

# Validation of Real Time Hardware in the Loop Simulation for ESC Testing with a 6×4 Tractor and Trailer Models

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## ABSTRACT

The tractor trailer models discussed in this paper were for a real-time hardware-in-the-loop (HIL) simulation to test heavy truck electronic stability control (ESC) systems [1]. The accuracy of the simulation results relies on the fidelity and accuracy of the vehicle parameters used. However in this case where hardware components are part of the simulation, their accuracy also affects the proper working of the simulation and ESC unit. Hence both the software and hardware components have to be validated.

The validation process discussed in this paper is divided into two sections. The first section deals with the validation of the TruckSim vehicle model, where experimental data is compared with simulation results from TruckSim. Once the vehicle models are validated, they are incorporated in the HIL simulation and the second section discusses the validation of the whole HIL system with ESC.

It is shown that the HIL simulation is able to predict the vehicle responses with a high degree of correlation even for limit dynamic maneuvers. This gives us confidence that the HIL simulations can be used to perform further, more severe tests which are not possible in the real world.

**CITATION:** Rao, S., Salaani, M., Heydinger, G., Guenther, D. et al., "Validation of Real Time Hardware in the Loop Simulation for ESC Testing with a 6×4 Tractor and Trailer Models," *SAE Int. J. Commer. Veh.* 6(1):2013, doi: 10.4271/2013-01-0692.

## INTRODUCTION

Testing heavy truck ESC systems is a cumbersome, time consuming, expensive and potentially dangerous process. Since the ESC algorithms used are proprietary, a purely software approach to testing is not feasible. Hence, validated HIL simulation is seen as a cost effective and reliable approach to quickly test commercial ESC systems for a diverse set of tractor-trailer and loading combinations.

This paper discusses the validation process of the vehicle models modeled in TruckSim followed by the validation of

the complete HIL simulation system. This is done to ensure first that the TruckSim models are accurate and have sufficient fidelity to reproduce experimental dynamics before incorporating it in the closed loop HIL system. The whole system is then validated to ensure that the hardware components incorporated into the simulation also produce accurate results.

For the TruckSim models, validation is done in two steps; the simulation is first validated using a quasi steady state maneuver followed by a more severe dynamic maneuver. This is done to ensure that the model is first able to replicate



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steady state responses of the vehicle. Dynamic validation maneuvers examine the ability of the model to replicate transient responses of the vehicle, like response time and overshoot.

## TRUCKSIM VEHICLE MODEL VALIDATION

A Volvo 6×4 tractor, a Great Dane 28' flat bed trailer and a Fruehauf 53' box trailer were modeled for use with a HIL system [1]. The validation of the two tractor trailer combination models with no ESC is discussed in this section.

### Volvo Tractor with Great Dane Flatbed Trailer

This section details the validation process of the Volvo tractor and Great Dane trailer combination. The Slowly Increasing Steer (SIS) maneuver results are discussed first, to compare the steady state response of the simulation with the experimental results, followed by the Sine with Dwell (SWD) and the Ramp Steer Maneuver (RSM) maneuvers which examine the transient response.

#### *Slowly increasing steer maneuver*

The SIS maneuver is used to characterize the vehicle behavior in steady state. This is a constant speed maneuver in which the steering angle is increased from 0 deg at a constant rate of 13.5 deg/s. In the results shown below, 30 mph (48 kph) was the maneuver speed with the tractor loaded to its gross vehicle weight rating (GVWR) using the tractor GVWR loading [1].

Figures 1, 2, 3, 4, 5 show the comparison between the TruckSim simulation and three experimental runs each for the left and right SIS maneuvers.

