IMPLEMENTATION OF STABILITY CONTROL FOR TRACTOR-TRAILERS USING THE NATIONAL ADVANCED DRIVING SIMULATOR

Alrik L. Svenson
Paul A. Grygier
National Highway Traffic Safety Administration

M. Kamel Salaani
Transportation Research Center, Inc.

Gary J. Heydinger
The Ohio State University

Timothy Brown
Chris Schwarz
National Advanced Driving Simulator
United States of America

Paper number 09-0190

ABSTRACT

Truck manufacturers are introducing Roll Stability Control (RSC) and Electronic Stability Control (ESC) systems on heavy trucks including tractor-trailer type vehicles. These systems are designed to assist a driver to avoid rollovers, and in the case of ESC, yaw instability in tractor-trailers. This paper reports on the implementation of stability control systems on the National Advanced Driving Simulator (NADS) for studying their effectiveness in mitigating tractor-trailer directional loss of control and rollover instability. Five driving scenarios were modeled to closely correspond to severe real-world driving situations. These included exit ramps, decreasing radius curves, and avoidance maneuvers. These were modeled using dry pavement and a snow-covered road surface. The simulator model was validated with actual test track data. This research provides a means to obtain simulator test data on drivers behavior in a tractor-trailer equipped with RSC and ESC during severe driving maneuvers which is new in this field of study. This paper describes the implementation of stability control systems on the NADS and validation of the NADS stability control model by NHTSA. Also, a brief overview of the experimental procedures and the designed driving scenarios used in the NADS study are given. Results of the validation indicate that the simulator study should provide data similar to what would be expected in actual vehicles, but due to limitations in the current NADS truck model it may not be possible to make direct comparisons of speeds achieved in maneuvers with an actual truck on a test track.

INTRODUCTION

Heavy trucks (trucks with a gross vehicle weight greater than 10,000 pounds) have long been the dominant mode of freight transport in North America, carrying an estimated 62 percent ($534 billion) of the total value of freight in 2006 and accounting for most of the growth in the value of North American freight between 1996 and 2006 [1]. Accordingly, the trucking industry has experienced significant growth, with the number of registered heavy trucks increasing by 26 percent from 1995 to 2005, and the miles traveled by heavy trucks increasing by 25 percent over the same time period [2].

The unique characteristics of heavy trucks – their size, weight distribution, articulation, and varying types of freight carried – make them particularly susceptible to single-vehicle crashes due to rollover or directional loss of control, such as jackknife. In their analysis of fatal heavy truck crash statistics, Moonesinghe et al. [3] found that a posted speed limit of 55 mph or higher, poor road conditions due to weather, and road curvature significantly increase the chance for rollover and jackknife, yet there is a

converse relationship between harmful events and the size and weight of the truck and trailer. Their analysis shows that the heavier the truck and cargo, the more prone the truck is to rollover, but that the increased weight serves as a deterrent for jackknife. On the other hand, the odds for jackknife increase with the increase in the length of the truck and trailer (from a single to a double or triple trailer), while the odds for rollover decrease.

The increased presence of heavy trucks on North American roadways, combined with a significant number of fatal, injury, and property-damage-only crashes and the unique characteristics of heavy trucks and heavy truck crashes, suggests that attention should be paid to developing countermeasures to crash-imminent situations for heavy trucks. Recent research documenting the substantial safety potential of electronic stability control (ESC) systems for passenger vehicles points to one such countermeasure. ESC is a technology designed to assist the driver in keeping the vehicle on the road during impending directional loss of control or rollover situations. These systems use sensors to detect when the motion of the vehicle differs from that indicated by the driver's inputs, and can control individual brake pressures at each wheel, as well as override authority over the engine throttle, and in the case of a heavy truck, the engine retarder in order to correct the vehicle's path prior to the onset of a rollover or loss of control [4].

NHTSA supported this simulator study primarily as an effort to increase the available data on driver behavior using stability control systems on heavy trucks and to stimulate academic research in the field of heavy truck safety. The findings of this study are currently under evaluation by NHTSA, and the results are being prepared in a report by the University of Iowa National Advanced Driving Simulator (NADS).

This paper describes the implementation of stability control on the NADS and validation of the NADS stability control model by NHTSA. Also a brief overview of the experimental procedures and the designed driving scenarios used in the NADS study are given.

