

## Analysis of Stability Control Systems for Tractor-Semitrailers



John Woodrooffe  
University of Michigan  
USA

Graduate of Ottawa University, Canada, 1976 and completed a MaSc degree in 1979. Currently Research Scientist, Head of Vehicle Safety Analytics and Commercial vehicle Research and Policy, University of Michigan Transportation Research Institute.



Daniel Blower  
University of Michigan  
USA

Graduate of the University of Michigan, 1972 and PhD 1984. Currently Associate Research Scientist, Vehicle Safety Analytics University of Michigan Transportation Research Institute.



Paul E. Green  
University of Michigan  
USA

Graduate of the University of Michigan, 1987. Completed a masters degree in 1989 in statistics. Completed a Ph.D. in biostatistics in 1995. Currently Assistant Research Scientist Vehicle Safety Analytics University of Michigan Transportation Research Institute.

### Abstract

This paper summarizes a study conducted by the University of Michigan Transportation Research Institute (UMTRI) under a Cooperative Agreement between NHTSA and Meritor WABCO to examine the performance of roll stability control systems (RSC), and electronic stability control systems (ESC) 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.

**Keywords:** ESC, RSC, Electronic Stability Control, Electronic Roll Stability Control, Heavy Vehicles, Stability, Benefit Analysis, Truck, Tractor Semitrailer.

## 1. Introduction

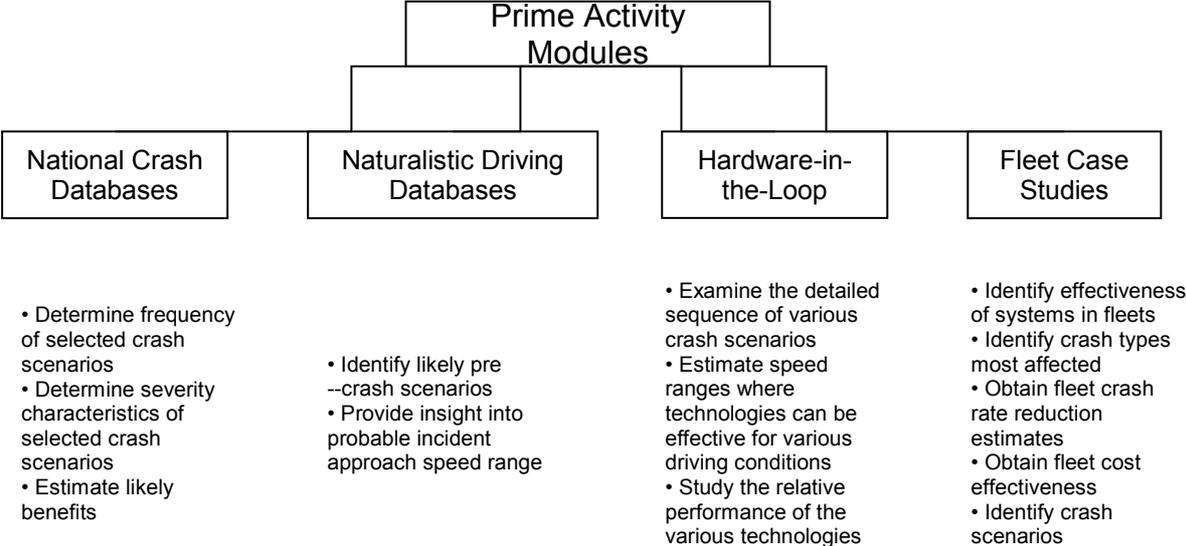
This paper examines the performance of roll stability control systems (RSC), and electronic stability control systems (ESC) for heavy truck tractor-semitrailers “Woodrooffe et al. 2009 Safety Benefits of Stability Control Systems for Tractor-Semitrailers”. The RSC system senses vehicle lateral acceleration 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. 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.

## 2. Study Design

The study was 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.

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 (HiL) 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.



**Figure 1. Modular Structure of Research Project**

**3. Crash Database Resources Used**

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.

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.