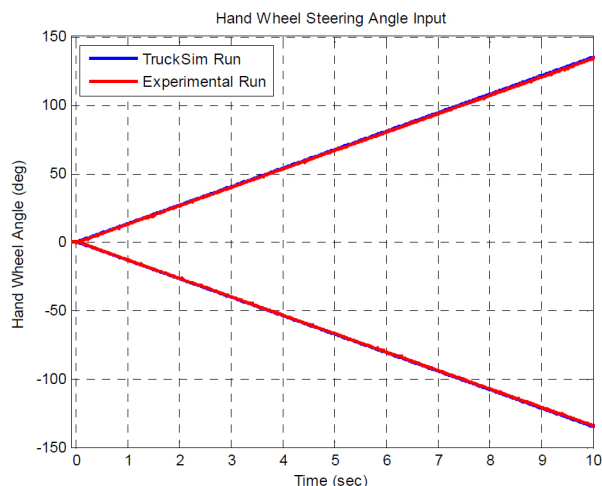


**Figure 1. SIS Maneuver Steering Wheel Angle Comparison for Volvo Tractor with Great Dane Trailer**

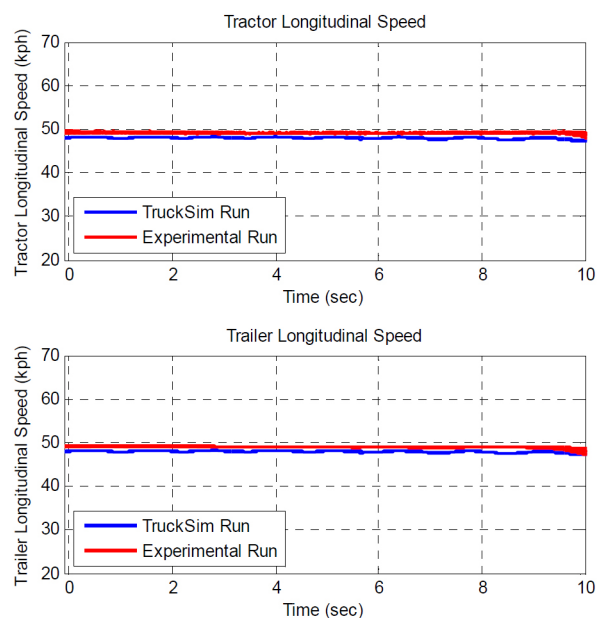


**Figure 2. SIS Maneuver, Tractor and Trailer Longitudinal Speed Comparison for Volvo Tractor with Great Dane Trailer**

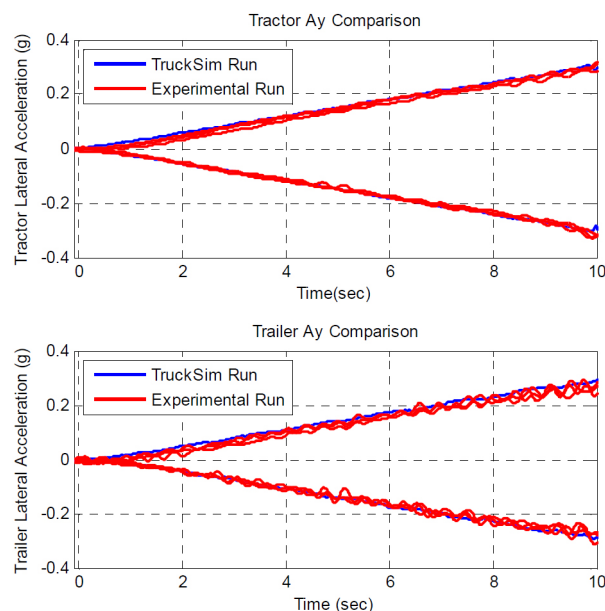


**Figure 3. SIS Maneuver, Tractor and Trailer Lateral Acceleration Comparison for Volvo Tractor with Great Dane Trailer**

It is apparent from the plots that there is good correlation between the TruckSim simulation and the experimental runs.