Background Information Relating to Benefits of Passenger Vehicle ESC

Research examining ESC systems on passenger vehicles and light trucks suggests a dramatic reduction in the number and severity of certain crashes caused by loss of control, including rollover [5]. For example, Dang [6] attributes ESC with the reduction in fatal run-off-road crashes, such as rollover, for passenger cars (36 percent reduction) and light trucks and vans (70 percent reduction), and the decline in rollover involvements in fatal crashes of 70 percent in passenger cars and 88 percent in light trucks and vans. Fatal single-vehicle crashes not involving pedestrians, bicyclists, or animals also experienced a reduction of 36 percent in passenger cars and 63 percent in light vehicles and vans due to ESC. Farmer [7] places the risk reduction for single-vehicle crashes due to ESC higher, at 41 percent, with a reduction in fatal crash risk for single vehicles of 56 percent. According to his analysis, ESC is most effective in preventing multi-vehicle fatal collisions for cars when driving on wet roads or curves at any speed, whereas ESC in SUVs appears to be most effective in avoiding multiple-vehicle fatal crashes only on high-speed roads [7]. NHTSA estimates that for passenger vehicles, 5,000-9,000 crashes and 5,300-9,600 fatalities could be avoided if all vehicles were equipped with ESC [8].

The primary objective of the simulator study was to estimate the extent to which heavy trucks may benefit from ESC systems, in light of recent results for passenger vehicles and more limited research on large trucks. Because of the limited exposure of ESC-equipped trucks currently in the fleet, a simple analysis of crash data for heavy trucks does not lend itself to determining the impact of ESC. Moreover, track testing of ESC systems are limited to the speed at which the experiments can be run with the proper safety requirements. On the other hand, hardware-in-the-loop systems and simulator experiments can be run at any speed provided the simulation results are properly validated for the events of interest.

TYPES OF STABILITY CONTROL TESTED

The specific types of stability control systems simulated in this study were Roll Stability Control (RSC) and Electronic Stability Control (ESC). ESC contains both roll and yaw stability functionality and shall be referred to as Roll and Yaw Stability Control (RSC+YSC) throughout the remainder of this paper. Stability control systems were tested in the following combinations: Baseline ABS only (no stability control), RSC, and RSC+YSC. Stability control system type and driving scenario were the independent variables in this study. Stability control system type was a between-subject variable, while scenario type was a within-subject variable. Each

participant experienced five driving scenarios in addition to a familiarization drive.

The study used the NADS heavy truck cab and vehicle dynamics model. A common 6x4 tractor configuration was selected for this test. The simulation included the tractor pulling a fully loaded 53-foot box semitrailer.

PARTICIPANT SELECTION

Sixty drivers with a Class A Commercial Drivers License (CDL-A) completed participation in this study. There were twenty participants assigned to each of the three conditions (baseline, RSC, RSC+YSC To participate in this study, drivers had to meet the following criteria: possession of a valid, unrestricted, Class A Commercial Drivers License (CDL-A), a minimum of 6 months experience after obtaining CDL-A, an average of at least 2000 miles per month over the last 6 months, be in good general health, between 22 and 55 years of age, and pass a visual exam testing for color-blindness

NADS

The study used a high-fidelity full motion simulator located at the National Advanced Driving Simulator (NADS) facility at The University of Iowa. The NADS was instrumented with a functioning 1999 Freightliner Century Class cab with an Eaton Fuller 9-speed transmission (Figure 1). The tractor-trailer modeled is a 1992 GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T, and a 1992 Fruehauf trailer, model FB-19.5NF2-53. A validation of the truck and tractor model was published previously by NHTSA [9]. The cab was mounted inside the 24-foot NADS dome. Four hydraulic actuators attach to the cab, producing vibrations emulating road feel. The dome is mounted on a yaw ring that can rotate the dome about its vertical axis by 330 degrees in each direction. The X-Y assembly produces lateral and longitudinal accelerations by moving about a 64-foot by 64-foot bay. The motion system provides the driver with realistic motion cues that allow the driver to feel acceleration, braking, and steering, as well as experience extreme maneuvers generally associated with critical driving events. For each run, the truck tractor was simulated pulling a fully loaded 53-foot box semitrailer.

Figure 1. Freightliner tractor cab in the NADS dome.

DAILY OPERATIONAL READINESS TEST

The Daily Operational Readiness Test (DORT) was a check of the NADS system before testing in the simulator would begin. For this project, an additional DORT was performed before each day of testing in the main study specifically checking the operation of the RSC and RSC+YSC systems. This test was also performed any time there was a change of hardware from RSC+YSC to RSC (or vice versa) during a single day of testing. The same test that was used to validate the simulation (explained later in this paper) was performed on the NADS to check the operation of the RSC and RSC+YSC systems. The results of this DORT test needed to match the expected parameter outputs before a main study drive could begin. These parameters included: tractor and trailer brake pressures, longitudinal and lateral acceleration of the tractor, tractor roll angle, and system activation. If these parameters did not match, the problem was diagnosed and fixed before testing resumed. This ensured that the operational performance of the RSC and RSC+YSC systems were correct for each day of testing or when a system hardware change was made between runs. A more complete description of the validation procedure used and DORT is included in reference [10].

