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Tractor Semitrailer Stability Objective Performance Test Research – Yaw Stability

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16. Abstract

This report documents the results from heavy-vehicle stability control (SC) system testing conducted by the National Highway Traffic Safety Administration's Vehicle Research and Test Center (VRTC) in 2008 and 2009. Tractor semitrailer SC research was conducted in three phases. Phase I (2006-2007) focused on understanding how heavy-vehicle stability control systems performed on the test track. Phase II (2007-2008) focused on the development of a dynamic test maneuver to challenge a tractor semitrailers roll propensity. This report documents Phase III research focused on the test track development of objective performance test maneuvers to challenge tractor semitrailers yaw stability.

Phase III of research focused on developing performance tests that challenged the capabilities of a tractor-based stability control system designed to mitigate loss-of-control situations related to tractor semitrailer yaw stability. Evaluated were automated maneuvers called the Sine With Dwell (SWD), Half-Sine With Dwell (HSWD), Ramp With Dwell (RWD), Ramp Steer Maneuver (RSM), 150 ft. Brake-in-Curve (BIC), and Slowly Increasing Steer (SIS). These maneuvers are representative of lane-change, obstacle-avoidance, or negotiating-a-curve crash scenarios. Using these maneuvers, three tractors (four stability conditions), and four trailers were tested, with and without stability control enabled. Tractors and SC systems were evaluated in bobtail and loaded conditions (in combination with the trailers), on high-friction dry asphalt and reduced-friction Jennite test surfaces. To keep the test matrices manageable, all maneuvers and tractors were evaluated with a single trailer for loaded test conditions. Data from these series was then used to select a surface, loading condition, and a reduced set of maneuvers with which to evaluate stability of the tractors combined with other trailers.

Using data from this test track research, several measures of performance (MOPs) were identified to have merit in evaluation of heavy-vehicle stability control systems. MOPs for both engine/power unit control and foundation braking were identified. Further, the SIS, RSM, and SWD test maneuvers were observed to be good performance maneuvers for evaluating tractor-trailer stability.

17. Key Words Heavy Vehicle, Tractor, Semitrailer, Trailer, Electronic Stability Control, Roll Stability Control, Rollover, Roll Propensity, Yaw Propensity, Yaw Control, Directional Control, Loss of Control, Jackknife, Ramp Steer Maneuver, Slowly Increasing Steer, Sine With Dwell, Half-Sine With Dwell, Lateral Acceleration Ratio, Yaw Rate Ratio	18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.gov

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report documents Phase III of tractor semitrailer stability control (SC) system testing conducted by the National Highway Traffic Safety Administration's Vehicle Research and Test Center (VRTC). Tractor semitrailer SC research at VRTC was conducted in three phases. Phase I (2006-2007) focused on understanding how tractor semitrailer SC systems performed on the test track. Phase II (2007-2008) focused on development of objective test maneuvers to challenge a tractor semitrailer's roll propensity. Phase III (2008-2009) focused on developing objective test track maneuvers that challenged the capabilities of a tractor-based SC system designed to mitigate loss-of-control situations related to yaw stability.

Initially, Phase III research was focused on evaluating maneuvers to assess the yaw stability of tractor semitrailer combinations. As preliminary test results were analyzed, it became apparent that the maneuvers and load conditions chosen for Phase III research were not only challenging these vehicles' yaw stability but additionally their roll stability. These initial results demonstrated that it was possible to have one maneuver and a single load condition that was capable of assessing both yaw and roll. This combined assessment of stability was referred to as lateral stability for this report.