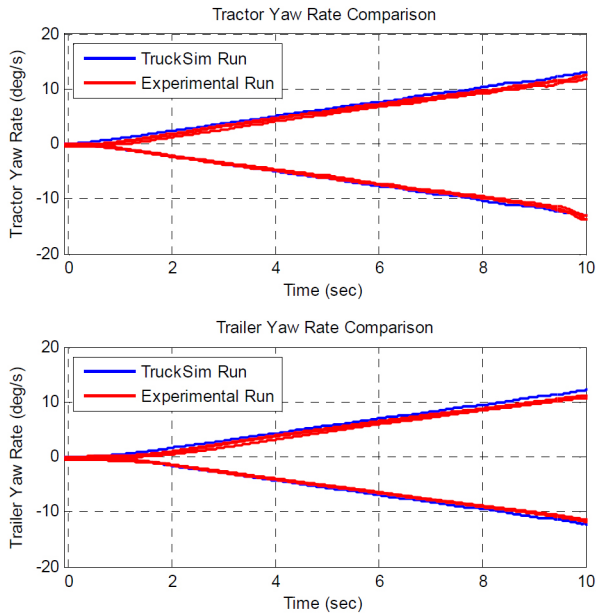


**Figure 4. SIS Maneuver, Tractor and Trailer Yaw Rate Comparison for Volvo Tractor with Great Dane Trailer**

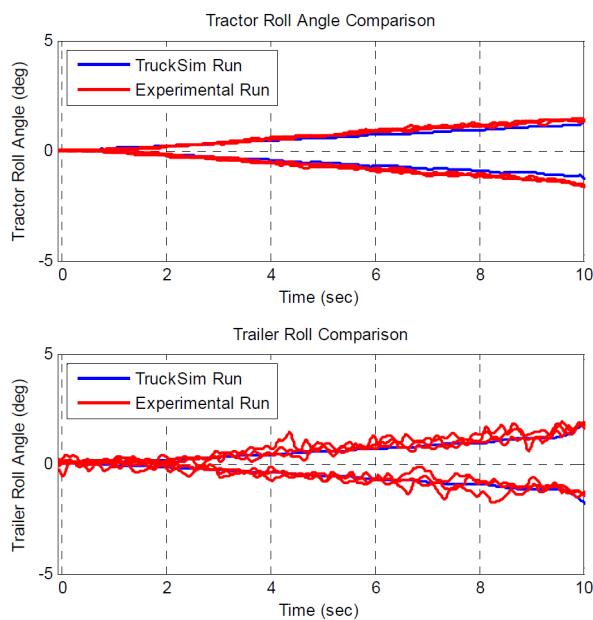


**Figure 5. SIS Maneuver, Tractor and Trailer Roll Angle Comparison for Volvo Tractor with Great Dane Trailer**

The SIS maneuver is also used as a characterization maneuver to find the steering wheel angle corresponding to 0.5 g of lateral acceleration. This is done by using a linear regression fit on the steering wheel angle versus lateral acceleration data up to 0.3 g. The regression equation is extrapolated to get the steering wheel angle corresponding to 0.5 g of lateral acceleration. This is called the 0.5 g steering wheel angle (0.5 g SWA) and is used as the benchmark for the SWD maneuver.

The 0.5 g SWA for the TruckSim simulation was calculated to be 220 deg, compared to 209 deg for the experimental runs. This is a difference of 5 %. This reiterates the fact that there is good correlation between the simulation and experimental runs with regards to steady state response.

### ***Sine with dwell maneuver***

The sine with dwell maneuver developed and used by NHTSA was designed to impart large lateral disturbance to a vehicle in order to study ESC performance. The sine with dwell maneuver is used in this section to validate the dynamic response of the TruckSim models without ESC. This is a drop throttle maneuver, where the vehicle is allowed to coast down from a preset initial speed while the steering input is provided. The steering input used is a 0.5 Hz sinusoidal wave with a 1sec dwell between the third and fourth quarter cycles. The maneuver entry speed is chosen to be 40 mph and the tractor is loaded to its GVWR using the tractor GVWR loading [1]. The test is repeated for various steering amplitudes, ranging from 25% of the 0.5 g SWA to when instability occurs, in 8.5% increments. Instability is said to occur when wheel lift is noticed (roll instability) or if the vehicle spins out/jackknifes (yaw instability).

