VALIDATION OF HARDWARE IN THE LOOP (HIL) SIMULATION FOR USE IN HEAVY TRUCK STABILITY CONTROL SYSTEM EFFECTIVENESS RESEARCH

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ABSTRACT

A Hardware in the Loop (HiL) system was developed to investigate heavy truck instability due to loss of control and rollover situations with and without ESC/RSC systems for a wide range of maneuvers and speeds. The purpose of this HiL model is to examine the safety benefits of the emerging electronic stability systems (ESC/RSC) in heavy trucks that are designed to prevent yaw instabilities (e.g., jackknife) and rollovers. This paper outlines the process for validating the HiL model so that the simulation closely represents the expected outcome for a similar maneuver conducted on a test track. The HiL system was built in a laboratory using the brake system of a truck and the actual stability control system control units supplied from a manufacturer. The dynamics software uses TruckSim, and the simulation results were validated using NHTSA collected field data. The HiL model is being used to examine yaw instability and rollover scenarios that would not be possible to conduct in actual track testing. Driving scenarios were developed through an examination of Large Truck Crash Causation Study (LTCCS) cases. These scenarios were based on realistic events and were developed to replicate typical crash situations. The scenarios use a path-following driver model to drive through curves of various radii, a curve with a reduced radius, and variations of lane change maneuvers that are representative of obstacle avoidance. An overview of the scenario development, HiL system design, and the results of the validation of the HiL model are presented. The results of the validation show that the vehicle dynamics and hardware responses of the HiL are comparable to actual heavy truck test track results and can be helpful in determining the benefits of stability control technologies in varied driving situations.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) has funded the University of Michigan Transportation Research Institute (UMTRI) to study the potential safety benefits from two stability control systems developed for heavy truck tractor-trailers, Roll Stability Control (RSC) and Electronic Stability Control (ESC). The RSC systems sense lateral acceleration and apply the brakes when rollover is imminent. ESC systems sense vehicle speed, yaw rate, lateral acceleration, and apply brakes to assist a driver in avoiding directional instabilities as a result of an understeer or oversteer mitigation process. ESC can also address vehicle rollover as well. Stability control technology is needed because by the time a driver is aware that the truck is beginning to roll or lose control, it is usually too late for a corrective action by the driver. Since these systems have been only recently introduced in heavy vehicles, there is a limited amount of heavy truck crash data to base a determination of system effectiveness. Therefore, a hardware-in-the-loop (HiL) simulation model has been developed to assess system effectiveness. The observed system effectiveness in varied driving situations from the HiL can then be used to determine the potential benefits of stability control technologies by developing simulated driving scenarios that are linked to actual crash data populations. A validation of the HiL system by comparing simulation results to actual vehicle test experiments was required to ensure valid results. NHTSA validated the simulation results with experimental test track data from ramp steer maneuvers using tractor-trailers. An overview of the scenario development, HiL system design, the methods used for validation, and the validation results are presented in this paper.

SCENARIO DEVELOPMENT

In order to link the performance of stability control technologies to crash reduction benefits, data selection algorithms compatible with the national crash data files of the General Estimates System (GES), Trucks Involved in Fatal Accidents (TIFA), and Large Truck Crash Causation (LTCCS) databases were developed [1]. This information was used to create driving scenarios for the HiL simulation to study the effectiveness of ESC and RSC systems in addressing crashes involving directional loss of control and rollover.

The LTCCS database was analyzed to determine the factors that were used to define simulation scenarios. This analysis classified factors according to road radius of curvature (<100m, >100m, or straight), roadway friction (high or low), the position along the curve of rollover onset, driver control inputs (none, steer only, steer and brake, or brake only), trailer load (full, medium, or empty), center of gravity height (high, medium, or low), and whether the roll occurred at an intersection. UMTRI developed simulation scenarios representative of these factors that may lead to rollover and directional loss of control. [1] These scenarios were:

Transient to Constant Curve

This maneuver represents a typical entrance to a freeway exit ramp, and its geometry consists of two constant radius curves. The curve radii were 68 m and 227 m which represent the mean values for roads with a curvature less than 100 m or greater than 100 m respectively in the LTCCS database. The geometry is shown in Figure 1. The transition from a straight line to a constant radius curve provides a smooth vehicle dynamics transition as road curvature changes from infinity (straight roadway) to the desired radius. In this maneuver, increasing vehicle speed increases lateral acceleration and vehicle roll motion, and accordingly RSC, ESC, and ABS (baseline) have been evaluated iteratively to determine the speed for rollover onset, which is referred to as the critical speed.

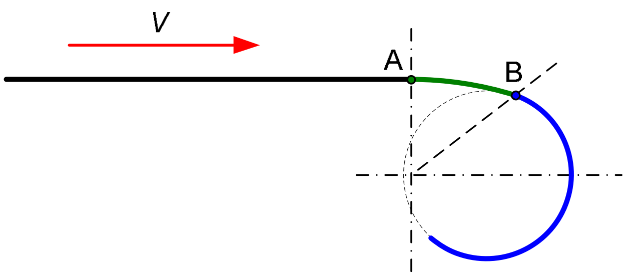

Figure 1. Transient to constant curve.

Constant Radius to Diminishing Curve

This maneuver represents a scenario where the vehicle enters the curve at a speed just below the critical speed, but the reduction in curvature increases the vehicle's lateral acceleration and roll angle to initiate rollover. The schematic of this maneuver is shown in Figure 2. The diminishing radius portion of the curve begins at 90 degrees beyond point A (see Figure 2). RSC, ESC, and ABS have been compared based on their critical speed.

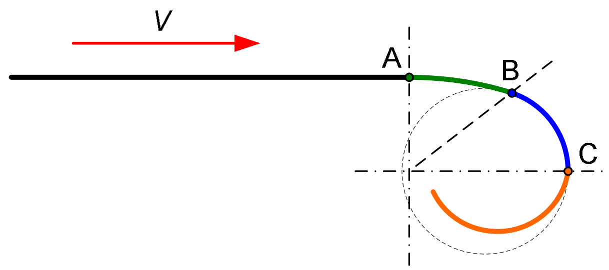

Figure 2. Constant radius to diminishing curve.

Single Lane Change in Curve

This maneuver represents the scenario of a truck changing lanes to the outside of the curve on a road resembling a freeway exit ramp with multiple lanes in the direction of travel. The schematic of this maneuver is shown in Figure 3. Critical speeds for the RSC, ESC, and ABS have been determined iteratively.

