

Evaluating the Effectiveness of Electronic Stability Systems in Reducing Truck Rollovers

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Abstract

The objective of this research is to develop a customized hardware-in-the-loop system that is used to test Electronic Stability Program (ESP) systems to prevent heavy truck rollovers when navigating horizontal roadway curves. While most of the published literature on electronic stability control focuses on the effectiveness of stability systems in passenger cars, very few researchers have considered its application as it pertains to commercial vehicles. Detailed crash data that have been extracted from the crashes that are represented in the Large Truck Crash Causation Study database have been used to draw conclusions regarding the main cause of the crashes and the geometry of the road upon which the crashes occurred. Those crash scenarios were run through a hardware-in-the-loop system that communicates between the TruckSim software, a vehicle dynamics based simulation program, and a real-time tractor-trailer braking rig. The simulations were first run without the ESP enabled to determine the critical speed which will cause the truck to roll, then the same simulation runs were executed with the Bendix stability system enabled to determine the difference in speeds in which a rollover is inevitable with and without the technology. A third speed that represents the lowest speed in which the stability system activates was also determined. As requested by the National Highway Traffic Safety Administration (NHTSA), this study also serves as a comparison between the Bendix system and the Meritor WABCO system which has already been tested by the University of Michigan Transportation Research Institute.

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Chapter 1: Introduction

According to the United States Bureau of Transportation Statistics (BTS), the truck transportation industry accounted for \$127.6 billion dollars in 2007, comprising 0.9% of the total U.S. Gross Domestic Product (GDP), and nearly one-third of the GDP attributed to transportation activities [1]. As such, commercial motor vehicles, including straight trucks and combination trucks, are an integral part of freight transportation within the United States. Straight trucks are primarily used for short range operations such as pickup and delivery services, and they typically serve within a 50-100 mile radius of their base location. Combination vehicles, in contrast, are typically used for regional and long-distance applications. While only 30% of commercial motor vehicles are long-range combination vehicles, they account for 65% of the commercial vehicle miles traveled. In addition to the high mileage accumulated by these long-range vehicles, they exhibit the highest lifespan crash-cost per vehicle, identifying them as a prime target for transportation safety research. A particularly dangerous type of accident that affects combination trucks is a rollover event, often occurring when a driver misjudges the vehicle speed when entering complex curves associated with highway interchanges. The purpose of this research is to investigate the circumstances leading to rollover events, and the potential effect that stability control could have on reducing annual crash rates [2].

1.1 Overview of Truck Rollovers and Rollover Mitigation

Though the trucking industry represents 4% of registered vehicles and 7% of the total vehicle miles traveled, the professional truck drivers are disproportionately involved in for 8% of fatal crashes and 4% of personal damage only crashes [3]. According to the Trucks Involved in Fatal Accidents database for the years 1999 to 2005, 13% of the fatal crashes involving heavy trucks were caused by rollovers. Research done by Wang and Council determined that there are approximately 4,400 to 5,000 truck rollovers on interchange ramps every year, with an associated cost of \$405 to \$460 million annually [4].



Figure 1: MUTCD signs W1-13 (top) and W13-1P (bottom)

Most of the research regarding rollover prevention and mitigation began in the early 1990's. The most frequently used method of mitigation involves signs that warn truck drivers as they enter a potentially dangerous curve. The optional sign, W1-13 should be accompanied by sign W13-1P in order to provide an advisory speed limit as seen in **Error! Reference source not found..** Although these signs are present at most of the locations that have a high rollover frequency, it is thought that

drivers become desensitized to these signs which then reduces the effectiveness of the warning [5]. Rollover warning devices can provide an additional or alternate technology to reduce rollovers around curves. The

rollover warning device technology utilizes sensors implanted in the pavement to measure the truck's speed, weight, load, height, and vehicle configuration as it traverses a section of the road [5]. If a truck is suspected of experiencing a potential rollover situation, a sign flashes or lights up to alert the offending vehicle, encouraging them to lower their speed to prevent a rollover. One study found that this type of dynamic sign produced a reduction in the number of rollovers in the Washington D.C. area over a three-year period beginning in 1993 [6]. Another alternate technology for rollover prevention, that of a rollover training device, which resides within the vehicle itself. This system monitors the rollover threshold of the truck and displays a diagram that shows how close the driver is getting to the condition where the truck may rollover [7]. Lastly, the most recently developed technologies for rollover prevention are known as electronic stability systems. These systems are multipurpose by monitoring the truck's motion, and to actively engaging brakes to prevent rolling over or jack-knifing. While a number of researchers have studied the benefits of stability control system applications in passenger cars and sports utility vehicles, their application to commercial motor vehicles has been largely overlooked until recently. By implementing stability control technology throughout the entire US fleet of trucks, a significant reduction in commercial vehicle accidents can be achieved, thus saving time, and money, and most importantly, lives.

1.2 Thesis Contributions

In order to assess the potential for electronic stability systems to decrease the number of truck rollover crashes and increase safety, the primary objectives of this thesis are twofold:

- Build a hardware-in-the-loop testbed in order to evaluate electronic stability systems in application with tractor-trailer
- Quantitatively evaluate the effectiveness of an electronic stability system to reduce speed and prevent rollovers.

1.3 Thesis Layout

This thesis includes:

- a literature review of relevant research;
- summary of the study's design;
- a detailed description of the hardware-in-the-loop setup;
- a description of the TruckSim program, the truck used in the simulations, and the method used to create the simulation scenarios;
- the procedures used to validate the setup;
- a summary of the findings from the simulation runs;
- conclusions of the research and possibilities for the expansion of this research topic.

Chapter 2: Literature Review

This literature review provides an overview of the history of safety technology testing in vehicles; a basic description of how stability systems analyze driving behavior and how they determine when to engage; a brief overview of rollover characteristics; a summary of previous roll stability control research and testing; an synopsis of the crash databases that were utilized; and a review of the various methods that have been used to calculate the effectiveness of safety technology.

2.1 Progression of Safety Technology Testing

In the early days of safety technology testing, vehicle designs and new technologies were tested on test tracks with controlled driving and environmental conditions. While test tracks provided insight into the vehicle's dynamics, the tests require professional drivers and specially-equipped trucks which lead to expensive and potentially dangerous situations.

Similar to test track testing, field operational tests (FOT) use fleets of vehicles to collect driving data; however, FOTs collect the data as normal drivers are going along with their everyday business. New systems can be installed on specific vehicles so researchers can monitor the vehicle's performance to evaluate the effectiveness of the technology [8]. This method has the benefit of capturing real-life driving situations; however, it does not evaluate the limits of the technology and it requires significant time and resources to complete such a study. Even within a long study period, the technology might not be pushed to the extreme and therefore cannot be evaluated in its entirety.

The next step in the evolution of dynamic vehicle testing involves modeling vehicles in a simulation software environment. These models are built to match the measured characteristics from test track experiments [9]. Safety technology models are then established and superimposed onto the vehicle models to evaluate their effectiveness. Effective modeling of the safety technologies is often difficult because the crash detection algorithms are typically proprietary information. Consequently, this method is useful for initial testing procedures, however, it is unable to provide detailed information on the idiosyncrasies of the technology since it is based on a model of idealistic performance.

The current state of the art in the development of testing new technologies is to physically integrate the technology with a simulation software by establishing a hardware-in-the-loop (HiL) system. These systems utilize vehicle characteristics provided by the simulation software and apply them to a physical mechanical setup of the remaining vehicle characteristics. This enables the system to be tested in a safe environment without the need for a professional driver or expensive adaptations to the trucks. In 1999, Lee and Suh utilized a HiL system to test an antilock brake system and a traction control system [10]. Since then, a few other systems were built to develop and test systems for passenger vehicles [11] and tractor-trailers [12].

2.2 Basic Stability Control Mechanisms

In general, electronic stability systems monitor a vehicle's wheel speed, steering wheel angle, lateral acceleration, and yaw rate. The system then compares the driver's steering input to the actual motion of the vehicle. If the sensors detect any movements that the driver does not intend, such as one tire spinning faster than the rest, the stability control system will intervene to reduce the risk of loss of control and rollover. The early versions of the active roll stability control systems for tractor-trailers only reduced the torque on the engine, commonly referred to as the "Jake Brake"; however, newer technology increases the effectiveness by also using the mechanical brakes to slow the vehicle in a quicker manner. Applying the brakes to individual tires creates an opposite moment that will work against the rollover forces to keep the vehicle on its intended path.

Since the stability systems respond to eminent loss of control events, it is pertinent to discuss the defining characteristics of loss of control. There are two main components that are important for the system to monitor: lateral tire slip and yaw rate. Judging the driver's control of the vehicle solely by the lateral slip measurement would be insufficient because vehicles utilize this lateral motion to create the directional change that makes a vehicle turn. Yaw rate, another parameter, measures of the vehicle's angular velocity about its vertical axis [13]. Each brand of technology uses different thresholds to determine what classifies as a loss of control event, but the systems all respond in similar ways. If a driver begins to lose control of his/her vehicle, the system will register the lateral tire slip and yaw rate as being over the limit and will take control by braking individual wheels [13]. The vehicle will brake the outer front wheel when the driver experiences an oversteering event and will brake the inner rear wheel to counteract for understeering.

2.3 Overview of Rollover Characteristics

Many researchers have noted that it is very difficult for a driver to accurately distinguish when they are about to rollover versus when they are safely traversing a curve or other maneuver [7, 14]. Even a small increase in roll stability can reduce the number of rollover crashes [14].

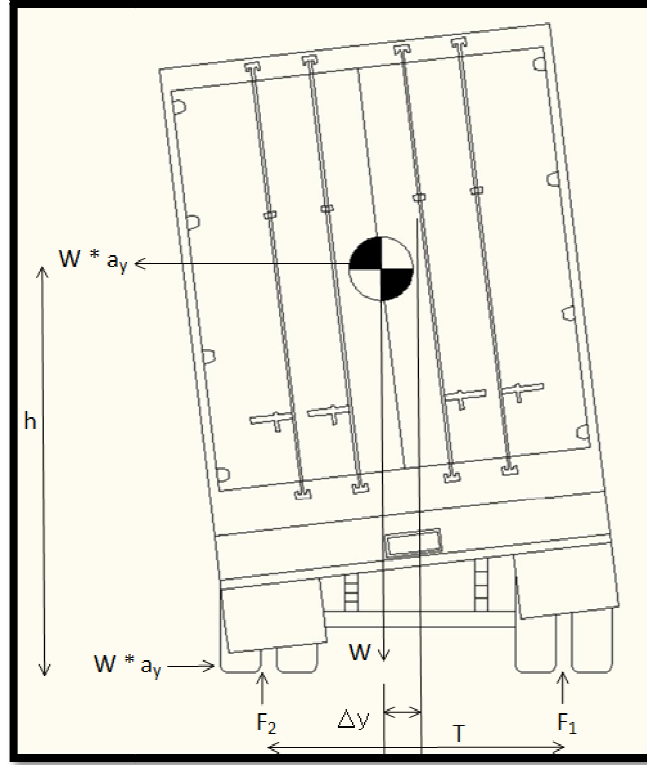


Figure 2: Free body diagram of the back of a semi-trailer during a steady turn

In a single-plane rollover scenario, as depicted in Figure 2, the destabilizing and stabilizing rolling moments must be equal in order for the truck to remain upright. The destabilizing moments are caused by the lateral acceleration at the center of gravity and the lateral offset of the center of gravity from the center of the truck's track. This equilibrium is represented in the following equation:

Equation 1

$$W * h * a_y = (F_2 - F_1) * \frac{T}{2} - W * \Delta y$$

Where, W is the weight of the truck,

h is the height of the truck,

a_y is the lateral acceleration,

F_i is the vertical force on the tires,

T is the track width of the truck, and

Δy is the lateral motion of the center of gravity with respect to the center of the truck's trackwidth.

The premise of roll stability systems is to counteract the rollover tendency by creating a stabilizing moment that leans the vehicle into the turn to help the center of sprung mass to stay on the inside of the vehicle centerline [14]. When a vehicle rolls over, the load goes from being equally distributed among the two sides of the truck to being solely supported on one side.

A tractor-semitrailer with a torsionally rigid frame, as described later in this report, has nine degrees of freedom. The tractor portion of the truck accounts for five degrees of freedom: yaw, side-slip, sprung mass, roll angle, steer angle roll angle, and drive axle roll angle. The trailer accounts for two: roll angle of the sprung section and roll angle of the trailer axle group. The last two degrees of freedom are from the articulation angle between the tractor and the trailer[14].

2.4 Previous Roll Stability Control Research

In 2006, the Federal Motor Carrier Safety Administration published a report on the test results from a Roll Advisor and Controller (RA&C) stability system. The purpose of this research was to determine the percent of rollovers that could be prevented if the system were to be nationally implemented. The research used recorded data from a previous field operational test (FOT) sponsored by the U.S. Department of Transportation. The FOT, titled the “Intelligent Vehicle Initiative,” tested the two components of the RA&C system that assists in preventing rollover crashes: the roll stability advisor and the roll stability control. While none of the test trucks rolled during the year-long data collection which spanned over 4 million miles, the data involved 137 “critical conflicts” where the lateral acceleration was measured to be approaching the static rollover threshold [8].

The RA&C system not only reduced engine torque, but it also engaged the engine retarder and applied pressure to the drive axle and trailer brakes. The roll stability controller activated when the trailer began to roll more than five degrees thus preventing the trailer from further increasing its roll angle. A trailer that was not equipped with the system could experience a very dangerous roll angle of up to fifteen degrees in the same situation. The research proved that the roll stability control system always intervened at speeds lower than what would cause an unequipped vehicle to roll [8]. Using the Vehicle Dynamics Analysis, Non-Linear (VDANL) software Version 6.0 to calculate the prevention ratio, the researchers determined that the roll stability controller yielded a 53% reduction of rollovers from vehicles that were traveling at excessive speeds in a curve and a 69% reduction for those using the combined advisor and controller system for vehicles traveling at excessive speeds in a curve. It was noted that these intelligent vehicle stability systems could also assist in preventing run-off-road crashes, which were not included in the original prevention calculations, because they are typically caused by the same type of maneuvers that cause rollovers, such as going too fast through a curve; however, those were not incorporated within the scope of the project.

In 2009, the University of Michigan’s Transportation Research Institute (UMTRI) performed a study on the efficacy of Meritor WABCO’s electronic stability control systems

(ESC) and roll stability control (RSC) systems for heavy trucks and tractor-semitrailers. UMTRI used an HiL system to simulate potential rollover events instead of collecting field data. The HiL data was augmented by information from detailed crash reports, input from an expert panel, field operation test results, and fleet crash data [12]. A brief overview of UMTRI's methods is presented in this section; more detailed information will be presented later.

UMTRI's team of experts identified crashes that might have been prevented if the stability systems were installed in the trucks. The primary databases used were the nationally representative sampling of truck crashes that are recorded in the Large Truck Crash Causation Study (LTCCS), Trucks Involved in Fatal Accidents (TIFA), and the General Estimates System (GES). Due to the high quality of the reports and its attention to detail, the LTCCS database was the main source for determining which cases would be used as simulation input, evaluated by the expert panel, or both. The other databases were used to determine the average number of annual truck crashes in order to establish the overall safety benefit that could be attributed to the stability system. UMTRI concluded that a total of approximately 3,500 crashes could be prevented by the Meritor WABCO roll stability control system and approximately 4,600 crashes could be prevented based on the implementation of the electronic stability system.

Table 1: Total crashes, deaths, and injuries that could be prevented if RSC and/or ESC were implemented[12]

	Annual Crash Rate	Prevented by:	
		RSC	ESC
Crashes	11,224	3,489	4,659
Deaths	255	106	126
Injuries	14,233	4,384	5,909

2.5 Crash Databases

The Large Truck Crash Causation Study (LTCCS), produced by the National Highway Traffic Safety Administration in combination with the Federal Motor Carrier Safety Administration, is a subset of the General Estimates System (GES) that aims to collect data with the intent of being used for countermeasure development. It contains 963 nationally representative crashes that were collected from April 2001 to December 2003 and that involved heavy trucks with a gross vehicle weight rating (GVWR) greater than 10,000 pounds. Of its 963 cases, it includes data involving 1,123 large trucks, 959 passenger vehicles, 249 fatalities and 1,654 injuries [15, 16]. It includes all crash types and injury severities ranging from fatal to non-incapacitating but evident injury (B-injury). Since the main goal of the LTCCS is to collect data that would be useful in developing crash prevention systems and countermeasures, it typically contains a detailed narrative of each crash, a scene diagram, photographs of the scene from multiple angles, vehicle information, and driver information. This database is available to the public at the following web address: [http://www-nass.nhtsa.dot.gov/LTCCS_PUB/SEARCH FORM.ASPX](http://www-nass.nhtsa.dot.gov/LTCCS_PUB/SEARCHFORM.ASPX).

The Center for National Truck and Bus Statistics at the University of Michigan produces a database called Trucks Involved in Fatal Accidents (TIFA). The TIFA database contains detailed information on all trucks with a GVWR greater than 10,000 lbs (classified as medium and heavy trucks) that were involved in a fatal crash within the United States each year. The General Estimates System (GES) is composed of a nationally representative sample of all police-reported crashes per year. The GES database can distinguish between trucks and cars and also contains important details that are necessary to identify relevant rollovers and loss of control (LOC) events. Between these two databases, an estimate of the number of trucks that could benefit from the implementation of stability systems can be determined while considering and drawing conclusions about various environmental and vehicle factors that are documented in these databases.

2.6 Literature Review of Benefit Estimation

The induced exposure and direct exposure method are the two main methodological ways used to find the effectiveness of safety technology in passenger vehicles. The induced exposure method requires crash data to be separated into two groups: case crash types which are crashes that are expected to be avoided by the presence of a safety system and control crash types which are not expected to be affected. This requires the researcher to make assumptions about the technology's capability to reduce crashes. In the collection of research that demonstrates the effectiveness of electronic stability control (ESC) in passenger vehicles, some researchers assumed that only single vehicle crashes would be affected while others took many more details into consideration. Some examples of control crashes would be rear-end crashes [17, 18] and multi-vehicle crashes[19, 20]. Loss of control is rarely a cause of a multi-vehicle crash yet some studies still counted some multi-vehicle crashes in their crash data if the crash was caused by a loss of control event. Since there are many multi-vehicle crashes, the few loss of control crashes that were included in this data set constitute a very small percentage of crashes; therefore, their presence in the analysis is left up to each individual researcher. Once the crashes were placed into the case or control group, the researcher completed an odds ratio which determines the percent change by dividing the ratio of case crashes to control crashes with ESC over the corresponding ratio of the crashes without ESC.

