. RSC was introduced into the company’s fleet with the addition of 2004-model-year tractors. The percentage of the company’s tractors equipped with RSC increased from 31 percent in 2004 to 59 percent in 2005 and to 78 percent in 2006. The number of rollovers per 100 million miles traveled began to decline in 2006, after remaining fairly steady over the five previous years. By 2007, the rate had decreased by almost 50 percent. Preceding the reduction in the rollover rate by a year, the jackknife rate also decreased, but in a step fashion, falling by about 45 percent.

In addition to RSC, a number of other factors were associated with rollover and jackknife. These factors included cargo loading, driver age and tenure with the company, the particular operational division of the company, whether the driver was part of a team or solo, whether the crash took place on a curve, and whether the roadway was dry or slippery. Each of these factors was associated with changes in the probability of rollover or jackknife, given involvement in a crash. Multivariate models were fitted to the data to estimate the separate effects of each of these factors. The primary goal was to determine the effect of RSC on rollover (or jackknife), taking into account the other factors that were also found to affect rollover (or jackknife).

Logistic regression was used to estimate the effect of these factors on rollover. RSC was found to reduce the odds of rollover, given a crash, by about 25 percent, relative to a vehicle without RSC, even taking into account the other factors, most of which had a larger effect. In the rollover model, roadway curvature had the largest effect, increasing the odds of rollover by 7.3

times over that of a straight road. Cargo weight also had a large effect: Cargoes weighing 5,000 or more pounds increased the odds of rollover by 2.3 times over lighter loads. Driver tenure, age, the type of driver team, and the division of the company also had statistically significant effects.

For jackknife, the modeling showed an association with RSC as well as ABS. However, the most important factor in the model was roadway surface condition. Slick roads (wet, snowy, or icy) increased the odds of jackknife by over 34 times. Other factors, while statistically significant, had much lower practical effect. ABS and RSC both reduced the odds of jackknife, by 0.56 and 0.63 times respectively, as did loads over 5,000 pounds and older drivers (over 30 years of age). While both ABS and RSC were associated with lower odds of jackknife, the presence of neither system can explain the step change in jackknife rates observed over the period. Neither can any other factor in the model, though the purpose of the model was not to explain that change but rather to sort out the overall association of the factors with jackknife. It is most likely that the change in jackknife rates was related to some exogenous factor, such as changes in driver training and monitoring.

Appendix D: Hardware-in-the-Loop Details

1 Mechanical System Integration

The hardware was set up to create a pneumatic brake system in the laboratory, physically analogous to the brake system in a real heavy truck. An in-house air supply was used as the pressurized air source for the pneumatic system to replace the air compressors in the truck.

All pneumatic line lengths and line diameters met the physical needs and technical specification of a pneumatic braking system. Parking and emergency brakes were installed in the system in a constantly released state. Figure 33 provides a schematic setup of the pneumatic braking system, and Figure 34 shows the integrated physical braking system in the laboratory.

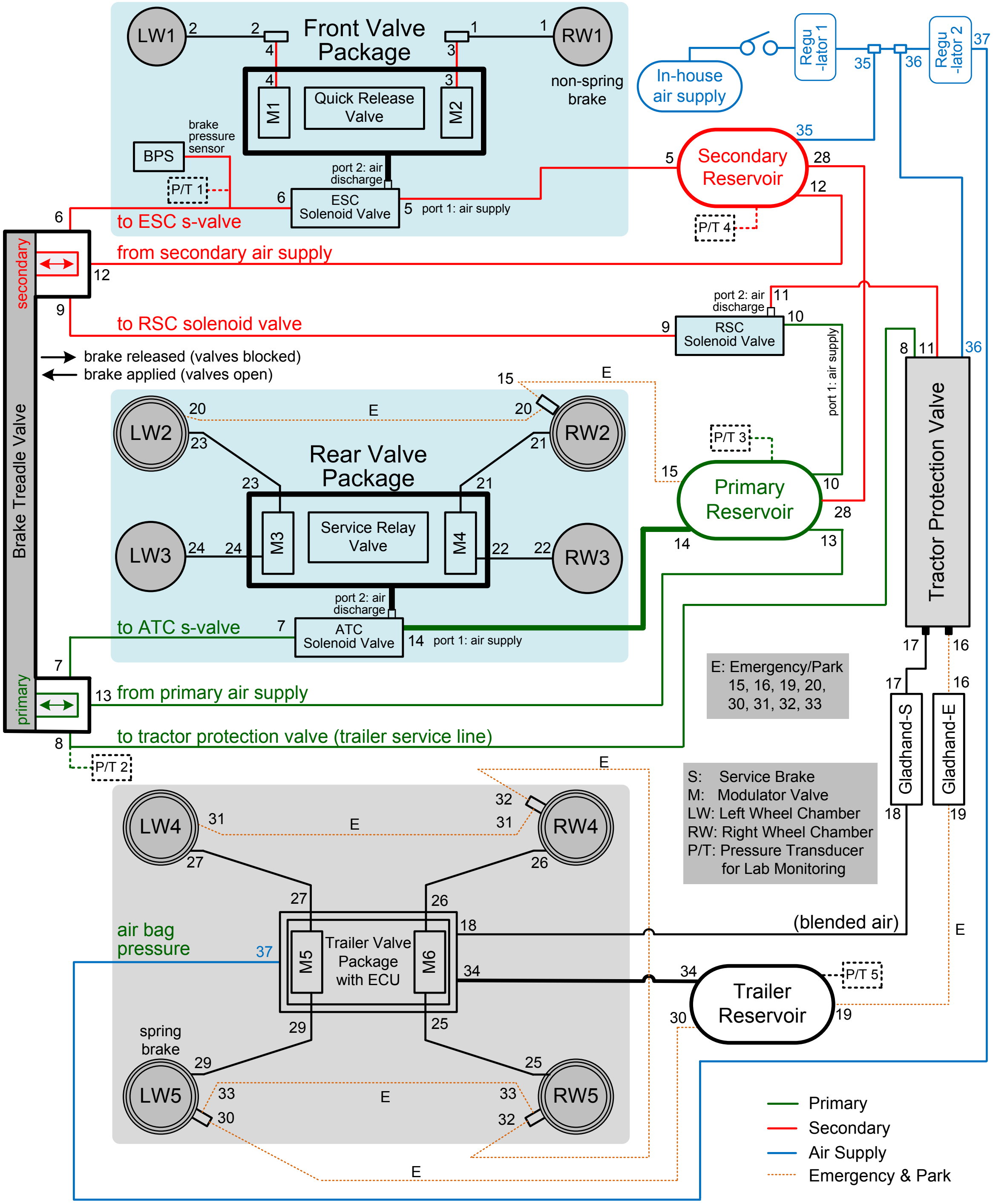


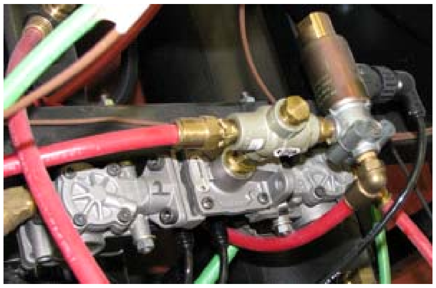
Figure 33. Schematic Setup and Connection of Pneumatic Brake System

Figure 34. Physical Pneumatic Brake System With 10 Brake Actuation Chambers

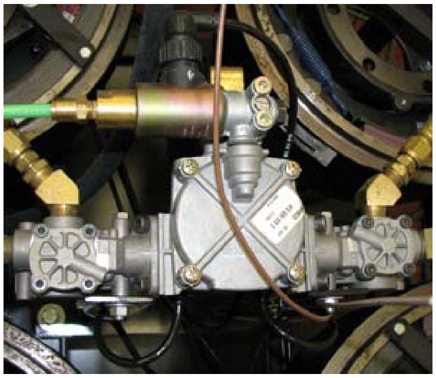
Two regulators were used to adjust air pressures that respectively supply the braking system and the trailer air-bag (refer to Figure 35). The air-bag pressure was loading-dependent and was changed when truck loading conditions varied. For the braking system, the air pressure was set to be 105 psi for all simulation runs in this report.

There are three packages in the braking system: front-axle package, rear-axle package, and trailer-axle package (refer to Figure 36). Three solenoid control valves are used in the system: an ESC solenoid valve (assembled with front-axle package), an ATC solenoid valve (assembled with rear-axle package), and an RSC solenoid valve (stand-alone and connected to tractor protection valve).