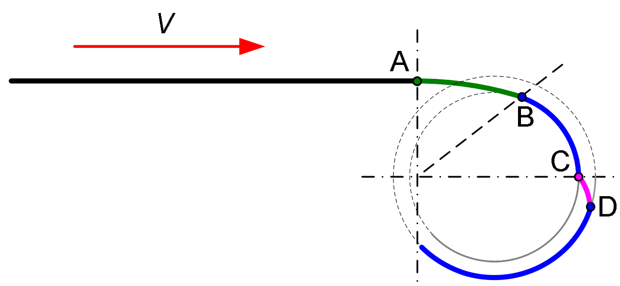

Figure 3. Single lane change in curve.

Single Lane Change on Straight Road

This maneuver is associated with most rollovers on straight roads. It tends to occur when truck drivers try to avoid an obstacle on the road, e.g., a slowing vehicle or an incursion from an intersecting road. ISO 14791 lane change geometry is used and critical speeds for RSC, ESC, and ABS have been determined iteratively.

Turn at an Intersection

Several rollover scenarios have been identified in the LTCCS that occur while the truck is turning at intersections. The radius of this maneuver is 20 m, and critical speeds for the RSC, ESC, and ABS system have been determined iteratively (see Figure 4).

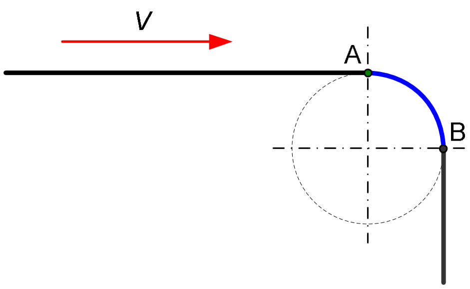

Figure 4. Turn at an intersection.

HIL SYSTEM DESIGN

To evaluate the effectiveness of stability control systems in the driving scenarios developed, a HiL system was built in the UMTRI laboratory. The HiL included the pneumatic brake system of a tractor-trailer and the actual stability control system control units supplied from a manufacturer. For this study, Meritor WABCO systems were used. The HiL system is a combination of hardware and software components, and includes simulated truck dynamics, a driver model, pneumatic brake system hardware, and the electronic control systems (RSC, ESC, and ABS). The dynamics were modeled using TruckSim software. Road geometry and surface conditions were modeled by variables in TruckSim. The driver model used a path-follower model at a constant speed. Also, the driver was modeled as a continuous controller. Using this method, lateral errors were reduced. The parameters of the controller were adjusted to provide a realistic closed loop vehicle driver simulation and were sufficient for this task.

The pneumatic brake system hardware is shown in Figure 5. Hardware was used to avoid modeling complex mechanical systems that included: compressible fluid mechanics, valve dynamics, and nonlinear frictional and system properties. This method eliminated the need for validating brake pressure models, as the actual hardware (typically installed on five axles and ten brake actuators) was used. The pressures that actuate the brakes were taken from TruckSim and the braking torque was determined from a table lookup of experimental data measured on a brake dynamometer. Brake line pressures and time delays were generated by a physical replica of an actual braking system.

Figure 5. Pneumatic brake system hardware.

Figure 6 shows the major components of the HiL system. TruckSim and Simulink were used and executed on real-time computers running on OPAL-RT software on a QNX operating system. System motion variables (speed, acceleration, yaw rate) were modeled in software (TruckSim and Simulink) and provided the inputs to the hardware control variables (steering and treadle displacement) and wheel speeds. The treadle displacement was converted to actual displacement via an electro-mechanical servo. Wheel speeds were transformed to appropriate hardware inputs that replicated wheel-speed magnetic pickups. The electronic stability system responded by providing control commands for engine brake applications, throttle inputs (disengage throttle), or actuation of the air brakes.

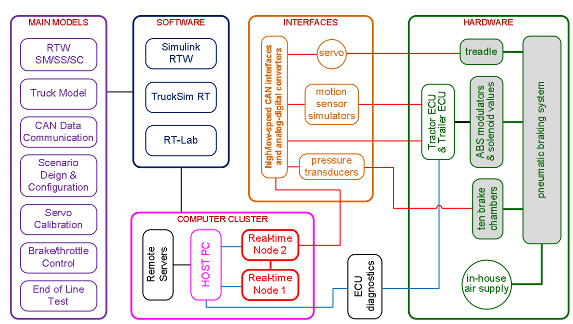

Figure 6. HiL system overview.

Heavy Truck Dynamics Model

The tractor-trailer modeled in TruckSim was based on collected test data from a 1992 White-GMC truck manufactured by Volvo GM Heavy Truck, model WIA64T, and a 1992 Fruehauf van trailer, model FB-19.5NF2-53. UMTRI measured geometric and inertial parameters for the chassis, steering, and suspension components. The performance properties of the three suspensions and torsional stiffness of the vehicle frames and fifth wheel coupling were also measured [2]. The geometric measures of the tractor and trailer are shown in Figure 7.

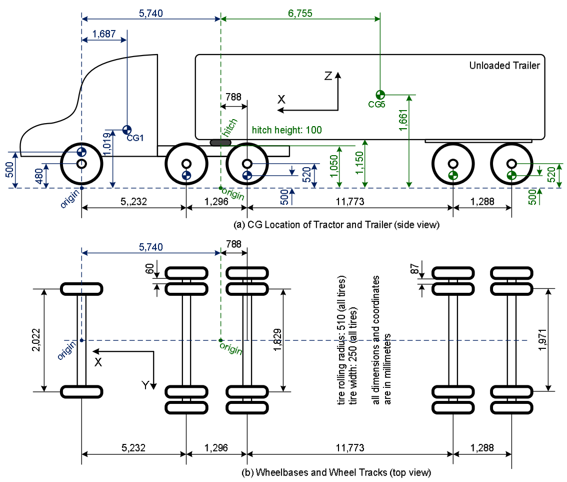

Figure 7. Heavy truck geometry.

Additional details for the TruckSim model used can be found in references [3-8].

Tire Data

Results from an SAE Cooperative Research Project [9] provided the tire data for the tractor-trailer. The SAE experimental tire data for lateral forces were limited to 16 degrees of slip angle, and data beyond that level were interpolated using the data point at pure sliding at 90 degrees of slip angle. These data represented typical tires produced in the 1990's as current data for state-of-the-art tire designs were not yet available. Despite this limitation, simulation results presented reasonable replications of typical heavy truck responses where comparative analysis can be done.