Equation 2

$$Odds\ Ratio = \frac{(\#\ of\ case\ crashes\ with\ ESC)/(\#\ of\ control\ crashes\ with\ ESC)}{(\#\ of\ case\ crashes\ without\ ESC)/(\#\ of\ control\ crashes\ without\ ESC)}$$

The odds ratio compares whether the probability of two events is the same. In the studies involving ESC, the odds ratio compares whether or not the probability of a crash occurring with an electronic stability system is the same as the probability of a crash occurring with a system.

When a larger database of crashes can be obtained, the direct exposure method may prove to be a more accurate analysis since it does not require any assumptions about which crash types will and will not be affected. The direct exposure method requires information regarding the number of registered vehicles with and without the safety system. The first step is to determine the number of expected crashes.

Equation 3

$$\begin{aligned} \text{Expected Crash Counts} \\ &= (\text{observed crash rates of "non – equipped" vehicles}) \\ &\quad * (\text{registration counts for equipped Vehicles}) \end{aligned}$$

Use the calculated number of expected crashes as the denominator of the risk ratio calculation.

Equation 4

$$\text{Risk Ratio} = \frac{\sum(\text{observed "equipped" vehicle crash counts})}{\text{expected crash counts}}$$

For both methods, indirect exposure and direct exposure, find the percent change to determine the effectiveness of the safety technology.

Equation 5

$$\text{Percent Change} = 100 * (1 - \text{ratio})$$

In Equation 5, the ratio can be either the risk ratio or the odds ratio. The problem with these types of statistical analyses is that there are typically multiple brands of the same type of safety technology and they are all programmed to react at different thresholds. Singling out each specific brand of safety system would yield such small sample sizes that it would be difficult to find statistically significant results[21].

Regardless of which statistical analysis method the researchers used and disregarding that the systems were not exactly the same, all of the studies came to similar conclusions that the electronic stability systems for passenger vehicles nearly always have positive effects. Specifically, the category of severe and fatal crashes had the highest percent reduction. When comparing cars and sports utility vehicles (SUVs), SUVs saw the greatest reduction of crashes due to their high center of gravity which makes them more susceptible to loss of control and rollovers.

Table 2: Ferguson's article entitled "The Effectiveness of Electronic Stability Control in Reducing Real-World Crashes: A Literature Review"[21]

Vehicle Type	Crash Type	Reductions
Cars	Single-vehicle	30-50%
SUV	Single-vehicle	50-70%
All passenger vehicles	Fatal Single-vehicle	70-90%
All passenger vehicles	Multi-vehicle	little to none

By applying the data from Table 2, a total of approximately 10,000 crashes could be prevented every year. This data represents average driving and weather conditions; however, the systems are believed to have increased benefits when roads are not dry.

Researchers at the University of Iowa analyzed the effectiveness of electronic stability control by utilizing the National Advanced Driving Simulator (NADS) [22]. The test subjects were taken through five scenarios on wet pavement. Three of the scenarios involved cars that suddenly pulled out or approached the test vehicle from the left lane, right lane, and head-on. Another one was an unforeseen wind gust that broadsided the vehicle and the last one involved navigating a difficult decreasing radius curve. An algorithm was developed to detect loss of control by using a combination of mathematical and subjective definitions, by recording excessive slip rates and by documenting the vehicle's orientation when it comes to rest. The NADS study made sure to clarify that there is a difference between road departure and loss of control. This study defined road departure as when a driver is still able to maintain directional control of the vehicle even though the vehicle has departed from the pavement. Loss of control is defined as when the vehicle leaves the roadway and comes to a final resting position in which the vehicle is not facing in the direction it was traveling in originally. Road departure was considered less severe than loss of control because the driver is able to maintain some control over his vehicle in order to avoid other obstacles which a true loss of control event would not have been able to avoid. This simulation helps to distinguish whether the stability system can provide the benefit of maintaining directional control even when a vehicle leaves the roadway [22].

Table 3: Simulation results with and without the electronic stability system where LOC is a loss of control event and RD is a road departure event [22]

Scenario	LOC, system ON (N=160)		LOC, system OFF (N=40)		RD, system ON (N=160)		RD, system OFF (N=40)	
	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Dec. radius curve	0	0	3	7.5	35	21.9	13	32.5
Wind gust	5	3.1	32	80	24	15	7	17.5
Left incursion	0	0	15	37.5	0	0	4	10
Obs. avoidance	0	0	13	32.5	3	1.9	0	0
Right incursion	1	0.6	13	32.5	13	8.1	7	17.5

Table 3 shows that the decreasing-radius curve was less effective in demonstrating the positive effect of ESC on LOC, primarily because when ESC was enabled, vehicles skidded beyond the road and usually came to a complete stop parallel to the road. This was considered as road departure since the vehicle was still stable.

The estimated benefits for the implementation of RSC in tractor-trailers were derived from the General Estimates System (GES) and the Fatality Analysis Reporting System (FARS) from a five year period starting in 1995. The statistical results from the USDOT FOT were applied to the overall large truck crash statistics to find the potential benefits of the improved system. Using the 137 critical events from the FOT, Houser estimated the probability of each scenario becoming a true rollover crash through a series of calculations. The research used a form of the indirect exposure statistical method which gives “the overall probability of a crash without the RSC, both given that a driving conflict has occurred.” Calculating the prevention ratio was the first task. When the prevention ratio is less than one, it means that the technology is effective at preventing crashes as long as a critical event has occurred.

Equation 6

$$PR_1 = \frac{P_w(C|S_1)}{P_{wo}(C|S_1)}$$

Where, PR_1 is the prevention ratio of the probabilities of a crash occurring with RSC to a crash occurring without RSC given that a specific scenario occurs. P_{wo} is calculated based on the conditional probability with regards to the corporate rate of crashes for going too fast around a curve based on GES data divided by the rate at which scenarios occur. The two terms of this equation are calculated by Equation 7.

Equation 7

$$P_w(C|S_{1,j}) = 1 - \Phi\left(\frac{\Delta v_{j,R}}{\sigma * v_{j,M}}\right)$$

Where, $S_{1,j}$ indicates conflict number j,

$P_w(C|S_{1,j})$ is the probability of a crash resulting from conflict j,

$\Delta v_{j,R}$ is the increase in speed of conflict j that results in a rollover,

$v_{j,M}$ is the speed during the FOT of conflict j at the peak lateral acceleration,

$\Phi()$ is the Gaussian cumulative distribution, and

σ is a scaling factor which was estimated to be 0.0010 (Battelle, 2003)

The scaling factor was calculated by ensuring that $\sigma^2 \times v_j^2 = 0.000114$ as calculated by the $P_{wo}(C|S_1)$ in Houser’s research[8]. In other words, the squared scaling factor times the unperturbed velocity squared must equal the probability of a rollover without the system. This scales the variance of the perturbed velocity so that the FOT observations match the historical

crash data. The prevention ratios were applied to national crash statistics to yield the following table:

Table 4: Number of Crashes Prevented based on Houser’s research [8]

Type of Truck	Rollover (Fast Turn)			
	Number of Trucks in Crashes/Year	Number of Crashes Avoided		
		RSA (33%)	RSC (53%)	RA&C (69%)
HazMat Tankers	4	1.4	2.3	3
All Tankers	46	15	24	32
Tractor Trailers	471	155	250	325
Large Trucks	787	260	417	543

The research team recognizes that this study was not an exhaustive study including all possible rollover situations and that it only represents a small sample of possible rollover situations.

Chapter 3: Study Design

This study is meant to serve as a comparison to the report that was previously published by the University of Michigan Transportation Research Institute (UMTRI)[12]. The identification of crash types, detailed analysis of crash cases, and selection of curve radii to be used have all been established in the UMTRI report and will be summarized in section 3.1.

To compare the efficacy of the Bendix Electronic Stability Program to the Meritor-WABCO system, it will be tested through a hardware-in-the-loop system using the pneumatic braking system from an actual 5-axle tractor-trailer and inputs from TruckSim, a real-time simulation program. For this report, a rollover will be defined as when a truck trailer's roll angle reaches or exceeds six degrees. Physical rollover values will also be presented; however, these results hold less merit because TruckSim's mathematical model calculations become more unstable as the truck approaches physical rollover. Additionally, in the field data where the trucks are equipped with outriggers to prevent complete rollovers, the trucks can not physically exceed six degrees of roll. So for validation purposes, a rollover will be considered at six degrees of roll. This research focuses on quantitatively identifying the difference in speed required to roll a truck without the ESP and to roll a truck with the ESP enabled through the novel approach of hardware-in-the-loop simulation since more traditional methods require historical crash data with and without the system which is not currently available.

3.1 Detailed Summary of the UMTRI Study

As mentioned in the Literature review, UMTRI performed a similar set of research tests to test the effectiveness of the Meritor-WABCO stability system for large trucks. This section will provide a summary of the methods that UMTRI used to create the rollover scenarios and the results that they found from their simulations.

3.1.1 Scope of the Problem

The UMTRI report states the percentages of trucks that could be affected by the implementation of stability systems and discusses the technology's ability to interact with antilock braking systems. UMTRI determined that 4.5% of the total number of crashes were due to loss of control and 1.2% of those resulted in a subsequent rollover. These types of crashes are likely to be reduced by implementing electronic stability control and rollover stability control systems. An additional 2.2% of crashes were tripped rollover crashes without a loss of control event that would not likely be affected.

3.1.2 Identification of Target Crash Types

Since this report intends to compare the results of UMTRI's study of the Meritor-WABCO electronic stability control and roll stability control systems, this report will summarize the methods and procedure that UMTRI followed in determining which crash types to include in this research endeavor.

Crash Databases

The two rollover definitions that were included in the database search algorithm were untripped rollovers and rollovers as the first harmful event. Tripped rollovers and subsequent event rollovers were not included because they are unlikely to be affected by the technology. The loss of control cases that were included are loss of control caused by control/traction loss or completing a collision avoidance maneuver, poor road conditions that lead to a first harmful event, and loss of control due to a first event jackknife. Crash causes not included were loss of control due to pre-crash instability and run-off-the-road crashes involving a single vehicle due to an avoidance maneuver. The pre-crash instability cases were excluded because after further evaluation, these crashes were incorrectly classified.

UMTRI used a combination of crash databases to determine which crashes should be utilized in these studies. Between the GES and the TIFA databases, an estimate of the number of trucks that could benefit from the implementation of stability systems can be determined while considering and drawing conclusions about various environmental and vehicle factors that are documented in these databases. The LTCCS database was used to test the crash selection algorithms to ensure that it was correctly identifying valid crashes since it provides the most detailed crash information. Selection algorithms were applied to the LTCCS database and evaluated to determine their applicability to the study by reviewing the crash narrative, the scene diagrams, and scene photos. If the results included crashes that were not relevant to stability control, the algorithm was revised and evaluated again until the search resulted in relevant crashes.

There were two specific crash databases that were not utilized by the University of Michigan: the NASS Crashworthiness Data System file and FMCSA's Motor Carrier Management Information System Crash file. The Crashworthiness Data System file was not included because it mainly focused on passenger vehicle crashes and only included information on trucks if the truck was involved in a crash with a passenger vehicle. The Motor Carrier Management Information System Crash file provides information on trucks and buses, but it is primarily used as a census of crashes that contain injuries or fatalities of certain levels of severity, rather than a detailed account of those crashes.

Selection Algorithms for Relevant Crash Types

The three databases that are being utilized, TIFA, GES, and LTCCS, contain similar information that makes it possible to identify the same crash in all three databases. When looking for crash types that will be affected by stability control systems, a rollover is simple to detect; however, the cause of the rollover is not usually evident. The crash files may specify excessive speed in a curve as the cause but after further review, an expert panel may identify the tire skids as typical for rollovers that are not related to high speeds around a curve. To weed out irrelevant tripped rollovers, the researchers searched for crashes where the rollover was the first harmful event in the crash. They were also interested in crashes where there was excessive yaw or insufficient yaw prior to the crash which could have been mitigated by a stability system.

The researchers in the UMTRI study developed an algorithm to identify probable crashes in the GES database and then used the same algorithm in the LTCCS database. The researchers then read the crash description given in LTCCS to see how adequately the algorithm performed.

The algorithm captures untripped rollovers and loss of control events. Loss of control events are more difficult to identify because they usually occur before a crash and sometimes it can be improperly documented or not documented at all. The GES database reports the vehicle's role in the crash including a specific code if the vehicle lost control. UMTRI included single vehicle crashes that were coded as control/traction loss, left or right roadway departures, avoidance maneuvers, and road departures. Multiple vehicle crashes were also included if they were coded as control/traction loss that also had a collision with another vehicle traveling in the same or opposite direction. The crashes in GES that were coded as LOC due to excessive speed were typically not included because the expert panel evaluation revealed that the skid marks that were left on the scene were typical of a simple rollover and that a LOC event did not occur separate from the rollover. Relevant jackknife crashes were included if they were identified by the GES, LTCCS, and TIFA databases as first harmful event jackknives. First event jackknives directly correspond to yaw instability and LOC.

As the UMTRI report states, their algorithm selects the crashes that will most likely benefit from the implementation of a stability system. They do not intend to imply that those are the exclusive crashes that will benefit. There may be some more crashes hidden within the codes that could still benefit from the technology.

3.1.3 Linking the Crash Data with the HiL System

After removing the loss of control crashes that were analyzed separately by an expert panel of researchers, the remaining 74 relevant rollover cases are divided up into curve radii bins to simplify the estimations. For the first set of tests, the cases are placed into one of four bins:

1. Radius of <100m with a high center of gravity
2. Radius of <100m with a medium center of gravity
3. Radius of >100m with a high center of gravity
4. Radius of >100m with a medium center of gravity

Cases with a radius of less than 100m will be run as a radius of 68m which is the average radius of all the radii in that bin and cases with a radius greater than 100m will be simulated with a radius of 227m which is the average of the radii greater than 100m. Similarly, a high center of gravity is assumed to be located at 2.3m height and a medium center of gravity is located at 2.0m height.

In addition to the two curve radii that UMTRI used in their research, a curve radius of 150 meters will also be included in this report in order to verify the conclusions about the behavior of the Bendix electronic stability program. The curves presented in this approach were designed using the American Association of State Highway and Transportation Officials (AASHTO) Greenbook to as a guide to create spiral curves that gradually increase from

an infinite radius curve into the intended constant radius curve. We assumed a rate of centripetal acceleration of 1.3 ft/s^3 and a design coefficient of friction of 0.4. The equations and method used to determine the centerline coordinates of the curves are presented in Appendix A.

Evaluating Effectiveness

For each curve radius mentioned above, a critical velocity was determined which represented the highest speed a truck could enter a curve and not experience a rollover. Entry speeds that were greater than the critical speed lead to the rollover occurring early in the curve. From that observation, it can be noted that if a truck rolls over at a point farther in the curve than where the truck traveling at the critical speed rolls, then the driver's behavior or response must have caused the rollover. UMTRI found that for radii between 100-200m, any truck that could successfully make it through the first 100m of the curve should be able to complete the maneuver as long as the driver does not do anything to perturb the truck [12].

3.2 Evaluating Rollovers with the HiL Simulator

In our study and the UMTRI study, the rollover scenarios that were developed in section 3.1 of this report were modeled in a simulation software called TruckSim. These scenarios were then run through the hardware-in-the-loop setup to determine the speed at which critical events occurred.

3.2.1 Truck Modeling

The truck that is modeled in TruckSim for this research is based on a Volvo tractor pulling a Fruehauf box trailer, with dimensions as shown in Figure 3. This truck was modeled due to the field test data from NHTSA and Vehicle Research and Test Center (VRTC) that was available to validate this model. The validation of this model is explained in the Transportation Research Board paper in Chapter 4 and further validation procedures are explained in section Chapter 5.

There are two box-shaped loads that are placed on the trailer to modify the truck's center of gravity. The front load weighs 10,464.4 kg and the rear load weighs 8,650 kg. These loads are selected and located above the trailer axles to create realistic values for the roll inertia and radius of gyration. In order to increase or decrease the center of gravity of the truck the loads are simply raised or lowered without changing their weights. The braking capacity of the truck model is consistent with S-Cam brakes that have a maximum torque of 7,500 N-m at a maximum brake pressure of 0.8 MPa.

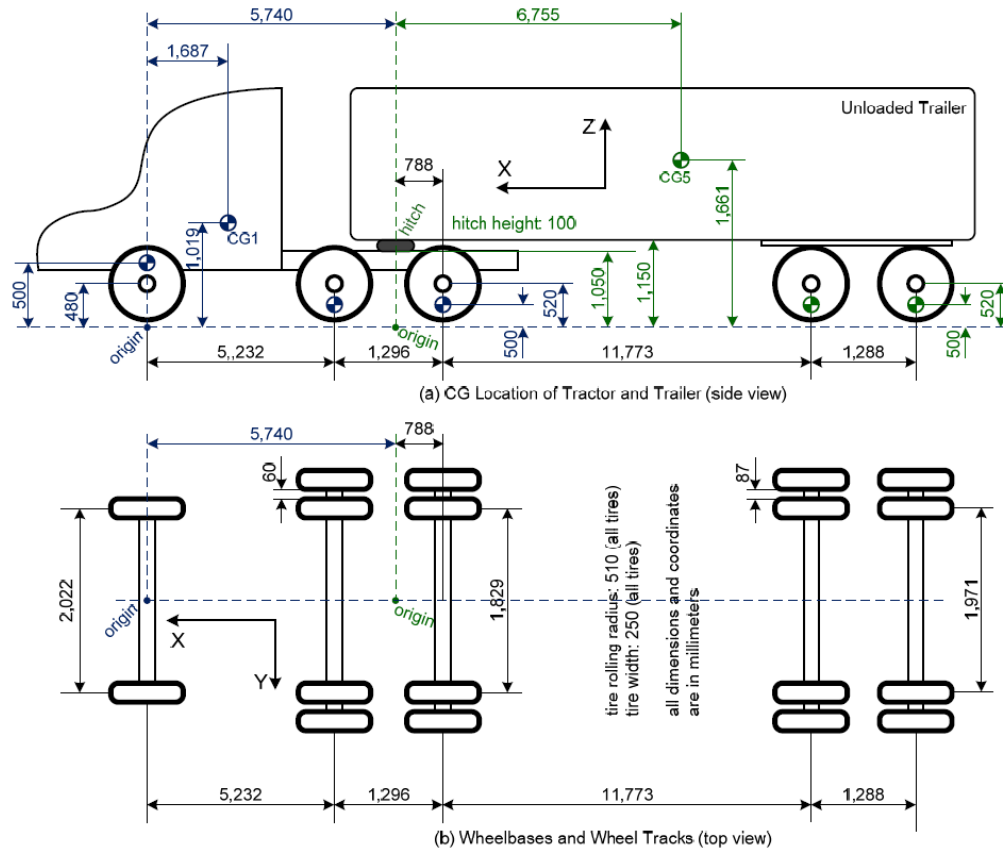


Figure 3: Truck Configuration Diagram [12]

3.2.2 Driver Model

For this report, the driver is set to steer the truck along the curve of the road in order to keep the truck on the intended path. TruckSim's steering algorithm optimizes the steering input and avoids any sudden or unnecessary corrections.

