

Safety Performance and Benefits of Heavy Truck Stability Control: Providing Insight into Compliance Evaluation

John Woodrooffe
Univ. of Michigan-Ann Arbor

Daniel Blower
Transportation Research Inc.

Paul E. Green
Univ. of Michigan

ABSTRACT

This paper contains an analysis of the potential safety benefits of electronic stability control (ESC) for single unit trucks and tractor semitrailers within the U.S. operating environment. It is based on research projects [1,2] which combined hardware-in-the-loop simulation and vehicle testing with 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 and single unit trucks. The characteristics of ESC-relevant crashes involving these two vehicle classes were found to be very different as were the control strategies needed for crash avoidance. Rollover was the dominant ESC relevant crash type for tractor semitrailers while loss of control was the dominant ESC relevant crash for straight trucks.

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 ESC for large trucks is in its infancy, national crash databases do not yet have sufficient 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. This paper focuses on heavy truck loss of yaw control and on un-tripped rollover in curves. The analysis is based on the examination of crash scenarios that could likely benefit from ESC. Since crash databases cannot identify trucks equipped with ESC, the analysis identifies the primary ESC-relevant crash scenarios, derives probable outcome estimates from hardware-in-the-loop simulation, field test experience, and expert panel assessment. National safety benefit estimates are then computed. The process of ESC evaluation provides insight into compliance evaluation options that may prove useful in the regulatory evaluation of ESC for heavy trucks. A discussion of possible compliance test options is provided.

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INTRODUCTION

Heavy truck stability-enhancing technologies referred to as Electronic Stability Control (ESC) sense when a loss of control or rollover of a vehicle is imminent and then take corrective action independent of the driver. The technology senses vehicle deviation from acceptable limits in advance of driver perception and initiates corrective action thereby increasing the likelihood that the driver can maintain control. [1] This paper examines the nature of vehicle stability related crashes for tractor semitrailers and single unit trucks and

estimates the potential benefit of ESC for these two vehicle types.

ESC systems resolve the state of vehicle stability (understeer and oversteer) in loss of control scenarios. When developing loss of control is detected, the technology applies brake torque at selected wheels using strategies to mitigate oversteer or understeer tendency. During curve maneuvers related to rollover, ESC assesses how close the vehicle is to the rollover threshold and when excessive curve speed is detected, the system intervenes to slow the vehicle. The deceleration interventions are graduated in the following

order: de-throttling; engine brake; and foundation brake application.

For the purpose of this analysis, single unit trucks are defined as non-articulated vehicles without trailers; tractor semitrailers are restricted to tractors with one trailer operating within the U.S. The study is based on the analysis of a number of independent crash datasets using engineering and statistical techniques to estimate the probable benefits of ESC. Because this technology has only recently been introduced, none of the established crash sets have enough data for a traditional evaluation and it is not possible to distinguish trucks using ESC from those that do not. This limitation required the development of a novel method of examining the potential benefits of these systems.

This paper is based largely on elements of two studies conducted by the University of Michigan Transportation Research Institute (UMTRI) focusing on the performance of electronic stability control systems for heavy truck tractor-semitrailers [1] straight trucks and motorcoaches. [2]

STUDY DESIGN AND APPROACH

Because of the data limitations discussed above, this study uses an indirect method of predicting the safety performance of ESC, 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. Additional knowledge was gained through independent study, hardware-in-the-loop simulation and track tests. Linking the performance of the stability technologies to benefits based on estimates of national crash reduction was achieved through the following steps.

1. Identify the population of crashes that can be addressed by the ESC technology by a survey of fatal and nonfatal crash reports.
2. Estimate the effectiveness of the stability technology in preventing the candidate crashes through track testing, hardware-in-the-loop simulation and engineering judgment.
3. Apply those effectiveness estimates to the crash population.

The population of crashes that can be addressed by ESC was developed through a comprehensive survey of crash reports on fatal and nonfatal crashes. Crash reports from UMTRI's Trucks Involved in Fatal Accidents (TIFA) survey were used for fatal truck crashes. Crash reports from two states, Florida and Louisiana, were reviewed to identify the proportion of ESC-relevant crashes in nonfatal crashes.