Figures 6, 7, 8, 9, 10 show the comparison between the TruckSim simulation and experimental run at 68 % of the 0.5 g SWA. This corresponds to a hand wheel angle of 150 deg for the simulation and 143 deg for the experimental vehicle. The tractor GVWR loading [1] is used for this test. This is a near limit maneuver since both the simulation and experimental vehicles are unstable in the run of the next higher severity of 76 % of 0.5g SWA, where wheel lift was noticed in both the experimental and simulation runs.

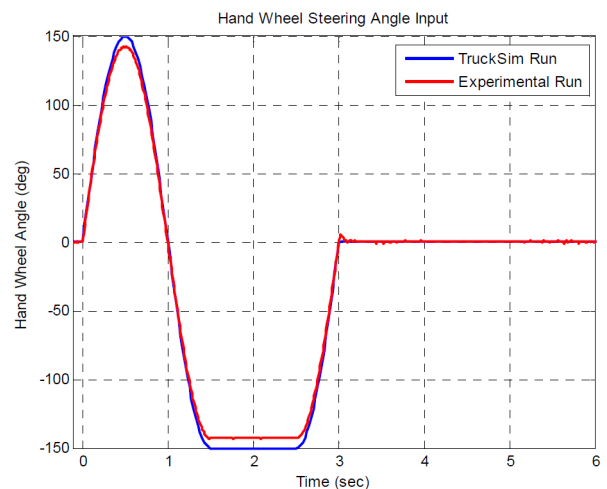


**Figure 6. SWD Maneuver Steering Wheel Angle Comparison for Volvo Tractor with Great Dane Trailer**

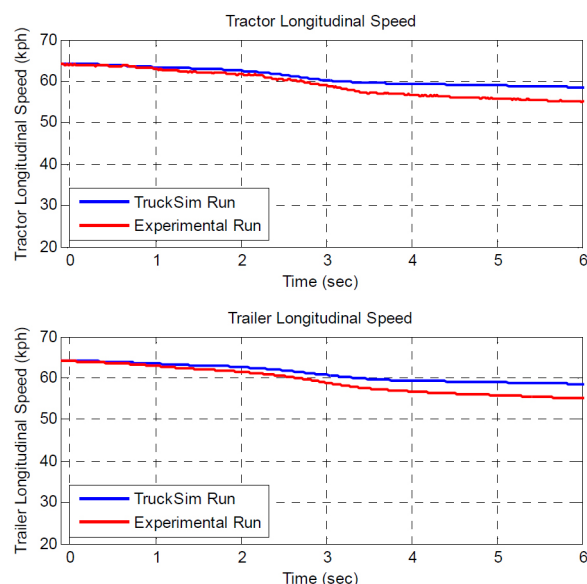


**Figure 7. SWD Maneuver, Longitudinal Tractor and Trailer Speed Comparison for Volvo Tractor with Great Dane Trailer**

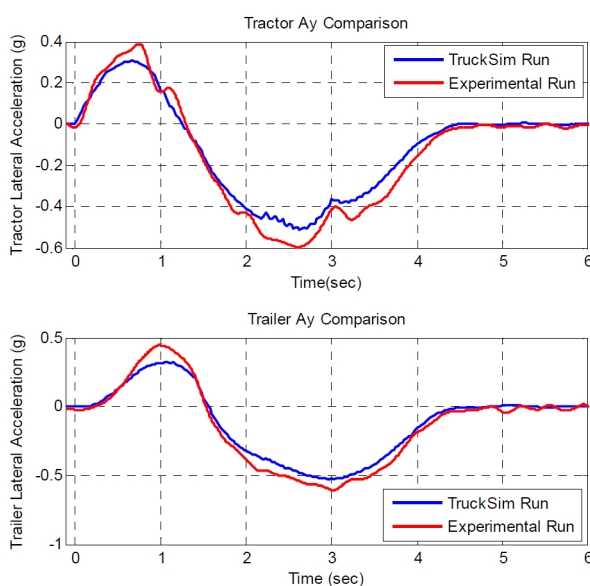


**Figure 8. SWD Maneuver, Tractor and Trailer Lateral Acceleration Comparison for Volvo Tractor with Great Dane Trailer**