Figure 35. Two Pressure Regulators to Customize Pressure From In-House Air Supply for Braking System and Suspension Air Bag (Loading-Dependent)



(a) front-axle package assembled with ESC solenoid valve



(b) rear-axle package assembled with ATC solenoid valve

(c) trailer-axle package integrated with trailer ECU

(d) RSC solenoid valve

Figure 36. Packages of Front Axle, Rear Axle, Trailer Axle, and Three Solenoid Valves

2 Electrical System Integration

Figure 37 shows the overall design of the electrical system. Because of the high volume of noise generated by the pneumatic braking system, two adjacent rooms are used for system operation (“hardware room” and “control room”) with sound insulation between them; this affected the layout of the electrical connections. Figure 38 and Figure 39 show the electrical connections between the tractor and trailer ECUs and all other components in the hardware room, plus the electrical connections in the control room. Two interface boards were designed for the connections respectively in the hardware and control rooms, as shown in Figure 40 below.

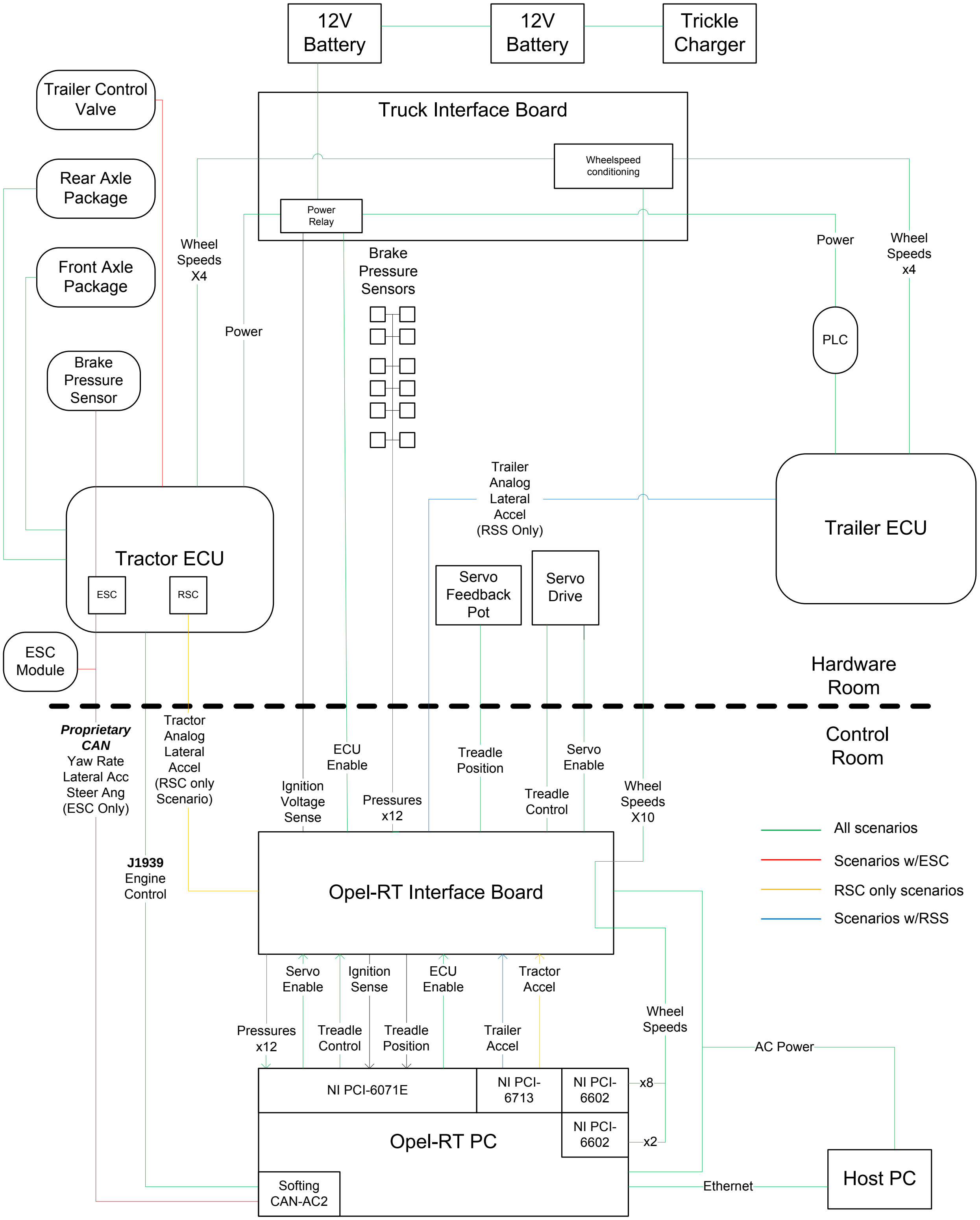


Figure 37. Electrical Systems Setup With Separation of Hardware Room From Control Room

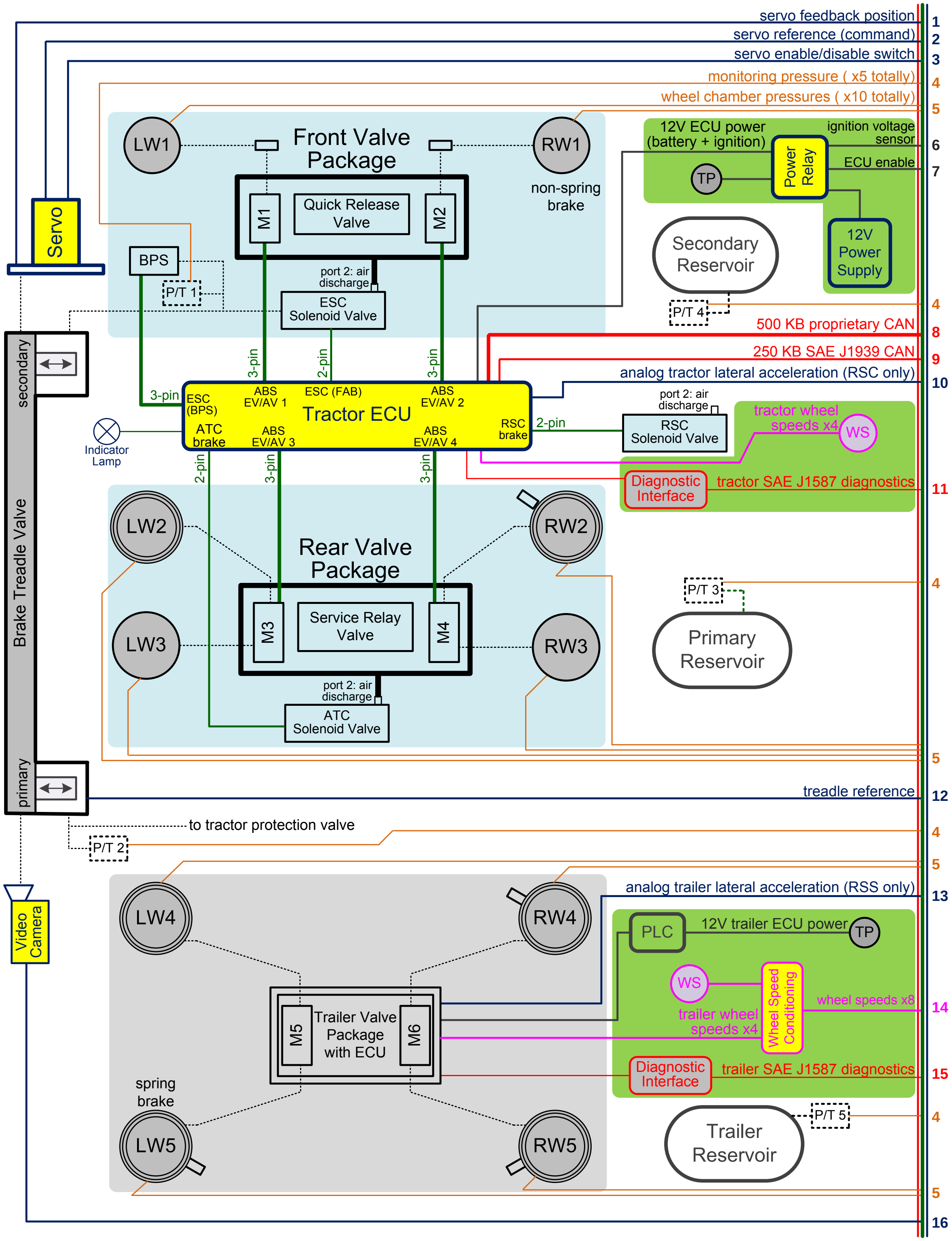


Figure 38. Schematic Electrical Block Diagram (Hardware Room)