The dynamics delay or relaxation length for lateral force was set to 300 mm and for the longitudinal force it was 100 mm. The lateral relaxation length was not based on direct measurements of tire forces, but it was set to produce reasonable frequency response of lateral dynamics [10]. The longitudinal relaxation was set to produce reasonable stopping dynamics at zero speed after hard braking, and it had a secondary effect on the ESC/RSC systems.

HIL MODEL VALIDATION

NHTSA conducted the validation of the heavy truck HiL system developed by UMTRI. The simulation results were compared to experimental test track data for a typical tractor with a 53-foot semitrailer that was heavily loaded with a high C.G. location. Test track data were collected at the NHTSA Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. These data were taken from the NHTSA stability control research program and were not conducted solely for the purpose of this validation. This resulted in some differences in the test track conditions and the HiL system. However, the data were useful for qualitatively checking the response of the HiL.

Ramp Steer Maneuver

The Ramp Steer Maneuver (RSM) formed the basis of the validation of the HiL simulation with test track data. The RSM is similar to a J-Turn maneuver. It was performed by inputting the steering profile shown in Figure 8. The severity of the maneuver was controlled by incrementally increasing speed until rollover occurred.

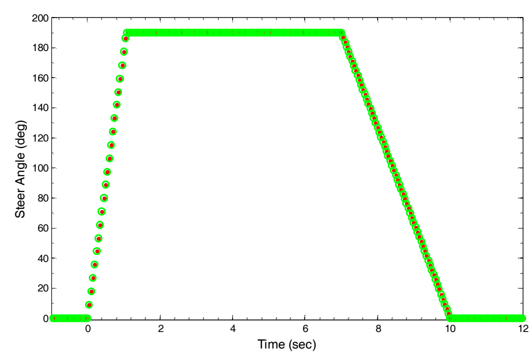

Figure 8. RSM steering profile.

Validation Results

For the HiL simulation, the RSM (using the steering profile shown in Figure 8) was applied to these three configurations: ABS-only (baseline), RSC, and ESC. The speed was increased gradually until rollover occurred. The ABS-only configuration did not involve ABS operations because driver braking was not included in the maneuver. For all runs, the driver input consisted of steering actions only. Differences between test track and HiL conditions were that the track maneuver was performed with a dropped throttle and for the HiL it was performed at a constant speed provided by the simulated driver model. Also, there were some differences in the tires, suspensions, and compliances used on the actual truck, as opposed to the simulation.

When analyzing simulation results, it should be noted the extent of roll motion where model predictions are accurate. The parameters used in simulation models such as for TruckSim are typically based on measurements and estimations of vehicle motion that do not have excessive roll. Rollover events in simulations may result in numerical inaccuracies in the model as a result of complete vehicle roll. Although the predicted rollover mechanics beyond a certain roll angle (typically higher than six degrees) are not entirely valid, the simulation is useful for predicting the onset of vehicle rollover.

The tire data did not account for excessive vehicle roll and inclination effects. Data for the roll centers at each axle, suspension compliances, suspension kinematics, and many other aspects of the vehicle model were not formulated to accurately handle extreme roll mechanics. From a physical standpoint, it was sufficient to analyze wheel liftoff as a sign of rollover when using simulation results. The Load Transfer Ratio (LTR) metric was used to analyze rollover potential for both the tractor and trailer. This method was valid and yielded accurate and consistent results.

LTR is given by:

$$LTR = \left| \frac{\sum_{Left} F_{Ni} - \sum_{Right} F_{Ni}}{\sum_{Left} F_{Ni} + \sum_{Right} F_{Ni}} \right| \qquad (1)$$

LTR varies from 0 to 1. When LTR is equal to 1, it indicates a complete rollover. This is because, at the onset of rollover, all of the tires do not lift from the ground at the same time. An LTR value of approximately 0.9 indicates an onset of rollover.

Table 1 lists the HiL simulation and experimental results. The threshold speeds of the ABS-only and the RSC conditions were comparable with the speeds observed during test track testing (within 1 mph difference). However, the ESC speeds were quite different. The HiL driver model maintained throttle (in order to maintain constant speed) during the test maneuver. This likely produced a different response by the ESC controller for the HiL than observed in the test track runs.

When compared with test track data, the HiL simulation results showed the correct trends for ABS and RSC. For ESC the differences in the constant speed maintained by the driver model had a pronounced effect on system activation. The fact that the driver model in the HiL simulation maintained throttle resulted in the ESC controller intervening very quickly and earlier than on the test track. This permitted a higher speed at the start of the maneuver than what was achieved on the test track. As the test track runs were performed with dropped throttle, the ESC controller delayed intervention until it identified a loss-of-control situation. Therefore, the results were not expected to exactly match the speed obtained from test track measurements given this difference. However, the activations of the ESC were appropriate for the given simulated conditions.

Table 1.
RSM results – Speed (mph) at which first wheel lift occurs

Type	HiL Simulation		VRTC Data
	LEFT	RIGHT	LEFT
ABS only	27	27	27
RSC	34	35	35
ESC	42	41	32

Figure 9 shows a comparison of lateral accelerations, yaw rates, and roll angles for the three tractor-trailer electronic stability configurations for the RSM. Simulation results show that the truck dynamics model and the HiL systems were tuned appropriately. Both systems showed a substantial advantage in improving tractor-trailer stability as evidenced by the greater speed at which rollover was initiated for the RSC and ESC runs over the baseline condition of ABS. Figure 10 shows tractor decelerations for the three configurations. The ESC system had a higher deceleration level than the RSC system due to the additional steer axle braking of the ESC system. The ESC and RSC systems showed that wheel liftoff occurred at a higher speed than with the ABS-only system.

Figures 11 and 12 show experimental test track results from RSC and ESC systems compared to baseline runs (ABS only). Figures 13 and 14 show the generated brake line pressures as a result of RSC and ESC system activations respectively. Figures 15 and 16 show the simulation results that can be compared to the experimental results in Figures 11 and 12.