Track tests of the technology were conducted using maneuvers characteristic of loss of control and rollover crashes, as identified in the review of the various crash data sets. These tests provided a detailed understanding of how the technology responds under conditions similar to those

identified in the crashes, as well as a demonstration of how ESC extends the performance envelope of the vehicles.

Probable effects of the stability technologies were then developed using the well-documented cases in the Large Truck Crash Causation Study (LTCCS). 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.

Once the technology effectiveness estimates were completed for the LTCCS cases, scaling the benefits to the national population was achieved by mapping the LTCCS effectiveness ratio to the corresponding crash populations identified in TIFA for fatal crashes and in NHTSA's General Estimates System (GES) for nonfatal crashes. The mapping was achieved by aggregating the candidate crash involvements into common crash characteristics (roadway alignment and road surface condition) that can be identified identically in each of the three crash files (LTCCS, TIFA, and GES).

Engineering judgment was 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 ESC technology was estimated separately. The effectiveness was estimated for each crash using expert judgment informed by track tests 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 ESC in reducing crashes.

CRASH DATA FILES USED IN THE ANALYSIS

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 is the product of a sample survey with clustering, stratification, and weighting that allows calculation of national estimates. GES covers all vehicles involved in a traffic accident, not just trucks. The GES file includes vehicle information that allows tractor-semitrailers to be identified and variables that describe the cases that permit relevant rollover and loss of control (LOC) crashes to be identified. 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. [3]

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 a fatal crash 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 a fatality 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 a fatal crash each year. [4]

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.

The LTCCS was undertaken jointly by the Federal Motor Carrier Safety Administration (FMCSA) and NHTSA. LTCCS was based on a sample of 963 injury and 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 provide 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. [5, 6, 7]

The LTCCS data share 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. 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 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 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 identified actually included 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 ESC, 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 hardware-in-the-loop (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.

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.

Rollovers relevant to the technologies are those that occur 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 ESC and 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.

ENGINEERING EVALUATION OF RELEVANT CRASHES

One of the most complex challenges of the analysis was establishing a reliable estimate of the proportion of crashes that could be addressed by ESC. 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.

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. This review resulted in a classification of each crash as rollover 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. In the tractor semitrailer analysis, based on LTCCS cases, 37 of the 83 LOC cases did not show any evidence of identifiable yaw instability which is a key attribute of vehicle dynamics LOC definition. Thirty-two of these included a rollover, 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 ESC.

In making this adjustment, the LTCCS case weights are not used. The LTCCS cases are used as a very high quality set of in-depth crash investigations. Using the weights in LTCCS tends to overestimate the number of rollovers and

single-vehicle crashes, so they were not used. Instead, the combination of TIFA and GES was used as the best representation of the national crash population. Case weights for GES are used, and since TIFA is a census file, TIFA case weights are 1, effectively, for all TIFA cases.

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.

Table 1 shows the adjusted estimates of the annual average number of tractor semitrailer crashes relevant to the technologies, reflecting the reallocation of cases based on the results of the LTCCS review.

Table 1. Adjusted Annual Average Estimates of Relevant Tractor Semitrailer 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

Single unit truck crashes were more strongly associated with LOC than rollover when compared with tractor semitrailers. The typical LOC scenario for single unit trucks was more representative of sport utility vehicle LOC such as oversteer resulting from excessive corrective steer input following unintended encroachment onto the shoulder of the road. There were very few LOC cases involving tractor semitrailers that were linked to shoulder encroachment. Table 2 shows the overall distribution of single unit truck involvements in fatal crashes by the type of crash and whether the ESC technology was relevant. The cell frequencies include all straight trucks involved in a fatal crash. The top half of the table shows the weighted frequencies and the bottom shows the row percentages of ESC-relevance for each crash type. The data cover the period from 2003-2007 and are not annualized. In the period, almost