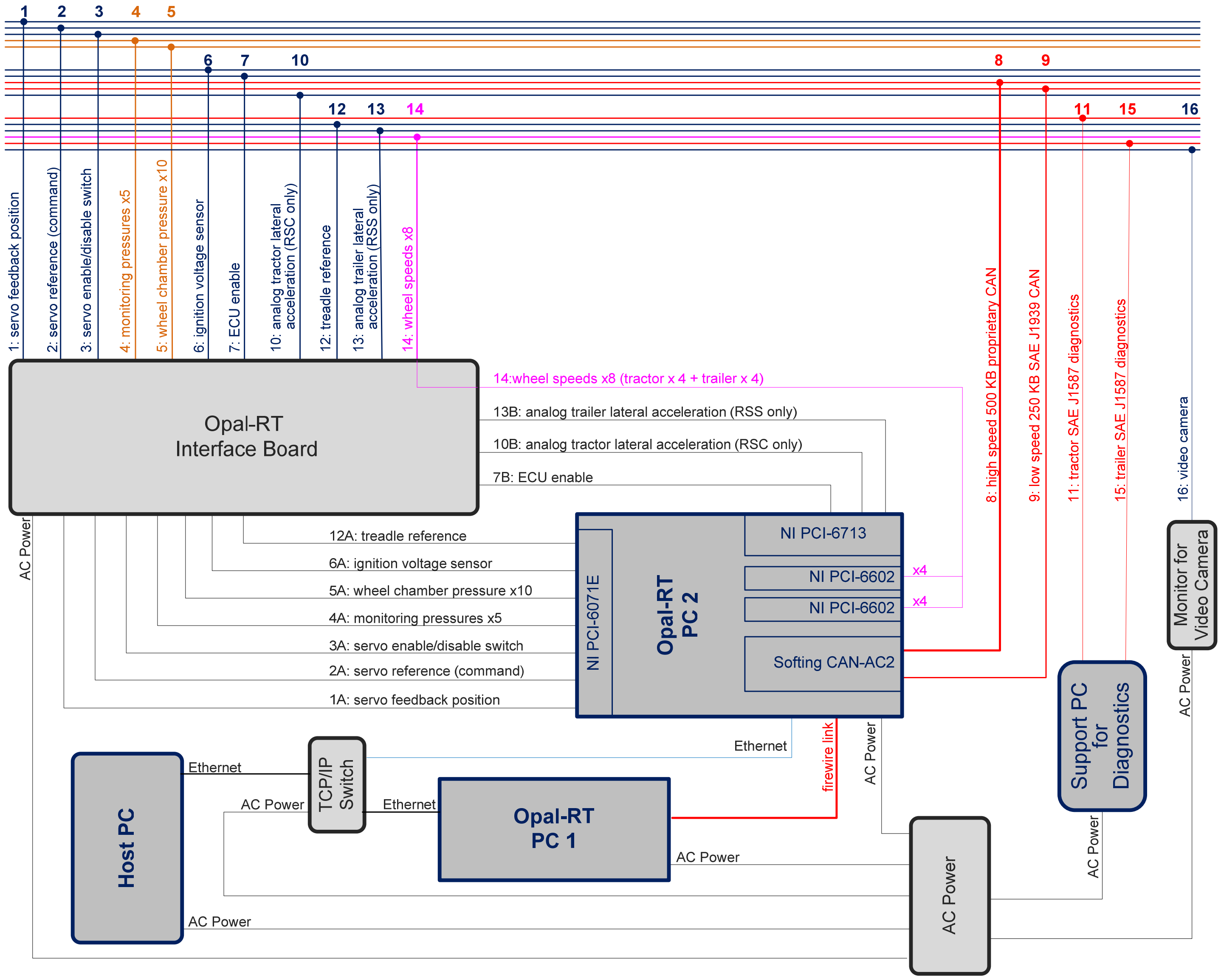


Figure 39. Schematic Electrical Block Diagram (Control Room)

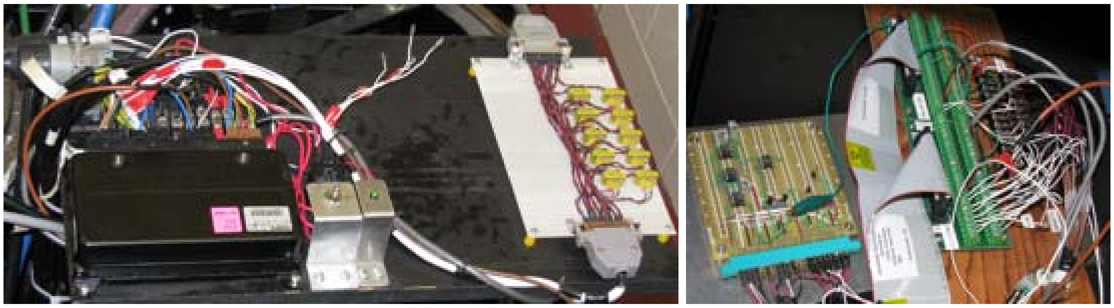
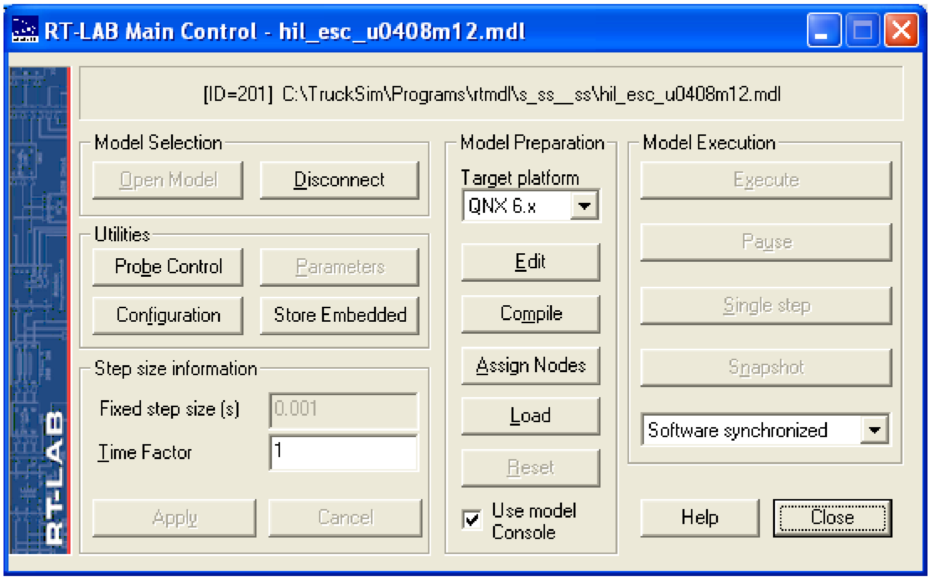


Figure 40. Interface Boards for Tractor ECU (left) and Connection With Real-Time PC (right)

3 Software and Computer Systems

As mentioned above, it was necessary to integrate three different software packages for real-time HiL simulation. A full-vehicle dynamics model (see Figure 41) was created in the real-time version of TruckSim (TruckSim RT). The TruckSim model provided all necessary signals to the brake system hardware. Figure 42 shows the RT-Lab interface. The HiL simulation system configuration is shown in Figure 43. RT-Lab was selected as the real-time simulation environment. RT-Lab ran on two Opal-RT real-time target PCs. A host PC acted as a console and supervised the target PCs. Each standalone PC had its own operating system, and additional target PCs could have been added as needed. Two NIC cards were inserted in the host PC, one for communication with the real-time local area network and another for communication with remote servers and Internet access.

Figure 41. Five-Axle Heavy-Truck with Semitrailer in TruckSim



RT-LAB Main Control - hil_esc_u0408m12.mdl

[ID=201] C:\TruckSim\Programs\rtmdl\s_ss__ss\hil_esc_u0408m12.mdl

Target platform: QNX 6.x

Fixed step size (s): 0.001

Time Factor: 1

Software synchronized

☑ Use model Console

Figure 42. RT-Lab Main Control Interface (1 ms fixed time step used in this report)