EXPERIMENTAL DESIGN

The experiment was a split plot (i.e., combination between and within subject design). The between-subjects independent variable was stability control condition. There were three configurations that were being tested, Baseline ABS only (no stability control), RSC, and RSC+YSC. There were 20 subjects per test condition for a total of 60

participants. The within-subject independent variable was Scenario Event.

Scenarios

Each participant completed an initial familiarization drive and then drove five experimental study drives. The study drives can be categorized into two distinct groups, rollover and loss of control. The first group was designed to induce the potential for a rollover. These drives were modeled as occurring on dry pavement with a coefficient of friction of 0.85. The rollover scenarios were:

Incursion Right Event – The roadway has a posted speed limit of 60 mph and the driver encounters a vehicle that pulls onto the roadway, necessitating the driver to go around the incurring vehicles by steering into the oncoming lane, where the driver encounters oncoming traffic that requires a lane change back to the original lane. Figure 2 illustrates the right incursion.

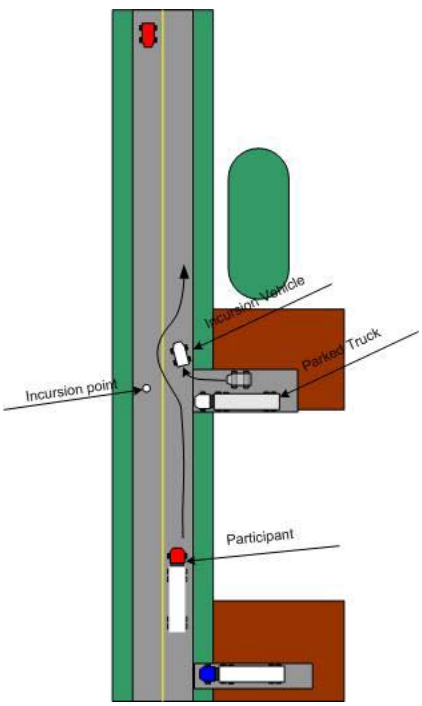

Figure 2. Incursion right event.

Decreasing Radius Curve – The driver encounters a decreasing radius curvature for which the driver is traveling at too great a speed. The posted speed limit of the decreasing radius portion of the curve is 35 mph. The curve has a road bank of 3 percent. Figure 3 illustrates the decreasing radius curve.

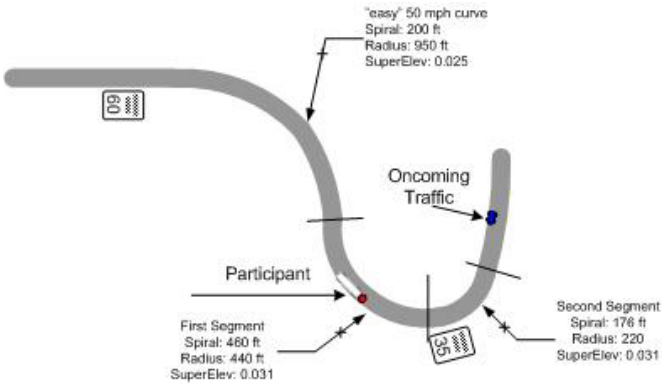

Figure 3. Decreasing radius curve.

Dry Exit Ramp – The driver enters an exit ramp too fast. The bank of the dry exit is 2 percent. The posted speed limit is 35 mph. Figure 4 illustrates the exit ramp.

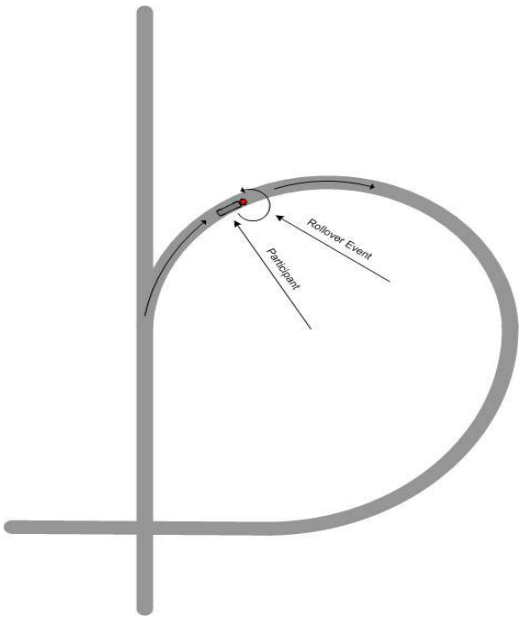

Figure 4. Exit ramp.