It is apparent from the above plots that even for this near limit maneuver, there is very good correlation between the HIL simulation and the experimental run. These results reiterate the fact that the model predicts the vehicle behavior accurately and can be used for making further predictions about the behavior of the vehicle.

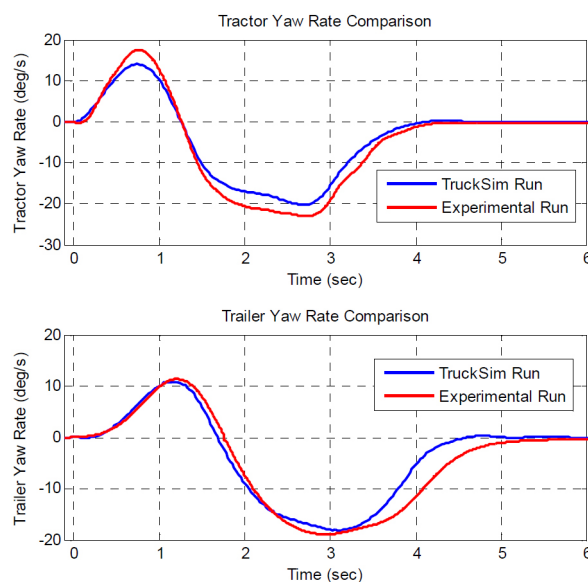


**Figure 9. SWD Maneuver, Tractor and Trailer Yaw Rate Comparison for Volvo Tractor with Great Dane Trailer**

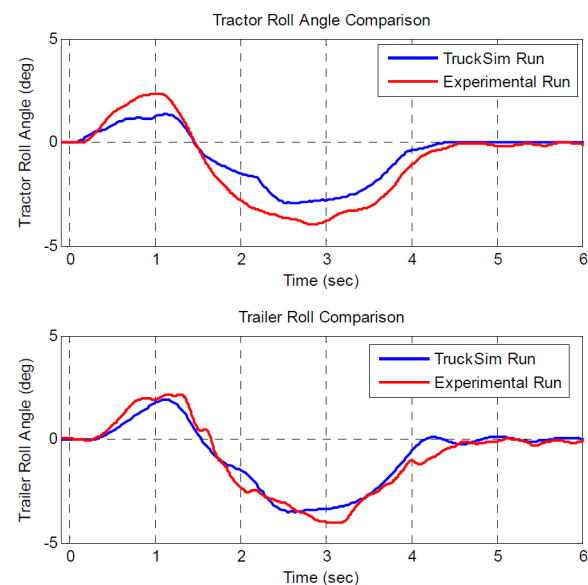


**Figure 10. SWD Maneuver, Tractor and Trailer Roll Angle Comparison for the Volvo Tractor and Great Dane Trailer**

## Volvo Tractor with Fruehauf Box Trailer

The validation of the Volvo tractor with the Fruehauf box trailer is detailed below. Here again the SIS maneuver is used to validate the steady state response of the simulation and the Ramp Steer Maneuver (RSM) is used to validate the dynamic response of the simulation. ESC is not activated in this section.

### Slowly increasing steer maneuver

As discussed earlier, the SIS maneuver is a quasi steady state maneuver. It is a constant speed maneuver where the hand wheel steering angle is changed from 0 deg at a constant rate of 13.5 deg/s. The maneuver speed is chosen to be 25 mph (40 kph) and a load of 9398 kg with an overall CG height of 2.26 m above the ground plane (High CG load [1]) is used.

Figures 11, 12, 13, 14, 15 show the comparison between the TruckSim simulation and three experimental runs each for the left and right SIS maneuvers.