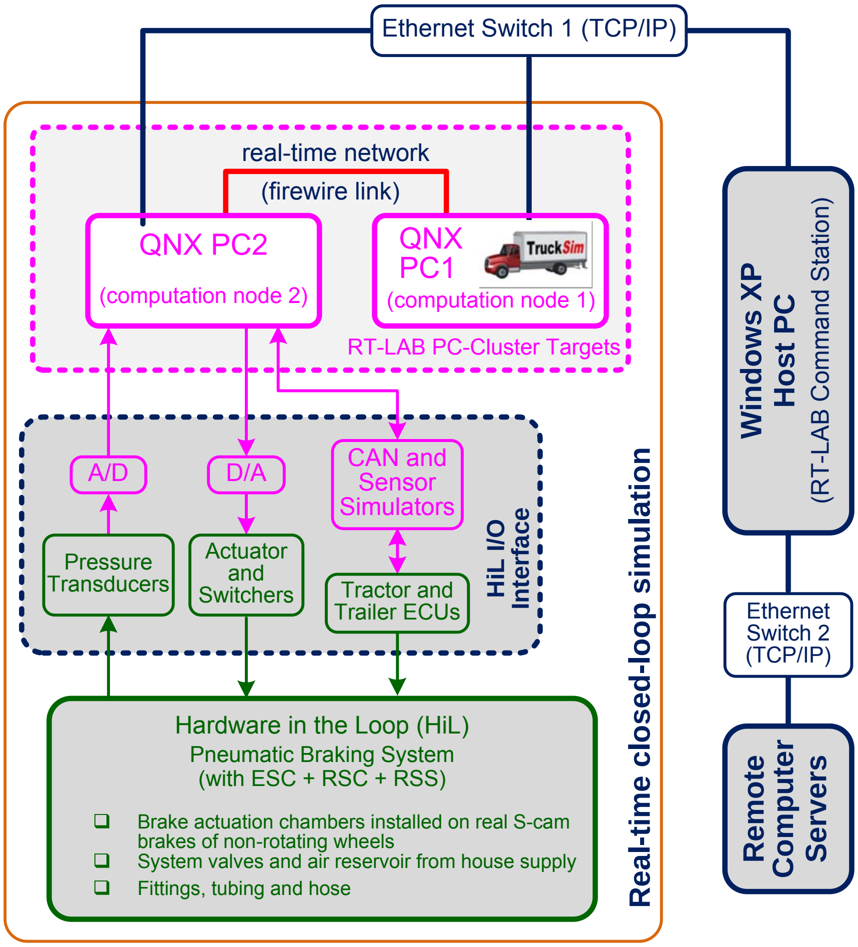


Figure 43. HiL Simulation System Configuration

Figure 44, Figure 45 and Table 58 provide more information about how the software and computer systems were configured in this project. Each of the three subsystems shown in Figure 44 ran on a single PC. RTW generated C-codes from Simulink models. RT-Lab managed real-time communication. TruckSim ran an S-function in RTW.

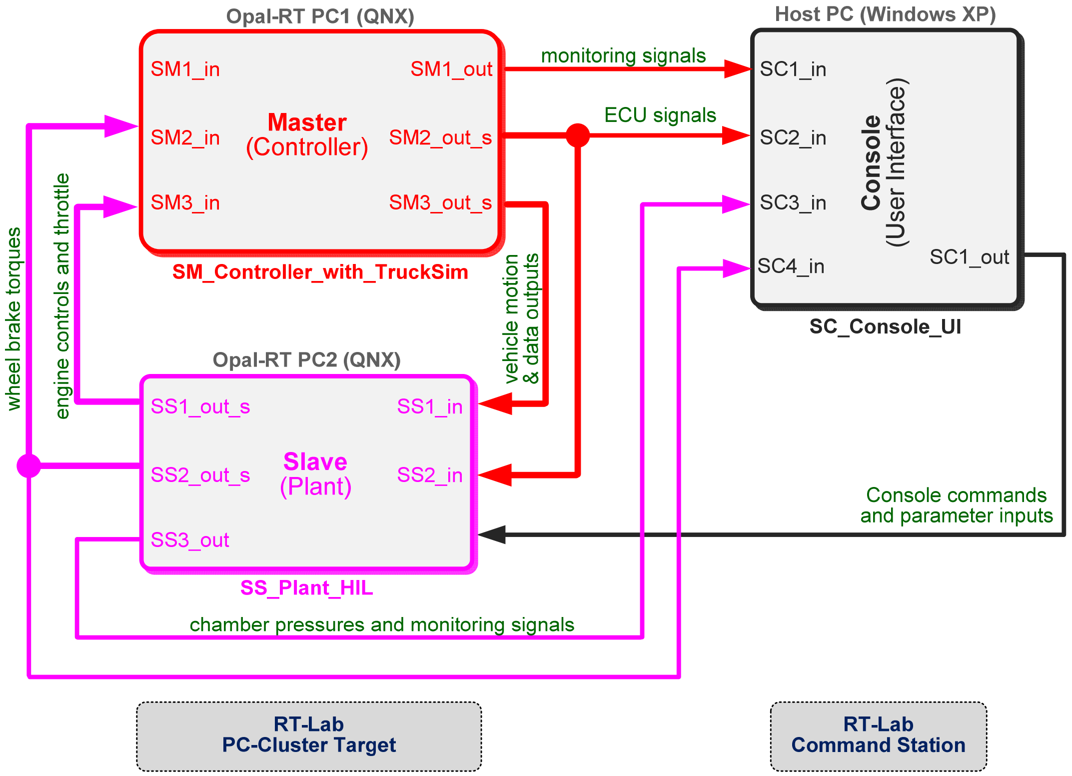


Figure 44. Top-Level Real-Time Schematic Diagram in RT-Lab

Table 58. Computer IP and Network Setup

Network		HiL LAN		Internet
Host PC	IP Address	IP Address: 192.168.10.19 Subnet Mask: 255.255.255.0 Default Gateway: 192.168.10.19 DNS Servers: 141.211.3.111 141.211.125.23		IP Address: 141.211.78.12 Subnet Mask: 255.255.255.0 Default Gateway: 141.211.78.1 DNS Servers: 141.211.3.111 141.211.125.23
	NIC card	NIC card 1 for LAN		NIC card 2 for access to remote servers and Internet
Switch		Ethernet TCP/IP switch 1		Ethernet TCP/IP switch 2
Real-time Node 1		192.168.10.101	firewire link (real-time network)	N/A
Real-time Node 2		192.168.10.102		N/A
Note: Real-time nodes 1 and 2 can be accessed remotely at the Host PC through Telnet and FTP (user name and password are required)				

Figure 45. Physical Computer Setup for HiL Simulation

Table 59. Software Version and License Information

Software Name	Manufacturer	Version	Operating System	Local license and license expiration information
Simulink RTW	The MathWorks Inc.	6.1	Windows XP	Required Matlab and Simulink License file (text file) locates at: C:\MATLAB701\bin\win32\ license.dat MATLAB Version 7.0.1.24704 (R14) Service Pack 1 Simulink Version 6.1
TruckSim RT	Mechanical Simulation Corporation	6.01a Sep. 1995	Windows XP	License file (text file) locates at: C:\FlexLM\trucksim_rt_license.lic host-name-based host ID is required
RT-Lab	Opal-RT Technologies Inc.	7.2.4	QNX (real-time)	License file (text file) locates at: C:\OPAL-RT\LicServer\opal_rt_license.lic

Appendix E: LTCCS Case Review Evaluation Results

LTCCS cases found to be relevant to stability control technology were evaluated by the study panel. Tables 54-59 present the subjective scores given by both of the panel members (J- John Woodrooffe, P- Peter Sweatman) for each of the cases. Scores are given in percent effectiveness unless indicated by the notes at the bottom of each table. Blank entries in the tables represent not applicable for that case.

Table 60. LTCCS Case Panel Evaluation Scores for Driver Distraction, Path, Oversteer, and Understeer Variables

case_ID	dr_distracJ	dr_distracP	path_faithfulJ	path_faithful	oversteer	oversteerP	understeerJ	understeerP
207004905	100	100	60	80	80	60	10	10
222004325	10	10			100	100		
331006312	90	90						
332006751	100	80						
333006958	10	10			100	100		
337006323	100	100	80	80	70	10		
339006451	50	50			0	0	0	0
339006771	20	20			0	0	0	0
339006915	0	0	30	30	10	10	10	10
339006971	0	0			0	0	0	0
340006566	0	0			100	100	0	0
340006826	70	70			0	0	0	0
344007015	60	60			100	100	0	0
348006908	100	100			0	0	0	0
350007220	20	40	20	20	100	100	0	0
352006482	30	30			0	0	100	100
495005661	20	40	10	10	0	0	100	100
620006805	10	10	40	40	100	100	0	0
801003890	50	70			70	70	0	0
801005488	10	10			100	100	0	0
801005488	40	40			100	100	0	0
803004276	50	50			50	50	0	0
803004794	70	70	0	0	100	100	0	0
803005076	70	70			100	100	0	0
807004925	20	20	80	80	50	50		
807005712	80	80	70	70	60	60	0	0

case_ID	dr_distracJ	dr_distracP	path_faithfulJ	path_faithful	oversteer	oversteerP	understeerJ	understeerP
807005713	100	100	80	80	0	0	0	0
808005621	10	10	80	80	0	0	0	0
810005468	60	60	10	10	100	100	0	0
810005522	80	80	20	20	100	100	0	0
811004362	0	0			0	0	0	0
811006302	30	30			50	50	0	0
812004351	60	60			100	100	0	0
813004046	100	100	50	50	100	100	0	0
813004406	60	60			100	100	0	0
813005626	100	100			0	0	0	0
814000341	100	100			0	0	0	0
815004312	70	70			0	0	0	0
816005042	60	60			100	100	0	0
816005321	80	80			0	0	0	0
817005748	100	100	40	40	100	100	0	0
819005325	100	100	100	100	0	0	0	0
819005527	100	100	100	100	0	0	0	0
819005808	100	100			0	0	0	0
820003982	100	100			0	0	0	0
820004643	80	80			0	0	0	0
821003867	30	50			100	100	0	0
821005450	10	10			0	0	0	0
821005589	100	100			100	100	0	0
821006149	80	80			100	100	0	0
823005424	100	100	80	80	0	0	0	0
864004487	100	100			100	100	0	0
864004729	100	100			100	100	0	0
870004733	80	80	20	20	100	100	100	100
870004748	50	50			0	0	0	0
884004485	100	100			100	100	0	0