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 but, the variables are structured to provide general descriptions. In the present context, selection algorithms were developed to capture events that could be addressed by specific technologies. In the case of rollover, which is addressed by both systems, it is straightforward to identify the set of crashes that contain the relevant rollovers. 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 (LOC) 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. A good example is 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 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 a collision 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.

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

GES	Variable		Description
	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).
JACKKNIFE	V126 (from FARS J_KNIFE)	AJKType	Jackknife. The GES records whether the truck jackknifed; the TIFA variable (from FARS) distinguishes first event jackknives from subsequent events. The LTCCS variable distinguishes tractor yaw from trailer swing.
ROLLOVER	V125 (from FARS ROLLOVER)	ROLLINITYPE	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.

Table 1 above 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.

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.

#### **4. 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 (HiL) 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. This following section describes the LTCCS crash data used in preparing the estimates.

##### **4.1 Use of LTCCS Crash Data**

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.

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.

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 of 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.

## **5. Hardware in the loop system (HiL)**

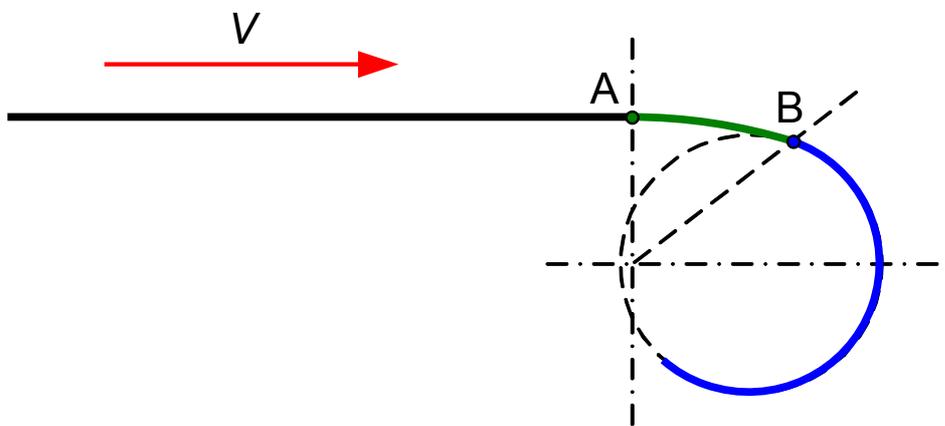
The HiL system was designed to represent the dynamics of a loaded truck in safety critical situations appropriate to the crash types and technologies considered in this project. HiL is a hybrid of hardware and software components, designed to represent, with as much fidelity as necessary, the interacting 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.)