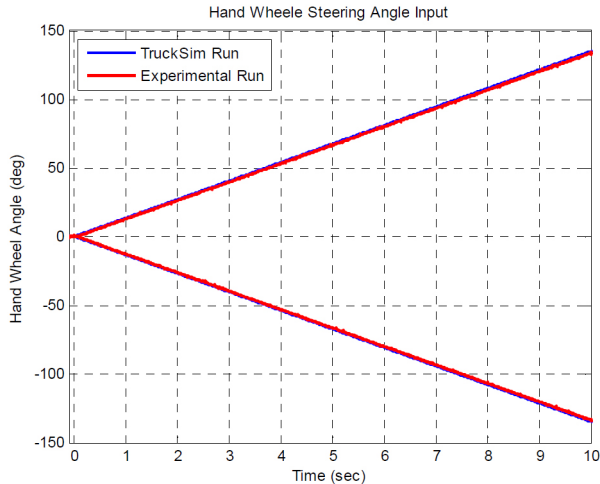


**Figure 11. SIS Maneuver Hand Steering Wheel Angle Comparison for Volvo Tractor with Fruehauf Box Trailer**

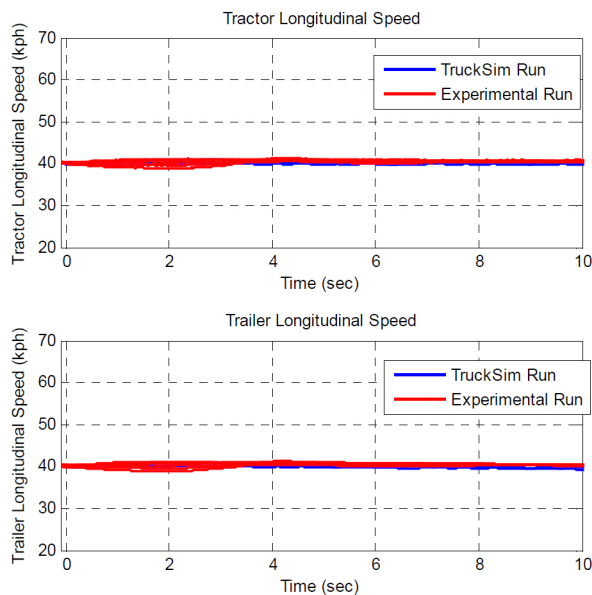


**Figure 12. SIS Maneuver, Tractor and Trailer Longitudinal Speed Comparison for Volvo Tractor with Fruehauf Box Trailer**

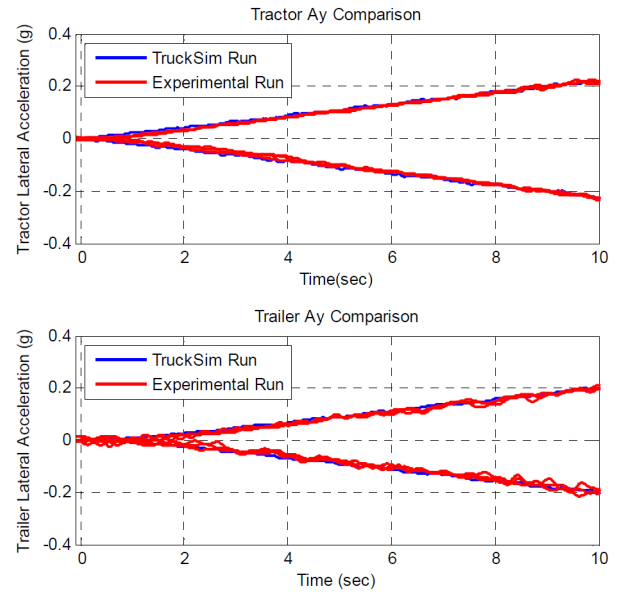


**Figure 13. SIS Maneuver, Tractor and Trailer Lateral Acceleration Comparison for Volvo Tractor with Fruehauf Box Trailer**