3.2.3 Testing Procedures

To run the simulations, the truck is set to accelerate from a stopped position until it reaches the desired speed for the simulation. This occurs on a straight-line section of the designed roadway before the truck reaches the beginning of the curve. During this acceleration period, small sinusoidal steering maneuvers are completed so that the stability control program is able to identify and estimate the trailer load based on its own algorithm. Essentially, once the truck reaches the desired speed, it is held constant at that speed until the truck reaches the point in the road where the curve begins. At this point, the truck's throttle is dropped down to zero for the remainder of the maneuver.

In order to find the critical speeds at which the truck's roll angle surpasses six degrees of roll or until a physical rollover occurs in the simulation, the simulations are run at increasing speed in 0.5 kph intervals until the critical speed is identified. This procedure was followed for all of the validation runs and for the results presented in this report.

Chapter 4:

Development of a Hardware-in-the-Loop Testbed for Evaluating Truck Safety Systems

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Abstract

The research presented in the paper develops a hardware-in-the-loop system that can be used to test in-truck safety technology. The paper describes the various hardware and software components that are required to develop the system, how the various components are integrated, and some initial validation tests of the system. Specifically, the paper describes how the hardware-in-the-loop system interacts with the TruckSim simulator to produce realistic results. The models used for the validation of the system are described, followed by a demonstration of the system validity. The absolute and relative errors between the TruckSim simulation results and the hardware-in-the-loop simulation are demonstrated by comparing the temporal variation in velocity and the truck roll angle. The paper demonstrates the benefits of utilizing an accurate hardware-in-the-loop system for the testing of future in-vehicle safety systems.

Introduction

The trucking industry statistically represents 4% of registered vehicles and 7% of the total vehicle miles traveled; however, when it comes to accident fatalities, trucks are overrepresented as evidenced by their involvement in 8% of fatal crashes in comparison to their involvement in only 4% of property damage only crashes.” Additionally, the vehicle involvement rate of trucks in injury crashes has been reduced from 45% to 33% over the past ten years from 1998 to 2008 while the corresponding involvement rate for fatal crashes has only been reduced by 0.5% over the same ten year span [3]. It is clear that while the rate of lower severity crashes have been reduced, the high severity crashes need to be further researched in order to improve the overall crash ratings. Building a hardware-in-the-loop (HiL) system that is capable of testing new truck crash avoidance technologies in a safe and realistic manner is critical in order to test and verify the effectiveness of these technologies. Having a direct comparison of various systems will assist in selecting the optimum system.

Previous research

Before the invention of HiL systems, vehicle designs and new technologies were tested on controlled test tracks. While test tracks provided insight into the vehicle’s dynamics, the tests required professional drivers and specially equipped trucks which lead to expensive and potentially dangerous situations.

Similar to test track testing, field operational tests (FOT) use fleets of vehicles to collect real driving data. New systems can be installed on specific trucks so researchers can monitor the truck’s performance to evaluate the effectiveness of the technology [24]. This method has the benefit of capturing real-life driving situations; however, it does not evaluate the limits of the technology and it requires significant time and resources to complete such a study. Even within a long study period, the technology might not be pushed to the extreme and therefore cannot be evaluated in its entirety. For example, a U.S. Department of Transportation study on testing the effectiveness of a system called the Roll Advisor and Controller (RA&C) collected field data for

one year and although the experiment collected over 4 million miles of data, there were only 137 “critical conflicts” where the lateral acceleration was measured to be approaching the static rollover threshold, but no physical rollovers occurred [24].

The next step in the evolution of dynamic vehicle testing involves modeling vehicles in a simulation software environment. These models are built to match the measured characteristics from test track experiments [9]. Safety technology models are then established and superimposed onto the vehicle models to evaluate their effectiveness. Effective modeling of the safety technologies is often difficult because the crash detection algorithms are typically proprietary information. Consequently, this method is useful for initial testing procedures, however, it is unable to provide detailed information on the idiosyncrasies of the technology since it is based on a model of idealistic performance.

The next step in the development of testing new technologies is to physically integrate the technology with the simulation software by establishing a HiL system. These systems utilize vehicle characteristics provided by the simulation software and apply them to a physical mechanical setup of the remaining vehicle characteristics. This enables the system to be tested in a safe environment without the need for a professional driver or expensive adaptations to the trucks. Lee and Suh utilized a HiL system to test an antilock brake system and a traction control system [10]. A few other systems were built to develop and test systems for passenger vehicles [11] and tractor trailers [23]. The University of Michigan Transportation Research Institute (UMTRI) performed a study for the National Highway Traffic Administration (NHTSA) to evaluate the performance and the potential safety benefits of electronic stability control systems (ESC) and roll stability control systems (RSC) for heavy trucks and tractor-semitrailers. Due to the unavailability of detailed crash data that would compare crashes that involved trucks with and without the system, an analysis was performed by using a combination of hardware-in-the-loop simulations, input from an expert panel, field operation test results, and fleet crash data [23]. The system that was built at the Virginia Tech Transportation Institute for the research presented in this paper is able to model vehicle handling maneuvers using input information including but not limited to: steering angles, brake application, load characteristics, truck characteristics, and road characteristics.

Hardware-in-the-Loop System

The HiL simulator is based on a commercially available simulation engine, TruckSim, and a pneumatic tractor trailer braking system. Software developed in National Instruments’ LabVIEW 8.6.1 environment provides an interface to the TruckSim simulation engine Dynamic Link Library. Figure 4 shows a simplified schematic diagram of the HiL system to further clarify how the software and hardware interact.

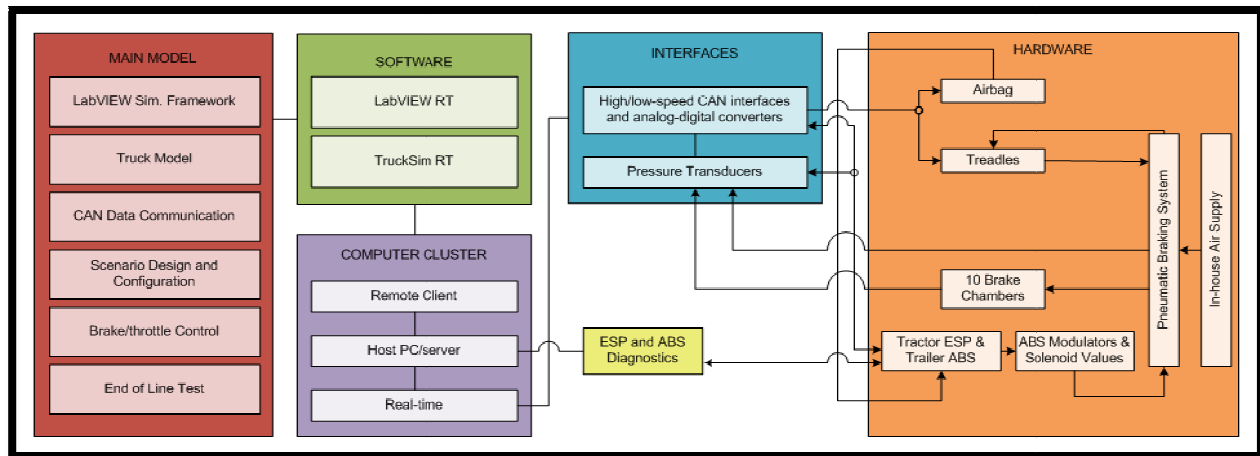


Figure 4: Schematic diagram of the Hardware-in-the-Loop system.

Hardware

The braking rig that was used in this study is based on a stock 2006 Volvo VNL pulling a 2007 Utility MX6000 van trailer per NHTSA's recommendation. The essential components of the braking system were assembled in a 35"d x 38"w x 78"h frame in order to reduce the overall space that the rig occupies. The pneumatic tubing and electrical wires were sized to the equivalent lengths used in an actual truck and coiled up in order to preserve the airflow characteristics of the system.

The truck is fitted with an anti-lock brake system (ABS), traction control, and an electronic stability system. According to Federal Motor Vehicle Safety Standard 121, NHTSA has required since 1997 that tractors have antilock control on at least one rear axle and that for at least one of the axles, the wheels on that axle must be individually controlled by a separate modulator. A semitrailer must have at least one axle with antilock control, and full trailers must have it on at least one front and one rear axle. In accordance with the NHTSA mandate, each brake chamber on the tractor is controlled by its own modulator and the trailer brakes are augmented with a trailer ABS [25].

In addition to the required hardware, the VTTI rig is equipped with a Bendix Electronic Stability Program (ESP). The ESP is the first of many technologies that can be incorporated into the rig. This system utilizes the same sensors as the ABS that evaluates wheel speeds, steering angle, lateral acceleration, and yaw rate. The Bendix ESP communicates with the truck ECU in order to inform the system when to engage and intervenes when there is excessive lateral acceleration or a large yaw rate in which the system's algorithm identifies as a potential loss of control event. When this happens, the system engages individual brakes in order to reduce the risk of a rollover.

For the current project, the Bendix ESP will be initially disabled in order to determine the critical speed which will guarantee a rollover if none of the other inputs change. Once the critical speed is determined, the Bendix system is enabled and evaluated based on its ability to prevent the rollover.

Simulation Software

TruckSim is a software program that can be used to model, analyze, and simulate the dynamic behavior of large vehicles such as tractor trailers, buses, military vehicles, and articulated vehicles. TruckSim contains a series of data input screens as shown in Figure 6 which contain both graphical and numerical data for the characteristics of the truck, roadway, and driver. The discussion in this paper will focus on the elements of TruckSim that were utilized in the study. It does not intend to imply that the aspects presented below represent the limitations of the software.



Figure 5: Front view of full braking system incorporated in the HiL system. The Bendix Electronic Stability Program is outlined in the white box. The gray computer on the left is the server and the off white computer on the right is the real-time unit. Below the computers are the brake chambers for both the tractor and the trailer.

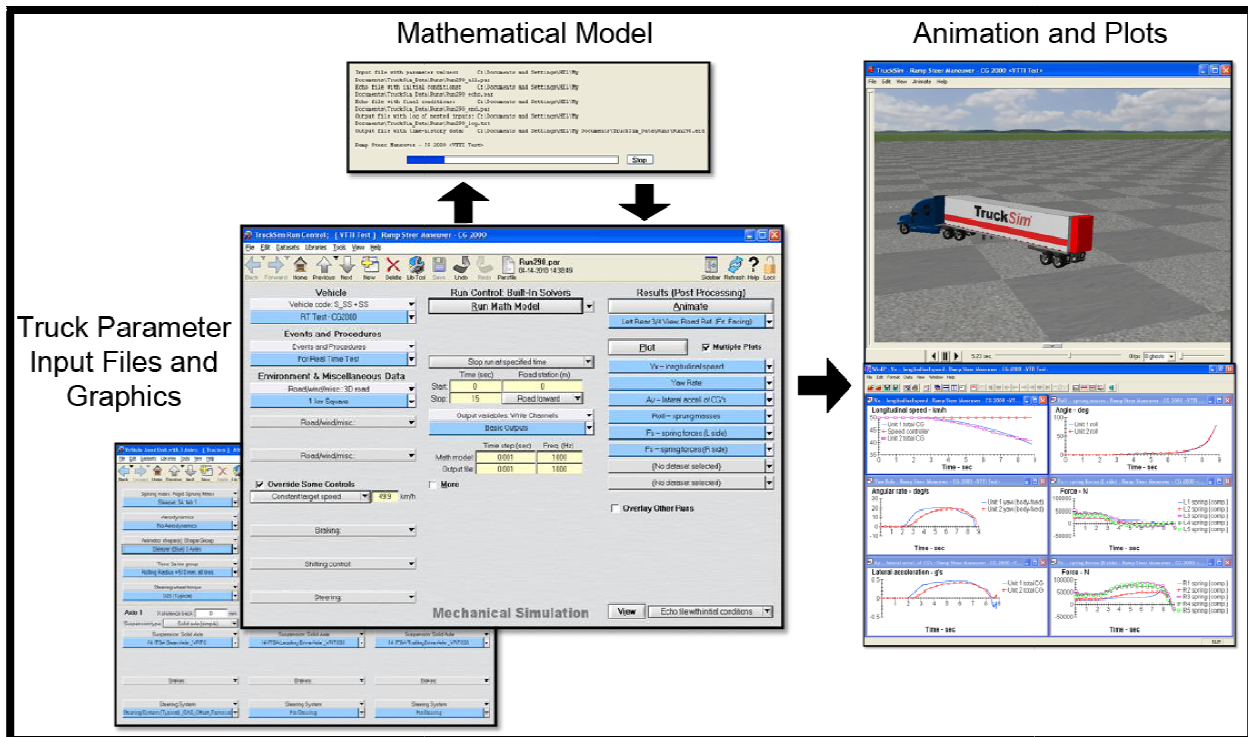


Figure 6: Diagram to show the three main components of TruckSim: Truck parameters, a modeling system (mathematical modeling pictured here), and Animation and/or plots of the dynamic characteristics of the truck.

In TruckSim, the user is able to define the characteristics of the vehicle as well as the geometric properties of the road. The user has the option of specifying vehicle characteristics such that, when the various characteristics are combined together, they can simulate almost any type of large vehicle. These characteristics include, but are not limited to, the following properties for the tractor and the trailer:

- Sprung mass- weight; roll, pitch, and yaw inertia
- Aerodynamics - lateral, longitudinal, and vertical forces; roll, pitch, and yaw moments
- Tires - (assigned by axle) mixed type; dual tires and their spacing from each other; rolling radius, rolling resistance, width, spring rate, and max allowable force
- Steering wheel torque - a plot of total kingpin moment with respect to steering-wheel torque
- Power train - engine model; torque converter model; transition model; transfer case; front and rear differential (for four wheel drive)

There is also a section to specify characteristics by axle which include suspension type, brakes, steering system and the distance from the front axle. Anything that is not specified in the program can either be modeled with a specifically created parameter file or run through a hardware-in-the-loop setup while utilizing the real-time setting.

Additionally, a load can be added to the trailer and assigned values for roll, pitch, and yaw inertia. These loads are theoretical loads that are meant to represent an actual load. It is important to note that two or more hypothetical loads can overlap in order to simulate a different load. This is acceptable as long as the combined loads have the same static and dynamic properties as the actual load they are meant to embody.

The roadway has its own set of programmable characteristics. The following are options that may be adjusted depending on what type of scenario the user wants to run.

- Centerline geometry - can be input as an X-Y table of horizontal coordinates or can be built with the segment builder
- Centerline and off-center elevation
- Friction

Once the parameters are set, the user is ready to run the mathematical model through TruckSim. The run can be set to start and end at a user specified time or distance. After the mathematical model has finished running, the user is able to view a video of the truck during the simulation in the surface animator or view graphs of forces or properties of engine components in the post processor section of the screen. The plotter reports the results at previously specified output time steps. From these plots, determining the minimum and maximum values is simple. By default, only one simulation run is plotted and simulated, however, the user can overlay other completed runs in order to easily compare values.

HiL Computing Platform

The HiL computing platform consists of two central computers, the HiL Simulator real-time system and the HiL Server management PC. End user access to the system is through a HiL Client PC. Each of these systems is briefly described in the following sections. More detail can be found in the final report.

Table 5: Hardware computing requirements

TruckSim RT	Mechanical Simulation Corporation	8.00	Windows XP	License file located at: C:\Flexlm\k107302.lic requires USB hardware key authentication (license renewed annually)
LabVIEW	National Instruments Corporation	8.60	Windows XP	License file located at: C:\Program Files\National Instruments\Shared\License Manager\Licenses\LabVIEW\RealTime_PKG_080
LabVIEW RT	National Instruments Corporation	8.60	ETS RT	Operating system for Real Time PC (never expires)

HiL Client

The HiL Client is a PC running Microsoft Windows that has both TruckSim and the HiL Client software installed. The researcher uses the TruckSim software to generate simulation case runs, and the HiL Client software to submit and receive these runs to and from the HiL Server. The client computer has a network connection to the HiL Server computer via the local area network. Figure 7 shows a screenshot of the LabVIEW graphic user interface that was designed to run and monitor the simulations.

HiL Server

The HiL Server is a PC running Microsoft Windows that is located with the simulator hardware. The computer has two network interfaces. The first network interface connects to the local area network. This network interface has a static IP address so the HiL Client software can identify (via a local configuration file) the HiL Server. This interface is used to connect to the HiL Clients. The second network interface connects the HiL Server via Ethernet crossover cable directly to the HiL Simulator.

The HiL Server computer runs two main applications that are associated with this project. FTP server using Microsoft IIS services is configured. The computer also has the HiL Server software running. The HiL Server software monitors the HiL Simulator software. Depending on the status of the HiL Simulator, the HiL Server will perform different tasks. If the HiL Simulator is idle, then the HiL Server will check its queue for jobs to be processed. If the queue contains a job, the software then FTPs the files to the HiL Simulator and requests that the simulation start.