The vehicles used in this phase of research include three tractors and four trailers that were also used in Phase II research. Those tractors were the 2006 Volvo 6x4 tractor equipped with electronic stability control (ESC): the 2006 Freightliner 6x4 tractor that was evaluated both ESC and roll stability control (RSC) controller modules: and the 2008 Sterling 4x2 equipped with RSC. These tractors were tested bobtail and in combination with VRTC's 28-foot Great Dane flatbed trailer. A limited number of tests were also performed with a 53-foot Strick box van trailer, a 48-foot Fontaine spread-axle flatbed trailer and a 43-foot Heil liquid tanker trailer. Trailers were tested with and without the trailer brake service line connected. With the service line disconnected the trailer brakes were rendered inactive (unbraked trailer)

Two load conditions were primarily used during Phase III testing: a bobtail configuration and a 60% of tractor gross axle weight rating (GAWR) configuration. Bobtail loading was chosen because it would evaluate the test vehicle's lateral stability and SC effectiveness without any undue influence of a trailer or ballast. The second loading condition, the 60% tractor GAWR, was chosen because crash data indicated that loss-of-control crashes were occurring with payloads as low as 5,000 lbs. For this load condition, between 6,800 and 15,500 lbs of ballast was placed onto the 28-foot flatbed trailer to achieve the desired 60% GAWR on the tractor's drive axles. Additional, testing with this load condition was also performed with the other three trailers.

This research evaluated the following maneuvers as possible objective tests: Sine With Dwell (SWD), Half-Sine With Dwell (HSWD), Ramp With Dwell (RWD), Ramp Steer Maneuver (RSM), 150-foot Brake-in-Curve, and Slowly Increasing Steer (SIS). These maneuvers are representative of lane change, obstacle avoidance, or negotiating-a-curve crash scenarios. All maneuvers were performed using a robot to control vehicle steering.

The Phase III research was initially started with the 0.7 Hz sine with 0.5-second dwell maneuver that is used in FMVSS No. 126 for light vehicles. A consequence of the physical size and mass of a tractor semitrailer combination vehicle is less sensitivity to quick transitional (left-right or right-left) steering inputs. For that reason, single direction steering inputs like the HSWD and RWD were also evaluated for lateral stability objective test development. The dynamic maneuvers were also performed at lower speeds, lower frequencies, and at multiple steering amplitudes with longer dwell times.

As with Phase II and FMVSS No. 126, the SIS test data were used to normalize steering inputs to be used for maneuvers. The steady-state SIS data were used to determine the steering wheel angle (SWA) projected to generate 0.5 g of lateral acceleration when traveling at 30 mph.

The Phase III research program used two test track surfaces with different levels of friction. Maneuvers were performed on dry asphalt (peak coefficient of friction of 0.9 to 1.0) and wet sealed asphalt (peak coefficient of friction of 0.2 to 0.5). The dry asphalt surface is desirable for repeatability and availability but is often perceived as generating rollover before loss of control. The lower friction surface was of interest to reduce the likelihood of rollover and to observe SC's ability to identify a yaw event and improve yaw stability.

Only a few yaw instabilities were observed during testing on the wet Jennite surface. For all maneuvers on this surface, 9 of 77 (4 of 43 SWD, 3 of 20 RSM, and 2 of 14 RWD) test series were terminated due to yaw instability (oversteer/spinout events). More yaw instabilities (oversteer/spinout events) were observed on high-friction dry asphalt compared to the number observed on the lower friction Jennite surface. On dry asphalt, 35 of 84 SWD test series and 28 of 56 HSWD series were stopped due to yaw instability. So, the remaining discussion for this summary of Phase III test results will focus on dry asphalt testing.

Selecting a Candidate Performance Maneuver

Comparing test results from the SWD and HSWD maneuvers conducted on the dry high-friction asphalt surface: both were capable of being developed into an objective performance maneuver. The large differences in test results between SC-enabled and disabled test series indicated that each would discriminate whether a tractor was equipped with an adequate SC system. The lowest steering scalar needed to attain a test series terminating condition was observed at frequencies that ranged from 0.4 to 0.5 Hz for the SWD and from 0.3 to 0.5 Hz for the HSWD. For two of the three series at these frequencies, the spread in the steering scalars needed to achieve instability was smaller for the SWD. This indicated that the vehicles were more sensitive to changes in the SWD's frequency and steering amplitudes.