Table 61. LTCCS Case Panel Evaluation Scores for Brake Steer, Excessive Speed, First Event Jackknife, Trailer Swing, and Algorithm Trigger Variables

case_ID	brake_stee	ex_speed	ex_speed	jackknife	trlr_swing	rapid_stee	yaw_rate	lat_accel	wheel_sli
20700490	2	20	20	2	2	1	1	1	
22200432	1	10	10	1	1		1		1
33100631		80	80	2	2				
33200675		100	100	2	2	1	1	1	
33300695	1	10	40	1	2		1		1
33700632	2	60	50	2	2	1	1	1	
33900645		100	100	4	1			1	1
33900677		100	100	2	2		1	1	
33900691	3	50	50	2	1	1	1		1
33900697	1	50	50	2	2				
34000656	1	70	70	1	2		1		1
34000682		100	100	2	2		1		
34400701		100	100	2	1		1	1	1
34800690	3	100	100	2	2	1	1	1	
35000722	3	50	50	1	2				
35200648	1	100	100	2	2		1	1	1
49500566		100	100	2	2		1		1
62000680	2	100	100	2	2	1	1	1	
80100389		100	100	2	1		1	1	1
80100548	1	100	100	1	1				1
80100548	3	100	100	1	2	1	1		1
80300427	2	70	70	2	2	1	1	1	
80300479	3	100	100	1	2	1	1	1	1
80300507	1	100	100	1	2				1
80700492		100	100	2	2				
80700571	2	50	50	2	2	1	1	1	
80700571	2	70	70	2	2	1	1	1	
80800562	2	60	60	2	2	1		1	
81000546	3	50	50	1	2	1	1	1	1
81000552	3	100	100	1	1	1	1		1
81100436	3			2	2	1	1	1	
81100630	3	50	50	2	2	1	1	1	
81200435				2	1	1	1		
	3	100	100						

case_ID	brake_stee	ex_speed	ex_speed	jackknife	trlr_swing	rapid_stee	yaw_rate	lat_accel	wheel_sli
81300404	2			2	2	1	1	1	
81300440	3	100	100	1	2	1	1		1
81300562	2	50	5	2	2	1	1	1	
81400034		80	80	2	2	1	1	1	
81500431		100	100	2	1	1		1	1
81600504	2	100	100	2	2	1	1	1	
81600532	1	100	100	2	1				1
81700574	2	100	100	2	2	1	1	1	1
81900532	2	100	100	2	2	1	1	1	
81900552	2	100	100						
81900580	2	50	50	2	2	1	1	1	
82000398	2	50	50	2	2	1	1	1	
82000464	2	50	50	2	2	1	1	1	
82100386	1	50	50	1	2		1		1
82100545	2	50	50	1	2	1	1		
82100558	3	50	50	1	2	1	1		1
82100614	3	100	100	2	1	1	1		1
82300542	3	100	100	2	2				1
86400448	3	100	100	2	1	1			1
86400472	1	100	100	1	2		1		1
87000473	1	100	100	1	2	1	1	1	1
87000474	1	100	100	2	1				1
88400448	3	100	100	1	2	1	1		1

Note: For brake_steer variable: 1=brake only, 2=steer only, 3=brake & steer; For jackknife variable: 1=yes, 2=no, 3=unknown, 4=30% chance; For trlr_swing variable: 1=yes, 2=no, 3=unknown; For algorithm trigger variables (rapid_steer, yaw_rate, lat_accel, wheel_slip): 1=yes.

Table 62. LTCCS Case Panel Evaluation Scores for Travel Speed, Surface Condition, ABS Likely, and Roll /Loss of Control Variables

case_ID	travel_sp	surface	abs_likely_trac	abs_likely_trlr	roll_loc
207004905	1	1	100	10	2
222004325	1	2	0	0	2
331006312	1	1	100	0	2
332006751	1	2	100	10	3
333006958	1		0	0	

2

case_ID	travel_sp	surface	abs_likely_trac	abs_likely_trlr	roll_loc
337006323	1	1	100	50	3
339006451	1	1	100	0	1
339006771	1	1	100	100	1
339006915	1	2	100	0	2
339006971	2	2	100	0	2
340006566	1	1	20	60	2
340006826	2	1	0	100	1
344007015	1	2	100	100	2
348006908	2	1	100	0	1
350007220	2	2	100	100	2
352006482	2	2	100	100	3
495005661	2	3	0	0	2
620006805	1	1	0	0	2
801003890	2	2	100	50	2
801005488	2	3	100	50	2
801005488	2	3	0	0	2
803004276	2	1	0	100	3
803004794	1	2	0	30	2
803005076	2	2	0	0	2
807004925	1	1	0	0	1
807005712	1	1	100	0	3
807005713	1	2	100	0	3
808005621	1	1	100	100	3
810005468	1	1	0	0	2
810005522	1	2	100	20	2
811004362	1	1	0	0	3
811006302	1	1	0	0	2
812004351	1	2	100	0	2
813004046	1	1			3
813004406	2	2	0	0	2
813005626	1	1	0	0	3
814000341	1	1	0	0	3
815004312	1	2	100	100	3
816005042	1	2	100	50	2

case_ID	travel_sp	surface	abs_likely_trac	abs_likely_trlr	roll_loc
816005321	1	2	100	50	2
817005748	1	2	100	100	2
819005325	2	2	100	0	1
819005527			100	0	
819005808	1	1	100	100	3
820003982	1	2	100	50	3
820004643	1	1	0	100	3
821003867	1	1	0	0	2
821005450	1	1	0	0	2
821005589	1	1	0	0	2
821006149	1	2	0	100	2
823005424	1	2	0	0	2
864004487	2	2	0	0	2
864004729	1	2	0	0	2
870004733	2	2	100	100	2
870004748	2	2	0	100	2
884004485	2	2	0	0	2

Note: For travel_spd variable: 1=>60 km/h, 2=40-60km/h, 3=<40 km/h; for surface variable: 1=dry, 2=wet, 3=ice, for roll_loc variable: 1=roll yes, loc no; 2=roll no, loc yes; 3=roll yes, loc yes.

Table 63. LTCCS Case Panel Evaluation Scores for c1 Variables. (Would the event likely trigger the algorithm?)

case_ID	c1_abs_trac	c1_abs_trac	c1_abs_trlr	c1_abs_trlr	c1_rscJ	c1_rscP	c1_escJ	c1_escP
207004905			0	0	10	10	90	90
222004325	100	100	100	100	0	10	100	100
331006312			0	0	0	0	0	0
332006751			0	0	100	70	100	100
333006958	100	100	100	100	10	10	100	100
337006323			0	0	80	70	100	100
339006451			100	100	100	100	100	100
339006771			0	0	100	100	100	100
339006915			100	100	0	0	100	100
339006971			20	20	0	0	0	0
340006566	100	100			0	0	30	20

case_ID	c1_abs_trac	c1_abs_trac	c1_abs_trlr	c1_abs_trlr	c1_rscJ	c1_rscP	c1_escJ	c1_escP
340006826	25	25			100	100	100	100
344007015					100	100	100	100
348006908			0	0	100	100	100	100
350007220					0	0	100	100
352006482					100	100	100	100
495005661	100	100	0	0	0	0	100	100
620006805	0	0	0	0	80	80	100	100
801003890			100	100	100	100	100	100
801005488			100	100	10	10	100	100
801005488	100	100	20	20	0	0	100	100
803004276	0	0			50	70	100	100
803004794	100	100	60	60	80	80	100	100
803005076	100	100	100	100	0	0	100	100
807004925	0	0	0	0	0	0	0	0
807005712			0	0	100	100	100	100
807005713			0	0	90	60	80	80
808005621					100	100	100	100
810005468	100	100	100	100	20	20	100	100
810005522			100	100	10	10	100	100
811004362	100	100	100	100	100	100	100	100
811006302	100	100	100	100	100	100	100	100
812004351			100	100	10	10	10	10
813004046					100	100	100	100
813004406	100	100	100	100	20	20	100	100
813005626	0	0	0	0	30	30	70	70
814000341	0	0	0	0	20	20	80	80
815004312					100	100	100	100
816005042			0	0	80	80	100	100
816005321			100	100	0	0	0	0
817005748					70	70	100	100
819005325			0	0	100	100	100	100
819005527			0	0	100	100	100	100
819005808					100	100	100	100
820003982			0	0	100	80	100	100

case_ID	c1_abs_trac	c1_abs_trac	c1_abs_trlr	c1_abs_trlr	c1_rscJ	c1_rscP	c1_escJ	c1_escP
820004643	0	0			80	80	100	100
821003867	100	100	100	100	0	0	0	0
821005450	0	0	0	0	10	10	10	10
821005589	100		0		0	0	100	100
821006149	100	100			10	10	100	100
823005424	100	100	100	100	0	0	0	0
864004487	100	100	100	100	10	10	100	100
864004729	100	100	100	100	10	10	100	100
870004733					80	80	100	100
870004748	50	50			10	10	50	50
884004485	100	100	80	80	10	10	100	100