### 5.1 Simulation Results

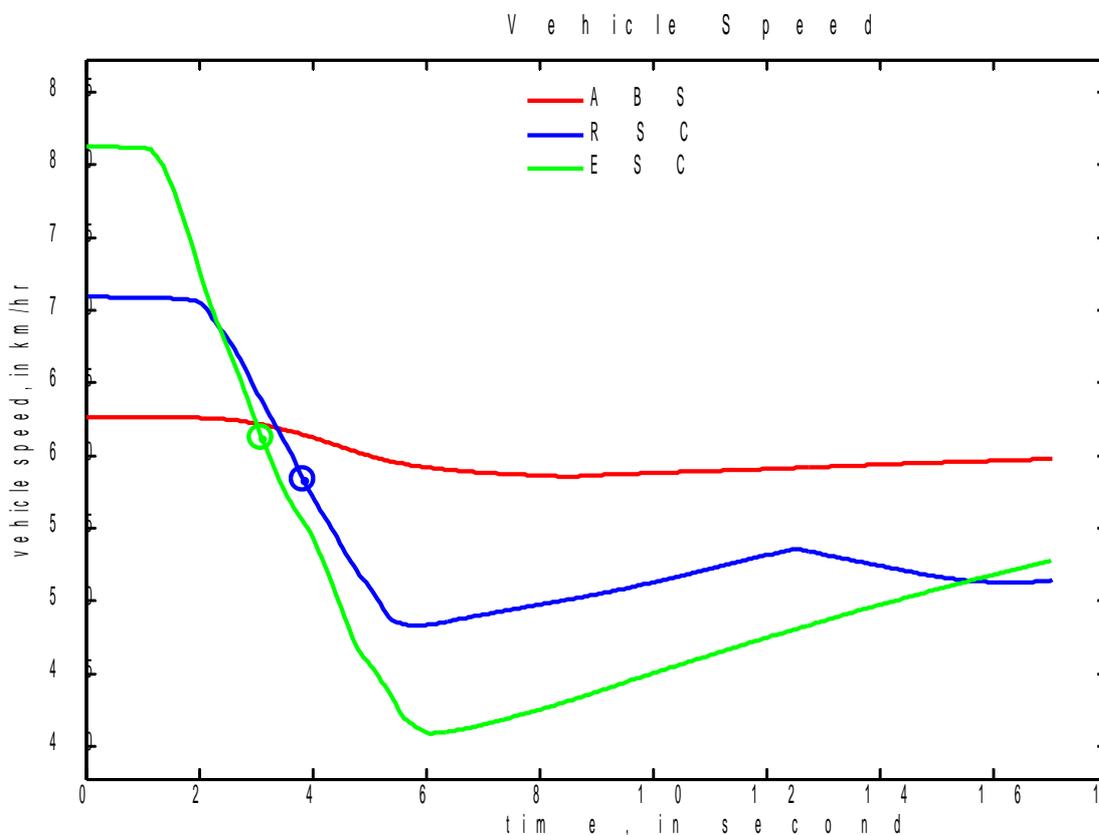
The following set of simulation results show the relative performance of RSC and ESC with respect to ABS control condition. The maneuver used for the simulation contained the geometrical characteristics of a freeway entry or exit ramp. It is referred to as the M9 tangent transition to constant curve maneuver shown in Figure 2. Developed for this study, the 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  $1.3 \text{ m/s}^3$  is based on the AASHTO prescribed curve entry geometry corresponding to a steady-state lateral acceleration of  $1.5 \text{ m/s}^2$ . All results shown are for a fully loaded 36,400 kg GVW 5-axle tractor semitrailer.



**Figure 2. Schematic Trajectory of Maneuver M9 (Transient to Constant Curve)**

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.

**Figure 3** 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 3 due to the addition of steer axle braking which is not used with the RSC system. In higher speed curves, ESC became increasingly more effective than RSC in mitigating rollover. This performance difference is attributed to the improved braking ability of ESC (steer axle brakes are not controlled by RSC) and the ability of ESC sensing technology to detect critical conditions earlier than the RSC system evaluated.



**Figure 3. 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**

## 6. Estimated Benefit Derived from an Active Safety Technology

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 five year annual average, represent the numbers of crashes that may potentially benefit from the introduction of RSC and ESC technologies.

A benefit equation was 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. “McMillan et al. (2001) Estimating the Safety Benefits for the IVI Generation 0 Field Operational Tests”, “Najm et al. (2000) Estimation of Crash Injury Severity Reduction for Intelligent Vehicle Safety Systems”. 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

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

Terms in the equation are defined below:

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

$P_{wo}(S | C)$  : 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).

$\frac{P_w(C | S)}{P_{wo}(C | S)}$  : 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*.

$\frac{P_w(S)}{P_{wo}(S)}$  : 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.

Benefits were applied per victim injured according to economic estimates of costs of highway crashes involving large trucks “Zaloshnja and Miller, (2006) Unit Costs of Medium/Heavy Truck Crashes”. 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”.

Figure 2 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 2. Estimated Total Cost Benefits from RSC and from ESC (in 2007 dollars)**

Crash type	Benefit	
	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 3. 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 3. 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

## 7. 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 five-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 paper 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.

## 8. 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 five-axle tractor-semitrailers, the estimated benefits apply only to this particular vehicle configuration operating within the U.S. The research project resulted in the following conclusions:

1. Electronic stability systems were found to provide substantial safety benefits.

Assuming that all existing five-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 U.S. 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 analysis 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 (HiL) simulation.
4. The benefit estimates are limited to five-axle tractor-semitrailers operating within the U.S. 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.

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