The remaining two drives were designed to induce the potential for a directional loss of control (e.g., jackknife). These drives were modeled as occurring on snow-covered pavement. The snow-covered

pavement used modeled a surface with a coefficient of friction of 0.3. The loss of control scenarios were:

Incursion Left Event – On a roadway with a posted speed limit of 60 mph, the driver encounters a vehicle that pulls into the driver's lane, necessitating the driver to go around the incurring vehicles by steering onto the shoulder, requiring a countersteer. Figure 5 illustrates the incursion left event.

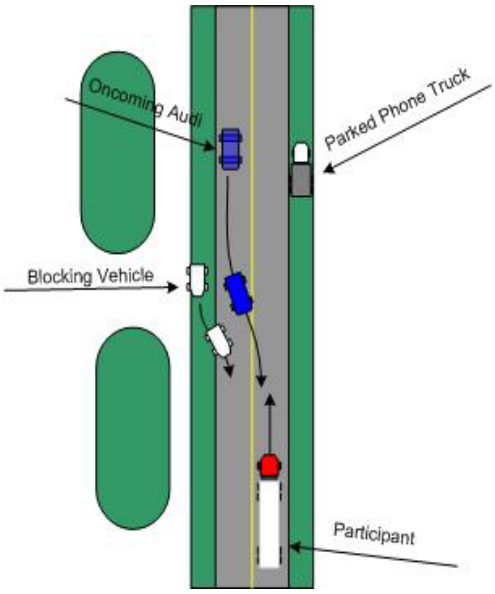

Figure 5. Incursion left event.

Snow Exit Ramp – The driver enters an exit ramp too fast. The snow exit ramp has a bank angle of 2 percent. The posted speed limit is 35 mph. The geometry is identical to the dry exit ramp (see Figure 4).

The familiarization drive, incursion right, decreasing radius curve, and dry exit ramps were completed on a dry pavement surface, whereas the incursion left and the snow exit ramp were completed on snow covered pavement.

NADS MODEL VALIDATION

The NADS truck model was compared with test track data from the NHTSA Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. The test maneuver used was a Ramp Steer Maneuver (RSM) with maximum steering angle at 190 deg with an angular rate of 177 deg/s. The steering angle was held constant for 5 seconds after reaching 190 deg. The RSM was run for the baseline (ABS only), RSC, and RSC+YSC test conditions. Exact matching of values from test track data was not possible, as the NADS model was developed to simulate the braking properties of a Freightliner tractor and the inertial properties of a Volvo tractor. Also, the NADS truck was modeled with a rigid body trailer model and no torsional stiffness at the fifth wheel. All test track data were taken from VRTC tests of a Freightliner with Meritor WABCO stability control systems using a steering controller. Conversely, the NADS RSM runs had manual input of steering wheel angle. There were also slight differences in the actual test track surface coefficient of friction and that of the model. Because of these differences, data trends were compared and relative system performance was considered rather than matching exact parameter values.

Table 1 shows that the NADS and experimental Baseline threshold speeds were within one mph of each other. With RSC and with RSC+YSC both the NADS vehicle and experimental vehicle threshold speeds increased, in the range of 5 to 8 mph beyond the Baseline threshold speeds. For the experimental test vehicle, the RSC system provided a slightly greater margin of speed increase than the RSC+YSC system. On the test track, the RSC algorithm applied the brakes with more initial brake pressure than did the RSC+YSC thereby allowing a higher speed in the RSM than for the RSC+YSC runs. For the simulated NADS vehicle, the RSC+YSC and RSC threshold speeds were found to be within one mph of each other. These results indicated that the NADS RSC and RSC+YSC simulations did not exactly match but provided speed results that were close in magnitude to the actual vehicle.

Results from the simulator experiment should provide speed magnitudes that would be expected in

Table 1.
Rollover threshold speeds for RSM validation test

Rollover Speed (mph)	NADS	VRTC
RSC+YSC	33	32
RSC	32	35
Baseline	26	27

actual vehicles, but not in absolute terms. Therefore, direct comparisons to speeds achieved with an actual truck may not be possible with this model.

Comparison of Example RSM Runs

Figure 6 shows representative NADS simulation results from RSC runs of the Baseline vehicle and RSC-equipped vehicle. The runs shown on Figure 6 are the highest speed RSM runs conducted that did not result in vehicle rollover. The initial speed for the NADS Baseline run is 26 mph and for the RSC run it is 32 mph. Representative experimental results from the highest speed RSM runs conducted that did not result in vehicle tip-up onto the safety outriggers are shown on Figure 7. The initial speed for the experimental Baseline run is 27 mph and for the RSC run it is 35 mph.