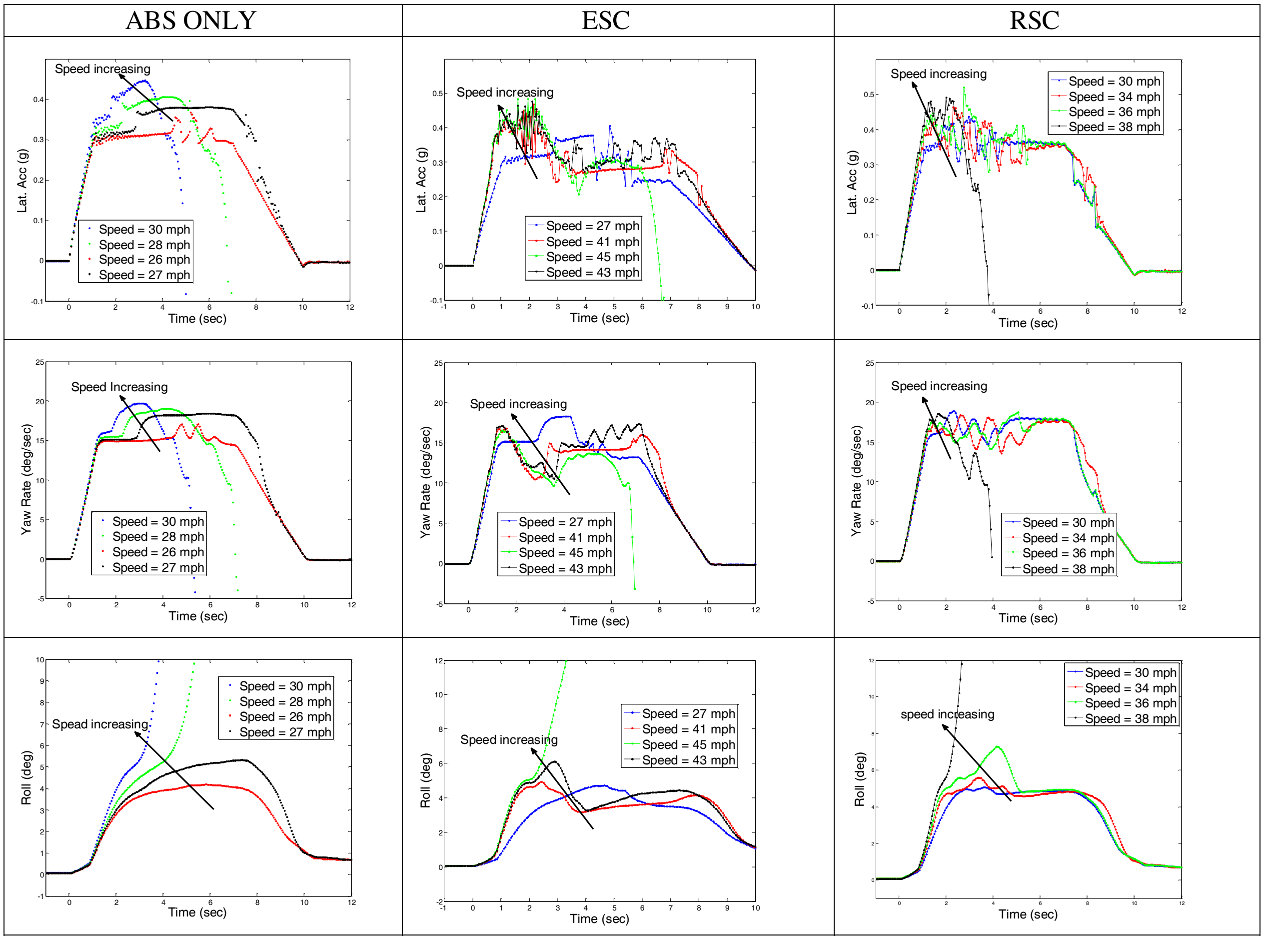

Figure 9. Lateral accelerations, yaw rates, and roll angles for the tractor.

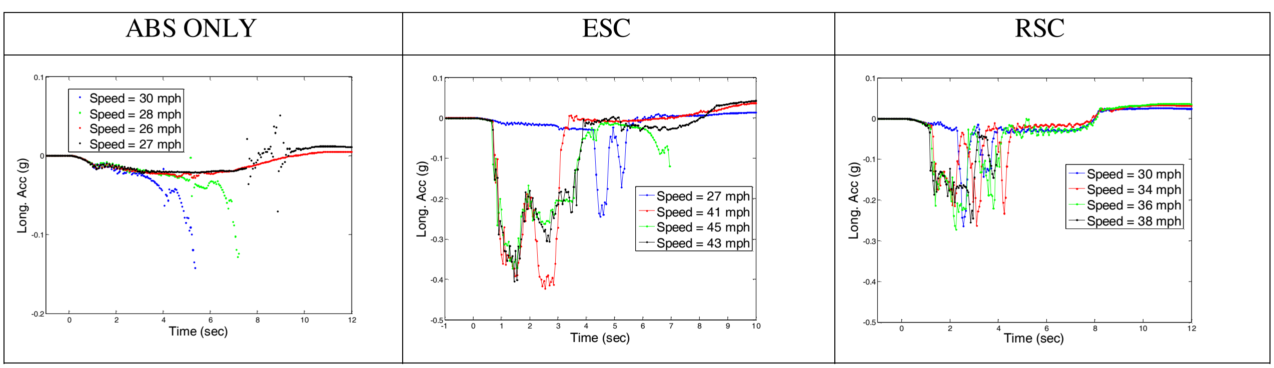

Figure 10. Longitudinal accelerations for the tractor.

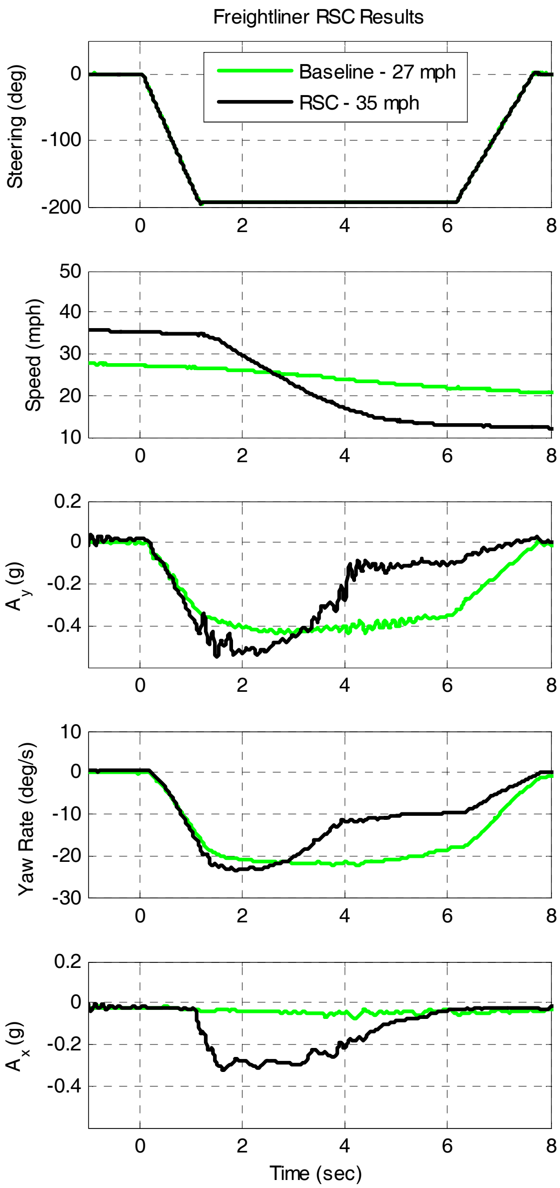

Figure 11. Experimental steering inputs and vehicle responses: baseline and RSC results: 2006 Freightliner.