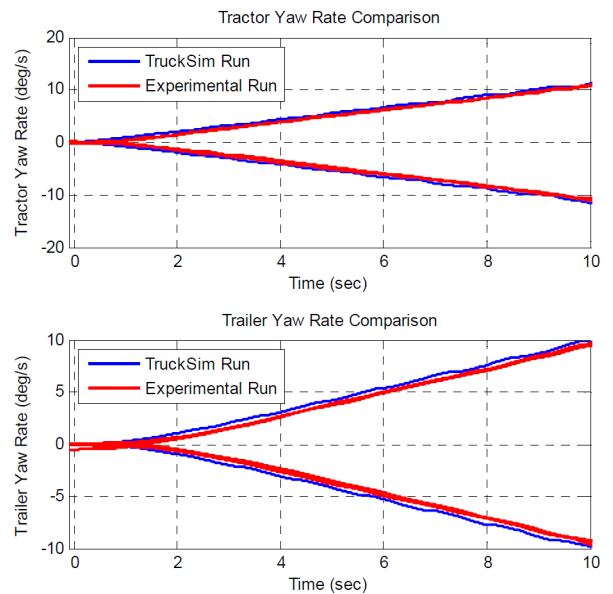


**Figure 14. SIS Maneuver, Tractor and Trailer Yaw Rate Comparison for Volvo Tractor with Fruehauf Box Trailer**

From the above plots, it is apparent that there is good correlation between the TruckSim simulation and the experimental runs for this maneuver. These results are used to calculate the 0.5 g SWA as discussed earlier. The 0.5 g SWA calculated from the TruckSim simulation is 303 deg, which compares to 291 deg from the experimental data. The difference is less than 4 % and this reiterates that the model predicts the vehicle behavior accurately.