The speed, lateral acceleration, yaw rate, and longitudinal deceleration of the NADS results (Figure 6) followed similar trends observed with the experimental data shown in Figure 7. The comparison shows similar decreases in lateral acceleration and yaw rate, and significant longitudinal deceleration due to the RSC brake activation. The RSC braking action slowed the vehicle and reduced the sustained lateral acceleration to a level that did not result in vehicle rollover. The activation of RSC was clearly demonstrated by the fact that the vehicle can be driven through the RSM without rollover at an initial higher speed than the Baseline vehicle without RSC.

Figures 8 and 9 show the brake line pressures for the NADS and experimental results respectively. In the figures, the left side brake pressures are shown in the left column and the right side pressures in the right column. Pressures 3-6 are the tractor drive axle brakes pressures and pressures 7-10 are the trailer brake pressures. There was no braking activity for the Baseline runs. With RSC, the NADS and experimental RSM runs showed similar trends in brake line pressures. For both the NADS and the experimental runs, the right side drive axle brake pressures nearly achieved their maximum of 100 psi for a sustained period of time. In addition to reducing the vehicle speed, this braking action resulted in reducing the yaw rate during these left turn RSM runs.

The Meritor WABCO RSC system was not designed to activate the tractor front axle (steer axle) brakes, and no brake line pressures were developed during the experimental RSM runs. However, the NADS did exhibit a slight amount of residual pressure up to 20 psi (137.9 kPa) on the steer axle brake lines during RSC activation. This amount of brake pressure was much smaller than what was applied on the tractor drive axles and trailer axles, and would only slightly affect RSC simulation results. However, resolving this issue would improve the overall accuracy and quality of the stability control hardware-in-the-loop implementation in the simulation.

LIMITATIONS OF SIMULATION

Every simulation model has limitations, and it is important to understand where those limitations may have been encountered in the study. There are two potential limitations related to the NADS vehicle dynamics and its interaction with the stability systems. The first is a known limitation, while the second is a potential limitation.

First, the fidelity of the NADS heavy truck model is limited by the rigid formulation of the model components. The major limitations of the current model are the lack of torsional stiffness in the fifth wheel and the lack of frame flexibility in the tractor. This resulted in the tractor roll response being equal to that of the simulated trailer. The tractor-trailer model is still valid for doing relative comparisons between the various study conditions. Another fundamental limitation is the use of table lookup data of tire forces measured in 1992. A full, functional tire model with recently tested tires would improve the fidelity and overall quality of the simulation results.

Second, the RSC and RSC+YSC systems are not simply “plug-and-play” devices, able to be installed in any tractor trailer interchangeably, although the RSC system requires much less tuning than the RSC+YSC, which must be configured with a variety of vehicle parameters. Indeed, it is necessary for a technician to configure the system to the truck by setting parameters related to the wheel size, wheelbase, etc. Every effort has been made to ensure that the hardware has been configured with the proper settings before delivery to the NADS. Additionally, the tractor-trailer model and its associated subsystems have been created with the highest fidelity possible within the constraints imposed by real-time simulation, and all the required signals have been supplied to the system’s hardware-in-the-loop.