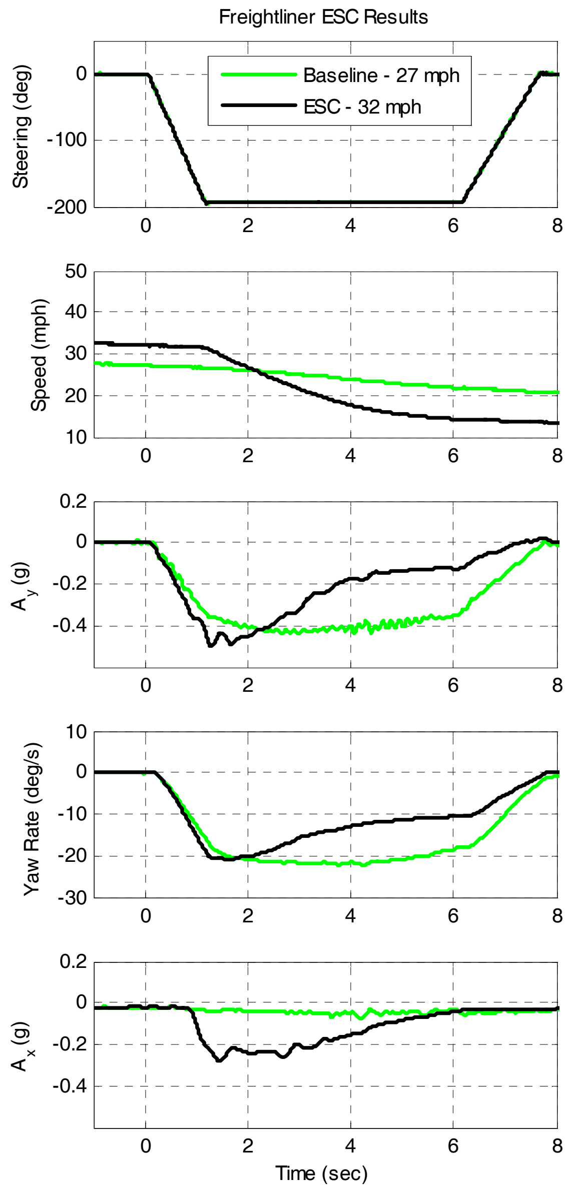

Figure 12. Experimental steering inputs and vehicle responses: baseline and ESC results: 2006 Freightliner.

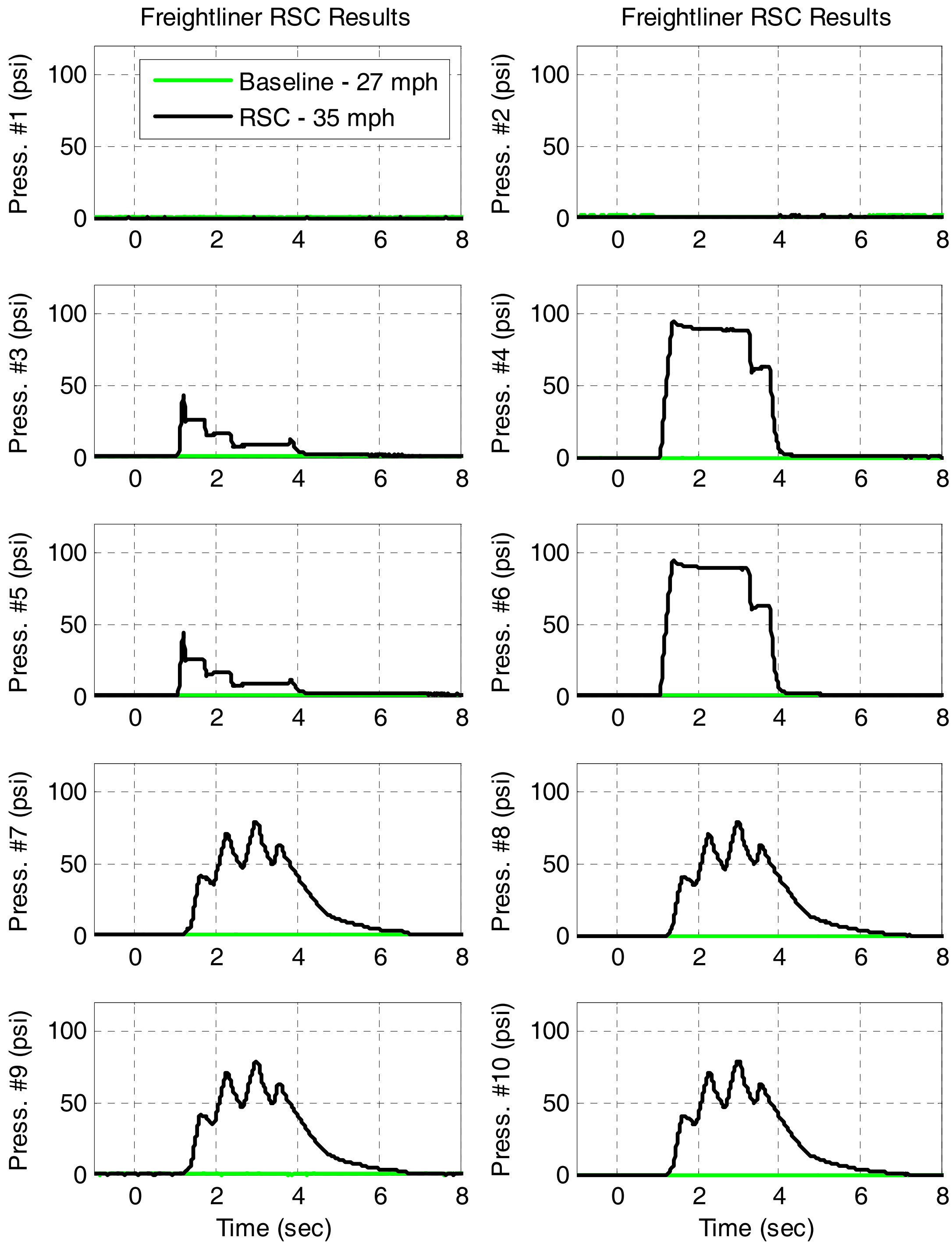

Figure 13. Experimental brake pressures: baseline and RSC results: 2006 Freightliner.