Based on these results from the maneuver development research, the 0.5 Hz sine with 1.0-second dwell was determined to be the best candidate for an objective performance maneuver. More roll and yaw instabilities were observed with the SWD maneuver on the dry high-friction surface than any of the maneuvers conducted on the reduced-friction Jennite surface (SIS, RWD, RSM or SWD). On the dry surface, the tractors were more sensitive to changes in the SWD maneuver's frequency and steering amplitudes than the HSWD. The SWD maneuver was observed to be more repeatable and required less testing area than the 150 ft brake-in-curve maneuver. While the test results indicate SWD was the best candidate, there were other reasons to support its selection. First, it is representative of obstacle avoidance maneuvers that have been shown to lead to yaw instability, and second, its previous use in FMVSS No. 126 (ESC regulation covering vehicles with a GVWR of less than 10,000 lbs) accelerated the measure of performance research.

Measures of Performance

Test results were used to determine potential measures of performance. Observations of results from Phases I through III have shown that SC was able to improve stability of vehicles in which it was installed by exerting control over the engine and\or foundation brakes installed on the tractor and the semitrailer. Engine control by itself was observed to improve stability in situations where a vehicle's lateral limits were approached in a gradual manner. In situations where the limits of the vehicle were approached rapidly, the SC system needed to use foundation brakes to maintain lateral stability.

Phase II test results showed that the SIS maneuvers required engine control to maintain stability. Phase III test results showed that the SWD was the best candidate for evaluating dynamic lateral stability and that to remain stable in this maneuver required the SC systems to use foundation braking, differentially applied at individual wheel-ends as appropriate for the conditions. With these findings, several measures of performance were explored that could be used to evaluate the degree to which SC systems improved the vehicle's roll and/or yaw stability. Additional measures where developed that could provide an indication of vehicle responsiveness to driver inputs.

Torque data collected during SIS maneuver testing at the 60% tractor GAWR load condition from the vehicles' communication buses were analyzed. Driver requested torque and engine torque output measures were concluded to be useful measures to indicate that engine torque was reduced. During normal operation, the "driver requested torque" and "engine torque" measures were observed to be equal to each other. During SIS maneuvers, and once SC activated and invoked engine control the two measures were observed to separate. In all cases, the "engine requested torque was much less than the "driver requested torque."

Using 60% tractor GAWR test data from the 0.5Hz SWD (1.0-second dwell) maneuver, several potential measures of performance were investigated for assessing the lateral stability of tractor semitrailer combinations. Lateral acceleration ratio (LAR) and yaw rate ratio (YRR, similar to FMVSS No. 126) measures were preferred because they were easy to measure, filter, correct, and calculate versus more involved measures such as yaw angle, articulation angle, and wheel height. While LAR was not originally developed for assessing stability in the SWD maneuver it was easily adapted and applied to the maneuver.

Each 0.5 Hz SWD (1.0-second dwell) maneuver was assessed and determined to be either stable or unstable and assessed against the LAR and YRR measures. After assessing each test in this manner, statistical models were created for each candidate measure of performance that were then used to predict the lateral stability of a tractor semitrailer combination based on its residual LAR and/or YRR from the SWD maneuver.

Results from the statistical models show that LAR was a better measure for assessing the roll stability than YRR. LAR and YRR were both capable of assessing yaw stability, but the YRR measure was considered to be a more direct assessment of the yaw state of the vehicle.

A hypothetical way to improve stability would be to make the base vehicle or its SC system intervention such that the vehicle is unresponsive to the steering inputs. This would degrade maneuverability required to avoid an obstacle. A "responsiveness" measure was used to assess the ability of the test vehicle to maintain a balance between lateral stability and the ability of the vehicle to respond to driver's inputs. The responsiveness or lateral displacement measure was determined the same way as prescribed by FMVSS No. 126. For tractor semitrailers the responsiveness would be measured at 1.5 seconds after the initialization of the maneuver.

Three SC test conditions were evaluated: SC disabled, SC enabled with semitrailer brakes, and SC enabled without semitrailer brakes. In each test condition, all three tractors demonstrated good lateral displacement response to the range of steering inputs. This means that the SC systems demonstrated a good balance between lateral stability and the ability of the vehicle to respond to the steering input.