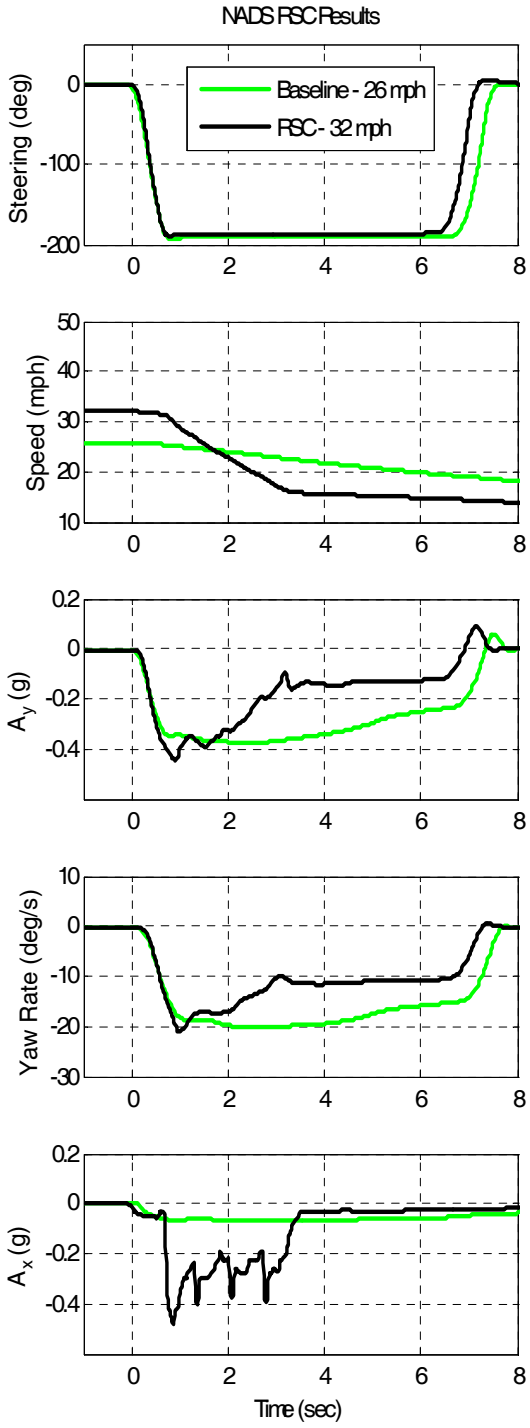

Figure 6. NADS RSC results.

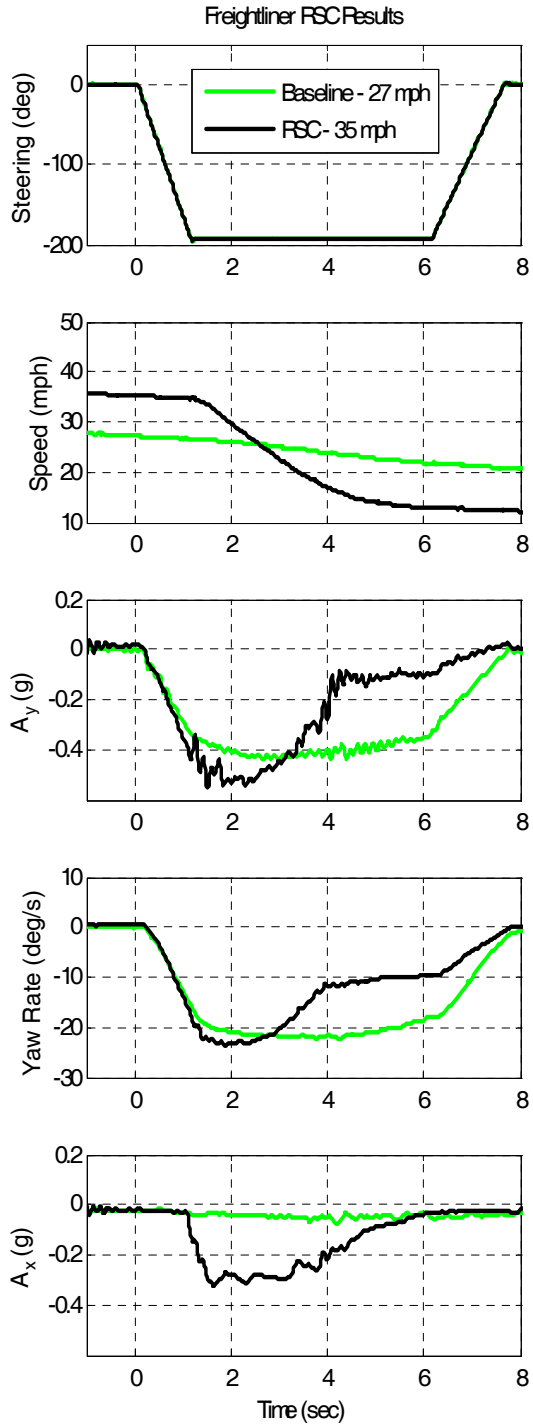

Figure 7. VRTC experimental RSC results.