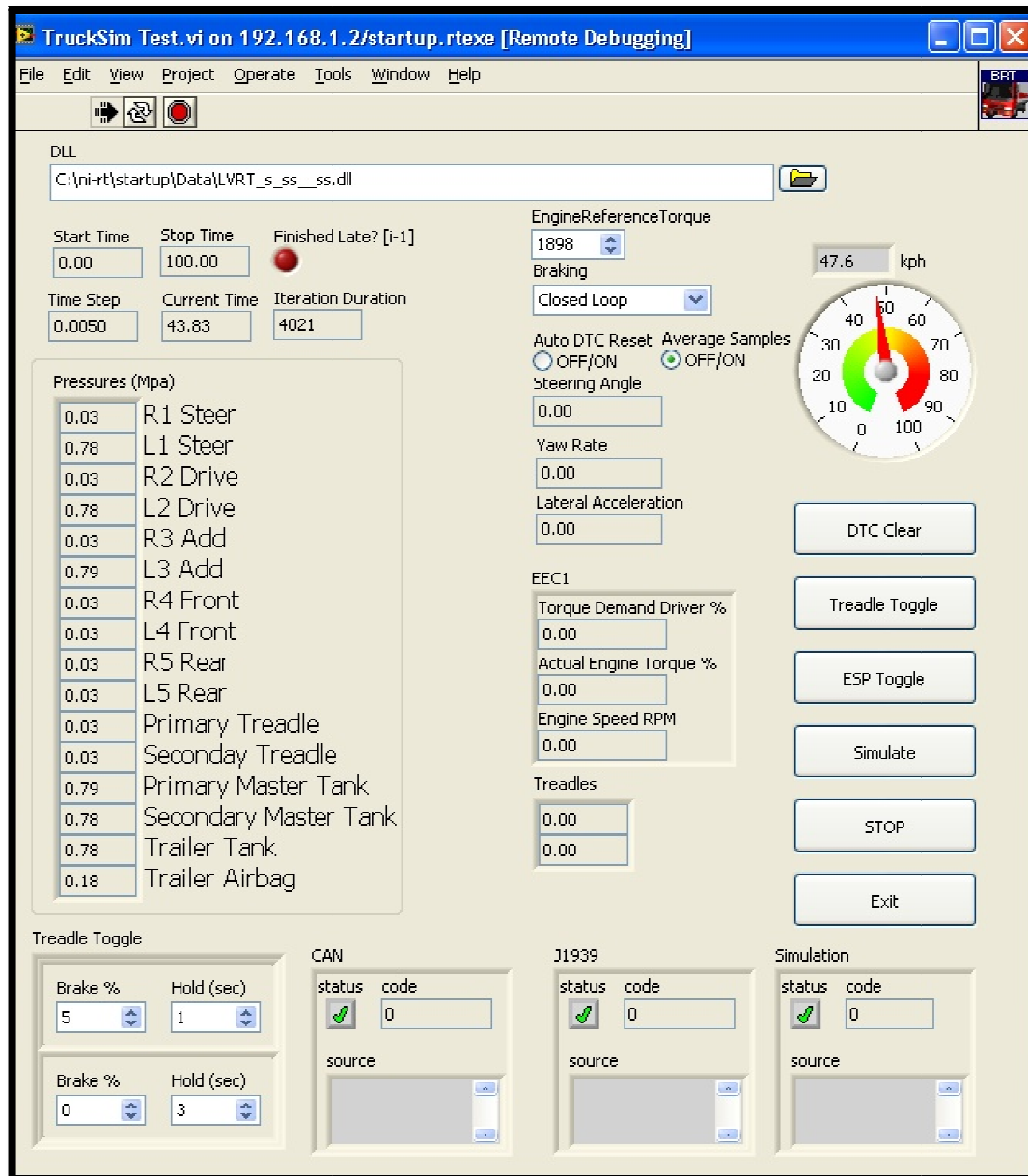


Figure 7: Screenshot of the LabVIEW graphical user interface.

Once the simulation is in progress, the HiL Server Software displays the current progress of the simulation. If the real-time system is taking longer than it should to complete each iteration of the simulation, the “Finished Late” light will be illuminated to inform the researcher that the machine is no longer running in real-time. While a simulation is running, the researcher can monitor the real-time brake pressures for each axle, treadle pressures, air tank pressures, steering angle, yaw rate, lateral acceleration, torque, engine revolutions per minute, and speed of the vehicle. If an error message appears in the bottom portion of the window, it can usually be cleared by pressing the “DTC Clear” button which clears all stored errors and restarts the Bendix stability system. The treadle control and electronic stability system can be toggled on or off

before or during a simulation by pressing the toggle buttons. The HiL system's toggle button makes it easy to run each simulation with the stability system disabled and later with it enabled to determine the speed at which the stability system is successful in preventing a critical event or rollover. When the simulate button is pressed the real-time simulation will start. The box in the bottom left-hand side of the window allows the researcher to manually apply brake pressures on the tractor or trailer brakes. After the simulation is complete, the HiL Server software FTPs the results from the HiL Simulator to the HiL Server.

HiL Simulator

The HiL Simulator computer is a National Instruments PXI-8108 chassis with an embedded controller running a real time operating system. The chassis includes multiple PXI modules:

- PXI-6251 Multi-Function Digital Acquisition (DAQ) Module
- PXI-6602 Timer/Counter Module
- PXI-6713 Analog Output Module
- PXI-8464/2 Two Port CAN Interface Module

The DAQ module reads system pressures throughout the simulator hardware. The simulator uses sixteen pressure transducers, occupying all analog input channels on the DAQ card. The two individual analog outputs on the DAQ card are used to control the primary and secondary brake treadle positions. The analog output card provides an analog output to control the trailer airbag pressure, as well as digital outputs to control the ignition line and the enable/disable line of the stability control feature of the Bendix brake ECU. Both CAN channels provide messages to the Bendix brake ECU: the first CAN channel interfaces to a proprietary CAN network, while the second CAN channel is configured to emulate an engine ECU using the J1939 protocol.

The PXI controller has an executable that launches at startup. The executable has multiple parallel timed loops. The executable immediately begins processing messages in the two communication loops. One timed loop provides proprietary CAN communications. A second time loop provides J1939 communications. The timer/counter timed loop immediately begins stimulating the digital waveforms for the wheel speed sensors with a period related to the wheel speed. The main timed loop waits until a simulation is requested. Once the request is made, the main timed loop resets the ignition line, initializes the TruckSim simulation, steps through the simulation at the specified time step and finally terminates the TruckSim simulation. During each iteration the software reads the pressure transducers and provides the results to the TruckSim simulation DLL as an input parameter. Upon terminating the TruckSim simulation, the output files are created. Once the files are created, the main loop sets the status to simulation complete and waits until the next simulation is requested.

The LabVIEW system communicates via the CAN 2.0 bus and runs a 100ms real-time loop which can be modified to run at higher or lower frequencies. The main concern regarding the hardware and software interactions are ensuring that all of the correct and necessary variables are being transferred to the stability systems. Since the stability systems typically contain proprietary algorithms to detect potential rollovers or loss of control situations, the companies are usually reluctant to release the information that is needed to ensure proper evaluation of the equipment.

System Validation

The VTTI TruckSim real-time simulation results were validated using vehicle test data provided by NHTSA. The vehicles were tested at the Vehicle Research and Test Center (VRTC) in East Liberty, Ohio and consisted of a Volvo tractor and a Fruehauf van trailer. A TruckSim model that had already been validated with experimental data was provided [9, 26]. VTTI and VRTC both used one truck with four different loading configurations. The different loading configurations had trailer center of gravities located at 2.0 m, 2.2 m, 2.3 m, and 2.73 m. Each loading configuration was placed on the truck and set to attempt a steering maneuver of 199 degrees at a rate of 175 degrees per second once it reached a specified speed. Each configuration was simulated to determine the speed at which the following events occurred:

1. Highest speed with no wheel lifts
2. Lowest speed with one wheel lift
3. Lowest speed with multiple wheel lifts
4. Lowest speed that creates at least six degrees of roll
5. Lowest speed that causes a physical rollover.

The speeds that VRTC determined for the aforementioned events were then compared against the speeds that were produced by the real-time system. These parameters were determined and found to be identical as shown in Table 6.

Table 6: Comparison of VRTC and VTTI values for validation purposes.

Volvo with CG at 2.3		
Outcome	VRTC	VTTI
No Wheel Lift No Rollover	29.5 mph (47.5 kph)	29.5 mph (47.5 kph)
Single Wheel Lift - LR Trailer No Rollover	30.0 mph (48.3 kph)	30.0 mph (48.3 kph)
Achieves > 6° Roll	not determined	30.5 mph (49.1 kph)
		6.4081 degree
Multiple Wheel Lift No Physical Rollover	31.0 mph (49.9 kph)	31.0 mph (49.9 kph)
Physical Rollover	31.5 mph (50.7 kph)	31.5 mph (50.7 kph)

Plots of the vertical wheel forces, yaw rate, lateral acceleration, and degrees of roll were generated to show the similarities of using the internal mathematical model within TruckSim and using the real-time system that will be used in the subsequent HiL tests. Examples of the velocity and roll angle results from the 2.2 m center of gravity truck are presented in Figure 8 through Figure 11. The first two plots show the results for a scenario that was run at an initial speed of 49.1 km/h where no rollover or wheel lift occurred. The last two plots show the results of a rollover scenario that occurred at an entry speed of 55.5 km/h. In all of these figures, the solid line represents the plot of the TruckSim non-real-time mathematical model (running the stand-alone simulation software) and the dashed line represents the results when the same simulation was run on the real-time HiL. Similarly, the red lines represent the tractor as Unit 1 and blue lines represent the trailer as Unit 2. In Figure 8 and Figure 10, subplot (a) shows the speed of the tractor and trailer with respect to time whereas the roll angle of the tractor and trailer with respect to time is shown in subplot (a) of Figure 9 and Figure 11. When the vehicle physically rolls over, the roll angle approaches 90 degrees of roll, indicating that the truck is on its side. Subplot (c) shows the associated error with respect to time. Subplot (b) and (d) in each of the four figures show a histogram of the error associated with subplot (a) of the same figure. The plots indicate that the error associated with the difference between the real-time and the non-real-time results are of small magnitude and close to zero. Specifically, the error between the simulation runs results from the slight offset of the real-time system from the non-real-time system.

Table 7: Table describing the absolute error in (a) velocity (km/h) and (b) roll angle (degrees) between the real-time and non-real-time simulation results

(a)

Absolute Error in Velocity (km/h)

		Average		Minimum		Maximum	
		Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
2.0	No wheel-lift	0.069	0.069	0	0	0.104	0.106
Center of Gravity	Rollover	0.094	0.071	0	0	0.481	0.147
2.2	No wheel-lift	0.066	0.067	0	0	0.097	0.101
Center of Gravity	Rollover	0.053	0.042	0	0	0.239	0.093
2.3	No wheel-lift	0.060	0.061	0	0	0.090	0.089
Center of Gravity	Rollover	0.060	0.051	0	0	0.239	0.095
2.73	No wheel-lift	0.052	0.053	0	0	0.090	0.090
Center of Gravity	Rollover	0.047	0.039	0	0	0.224	0.074

(b)

Absolute Error in Roll Angle (degree)

		Average		Minimum		Maximum	
		Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
2.0	No wheel-lift	0.000	0.001	0	0	0.215	0.223
Center of Gravity	Rollover	-0.692	-0.694	0	0	8.029	7.904
2.2	No wheel-lift	0.000	0.001	0	0	0.257	0.266
Center of Gravity	Rollover	-0.326	-0.327	0	0	3.231	3.135
2.3	No wheel-lift	0.000	0.001	0	0	0.275	0.285
Center of Gravity	Rollover	-0.375	-0.377	0	0	3.654	3.599
2.73	No wheel-lift	0.002	0.003	0	0	0.304	0.315
Center of Gravity	Rollover	-0.308	-0.310	0	0	2.902	2.852

The absolute error is shown to be very small in magnitude for the velocity and roll angle data, as summarized in Table 7, Figure 8 and Figure 9. Both sets of data have a minimum error of zero which indicates that the real-time and non-real-time simulation runs are exactly the same for part of the simulation. This usually occurs at the beginning of the simulation and the error increases with time. The cumulative nature of the error could spawn from the tendency for the real-time system to stop the simulation a few hundredths of a second earlier than the non-real-time system. The velocity errors are very consistent across the different center of gravity scenarios (less than 1 km/h). After six degrees of roll, the roll angle error becomes larger for the rollover situations. This instability happens because the truck does not include torsional stiffness in its model. In terms of relative error, the roll angle error of a rollover scenario is small when comparing three degrees to ninety degrees of roll.

Table 8: Table describing the relative error in (a) velocity (%) and (b) roll angle (%) between the real-time and non-real-time results

(a)

Relative Error in Velocity (%)

		Average		Minimum		Maximum	
		Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
2.0 Center of Gravity	No wheel-lift	0.151	0.153	0	0	0.225	0.232
	Rollover	0.188	0.158	0	0	1.032	0.280
2.2 Center of Gravity	No wheel-lift	0.152	0.153	0	0	0.229	0.239
	Rollover	0.153	0.136	0	0	0.517	0.239
2.3 Center of Gravity	No wheel-lift	0.166	0.150	0	0	0.517	0.239
	Rollover	0.168	0.150	0	0	0.561	0.239
2.73 Center of Gravity	No wheel-lift	0.166	0.150	0	0	0.517	0.240
	Rollover	0.167	0.149	0	0	0.585	0.240

(b)

Relative Error in Roll Angle (%)

		Average		Minimum		Maximum	
		Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
2.0 Center of Gravity	No wheel-lift	-1.383	-0.805	0	0	62.874	73.450
	Rollover	-2.581	-2.096	0	0	62.961	70.992
2.2 Center of Gravity	No wheel-lift	-1.363	-2.472	0	0	68.775	25507.9
	Rollover	-0.991	-0.507	0	0	62.947	77.008
2.3 Center of Gravity	No wheel-lift	-1.069	-0.506	0	0	68.662	36.526
	Rollover	-1.114	-0.557	0	0	56.404	30.393
2.73 Center of Gravity	No wheel-lift	-1.065	-0.501	0	0	70.117	32.565
	Rollover	-1.078	-0.531	0	0	53.456	68.575

The relative error compares the difference between the real-time and non-real-time data by normalizing the error with respect to the non-real-time system estimate. While the velocity errors are on average less than 0.2%, the relative error associated with the roll angle is much larger, as summarized in Table 8. The average error for the simulation runs are near 1.0%, but the maximum values are approach 60-70% error. While these errors appear large, it is important to look further into the data to find the reason why. For example, the maximum relative error for the trailer (unit 2) of a truck with the 2.2 center of gravity is 25,507% which occurs 0.159 seconds into the simulation. At this time, the truck is driving straight and the roll angle of the non-real-time system is 0.0000000352 degrees of roll. The difference between the real-time and non-real-time system is 0.000008985. Dividing the difference by the non-real-time value yields a very large percent error for a difference that is nearly zero. Though the percent errors of the roll angle may appear to be unreasonable, when looking at the histograms in subplots (b) and (d) of Figure 8 and Figure 10 it is clear that the errors are very close to zero.

Summary Findings and Conclusions

The HiL system that was developed as part of this research effort is an invaluable tool for accurately determining the effectiveness of new and improved truck technologies. Virtually any technology can be installed in the loop and can be activated or deactivated by the touch of a button. The HiL system allows vehicle technologies to be tested in extreme conditions that may not be safe on a test track without the risk of incurring actual crashes.

The validation results demonstrate that the HiL produces simulation results that are consistent with TruckSim, the standalone software. The absolute errors remain small, and the average percent errors are less than 0.2% different from the velocity data and average close to 1% different for the roll angle. These results demonstrate the validity of the testbed to accurately test and evaluate alternative in-truck safety systems.

While the current HiL system is set up to test the Bendix Electronic Stability Program (ESP), other various technologies can easily be integrated into the hardware rig. Safety benefits such as reduction in the number of crashes and lives lost, resources, and time saved can be calculated using the HiL thus reducing the costs of such evaluations.

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Comparison of Real-time and Non-real-time Results for the 2.2m Center of Gravity

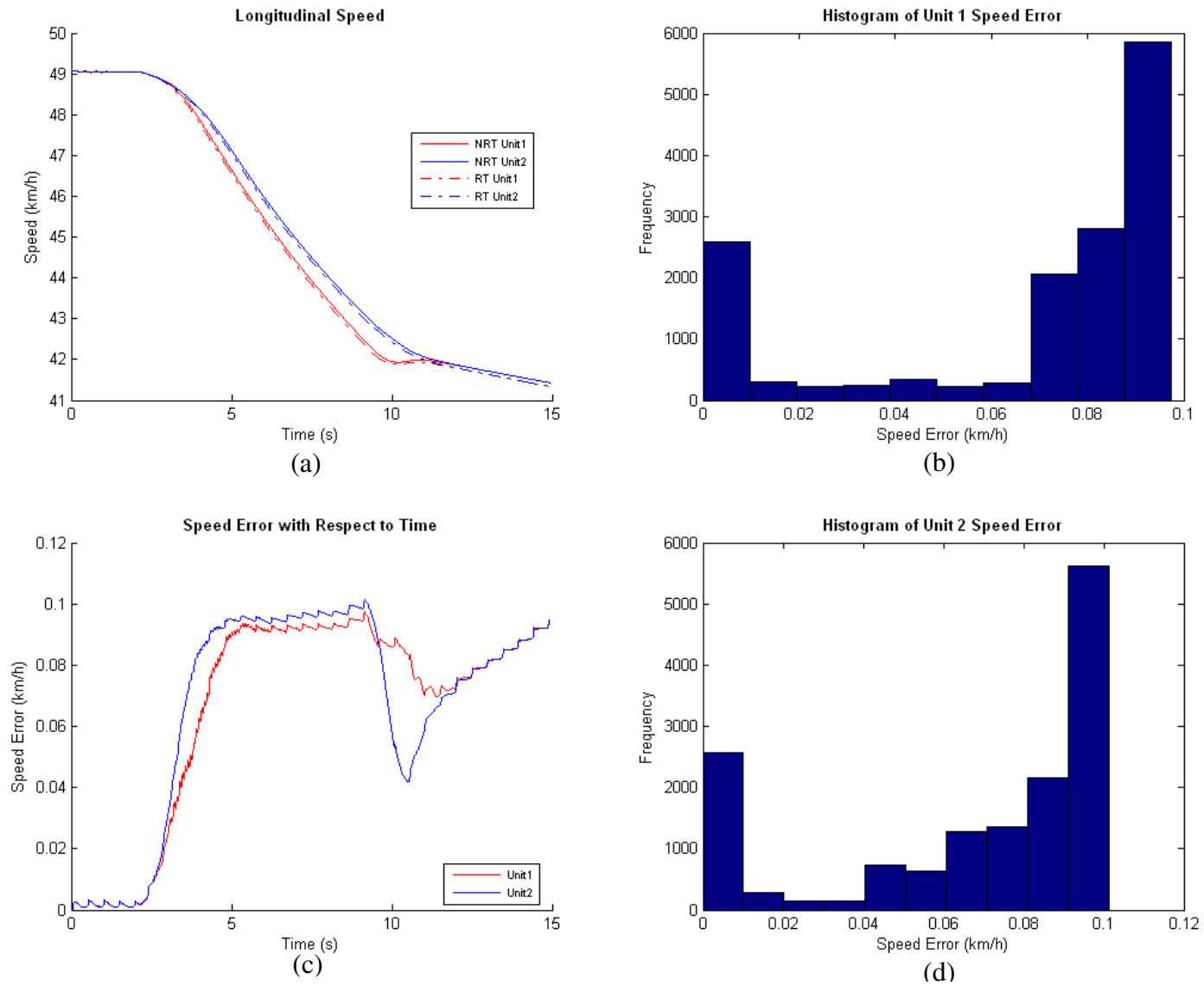


Figure 8: 30.5 mph (49.1 kph) – Plots of velocity and associated error for the rollover scenario