Table 64. LTCCS Case Panel Evaluation Scores for c2 Variables. (Would the technology have time to respond?)

case_ID	c2_abs_tracJ	c2_abs_tracP	c2_abs_trlrJ	c2_abs_trlrP	c2_rscJ	c2_rscP	c2_escJ	c2_escP
207004905			0	0	5	5	60	20
222004325	100	100	100	100			100	100
331006312								
332006751					10	50	70	70
333006958	100	100	100	100			100	100
337006323					10	10	70	30
339006451			100	100	100	100	100	100
339006771			0	0	100	100	100	100
339006915			100	80	0	0	80	80
339006971			10	60	0	0	0	0
340006566	100	100			0	0	80	80
340006826	10	10			50	50	70	70
344007015					80	80	100	100
348006908			0	0	20	20	30	30
350007220					0	0	100	100
352006482					70	70	100	100
495005661	100	100					100	100
620006805					20	20	60	60
801003890			100	100	100	100	100	100

case_ID	c2_abs_tracJ	c2_abs_tracP	c2_abs_trlrJ	c2_abs_trlrP	c2_rscJ	c2_rscP	c2_escJ	c2_escP
801005488			100	100	20	60	100	100
801005488	100	100					100	100
803004276					50	50	70	70
803004794	100	100	100	100	30	30	70	70
803005076	100	100	100	100			100	100
807004925	0	0	0	0	0	0	0	0
807005712			0	0	70	70	90	90
807005713			0	0	70	80	80	70
808005621					50	50	70	80
810005468	100	100			20	20	40	40
810005522			30	30	10	10	70	50
811004362	100	100	100	100	80	80	100	100
811006302	100	100	100	100	50	50	70	70
812004351			100	100	100	100	100	100
813004046					100	100	100	100
813004406	80	80	80	80	50	50	70	70
813005626					20	20	40	40
814000341	0	0	0	0	0	0	20	20
815004312					90	90	100	100
816005042			0	0	10	10	50	50
816005321			70	70	0	0	0	0
817005748					50	40	100	100
819005325			0	0	100	100	100	100
819005527			0	0	100	100	100	100
819005808					100	100	100	100
820003982			0	0	10	10	50	40
820004643	0	0			10	10	30	30
821003867								
821005450	0	0	0	0	0	0	0	0
821005589	50	50			0	0	10	10
821006149	80	80			20	50	100	100
823005424	100	100	100	100	0	0	0	0
864004487	100	100	100	100	0	0	40	40
864004729	100	100	100	100	100	100	100	100

case_ID	c2_abs_tracJ	c2_abs_tracP	c2_abs_trlrJ	c2_abs_trlrP	c2_rscJ	c2_rscP	c2_escJ	c2_escP
870004733					20	20	80	80
870004748	100	100			20	20	100	100
884004485	100	100	100	100	10	10	100	100

Table 65. LTCCS Case Panel Evaluation Scores for c3 Variables. (Would the crash likely have been avoided?)

case_ID	c3_abs_tracJ	c3_abs_tracP	c3_abs_trlrJ	c3_abs_trlrP	c3_rscJ	c3_rscP	c3_escJ	c3_escP
207004905			0	0	0	0	20	10
222004325	80	60	10	50			70	70
331006312			0	0	0	0	0	0
332006751			0	0	0	10	10	40
333006958	80	80	10	20	0	0	70	90
337006323			0	0	0	0	50	20
339006451			0	20	30	30	40	40
339006771			0	0	80	80	90	100
339006915			90	90	0	0	10	10
339006971			0	0	0	0	20	20
340006566	70	70			0	0	20	20
340006826	0	0			5	5	15	15
344007015					50	50	70	70
348006908			0	0	0	0	10	10
350007220					0	0	90	90
352006482					80	80	90	100
495005661	50	50			0	0	50	50
620006805	0	0	0	0	10	10	40	40
801003890			50	50	10	10	30	30
801005488			50	50	0	0	40	30
801005488	50	60			0	0	70	80
803004276	0	0			10	10	30	40
803004794	60	70	0	0	10	10	40	30
803005076	90	90	90	90	0	0	0	0
807004925	0	0	0	0	0	0	0	0
807005712			0	0	20	40	70	70
807005713			0	0	20	20	50	40

case_ID	c3_abs_tracJ	c3_abs_tracP	c3_abs_trlrJ	c3_abs_trlrP	c3_rscJ	c3_rscP	c3_escJ	c3_escP
808005621					30	30	50	50
810005468	50	50	0	0	0	0	20	20
810005522			20	20	10	10	30	30
811004362	50	50	10	10	5	5	15	15
811006302	80	80	10	10	0	0	20	20
812004351			60	60	0	0	20	20
813004046					10	10	20	20
813004406	80	70	10	10	5	5	25	25
813005626	0	0	0	0	5	5	20	20
814000341	0	0	0	0	0	0	20	20
815004312					60	60	70	70
816005042			0	0	10	10	50	50
816005321			0	0	0	0	0	0
817005748					20	20	90	90
819005325			0	0	40	40	60	60
819005527			0	0	10	10	15	15
819005808					10	10	30	30
820003982			0	0	5	5	10	10
820004643	0	0			0	0	10	10
821003867	90	90	0	0	0	0	10	10
821005450	0	0	0	0	0	0	0	0
821005589	20	40	0	0	0	0	10	10
821006149	70	70			5	5	20	30
823005424	80	80	0	0	0	0	0	0
864004487	20	40	100	100	0	0	0	0
864004729	80	80	10	10	0	0	10	10
870004733					0	0	30	30
870004748	0	0			0	0	20	40
884004485	50	50	10	10	0	0	20	20

Appendix F: ESC and RSC Effectiveness Ratings for LTCCS Cases With Corresponding Roadway Alignment and Surface Condition

Table 66. ESC and RSC Effectiveness for Rollover LTCCS Cases Corrected Assignment of Rollover

CaseID	Vehicle Number	Roadway Alignment	Surface condition	RSC	ESC
153006977	1	Curve	Dry	95	95
331005867	1	Curve	Dry	0	0
331006249	1	Curve	Dry	0	0
331006312	1	Curve	Dry	0	0
332006211	1	Curve	Dry	95	95
332006696	1	Curve	Dry	97	99
332006697	1	Curve	Dry	48	96
332006751	1	Curve	Not dry	5	25
333006294	1	Curve	Dry	62	62
335006545	1	Curve	Dry	95	95
338007508	2	Curve	Dry	95	95
338007582	1	Curve	Dry	95	95
339006276	1	Curve	Dry	97	99
339006316	1	Curve	Dry	95	95
339006771	1	Curve	Dry	80	95
339006971	2	Curve	Not dry	0	20
340006826	1	Curve	Dry	5	15
348006225	2	Curve	Dry	95	95
348006445	1	Curve	Dry	95	95
348006908	1	Curve	Dry	0	10
350006669	1	Curve	Dry	48	96
350006975	1	Curve	Dry	96	99
352006482	1	Curve	Not dry	80	95
620006525	1	Curve	Dry	95	95
620006805	1	Curve	Dry	10	40
800003927	2	Curve	Dry	95	95
800004246	1	Curve	Dry	95	95
800004865	1	Curve	Dry	95	95
802005383	1	Curve	Dry	95	95
803004492	1	Curve	Dry	97	99
803004652	1	Curve	Dry	95	95
805005055	1	Curve	Dry	0	0
807005713	1	Curve	Not dry	20	45
808004226	1	Curve	Dry	95	95
808005621	2	Curve	Dry	30	50
808006705	1	Curve	Dry	97	99
811005442	1	Curve	Dry	97	99
811005582	1	Curve	Dry	62	62
811006302	3	Curve	Dry	0	20
812004411	1	Curve	Dry	97	99
812004756	1	Curve	Dry	95	95
812006131	1	Curve	Dry	48	96