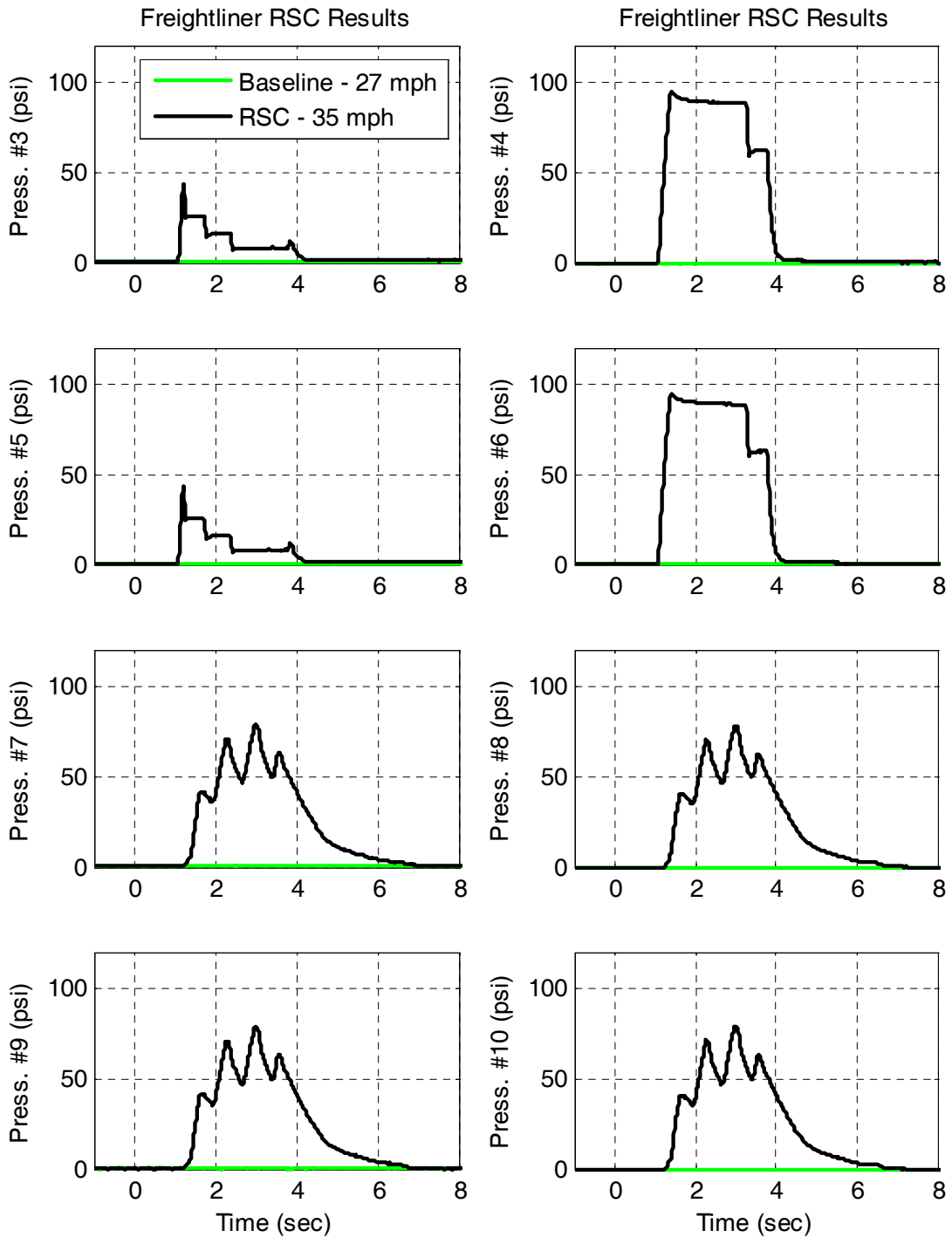

Figure 8. Experimental brake pressure lines – RSC.