Comparison of Real-time and Non-real-time Results for the 2.2m Center of Gravity

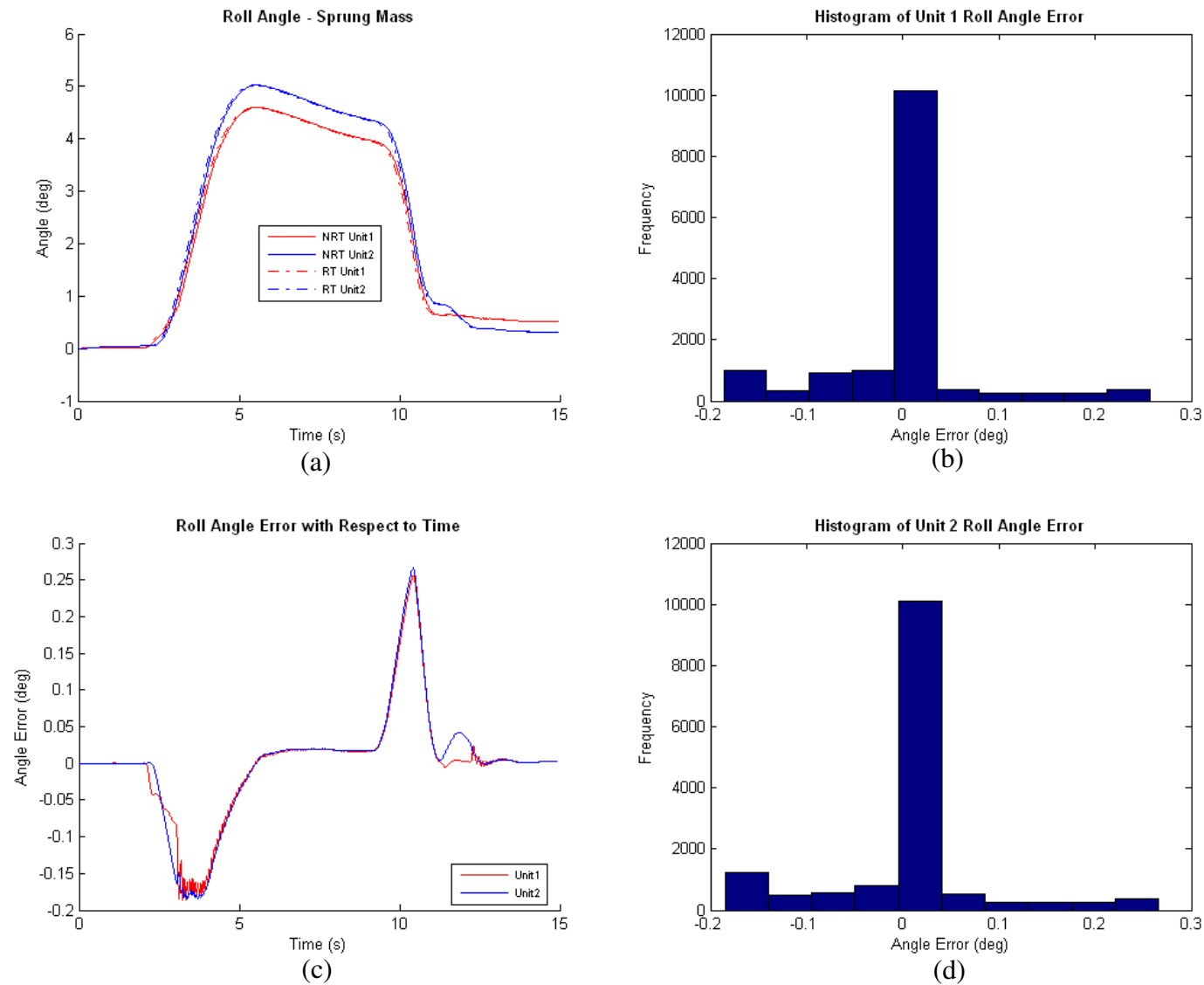


Figure 9: 30.5 mph (49.1 kph) – Plots of roll angle and associated error for the no wheel lift scenario.

Comparison of Real-time and Non-real-time Results for the 2.2m Center of Gravity

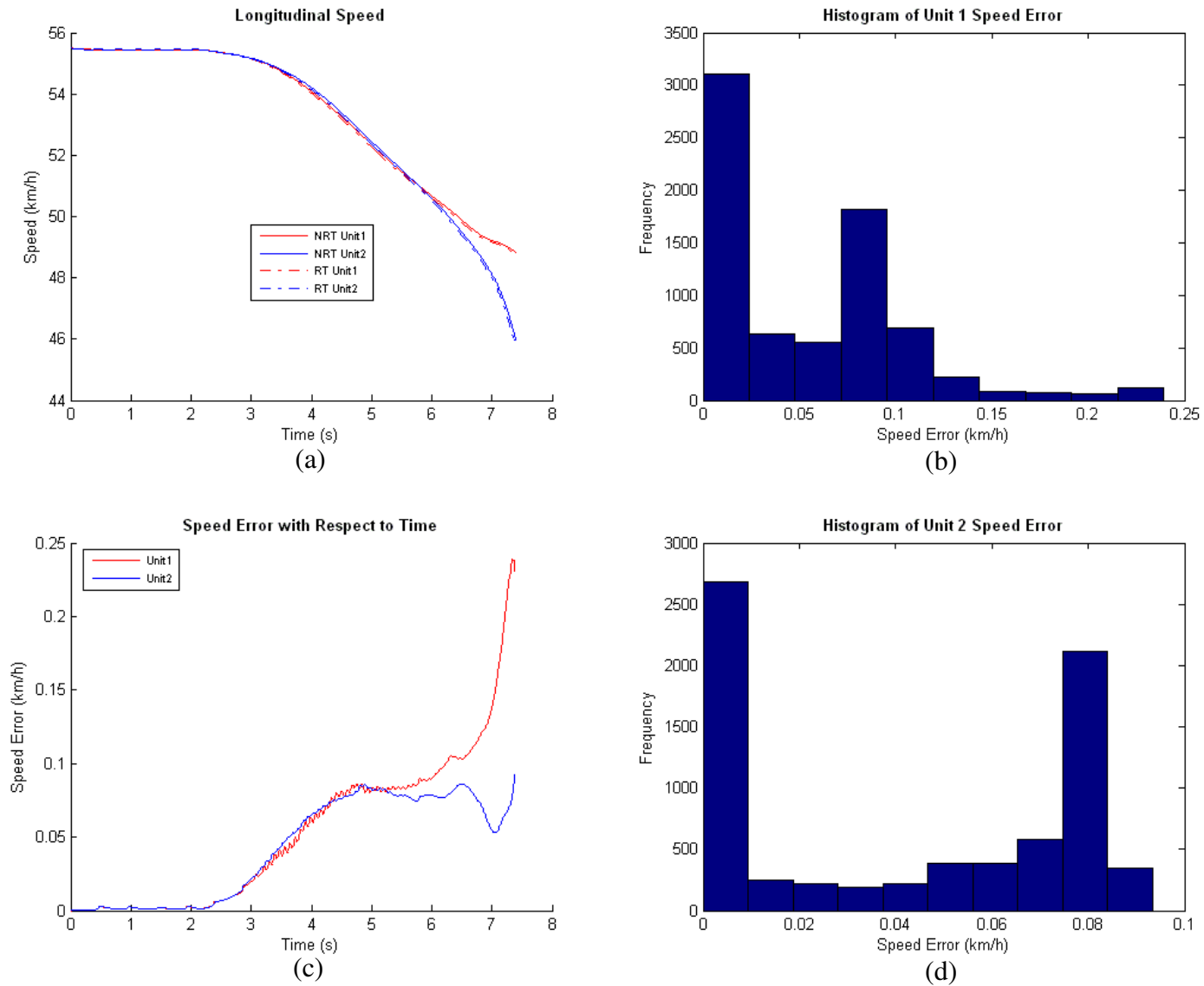


Figure 10: 34.5 mph (55.5 kph) – Plots of velocity and associated error for the rollover scenario.

Comparison of Real-time and Non-real-time Results for the 2.2m Center of Gravity

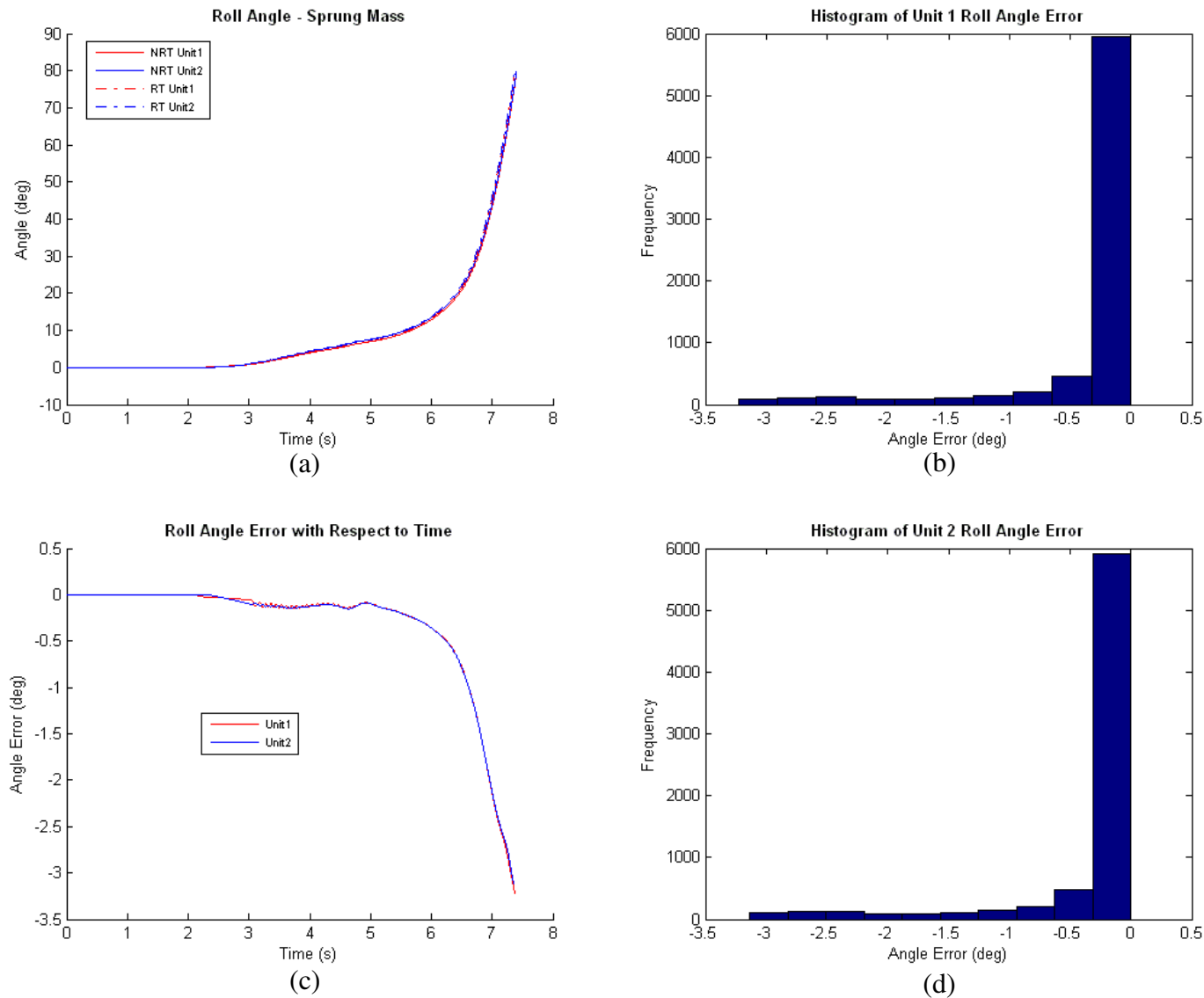


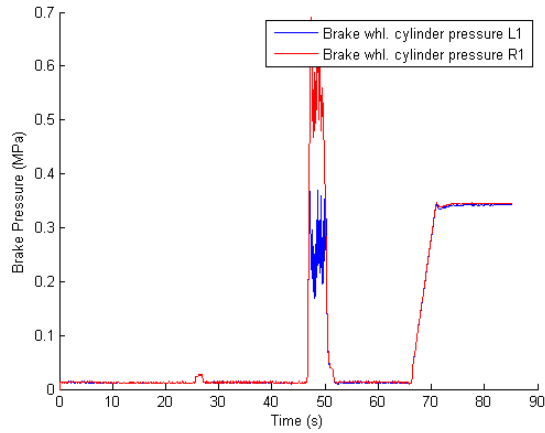
Figure 11: 34.5 mph (55.5 kph) – Plots of roll angle and associated error for the rollover scenario.

Chapter 5: Further Validation of HiL System

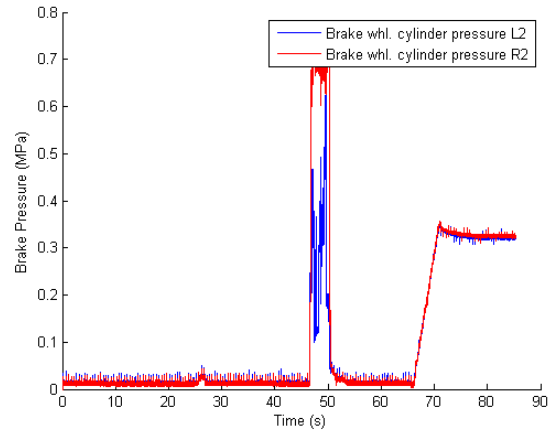
The HiL system went through several iterations of internal validation before it was deemed officially validated through VRTC and NHTSA. The first method of validation was described in the paper written for the Transportation Research Board and will be presented at the 2011 Transportation Research Board Annual Meeting. The second method of validation was performed to verify that the stability program was reacting in the manner expected by the manufacturer.

This was done by evaluating the brake pressures exerted by the stability program when a truck traverses a curve at a speed which activates the system. In the maneuver that activates the ESP, it is expected that the ESP will apply a higher modulated brake pressure to the side of the truck that is on the outside of the turn. For example, in the case of the 199 degree steering maneuver that was required by VRTC and NHTSA, the truck makes a turn to the left. In order to provide the stabilizing moment as discussed in section 2.3, the ESP must apply brakes on the right-hand side of the truck. Plotting the brake pressure over time confirms that this is happening.

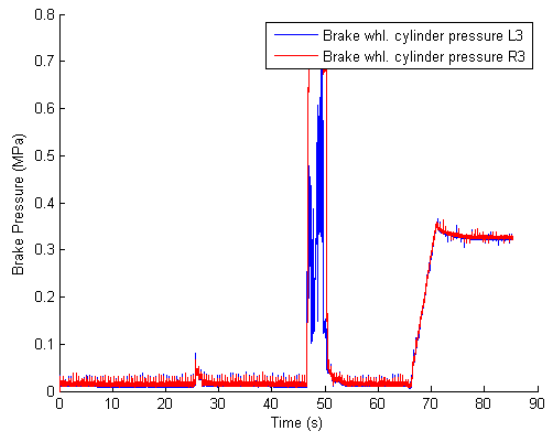
Figure 12 presents the plots of braking pressure over time for the 2.3 center of gravity truck as it completes the 199 degree steering maneuver that was required for the VRTC validation. In this specific scenario, the truck was traveling at 49.1 kph (30.5 mph) which is the speed at which the truck first achieves greater than six degrees of roll. Subfigures (a) through (e) correspond to axles one through five. The brake pressures are the highest on the first three axles where they achieve nearly 0.8 MPa which is the maximum braking pressure. As expected, the brake pressures are higher on the right side of the truck shown in red in Figure 12 compared to the left side which is shown in blue. It is interesting that the last two axles apply nearly the same pressure on both sides of the trailer. The rest of the plots of braking pressure for the various validation simulations are presented in Appendix B.



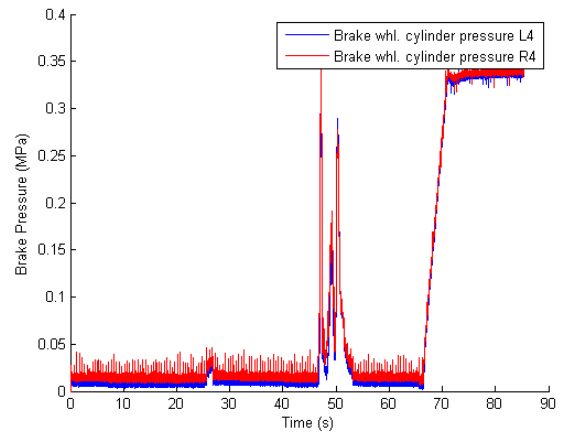
(a) Axle 1



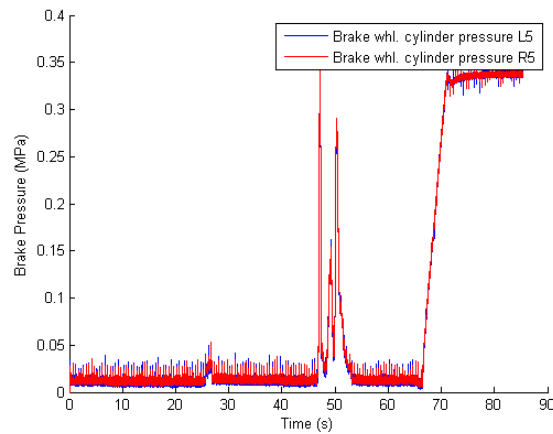
(b) Axle 2



(c) Axle 3



(d) Axle 4



(e) Axle 5

Figure 12: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that surpasses six degrees of roll when traveling around a curve too fast.

Another validation was run to determine whether the ESP was working properly when compared with field tests. The plots in Figure 13: NHTSA and VRTC's field test data with no wheel lift at 58 kph. Figure 13 and Figure 14 were created from the data that VRTC collected from the field tests performed on a Volvo tractor with a Fruehauf box trailer in East Liberty, Ohio. For these tests, the ESP-equipped truck accelerated from a stop to the desired speed then turns the steering wheel to the right at a rate of 175 degrees per second until it gets to 199 degrees. It holds that steering angle for five seconds and then it straightens out at the same rate in which it begun the maneuver. Figure 13 and Figure 14 show some of the variables that are pertinent to this research. The field test results of longitudinal speed, roll angle, longitudinal acceleration and lateral acceleration will be compared with the results from the simulator in order to validate the system.