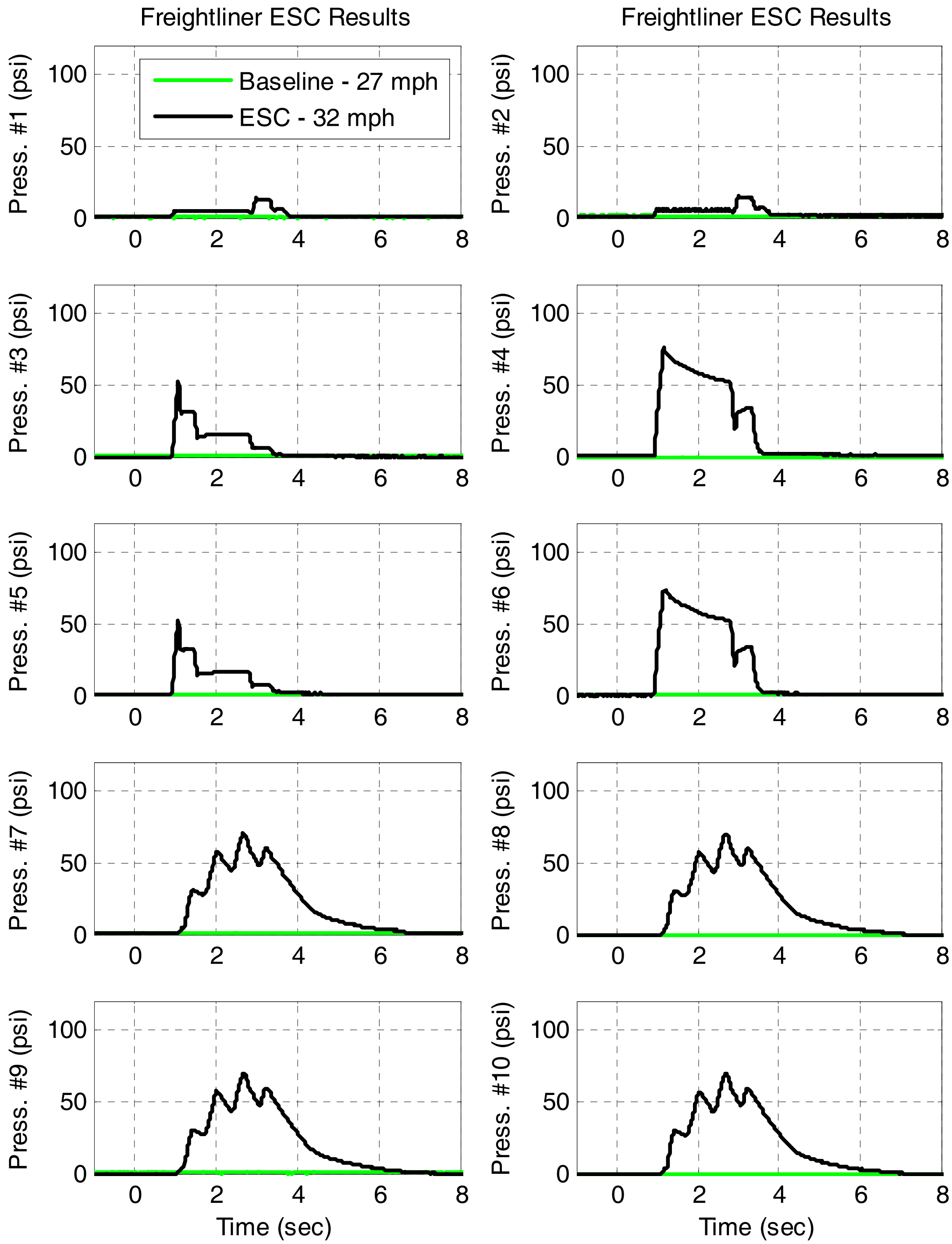

Figure 14. Experimental brake pressures: baseline and ESC results: 2006 Freightliner.

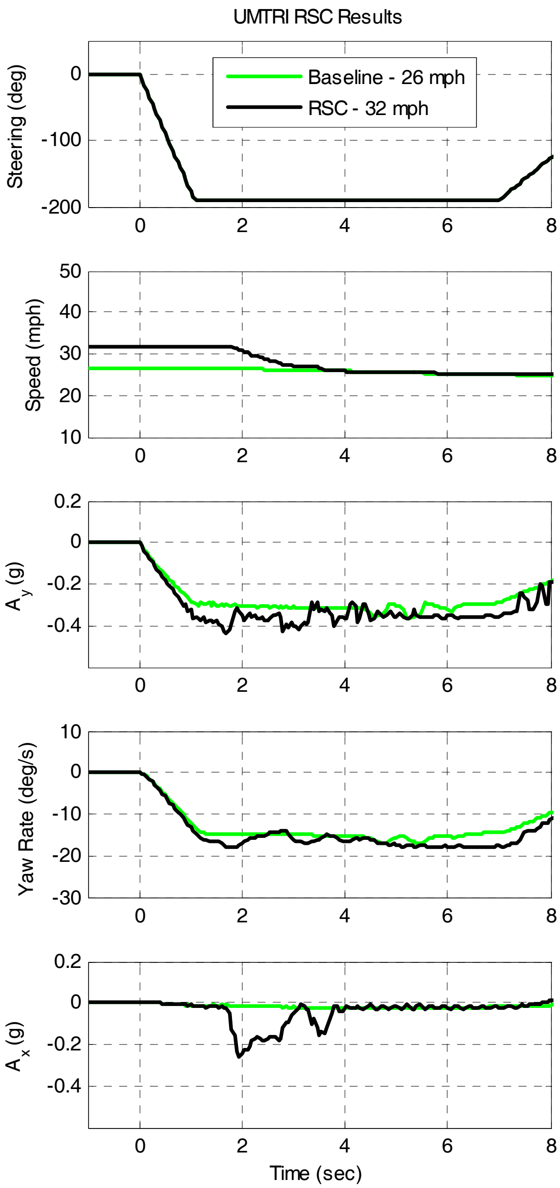

Figure 15. UMTRI HiL simulation steering inputs and vehicle responses-baseline and RSC results.