CaseID	Vehicle Number	Roadway Alignment	Surface condition	RSC	ESC
813003907	1	Curve	Dry	96	99
813004191	1	Curve	Dry	95	95
813004526	1	Curve	Dry	95	95
813004667	1	Curve	Dry	0	0
813004966	1	Curve	Not dry	95	95
813005190	1	Curve	Dry	95	95
813005655	1	Curve	Dry	95	95
813006119	1	Curve	Dry	95	95
813006120	2	Curve	Dry	95	95
814000361	1	Curve	Not dry	95	95
815004232	2	Curve	Dry	95	95
815004252	1	Curve	Dry	95	95
815005814	2	Curve	Dry	95	95
816004041	1	Curve	Dry	0	0
816004201	1	Curve	Dry	97	99
816004261	1	Curve	Dry	95	95
816006201	1	Curve	Dry	97	99
817003933	1	Curve	Dry	0	0
817005908	1	Curve	Dry	95	95
818004112	1	Curve	Dry	95	95
818004792	3	Curve	Dry	100	100
818004912	1	Curve	Dry	95	95
818005452	1	Curve	Dry	95	95
818005992	1	Curve	Dry	80	80
819004045	1	Curve	Dry	0	0
819004185	1	Curve	Dry	62	62
819004425	1	Curve	Dry	95	95
819005086	1	Curve	Dry	95	95
819005325	1	Curve	Not dry	20	30
819005527	1	Curve	Dry	10	15
819005585	1	Curve	Not dry	0	0
819005627	1	Curve	Dry	95	95
819005808	1	Curve	Dry	10	30
819005865	1	Curve	Dry	96	99
819006125	1	Curve	Dry	97	99
820004422	1	Curve	Dry	97	99
820004783	1	Curve	Dry	0	0
821005449	1	Curve	Dry	96	99
828004080	1	Curve	Not dry	95	95
864004267	1	Curve	Dry	0	0
864004907	1	Curve	Dry	95	95
884003927	1	Curve	Dry	97	99
884004325	1	Curve	Dry	95	95
884005168	1	Curve	Dry	95	95
884005425	1	Curve	Dry	95	95
884005486	2	Curve	Dry	0	0
329006101	1	Straight	Dry	0	0
331006250	1	Straight	Dry	90	90
337006323	1	Straight	Dry	0	35

CaseID	Vehicle Number	Roadway Alignment	Surface condition	RSC	ESC
337006565	2	Straight	Dry	0	0
340007050	1	Straight	Dry	0	0
803004433	3	Straight	Not dry	0	0
807004925	2	Straight	Dry	0	0
807005712	1	Straight	Dry	30	70
808006003	1	Straight	Dry	0	0
808006301	2	Straight	Dry	0	0
812005915	3	Straight	Dry	0	0
813004026	1	Straight	Dry	60	60
813004046	1	Straight	Dry	10	20
813004546	1	Straight	Dry	0	0
813005530	2	Straight	Dry	0	0
814000341	2	Straight	Dry	0	20
817004510	1	Straight	Dry	80	80
817006509	1	Straight	Not dry	0	0
818004012	1	Straight	Dry	0	0
820003962	1	Straight	Dry	0	0
821005769	1	Straight	Dry	0	0
823005982	1	Straight	Dry	90	90
864004488	1	Straight	Not dry	0	0
870004688	1	Straight	Dry	0	0
884005169	2	Straight	Dry	0	0

Table 67. ESC and RSC Effectiveness for Loss of Control LTCCS Cases, Corrected Assignment of LOC

CaseID		Vehicle Number	Roadway alignment	Surface condition	RSC	ESC
	339006451	1	Curve	Dry	30	40
	803004276	1	Curve	Dry	10	35
	810005647	1	Curve	Dry	48	96
	813005626	1	Curve	Dry	5	20
	820003982	1	Curve	Dry	5	10
	820004643	1	Curve	Dry	0	10
*	344007015	1	Curve	Not dry	50	70
*	495005661	1	Curve	Not dry	0	50
*	801003890	1	Curve	Not dry	10	30
	812005951	1	Curve	Not dry	0	0
	815004312	1	Curve	Not dry	60	70
*	817005748	1	Curve	Not dry	20	90
*	870004733	1	Curve	Not dry	0	30
*	870004748	1	Curve	Not dry	0	30
*	207004905	1	Straight	Dry	0	15
*	333006958	1	Straight	Dry	0	80
	811004362	1	Straight	Dry	5	15
	813005511	1	Straight	Dry	0	0

CaseID	Vehicle Number	Roadway alignment	Surface condition	RSC	ESC
* 812004351	1	Straight	Not dry	0	20
* 816005042	1	Straight	Not dry	10	50
* 823005424	1	Straight	Not dry	0	0
* 864004729	1	Straight	Not dry	0	10
* 821003867	2	Curve	Dry	0	10
* 339006411	2	Curve	Not dry	0	0
* 800006415	2	Curve	Not dry	0	0
* 801005488	2	Curve	Not dry	0	35
* 803004794	2	Curve	Not dry	10	35
* 810005468	2	Straight	Dry	0	20
* 817006028	2	Straight	Dry	0	0
* 821005450	2	Straight	Dry	0	0
* 812004892	2	Straight	Not dry	0	0
* 813004406	2	Straight	Not dry	5	25
* 821006149	2	Straight	Not dry	5	25
* 340006566	3	Straight	Dry	0	20
* 821005589	3	Straight	Dry	0	10
* 222004325	3	Straight	Not dry	0	70
* 350007220	3	Straight	Not dry	0	90
* 810005522	3	Straight	Not dry	10	30
* 816005321	3	Straight	Not dry	0	0
* 864004487	3	Straight	Not dry	0	0
* 801005488	4	Curve	Not dry	0	75
* 884004485	5	Straight	Not dry	0	20
* 803005076	6	Straight	Not dry	0	0
* 813006166	6	Straight	Not dry	0	0
* 339006915	8	Straight	Not dry	0	10
* 821005752	29	Straight	Not dry	0	0

*Indicates cases classified as LOC only. All other cases are classified as LOC and Roll.

Appendix G: Example Case Assessment by Expert Panel

Case 807005712 Vehicle # 1 - Roll instability, possible yaw instability

Case Summary

Vehicle 1, a 2000 Freightliner conventional tractor pulling a 53' 1998 Monteray van trailer, was northbound in lane 1 of 2 northbound lanes of a 4-lane divided interstate with a positive divider. The trailer contained 19,320 kg of brake caliper auto parts. The load did not exceed the GVWR of V1. The driver of V1 reportedly swerved right to avoid a non-contact vehicle cutting in front of him, overcorrected to the left and lost control. V1's trailer flipped onto it's right side in the middle of the roadway flipping the tractor onto it's right side on the inside shoulder of lane 2. V1 then slid into the median striking the median guardrail with its front. The trailer then broke free of its kingpin plate and impacted the rear of the tractor's cab. Before coming to final rest, the trailer's top broke open spilling some of its contents into the median. V1 was towed due to extensive damage.

Neither the road's design nor atmospheric conditions were found to have contributed to the cause of the crash. The road was straight, level and conformed to AASHTO requirements for sight/stopping distance. It was daylight and the road was dry.

The lone occupant of V1 was an experienced commercial vehicle operator, properly licensed for his vehicle, familiar with his truck and the roadway. He was on his way to make a delivery to a familiar location, was within 125 miles of his destination and on time. He was running with a co-worker in a similar truck heading for the same destination that was trailing V1 by about 1/8 of a mile. This truck was driven by his son. They had started together the previous day, stopped for the night together and resumed their trip together the morning of the crash. V1's driver was reportedly in good health and neither drugs, alcohol, nor fatigue appeared to have been involved. The driver was conversing with his son on the CB radio at the time of the crash and stated that he "had been cut off by a 4-wheeler!" prior to swerving to the right. This could not be substantiated and no such vehicle stopped. The unrestrained driver of V1sustained minor injuries but died at the scene of coronary complications shortly after being assisted from the vehicle. His body was removed by the medical examiner. It is unknown if the driver was aware of or on medication for a heart condition.

A level one inspection of V1 performed post-crash indicated no out of service mechanical conditions that may have contributed to the crash. The cargo was in unsecured bins that most probably shifted when the truck swerved, contributing to the trailer's flipping over.