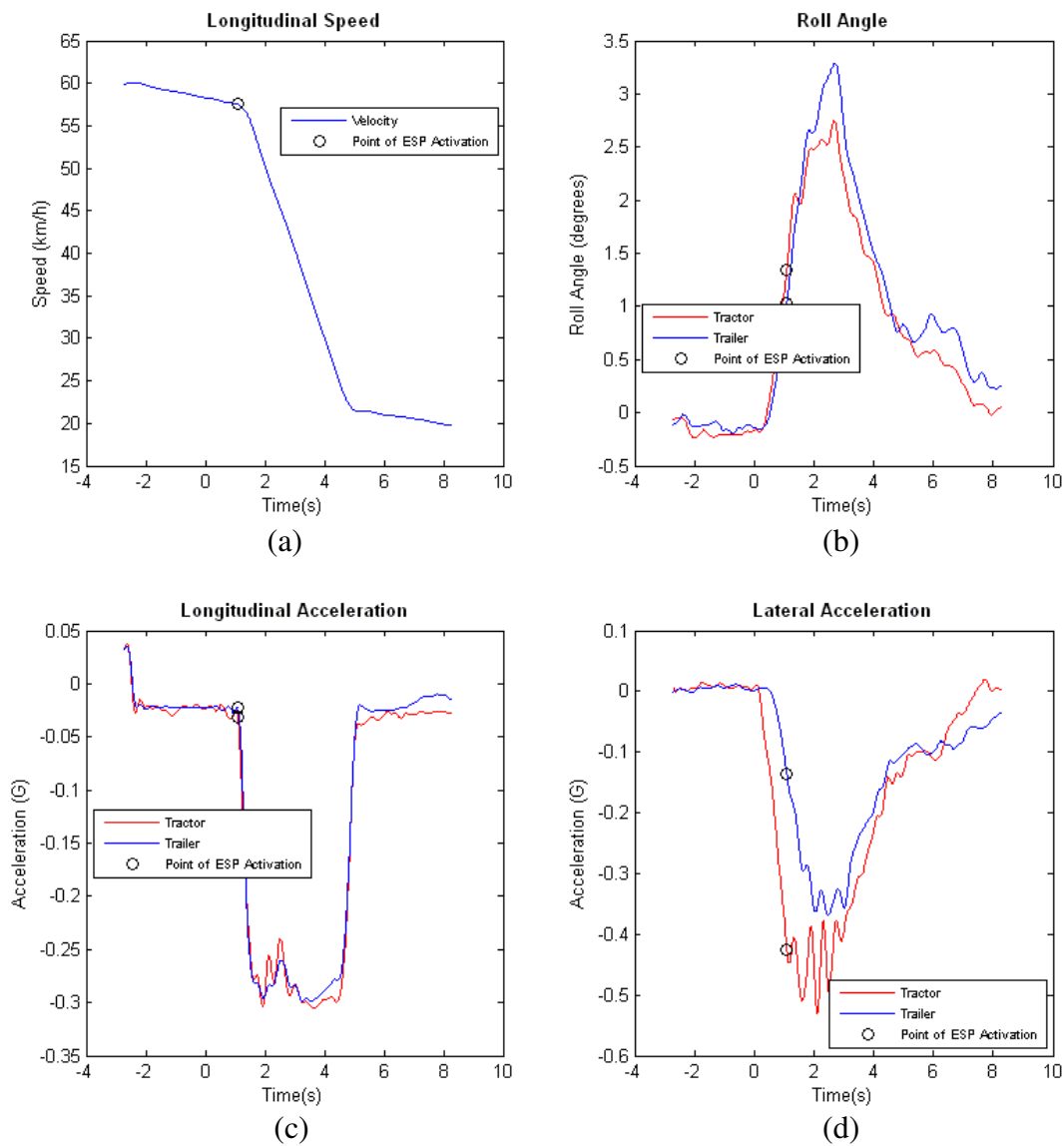


Figure 13: NHTSA and VRTC's field test data with no wheel lift at 58 kph.

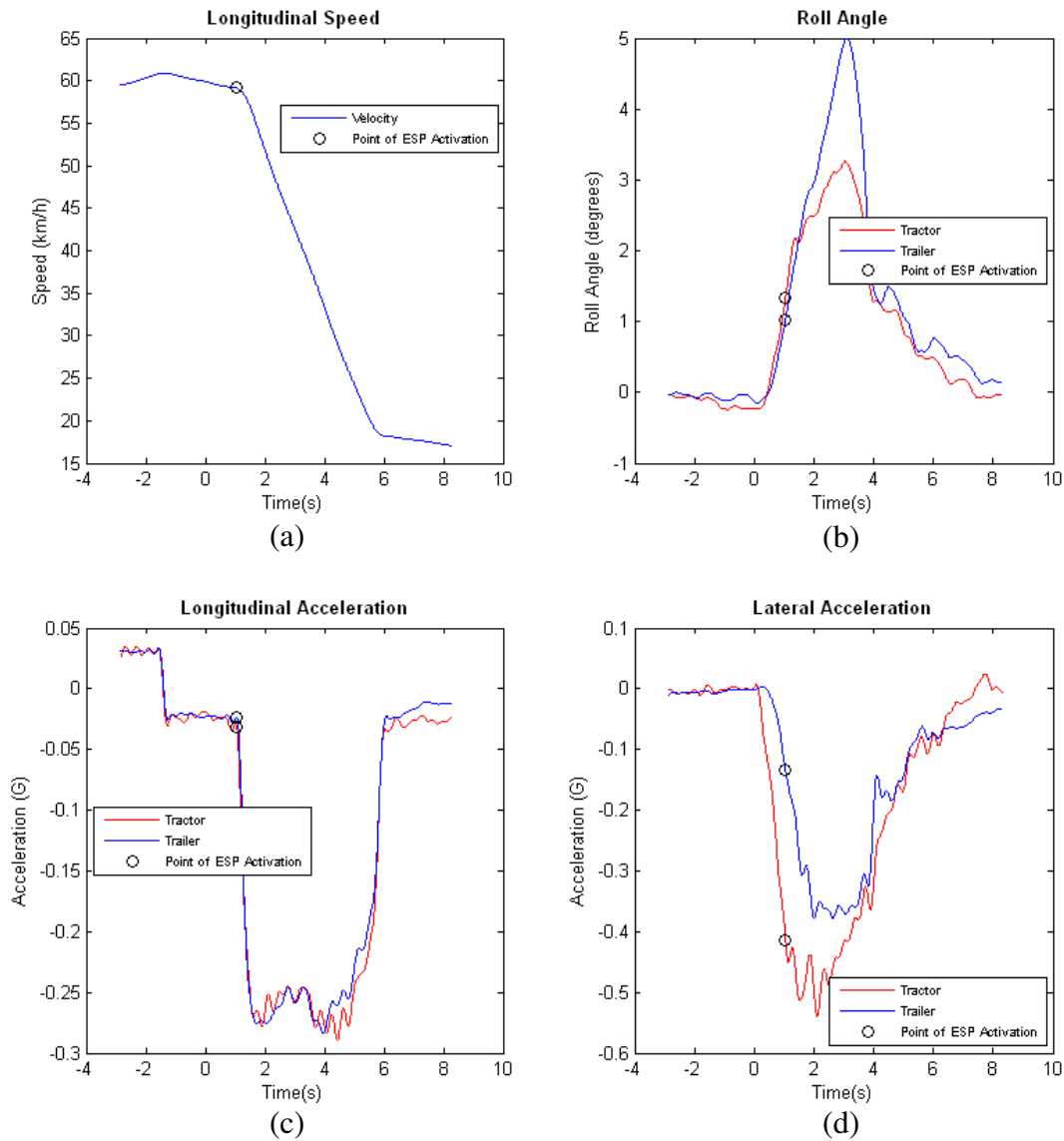


Figure 14: NHTSA and VRTC's field test data with wheel lift at 60 kph.

In these figures, the red line represents the values recorded on the tractor and the blue lines represent the values from the trailer. The ESP begins to intervene at a time of 1.050 seconds as indicated by the black circles on each of the plots. There is a significant drop in speed once the ESP intervenes as shown in the steep slope of subplot (a) and also shown in the large drop in longitudinal acceleration which represents an aggressive deceleration. The ESP consistently intervenes when the lateral acceleration of the tractor exceeds 0.40 G's. In the runs from VRTC, the ESP event lasts for just under five seconds which is almost equal to the amount of time that the vehicle is turning.

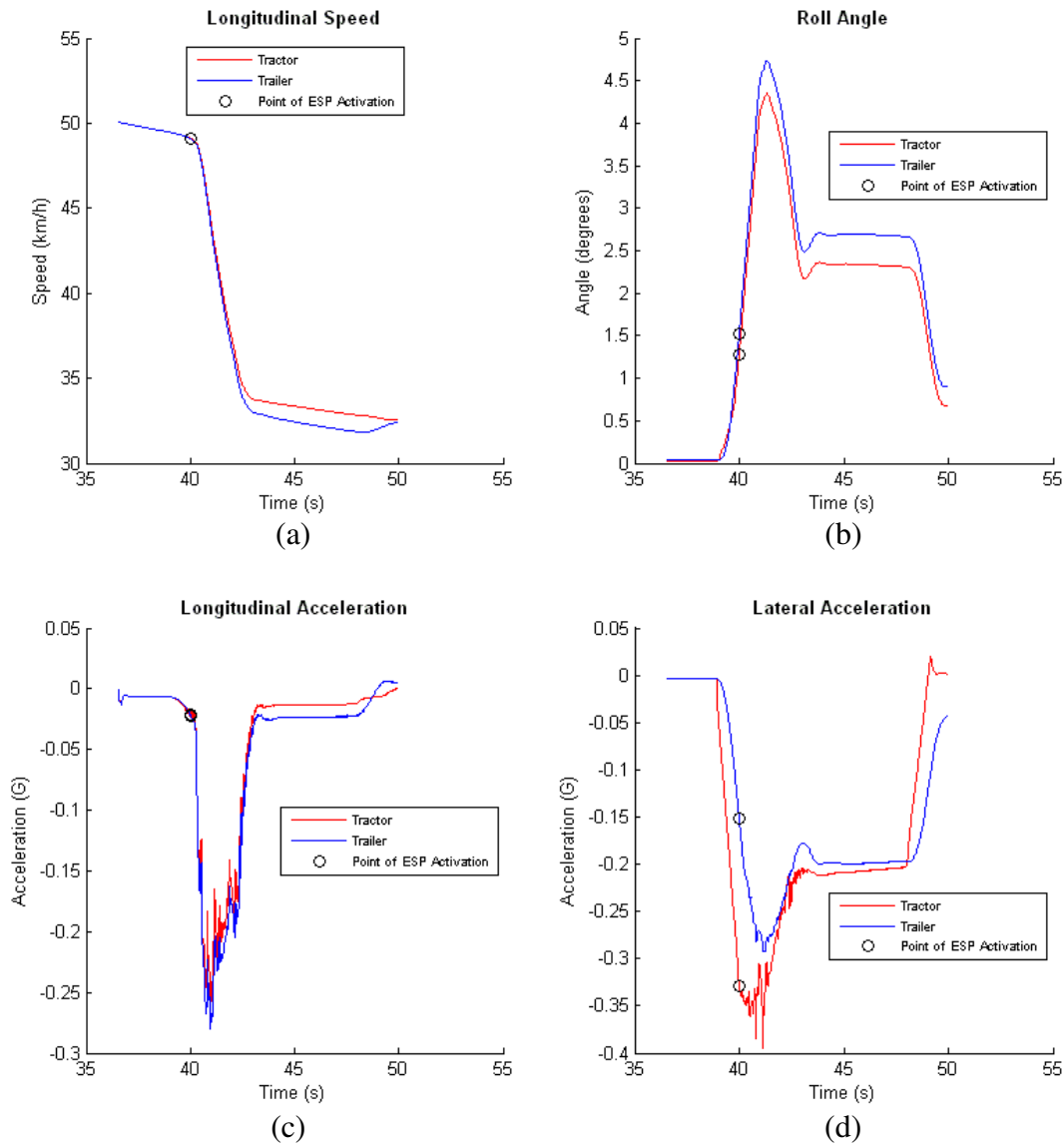


Figure 15: Simulation test data with no wheel lift at 42 kph.

In order to draw meaningful comparisons from the simulator data to the field data the differences between the two types of tests must be acknowledged. It should be noted that the velocities from the field tests were lower than the speeds of the trucks that were run on the simulator. Another difference is that the loads on the trailer were not configured in exactly the same manner. This would have an effect on the roll angle and the lateral acceleration. The lateral acceleration and the decrease in speed once ESP activates is affected by the truck's braking capacity. The simulation model used a braking model that represents S-Cam brakes whereas the Volvo tractor and Fruehauf trailer was equipped with more powerful brakes.

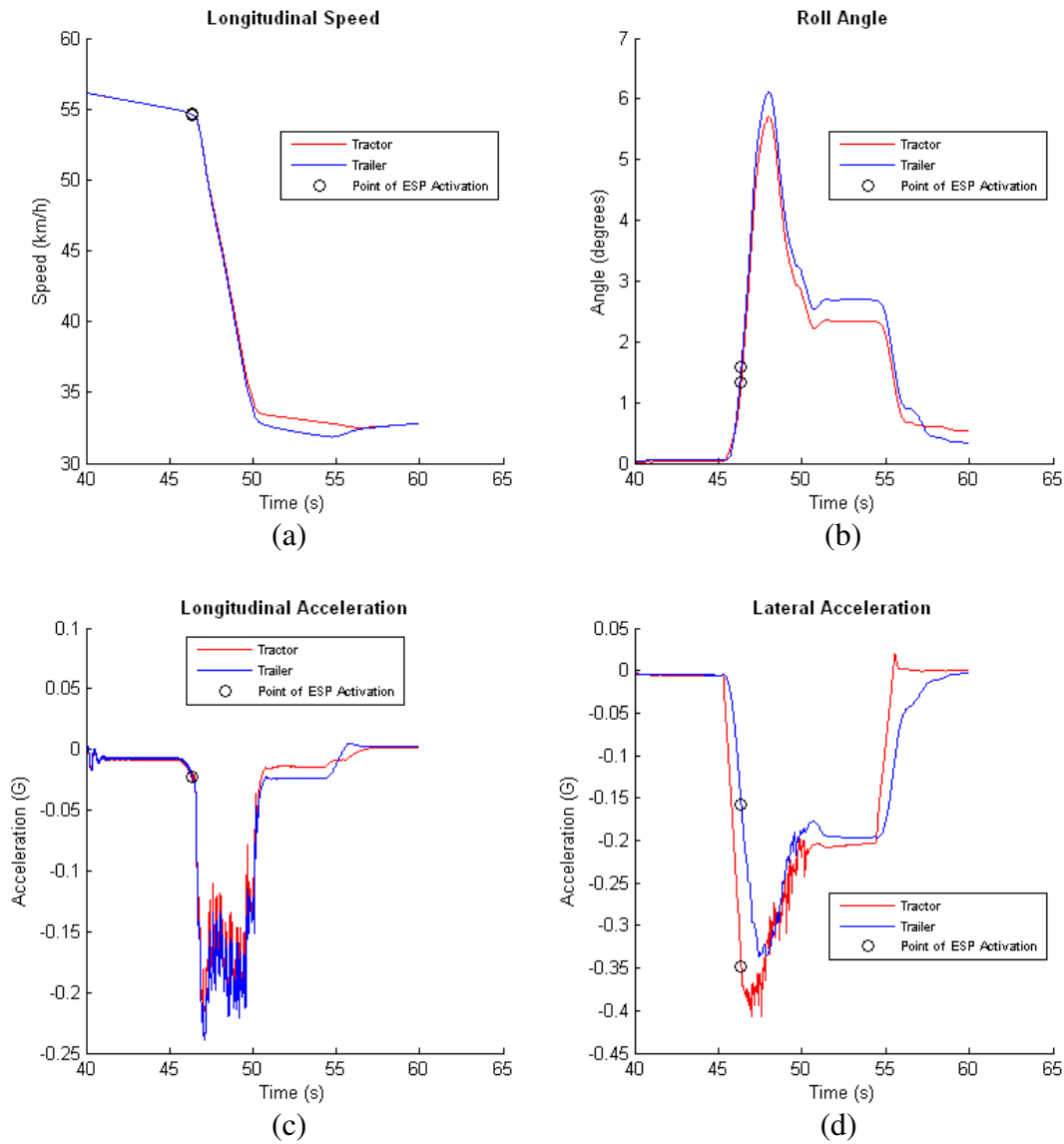


Figure 16: Simulation test data with wheel lift at 44 kph.

Regardless of the differences in models, the ESP still behaves in a predictable manner. The ESP activates at around 0.40 G's of lateral acceleration. In Figure 16, the plot shows less than 0.40 G's of lateral acceleration; however, that could be due to the smoothing function that was used to eliminate the noise in the data from the real-time simulation. The overall shapes of each plot looks similar with comparable peaks and plateaus.

Chapter 6: Simulation Results

This section contains results of the simulations that were run on trucks with center of gravities at 2.0 and 2.3 meters above the ground-level that were traversing curves at high speeds which would typically cause a truck to roll. These center of gravity locations and curve radii were chosen based on the report published by UMTRI as mentioned previously [12]. Three curve radii were modeled: one with a 68 meter radius, one with a 150 meter radius, and one with a 227 meter radius. The first and the last radii were selected to provide a direct comparison to the UMTRI report whereas the 150 meter curve was chosen to be able to draw more conclusive results of the performance of the Bendix electronic stability control system. The results will first be presented for all three radii, then the 68 meter radius curve and the 227 meter radius curve results will be compared with UMTRI's results.

The tables and plots on pages 45 and 46 show the results of our iterative simulations runs. Under the test conditions given in this report, the truck with a low center of gravity (2.0 meters) showed that the truck can enter a curve approximately 5.5 kph faster than the same truck without ESP. For the truck with a higher center of gravity (2.3 meters), the ESP-equipped truck can enter a curve at about 3.5 kph faster than if it was not equipped with ESP.