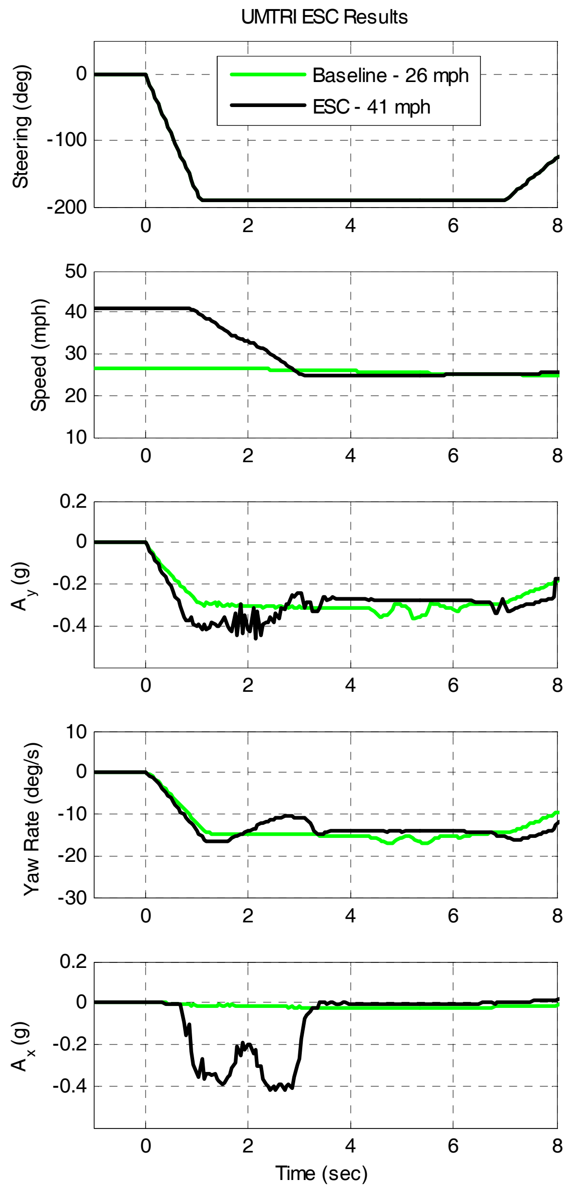

Figure 16. UMTRI HiL simulation steering inputs and vehicle responses-baseline and ESC results.

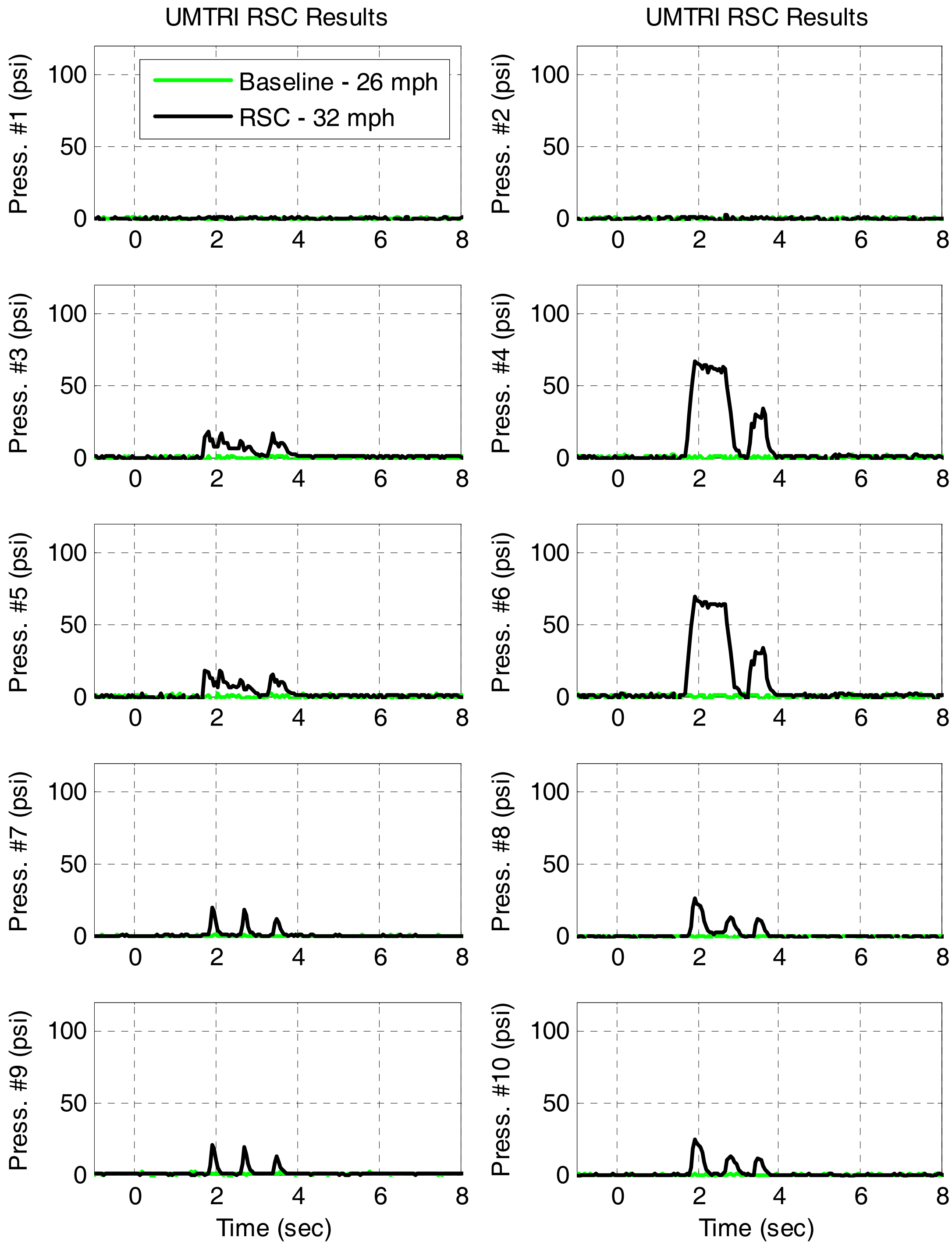

Figure 17. UMTRI simulation HiL brake pressures: baseline and RSC results.