Panel Score – RSC 30% ESC 70%

The following is a detailed explanation of the step-by-step evaluation process. Evaluation categories contained on the evaluation form (Figure 16) are represented by variable names (boldface in brackets) that correspond to the individual case scores presented in tables in Appendix E.

1. *Was driver distracted or incapacitated?* **[dr_distract]** – (scored on a scale of 0 to 100%; yes=100%). This question attempts to generate an estimate of how active the driver was during the crash sequence and the likely level of distraction the driver may have experienced prior to the incident. For example, a driver who became incapacitated due to a heart attack would be assigned a score of 100 percent while a driver partially distracted by in cab activities may be assigned a value of 50 percent. A driver who was judged as being alert was given a score approaching 0 percent.

   Panel Opinion – The driver was talking on the CB Radio at the time of the incident therefore a score of 80 percent was assigned.

2. *Was the vehicle path faithful to driver input?* [**path_faithful**] – (scored on a scale of 0 to 100%; yes=100%). Evidence that the vehicle did not follow the intended path indicates that ESC maybe relevant. The uncertainty in the assessment warrants a sliding scale.

   Panel Opinion – The truck responded to the initial evasive maneuver but then the driver/vehicle overcorrected resulting in LOC. A score of 70 percent was assigned.

3. *Was there an indication of oversteer (%) understeer(%)?* **[oversteer, understeer]** – (scored on a scale of 0 to 100%; yes=100%). Oversteer occurs when the yaw rate of the vehicle exceed that which the steer input would generate if the vehicle were in the neutral steer condition. Early stages of tractor jackknife is a good example of oversteer. Understeer is the opposite effect where the directional response of the vehicle becomes sluggish in response to steer input as would occur on an icy road. ESC is capable of responding to either of these two conditions but the intervention strategies are different. The sliding scale provides an estimate of the amount of understeer and oversteer that likely occurred.

   Panel Opinion – The driver/vehicle overcorrected resulting in LOC which is an indicator of oversteer. A score of 60 percent was assigned for oversteer and 0 percent for understeer.

4. *Excessive brake; steer; brake and steer* **[brake_steer]** – (scored categorically – yes/no). Excessive driver intervention of this type can result in understeer or oversteer including jackknife. Many of the LTCCS case narratives, scene diagrams, and photographs provide insight into such driver input.

Panel Opinion – There was clear indication of steer input but no indication of brake application prior to LOC. The panel cited steer only in the "brake steer" category.

5. *Excessive speed* **[ex_speed]** – (scored on a scale of 0 to 100%; yes=100%). From case reviews, the expert panel made a judgment as to the likelihood that excessive truck speed for the conditions was a factor in the crash. The ability for ESC and RSC to reliably function is highly dependent on vehicle speed for a given scenario.

   Panel Opinion – There was no direct evidence that the truck was traveling at excessive speed however the road was straight and level and the action of another vehicle cutting in front of the truck may have been exacerbated by excessive truck speed. Due to the uncertainty a score of 50 percent was assigned.

6. *Was there first event jackknife?* **[jackknife]**– (scored categorically – yes/no/unknown). An attempt was made to evaluate the crash sequence to determine if there was a first event jackknife which would be an indicator of loss of yaw control. Jackknife is a common occurrence in truck crashes but it often occurs as a subsequent event (i.e., after initial vehicle collision).

   Panel Opinion – There was no evidence of tractor jackknife therefore the panel selected no.

7. *Was there first event trailer swing?* **[trlr_swing] –** (scored categorically – yes/no/unknown). Trailer swing was cited as a first event occurrence in the LTCCS narratives more frequently than the panel had expected. This is a form of LOC that the technology can neither detect nor correct.

   Panel Opinion – There was no evidence of trailer swing therefore the panel selected no.

8. *Likely algorithm trigger*– (scored as rapid steer, yaw rate, lateral acceleration, and wheel slip) **[rapid_steer, yaw_rate, lat_accel, wheel_slip]**. Rapid steer and yaw rate are triggers associated with ESC technology. RSC cannot be triggered by these parameters; however, RSC and ESC are both triggered in a similar manner by lateral acceleration.

   Panel Opinion – There was rapid steer input to the vehicle and evidence of oversteer (yaw instability), there would also have been significant lateral acceleration. Since there was no apparent brake application wheel slip is assumed not to have occurred. Therefore the triggering mechanisms cited are rapid steer, yaw rate, and lateral acceleration.

9. *Travel speed* **[travel_spd]** – (estimated as greater than 60 mph, between 40 and 60 mph, less than 40 mph). There was very little information available on vehicle speed just prior

to the crash. Using posted speed limit and case details, the pre-crash speed was estimated within a fairly broad range.

Panel Opinion – Truck travel speed was estimated to be greater than 60 mph based on straight and level interstate highway and the 50 percent likelihood that the truck was traveling at excessive speed.

10. *Surface condition* **[surface]** – (scored as dry, wet ice). There was excellent data available on surface condition. Surface condition is of particular interest to LOC cases.

    Panel Opinion – The road surface condition was recorded as dry based on case data.

11. *ABS likely?* **[abs_likely_trac, abs_likely_trlr]** – (Tractor, trailer scored on a scale of 0 to 100%; yes=100%). If the tractor build date was after the date when tractor ABS systems became mandatory on new vehicles, it was assumed that ABS was functioning unless the LTCCS data field stated otherwise. For tractors manufactured prior to this date, it was assumed that it did not have the technology unless the LTCCS data field stated otherwise.

    Panel Opinion – The tractor was manufactured in 2000 and the trailer was manufactured in 1998. Based on these dates the panel concluded that the likelihood that the tractor had ABS was 100 percent and the likelihood that the trailer had ABS was 0 percent.

12. Using the above pre-crash information, the estimated technology response (by ABS, RSC, and ESC technologies) was determined independently by each panel member by formulating responses and assigning a percentage crash avoidance contribution to the following questions 17, 18 and 19. Note: Since ABS resides with both RSC and ESC systems, for vehicles equipped with functioning ABS systems, the contribution of ABS was taken as zero, reflecting the fact that it could provide no *additional* benefit to the particular case. Where ABS was not present or not functioning, the panel attempted to estimate the likely contribution of ABS to the likelihood of crash avoidance. In some cases it was determined that RSC or ESC may have provided additional benefit; however, the sum of the ABS plus ESC or RSC benefits could not exceed 100 percent. The intent of this accounting was to ensure to the extent possible that the benefit of the ABS technology was not double-counted by either ESC or RSC.

13. *Would the event likely trigger the algorithm?* **[c1 variables]** – (scored on a scale of 0 to 100%; yes=100%). Knowing the functional characteristics of the technology and considering the pre-crash information, a judgment was made by the panel members as to whether conditions were sufficient for the technology to intervene.

Panel Opinion – Since there was no apparent brake application prior to LOC, ABS would not have triggered. Because of the apparent tractor yaw and high lateral acceleration the probability that RSC and ESC systems would have triggered was assigned as 100 percent.

14. *Would(the technology have time to respond?* **[c2 variables] –** If it were judged that the conditions were sufficient for the technology to intervene, then the panel evaluated the particular pre-crash history to provide an opinion as to whether there was sufficient time within the pre-crash sequence for the technology to influence the crash outcome.

    Panel Opinion – The panel assessed the crash sequence and concluded that it was 70 percent likely that there was sufficient time for RSC to intervene and 90 percent likely that there was sufficient time for ESC to intervene. A higher value was assigned to ESC because it can detect yaw instability that in this case would have occurred prior to the buildup of lateral acceleration that triggers RSC.

15. *Would the crash likely have been avoided?* **[c3 variables] –** Finally, in full consideration of all the information generated by the evaluation process up to this point, an overall effectiveness score was assigned by each panel member reflecting the likelihood that each technology, acting independently, would avoid the crash. The evaluation process guided through steps 1-14 provided a systematic review of important factors that must be considered in the formulation of opinion regarding the effectiveness of the technology. There was no numerical formula tied to the questions in steps 1-14 leading to an overall score. Each case was evaluated using the identical disciplined thought process and the overall effectiveness score for each technology was independently assigned based on the information yielded by steps 1-14. The review panel members' individual effectiveness scores were averaged and recorded as the effectiveness rating for RSC and ESC. The effectiveness values for RSC and ESC are presented in Table 22.

    Panel Opinion – Based on the information available, the panel concluded that RSC would likely be 30 percent effective and ESC would likely be 70 percent effective. The two panelists were in agreement with ESC effectiveness but differed on RSC effectiveness. Panel member number 1 estimated RSC effectiveness at 20 percent; panel member number 2 estimated RSC effectiveness at 40 percent, therefore the resolved value used for RSC was 30 percent.

DOT HS 811 205
October 2009

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