Table 9: Critical speeds (kph) for the truck model with a center of gravity at 2.0 meters above ground level

2.0 meter Center of Gravity Truck				
		Lowest Speed that Engages ESP	Truck Achieves > 6 deg Roll	Truck Rolls Over
68 m Curve Radius	Without ESP	---	61.5	65
	With ESP	49	66	70
150 m Curve Radius	Without ESP	---	88	93
	With ESP	70	90.5	99
227 m Curve Radius	Without ESP	---	108.5	113.5
	With ESP	86	109.8	119

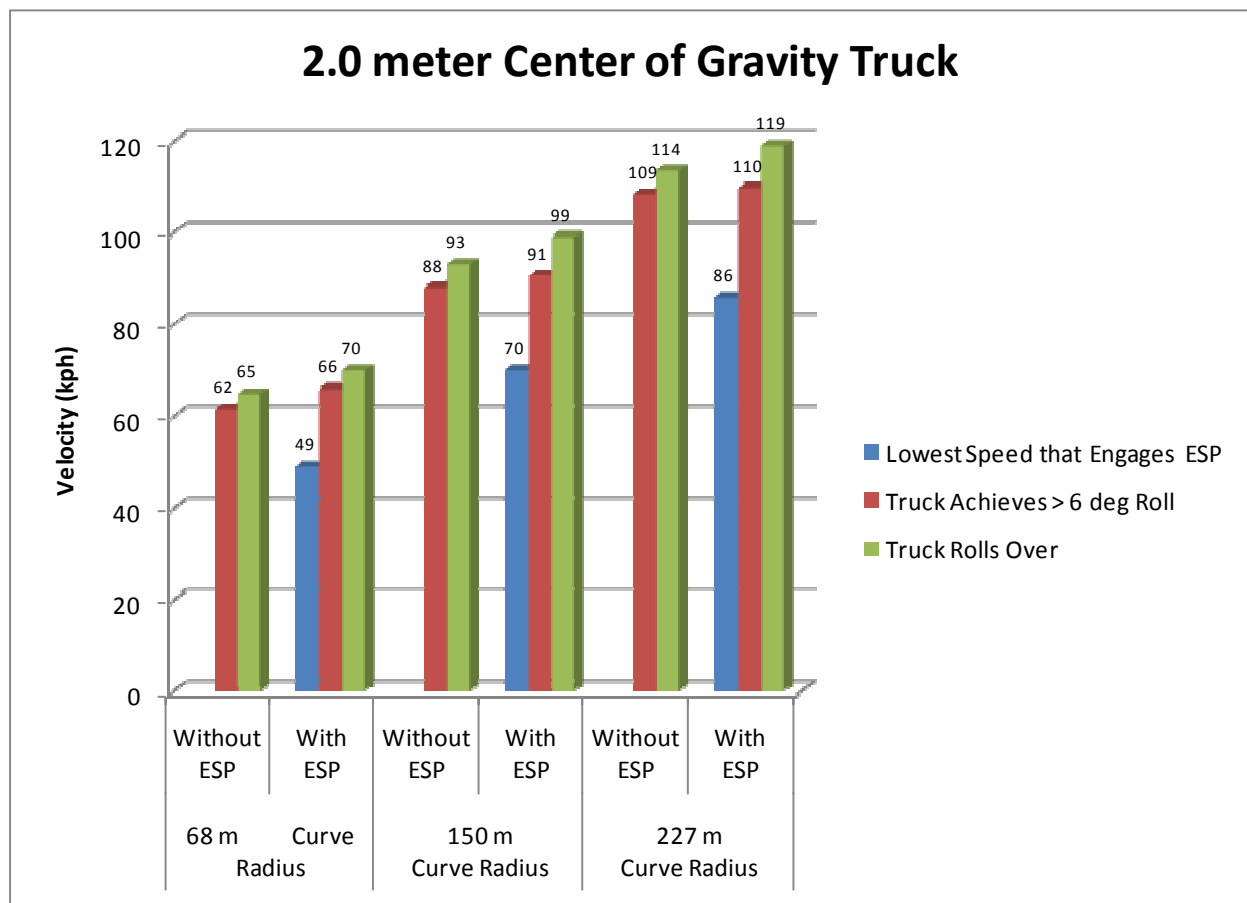


Figure 17: Plot of the lowest critical speeds that caused each of the following events for the truck model with a center of gravity located at 2.0 meters: initial ESP activation, at least six degrees of roll, and complete physical rollover.

Table 10: Critical speeds (kph) for the truck model with a center of gravity at 2.3 meters above ground level

2.3 meter Center of Gravity Truck				
		Lowest Speed that Engages ESP	Truck Achieves > 6 deg Roll	Truck Rolls Over
68 m Curve Radius	Without ESP	---	57	59
	With ESP	48.5	61	63
150 m Curve Radius	Without ESP	---	82	83.5
	With ESP	68.5	83.5	87
227 m Curve Radius	Without ESP	---	99.5	102
	With ESP	84.5	102	105

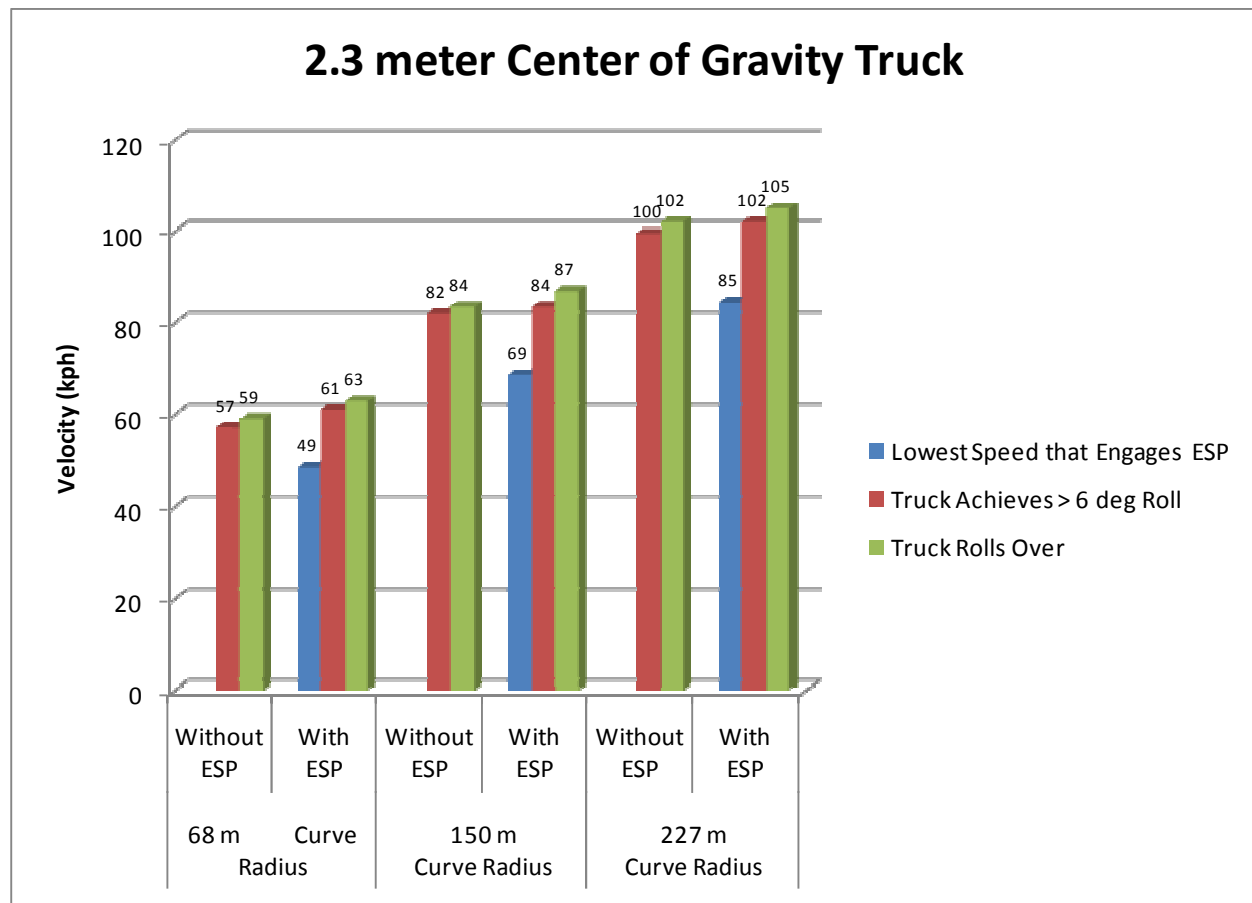


Figure 18: Plot of the lowest critical speeds that caused each of the following events for the truck model with a center of gravity located at 2.3 meters: initial ESP activation, at least six degrees of roll, and complete physical rollover.

UMTRI only presented their results for when their truck exceeded six degrees of roll, but the Meritor-WABCO system had two stability systems that were being tested in addition to the base case where the truck is only equipped with anti-lock brakes.

Table 11: Critical speeds (kph) for when the truck in UMTRI's study achieved greater than six degrees of roll with Meritor-WABCO system [12]

Critical Speeds (kph)		68 m Curve		227 m Curve	
		2.0m C of G	2.3m C of G	2.0m C of G	2.3m C of G
	ABS	62.8	57.9	109.4	101.4
	RSC	70.8	66	112.7	106.2
	ESC	80.5	70.8	120.7	106.2

Their results are similar to ours in showing that the trucks with the lower center of gravity locations are more affected by the stability systems than the higher center of gravity trucks; however, the magnitude of the difference in critical speeds from the ABS-only case to the ESC case is greater in the UMTRI model compared to what we found.

Table 12: Comparison of UMTRI's findings from their study on the Meritor-WABCO system (speeds listed in kph)

Difference in Critical Speeds (kph)		68 m Curve				227 m Curve			
		2.0m C of G		2.3m C of G		2.0m C of G		2.3m C of G	
		Absolute Error	Relative Error	Absolute Error	Relative Error	Absolute Error	Relative Error	Absolute Error	Relative Error
	ABS	1.3	2.1%	0.9	1.6%	0.9	0.8%	1.9	1.9%
	ESC	14.5	18.0%	9.8	13.8%	10.95	9.1%	4.2	4.0%

One main difference in the simulations that UMTRI performed is the model used for the truck brakes. They used propriety braking information from the manufacturer which was more powerful than the default braking model that we used from TruckSim. This default braking model is not as aggressive as the brakes that are usually installed in trucks during the twenty-first century. Additionally, UMTRI's procedure required the truck to maintain the target speed until pressure is applied to the brakes by the RSC or ESC system and the throttle position would go to zero. In discussions with VRTC and NHTSA, this latter difference was determined to be negligible since the change in speed from the short coast down experienced by our truck was less than 0.5 kph over the first four seconds of the curve.

Chapter 7: Conclusions

7.1 Summary

This research included building a valid hardware-in-the-loop (HiL) system to model and test the Bendix Electronic Stability Program (ESP) with real-time simulations. To build a valid HiL system, there are several key steps to complete. First, determine which components are not able to be modeled accurately through the simulation program. In this research, it was necessary to have a physical pneumatic braking system in order to have a correct measure of the air-line lag time, an ESP module with full sensor input and communication, and a partial vehicle electrical system to determine how a truck performs when the electronic stability control is utilized. Next, a computer program should be written to communicate the information generated by the simulation software, TruckSim, to the hardware. It is very important to be meticulous during this step because various components of the engine system require the messages to be sent in different formats and frequencies. If the messages are not sent correctly, the system will not yield accurate results. Once the signals to and from the modeling software were deemed to be correct, the next task is to ensure that the stability system is working properly. Since the manufactures of the stability systems typically keep their detection algorithms proprietary, it can be difficult to resolve what signals needed to be sent to the ESP and in what format these signals should be presented. After the system has been built and validated, it is important to run a simple maneuver each day to verify that all of the hardware components are still reacting correctly. This maneuver can be a simple straight-line braking maneuver that verifies the time it takes for the truck to reach the desired speed, the time it takes to decelerate to a complete stop, and the stopping distance of the truck. Additionally, wheel speeds and brake pressures should be checked to ensure that each of the brakes is working properly.

In building the HiL system, we discovered the criticality of manufacturer cooperation. When the manufacturer is not willing to communicate and assist in the wiring and programming of the HiL, the task will become much more challenging. It is also helpful to communicate with other organizations that have experience in building and debugging an HiL system. Debugging the system proved to be an extremely iterative process. During our building and validation stages, we would discover one problem that needed to be resolved and once that specific problem was fixed we would find additional errors that were masked by the initial problem. This appears to be a common occurrence among HiL systems. Once everything seems to be working properly, it is important to run several different types of validation runs to put the truck through different scenarios, then to verify that the truck performed as expected. After the system is completely validated, the data can be collected for the intended research.

In the research presented in this thesis, simulations were run on the HiL with trucks that have a center of gravity located at 2.0 meters and 2.3 meters above the ground, and along spiral curves that have radii of 68 meters, 150 meters, and 227 meters, respectively. The electronic stability system is found to activate at speeds lower than those required to result in a rollover for

non-ESP-equipped vehicles. For the scenarios and limitations presented, the ESP is found to provide more protection for trucks with a low center of gravity location, relative to those with a high center of gravity. Since the research presented here uses a braking model that is less powerful than what is typically seen on large trucks, it is anticipated that a braking model that uses greater torque capacities will result in a higher allowable curve entrance velocity when comparing the rollover potential of ESP-equipped vehicles in comparison to their non-ESP-equipped counterparts. With these adjustments, the results from this study are likely to be more comparable the results found by the University of Michigan Transportation Institute's study on the Meritor-WABCO electronic stability system [12].

The analysis in this thesis is limited to five-axle tractor-trailers, and does not consider other classes of heavy vehicles such as tankers, military vehicles, or buses. Additionally, this research does not consider the analysis or prevention of either tripped rollovers, or those rollovers caused by a sudden driver input.

7.2 Future Research Activities

With the development of the hardware-in-the-loop testbed, other truck configurations, brake types, and geometric configurations may be included in future research to more fully assess the effectiveness of implementing an electronic stability system. More specifically, future research may include additional curve radii, environmental conditions and more variation in the center of gravity and loading configurations. There exists a need for a database containing the distribution of curve radii within the United States. With this database, the number of preventable rollovers could be estimated based on the correlation between curve radii and occurrence of rollovers. These findings would be of special interest to the owners of truck fleets who are interested in determining how many accidents, and thus how much money, these systems would save them. Finally, further research may determine system benefits with respect to a more complete set of crash costs which include personal injury, physical vehicle damage, clean-up time, traffic delay and more.

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Appendix A: Formulas for the Calculation of the Curve Coordinates in Matlab

Equation 8

$$v = \sqrt{r * 15 * (f_s + e)}$$

Where v is the intended velocity of the vehicle in the curve (mph)

$(f_s + e)$ is the coefficient of side friction plus the superelevation (this term was assumed to be equal to 0.40)

Equation 9

$$L = \frac{3.15 * v^2}{r * c}$$

Where L is the length of the curve (ft)

r is the radius of the curve (ft)

c is the rate of centripetal acceleration (assumed to be 1.3 ft/s^3)

The angle of the spiral arc is given by:

Equation 10

$$\theta = \frac{L}{2 * r} * \frac{180}{\pi}$$

Where θ is given in degrees

Equation 11

$$\theta_s = \left(\frac{L_s}{L}\right)^2 * \theta$$

Where θ_s is the angle of the spiral based on the small step increments of L_s

The x and y coordinates (in feet) for the given angles of θ_s are given by:

Equation 12

$$x_s = \frac{L_s}{100} * (100 - 0.0030462 * \theta_s^2)$$

Equation 13

$$y_s = -\frac{L_s}{100} * 0.58178 * \theta_s - 0.000012659 * \theta_s^3$$

From there, the last coordinate of the spiral curve becomes the first coordinate for the circular part of the curve that is fitted according to the required radius.

Appendix B: Plots of HiL Brake Pressures for Validation

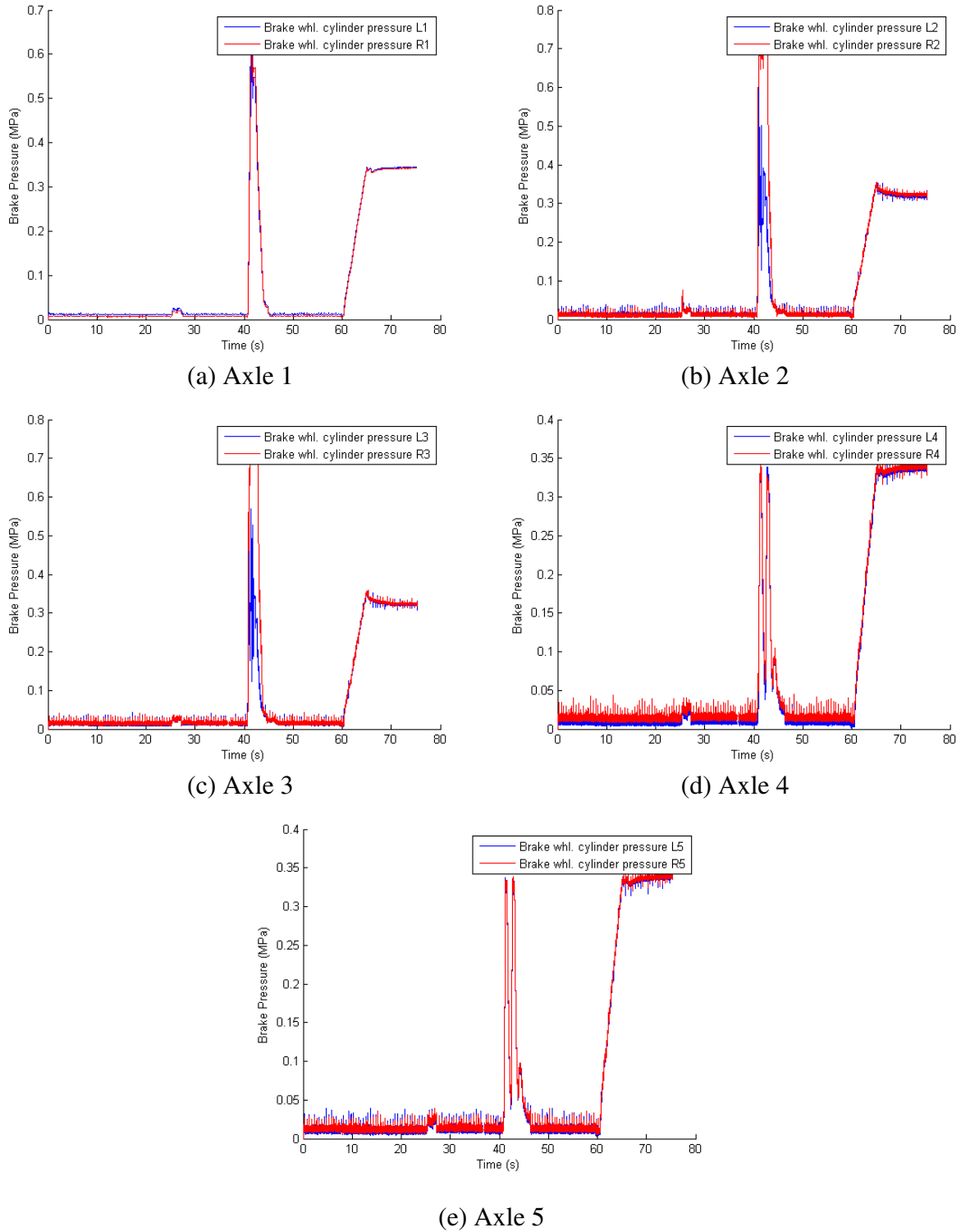
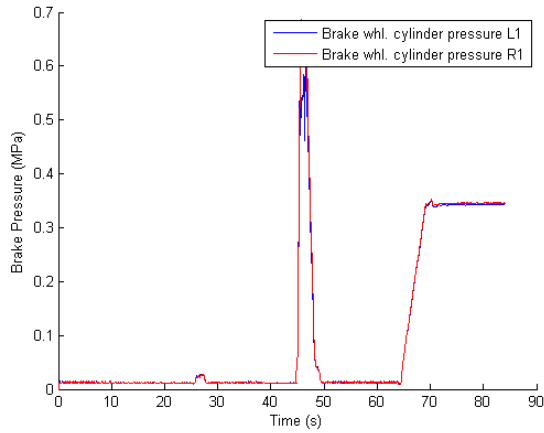
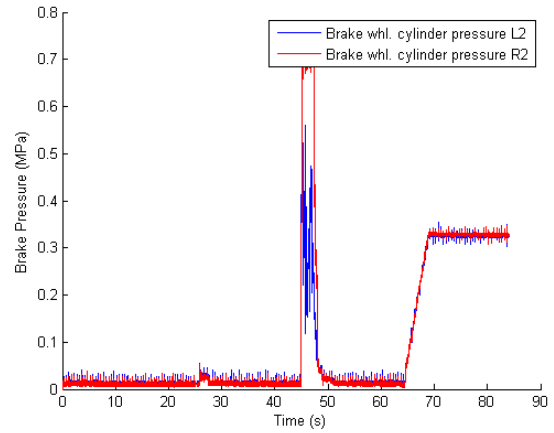


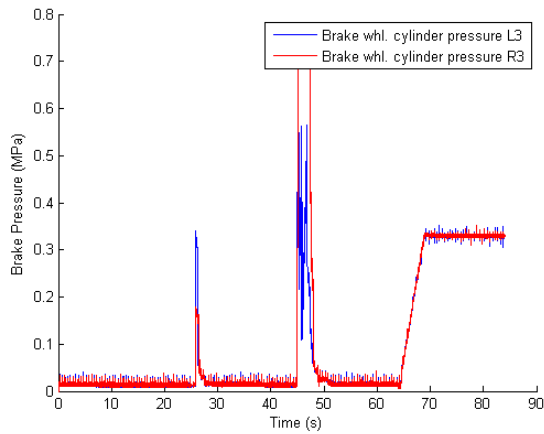
Figure 19: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that does not experience any wheel lift when traveling around a curve too fast.