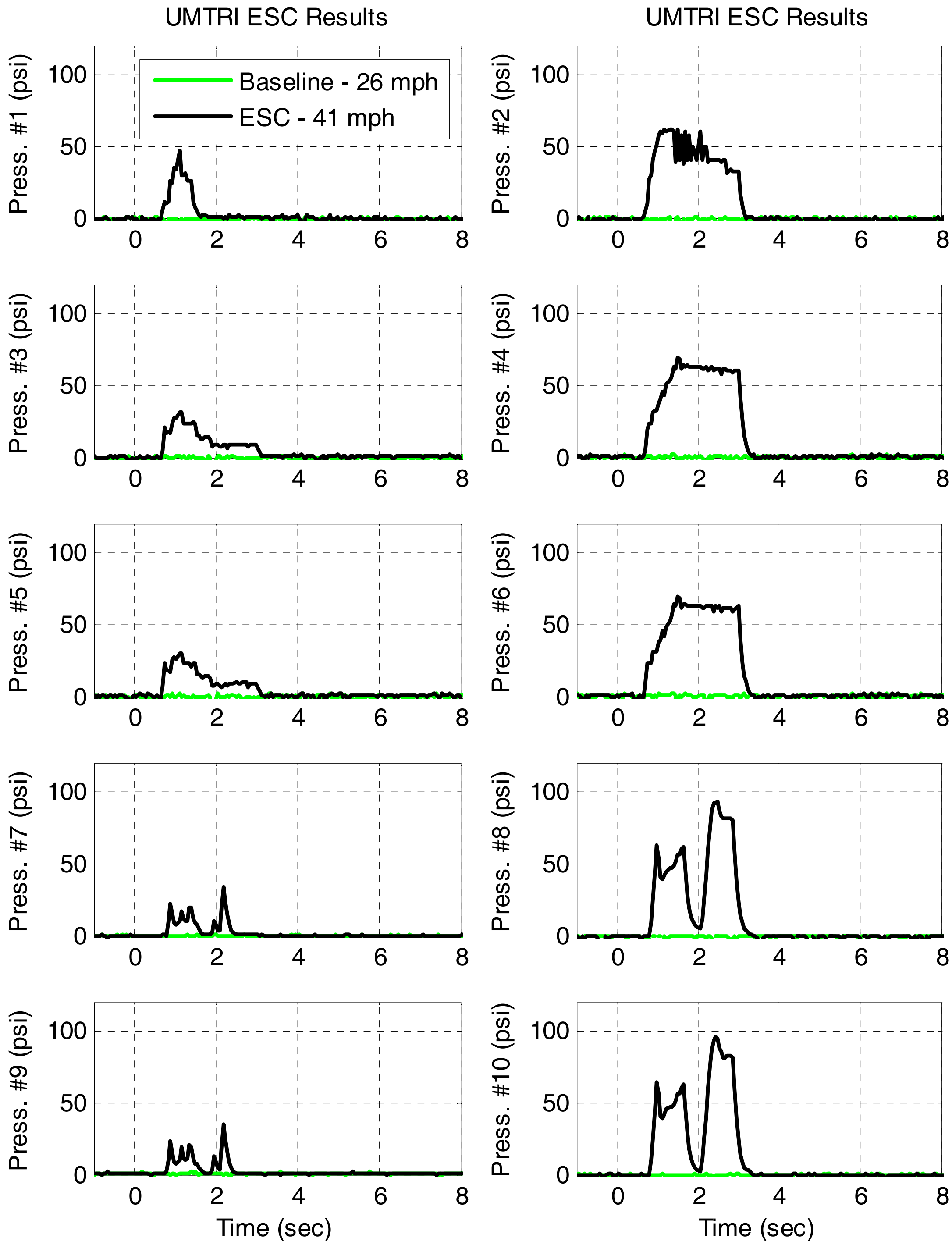

Figure 18. UMTRI simulation HiL brake pressures: baseline and ESC results.

The comparison shows that the lateral accelerations, yaw rates, and longitudinal decelerations reach about the same maximum levels. However, the driver model in the HiL attempted to keep the speed of the tractor-trailer constant, and the speed was not reduced further after rollover was avoided. This explains the constant speed profile and the change in deceleration after about 3 seconds of RSM initiation. The RSC system in both the HiL and the test track vehicle reduced the yaw rate and lateral acceleration levels to the baseline levels. The ESC system in the HiL activated slightly more than 0.2 seconds earlier than the system on the test track vehicle. Also, the longitudinal deceleration was almost twice as much.

Figures 17 and 18 show the brake line profiles at each wheel. Comparing Figures 14 and 18 reveal that the steering axle brakes of the simulated vehicle provided far more braking force than those of the test track vehicle, which explains the higher threshold speed achieved by the simulated vehicle.

Overall, the qualitative differences in results between the HiL simulations and test track experiments were minor. An exact match between test track and HiL data was not possible due to differences in the hardware between the tested vehicle and the simulation. Also, the constant speed maintained by the driver model in the HiL produced an effect that was more pronounced in the ESC than the RSC in the comparison with test track RSM data. However, the HiL system functionality and results were valid for a comparative analysis of system effectiveness for the constant speed driving scenarios developed in this study.

CONCLUSIONS

A HiL system has been developed by UMTRI to evaluate the effectiveness of stability control technologies in tractor-trailers. Driving scenarios have been developed to evaluate the effectiveness of ESC and RSC in addressing crashes involving directional loss of control and rollover. These scenarios have been created using LTCCS cases to replicate typical crash situations and have been linked to national crash data bases (GES, TIFA).

The HiL system was validated by NHTSA through a comparison of RSM test data. The results of the validation showed that the vehicle dynamics and hardware responses were comparable to actual tractor-trailer test track results. Differences in the test track conditions and the HiL system did not allow for a direct comparison of track data and simulated results. However, the data were useful for qualitatively checking the response of the HiL. The constant speed maintained by the driver model in the HiL produced an effect that was more pronounced in the ESC than the RSC in the comparison with test track RSM data. This resulted in the ESC system in the HiL activating approximately 0.2 seconds earlier than the system on the test track vehicle, but this was appropriate for the given simulated conditions. Despite the differences, the HiL system functionality and results were valid for a comparative analysis of system effectiveness for the constant speed driving scenarios developed in this study.

The fact that the HiL system provides valid predictions means that this HiL simulation environment can be used reliably to study heavy vehicle response with these technologies. This is true not only for evaluating RSC and ESC effectiveness in the driving scenarios developed in this study, but for other future scenarios that would be difficult or impractical test using an actual vehicle. The observed system effectiveness in varied driving situations from the HiL can be used for the determination of potential benefits of stability control by using driving scenarios that are linked to actual crash data populations.

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