1 INTRODUCTION

Heavy-vehicle stability control systems have been developed to help reduce crashes involving rollover and loss-of-control of truck tractors, motorcoaches, and other heavy vehicles. Two types of stability control systems have been developed for truck tractors– roll stability control (RSC) and electronic stability control (ESC). RSC is designed to mitigate on-road, untripped truck rollovers by automatically decelerating the vehicle by applying the foundation brakes and reducing engine torque. ESC is designed to mitigate oversteer or understeer conditions that can lead to vehicle loss-of-control, by automatically applying selective brakes to generate a yawing moment that helps the driver maintain directional control of the vehicle. On heavy vehicles, ESC also includes the RSC function described above.

1.1 Truck-Tractor Lateral Stability Prior Research

There is a large body of research and literature in the area of longitudinal dynamics as a result of the many years of heavy-vehicle braking research. Effects of load transfer, brake type, and Antilock Brake System (ABS) are well documented. However, much less is understood about the lateral dynamics of contemporary heavy vehicles.

Lateral dynamics can be discussed in terms of their effect on the roll and yaw planes of the vehicle. In recent years, a focus on untripped heavy-vehicle rollover has been emphasized in the research. This has largely been driven by technological advancements in sensing and braking technology. Since the mid 1990's researchers have had the ability to mitigate untripped rollover crashes by applying the brakes when a critical lateral acceleration level is exceeded. This technology was applied in terms of a driver warning system (roll stability advisor) and an active safety system (roll stability control) [4]. These stability systems were also shown to be effective in reducing rearward amplification of trailer oscillations in double and triple trailer combinations [5]. NHTSA has conducted field operational tests (FOT) [6, 7] and test track research that has demonstrated positive safety benefits for such systems.

In a recent review of the literature, much of our understanding of heavy-vehicle yaw stability comes from work performed over 30 years ago. In 1979, the University of Michigan's Transportation Research Institute (UMTRI) [8] examined the yaw stability of a tractor semitrailer during steering only maneuvers. The study found that tractor semitrailer yaw instability was found at "elevated" levels of lateral acceleration in a steady-turn maneuver. Their results demonstrated that yaw instability can occur well below the rollover threshold for certain vehicles under the right conditions.

UMTRI identified several factors that increase the likelihood of yaw instability with a loaded vehicle. These include a forward bias in the distribution of tire cornering stiffness, rearward placement of the fifth wheel coupling, a high center of gravity location of the trailer payload, and low roll stiffness of the trailer's suspension. UMTRI reported that a rear-biased distribution in suspension roll stiffness is the most significant factor that promotes yaw instability. Other tractor-based design parameters found to degrade yaw instability included: low torsional stiffness of the frame, a short wheelbase, and a single drive axle.

Over time many of these design parameters have changed. Improvements have been made in tire design, suspension roll and torsional stiffness, and overall tractor design. Nevertheless, the lateral stability testing described below has shown that it is still possible to experience severe oversteer conditions while operating modern tractors.

1.2 Recent NHTSA Truck Tractor Lateral Stability Research

Researchers at NHTSA's Vehicle Research and Test Center in East Liberty, Ohio, initiated a test program in 2006 to evaluate the performance of commercial vehicle stability control (SC) systems under controlled conditions on a test track. Test vehicles included three tractors equipped with either RSC or ESC, one semitrailer equipped with trailer-based RSC, and three motorcoaches equipped with ESC. Tractor performance was evaluated in conjunction with six baseline semitrailers not equipped with a SC system.

The testing was conducted in three phases. Phase I focused on understanding how heavy-vehicle stability control systems performed. Phase II focused on the development of a dynamic test maneuver to challenge a tractor semitrailer's roll propensity. Finally, Phase III focused on the development of a dynamic test maneuver to challenge tractor semitrailer's yaw stability.