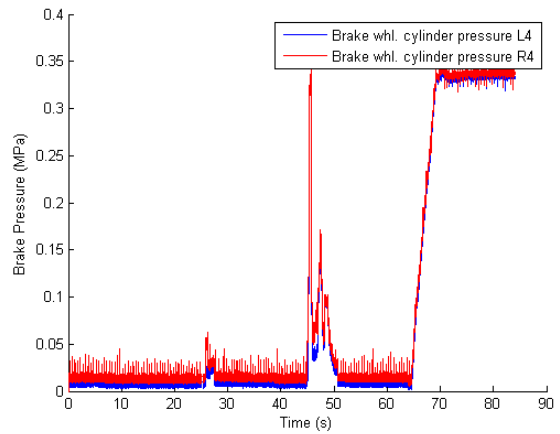
(a) Axle 1



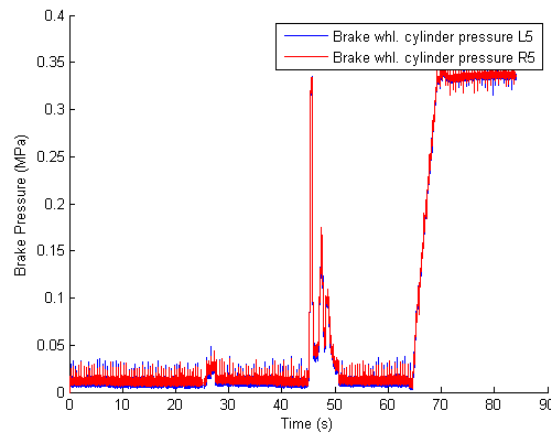
(b) Axle 2



(c) Axle 3

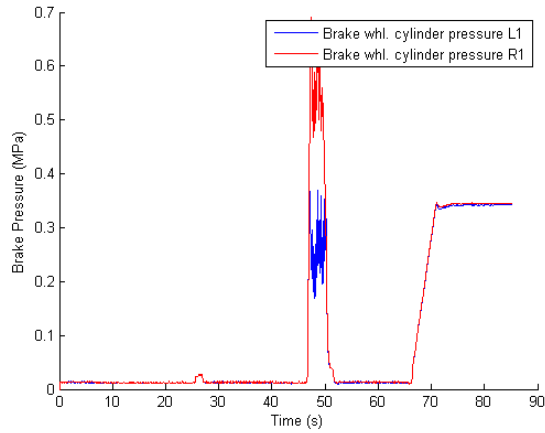


(d) Axle 4

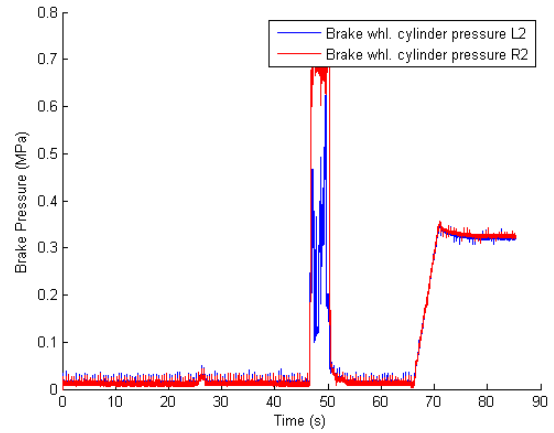


(e) Axle 5

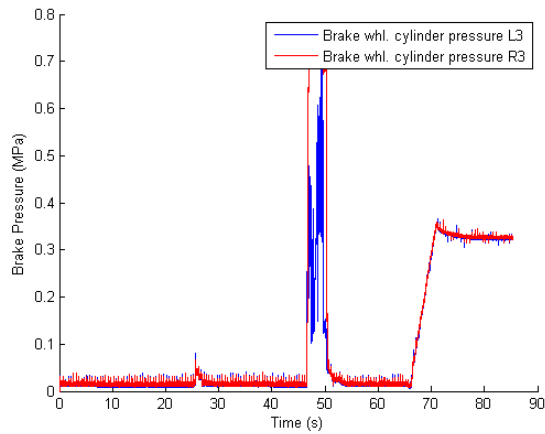
Figure 20: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that experiences single wheel lift while traveling around a curve too fast.



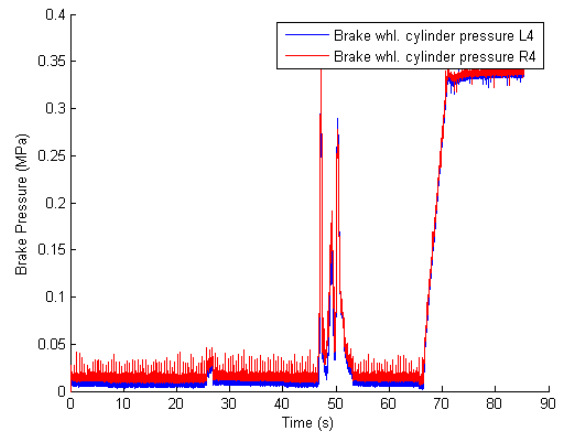
(a) Axle 1



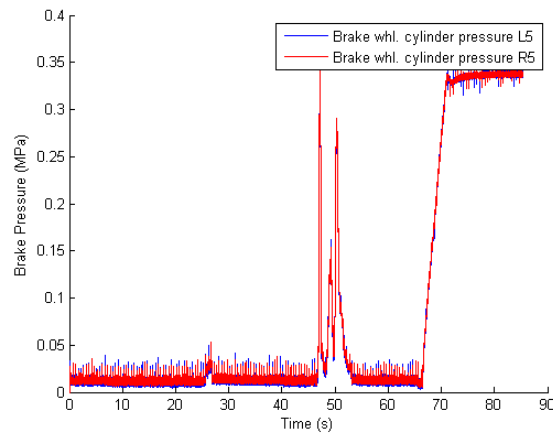
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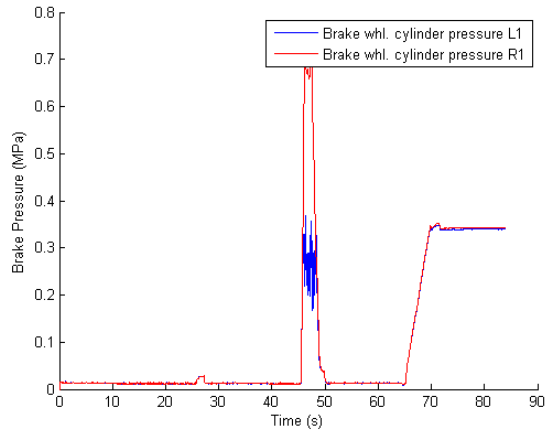


(d) Axle 4

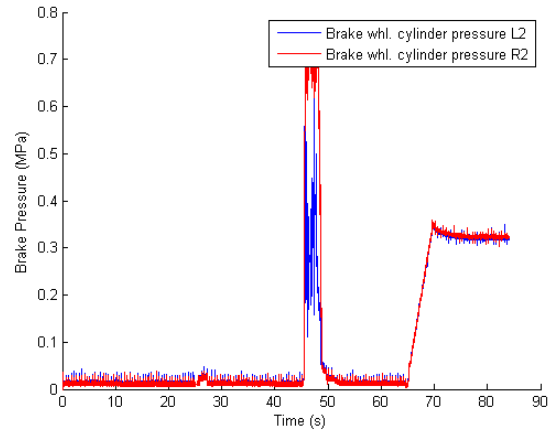


(e) Axle 5

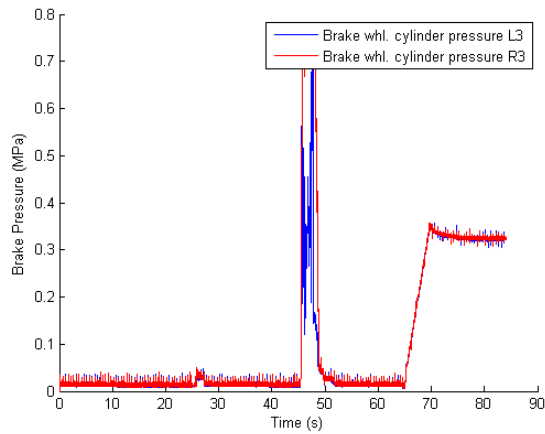
Figure 21: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that surpasses six degrees of roll when traveling around a curve too fast. (Previously shown as Figure 12)



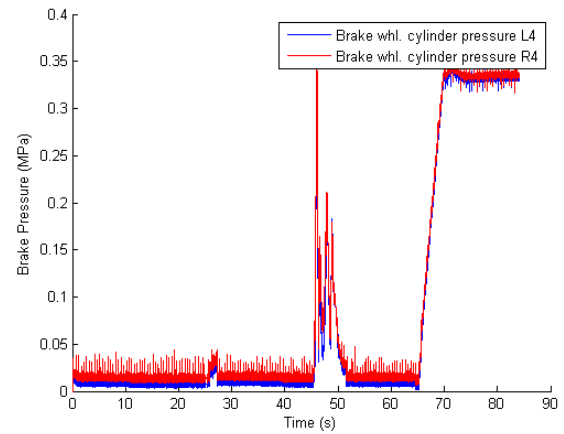
(a) Axle 1



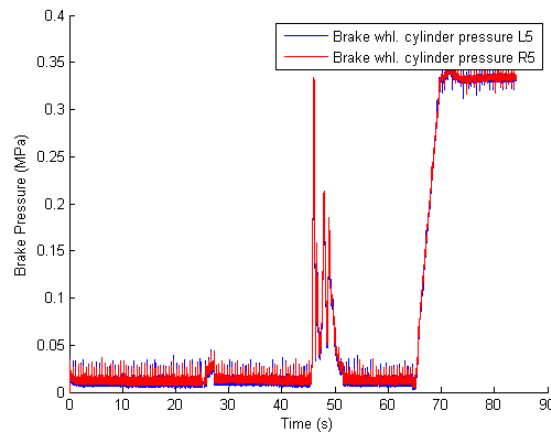
(b) Axle 2



(c) Axle 3

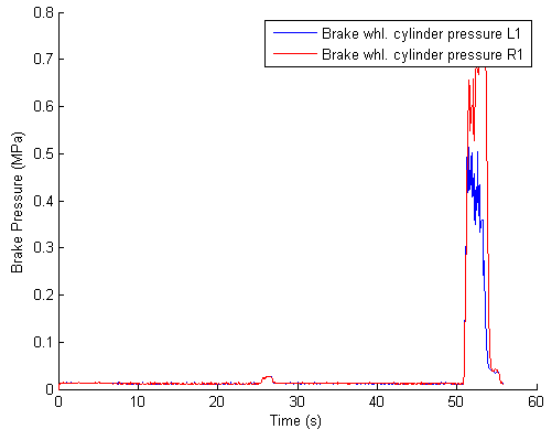


(d) Axle 4

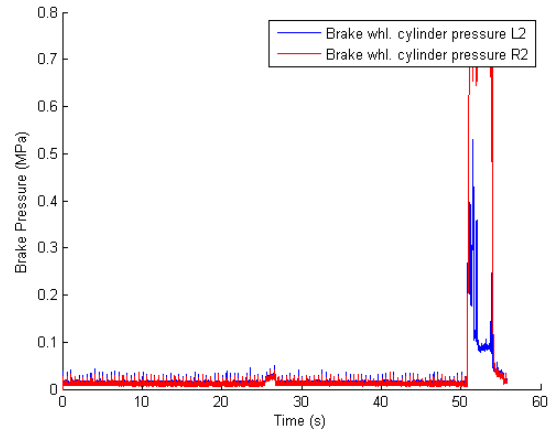


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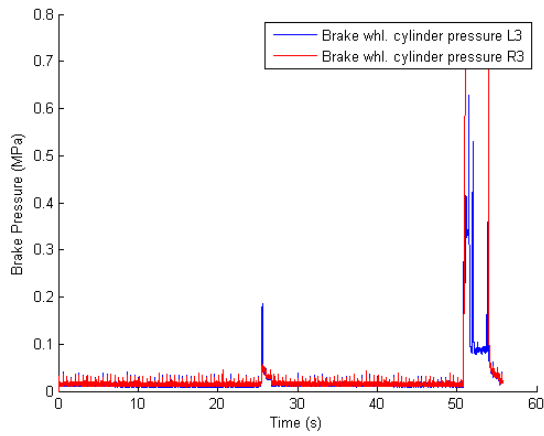
Figure 22: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that experiences multiple wheel lift when traveling around a curve too fast.



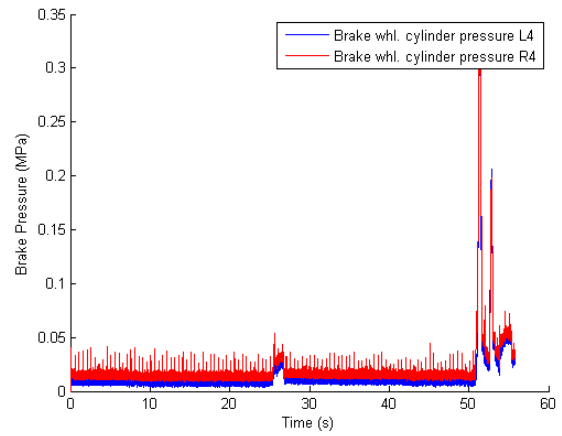
(a) Axle 1



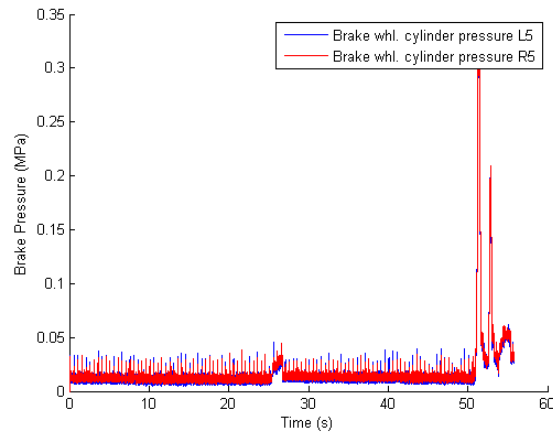
(b) Axle 2



(c) Axle 3



(d) Axle 4



(e) Axle 5

Figure 23: Plots of brake pressure over time for a truck with a center of gravity located at 2.3 meters that rolls over when traveling around a curve too fast.

Appendix C: Copyright Documentation

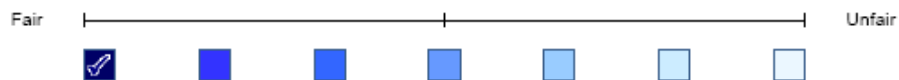
Fair Use Evaluation Documentation

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<http://librarycopyright.net/fairuse/>

Name:	Kelly Donoughe
Job Title:	Graduate Research Assistant
Institution:	Virginia Tech
Title of Work Used:	Safety Benefits of Stability Control Systems for Tractor-Semitrailers
Copyright Holder:	John Woodrooffe, Daniel Blower, Timothy Gordon, Paul E. Green, Brad Liu, Peter Sweatman
Publication Status:	Published
Publisher:	U.S. Department of Transportation, National Highway Traffic Safety Administration
Place of Publication:	Washington, DC
Publication Year:	2009
Description of Work:	160 page report authored by several people at the University of Michigan Transportation Research Institute to describe their findings about the benefits of a stability control system for tractor-semitrailers. This report was passed on to us by our sponsoring agency.
Date of Evaluation:	December 12, 2010
Date of Intended Use:	December 12, 2010

Describe the **Purpose** and Character of Your Intended Use:

The use of this diagram is transformative because I am using a previous truck model to build and test a new hardware-in-the-loop system that will test a different stability system. These results are then directly compared to the results that were found from the University of Michigan's study which utilized the same truck model. Additionally, it is socially beneficial because it provides a basis for comparing two different stability systems with the same initial conditions.



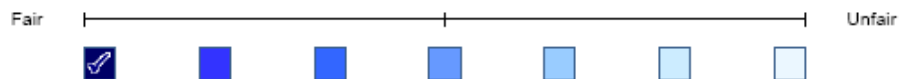
Describe the **Nature** of Your Intended Use:

This diagram was previously published in this report from the University of Michigan. It is a basic diagram of the dimensions of the truck that was used in the research which is entirely based in facts. This diagram was not created or marketed for the purpose in which I am using it.



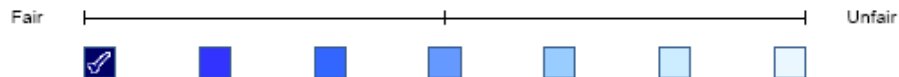
Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

Figure 20 in the University of Michigan report was the only figured used in my research. It only contributes to a portion of the research because we created all of the other components of the model and hardware-in-the-loop system.



Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

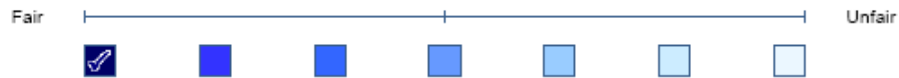
The work is not under commercial exploitation. By using this diagram, we were able to draw direct comparisons to the results that the University of Michigan. Presenting this daigram in my research means that others can conduct the same simulations and effectively further the field of research. The diagram is from a legal copy of the work and it was properly sited in my research.



The Average **"Fairness Level,"** Based on Your Rating of Each of the 4

Factors, Is:

[\[see tool disclaimer for important clarifying information\]:](#)



Based on the information and justification I have provided above, I, Kelly Donoughe, am asserting this use is **FAIR** under Section 107 of the U.S. Copyright Code.

Signature: Kelly M. Donoughe

Date of Signature: 12/12/2010

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