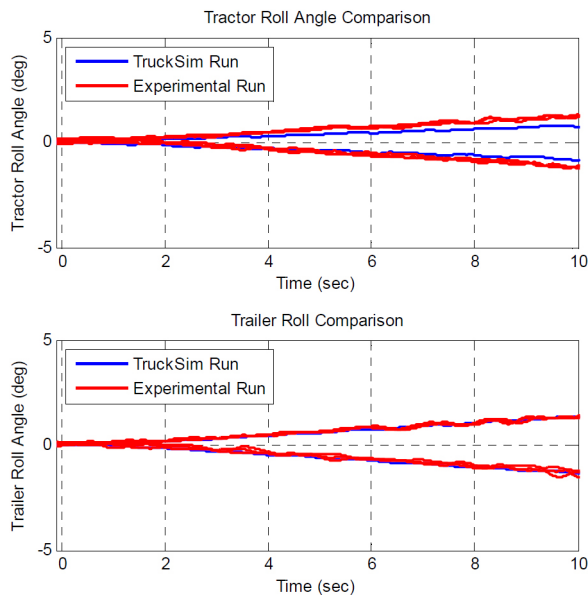


**Figure 15. SIS Maneuver, Tractor and Trailer Roll Angle Comparison for Volvo Tractor with Fruehauf Box Trailer**

### Ramp steer maneuver

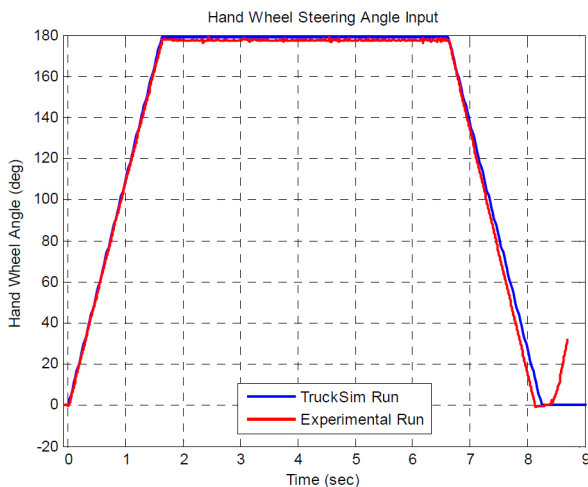


**Figure 16. RSM Maneuver Hand Wheel Angle Comparison for Volvo Tractor with Fruehauf Box Trailer**

The RSM, developed and used by NHTSA was designed to impart large roll disturbances to a vehicle in order to study rollover resistance. The RSM is used to validate the dynamic response of the model. This maneuver is a drop throttle maneuver, where the vehicle is let to coast down from a predetermined speed while the steering input is provided. The steering angle is increased from 0 deg to 179 deg at a rate of 110 deg/s and held there for 5 seconds and brought back to 0 at the same rate. The maneuver is repeated for initial vehicle speed starting from 20 mph in increments of 2 mph until

vehicle instability is noticed. Instability is when wheel lift greater than two inches is noticed.

Figures 16, 17, 18, 19, 20 show the results comparison for the 24 mph (40 kph) test. A load of 9398 kg with an overall CG height of 2.26 m above the ground plane (High CG load [1]) is used for this maneuver. The plots show that the model generates accurate predictions and that there is good correlation between the model and the experimental vehicle.

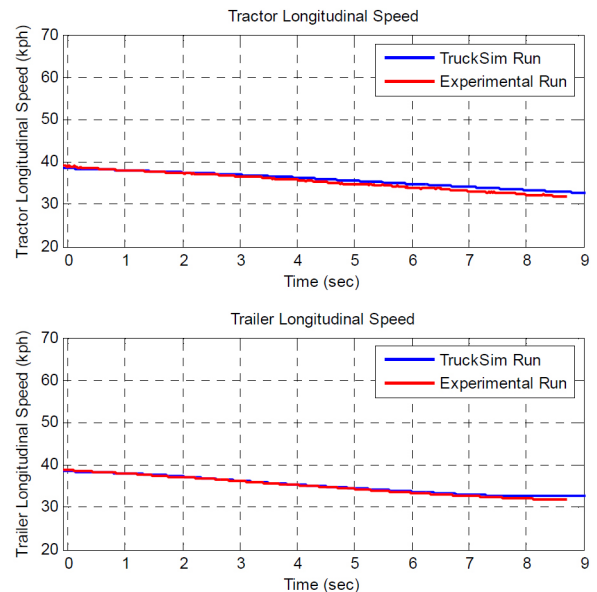


**Figure 17. RSM Maneuver, Tractor and Trailer Longitudinal Speed Comparison for Volvo Tractor with Fruehauf Box Trailer**

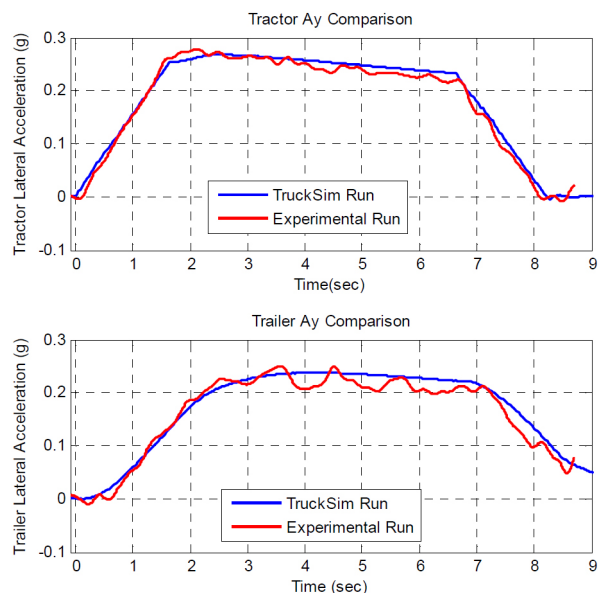


**Figure 18. RSM Maneuver, Tractor and Trailer Lateral Acceleration Comparison for Volvo Tractor with Fruehauf Box Trailer**