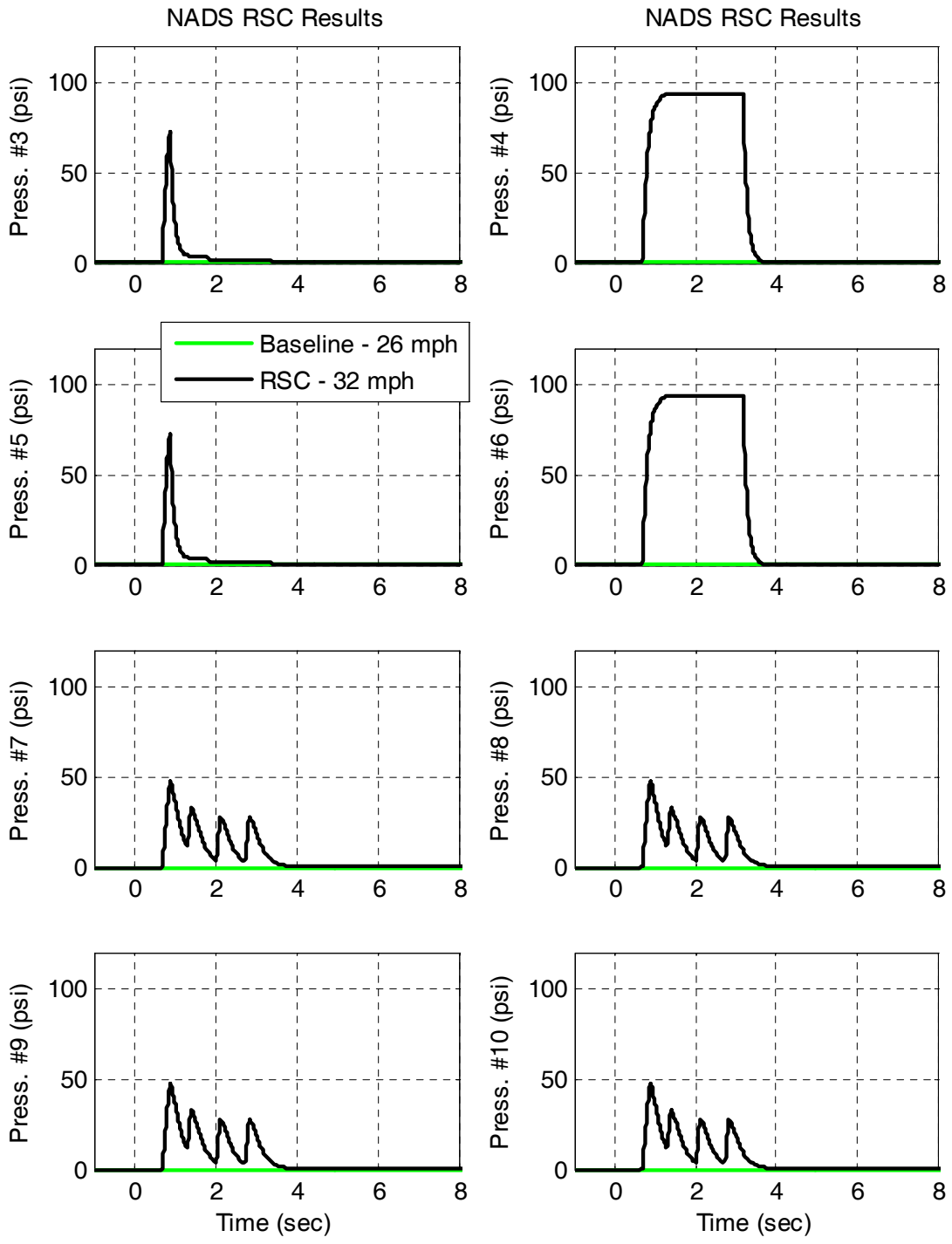

Figure 9. NADS brake pressure lines – RSC.

CONCLUSIONS

This paper presents NHTSA's effort into the implementation of electronic stability control systems for heavy trucks on the National Advanced Driving Simulator at the University of Iowa. The purpose of the study was primarily to increase the available data on driver behavior using stability control systems on heavy trucks, stimulate advanced academic research in this field, and to provide better means for understanding issues related to heavy truck safety.

A comparison of a RSM run on the NADS with actual test track experiments results in the following conclusions. First, speed at which rollover occurs in the RSM indicate that results from the simulator experiment provide similar results that would be expected in actual vehicles, but not in absolute terms. Second, direct comparisons to speeds achieved in maneuvers with an actual truck on a test track may not be possible with the current NADS model. And finally, further refinements to the NADS tractor-trailer model and the inclusion of a full, functional tire model with recently tested tires would improve the fidelity and quality of the overall simulation. The findings of the evaluation study on stability control for tractor-trailers are being prepared in a report by the NADS, University of Iowa.

REFERENCES

[1] Sprung, M.J. 2007. *Increased Trade Spurs Growth in North American Freight Transportation*. Research and Innovative Technology Administration, Bureau of Transportation Statistics. Accessed on 2/20/2008 at http://www.bts.gov/publications/bts_special_report/2007_05/html/entire.html.

[2] Federal Motor Carrier Safety Administration (FMCSA) 2007. *Large Truck Crash Facts 2005*. Analysis Division, February.

[3] Moonesinghe, R., Longthorne, A., Shankar, U., Singh, S., Subramanian, R., and Tessmer, J. 2003. *An Analysis of Fatal Large Truck Crashes*. National Center for Statistics and Analysis, National Highway Traffic Safety Administration. DOT HS 809 596.

[4] Federal Motor Vehicle Safety Standard (FMVSS) No. 126 Electronic Stability Control Systems, 49 CFR Part 571.

[5] National Highway Traffic Safety Administration (NHTSA). 2006. *Traffic Safety Facts 2005: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. National Center for Statistics and Analysis, DOT HS 810 631.

[6] Dang, Jennifer N. 2007. *Statistical Analysis of the Effectiveness of Electronic Stability Control (ESC) Systems – Final Report*. National Highway Traffic Safety Administration, National Center for Statistics and Analysis.

[7] Farmer, Charles M. 2006. Effects of electronic stability control: An update. *Traffic Injury Prevention* 7(4): 319-324.

[8] Final Regulatory Impact Analysis, FMVSS 126, Electronic Stability Control Systems, DOT Docket No. NHTSA-2007-27662.

[9] Salaani, M.K., Grygier, P.A., Heydinger, G.J. 2003. *Evaluation of Heavy Tractor-Trailer Model used in the National Advanced Driving Simulator*. SAE paper no. 2003-01-1324.

[10] Brown, T., Schwarz, C., Moeckli, J., Marshall, D., 2009. "Heavy Truck ESC Effectiveness Study Using NADS - Final Report," NHTSA, Washington, D.C., to be published.