The Phase I and II research results are documented in the VRTC report "Tractor Semitrailer Stability Objective Performance Test Research – Roll Stability" [1]. Results from Phase I are also summarized the in the paper "NHTSA's Class 8 Truck-Tractor Stability Control Test Track Effectiveness"[2].

This document contains Phase III information regarding NHTSA VRTC's development of performance tests for truck tractors equipped with ESC systems. Performance tests plus measures-of-performance (MOP) have been developed to evaluate ESC systems ability to mitigate loss of control of truck tractor semitrailer combinations.

1.3 Study Objectives

For this research, NHTSA performed objective testing of commercially available ESC systems. This testing included only truck tractor-based technologies. The goal of this testing was to:

1. Understand how tractor-based SC systems modify the handling characteristics of a tractor semitrailer as compared to the base vehicle without SC.
2. Determine which maneuvers best quantify truck semitrailer lateral stability performance.
3. Develop an objective test that can discriminate between a tractor with and without SC technology.
4. Develop an objective test that is valid in terms of a "real-world" maneuver that drivers of tractor semitrailer combinations may perform.
5. Develop metrics that ensure the SC system's ability to mitigate loss of stability.

1.4 Crash Problem

According to FMCSA's Large Truck and Bus Crash Facts 2008[3], the overall crash problem for tractor-trailer combination vehicles is approximately 181,000 crashes, 51,000 MAIS 1-5 injuries, and 3,151 fatalities annually. Tractor-trailer combination vehicles are involved in about 74 percent of the fatal crashes involving large trucks, annually. These vehicles had a fatal crash involvement rate of 1.92 crashes per 100 million vehicle miles traveled (VMT) during 2008, whereas single unit trucks had a fatal crash involvement rate of 1.24 crashes per 100 million VMT. Combination vehicles represent about 25 percent of large trucks registered but travel 63 percent of the large truck miles, annually. Heavy-truck loss-of-control (LOC, also referred to as loss of directional stability, loss of yaw stability, jackknife, spinout, or plow) and rollover crashes are also a major cause of traffic tie-ups, resulting in millions of dollars of lost productivity and excess energy consumption each year. Primarily because of the high crash exposure rate for tractor semitrailer combination vehicles, NHTSA is researching stability control systems for these vehicles first.

UMTRI [9] estimated the annual number of fatalities, injuries, and crashes for the two types of SC systems.

- If all tractors in the United States were equipped with RSC systems, then 3,489 crashes, 106 fatalities, and 4,384 injuries were projected to be prevented annually.

- If all tractors in the United States were equipped with ESC systems, then 4,659 crashes, 126 fatalities, and 5,909 injuries were projected to be prevented annually.

1.5 Contributing Factors in Rollover and Loss-of-Control Crashes

Many factors related to heavy-vehicle operation, as well as factors related to roadway design and road surface properties, can cause heavy vehicles to become yaw unstable or to experience a rollover. Described below are several real-world situations where roll or yaw instabilities might occur and stability control systems may prevent or lessen the severity of crashes[3]:

- **Speed too high to negotiate a curve** - Entry speed of vehicle is too high to safely negotiate a curve. When the lateral acceleration of a vehicle during a steering maneuver exceeds the vehicle's roll or yaw stability threshold rollover or loss of control is initiated. Curves can present both roll and yaw stability issues to these types of vehicles due to varying heights of loads (low versus high, empty versus full), and surface friction levels(ice versus snow versus wet versus dry)

- **Sudden steering maneuvers to avoid a crash** – Driver makes an abrupt steering maneuver, such as a single or double lane change maneuver, or attempts to perform an off-road recovery maneuver, generating a lateral acceleration that is sufficiently high to cause a rollover or causing the vehicle to become yaw unstable. Maneuvering a vehicle on off-road, unpaved surfaces such as grass, gravel, or dirt may require a larger steering input (larger wheel slip angle) to achieve a given vehicle response, and this can lead to a large increase in lateral acceleration once the vehicle returns to the paved surface.

- **Loading conditions** – Vehicle yaw due to over-steer is more likely to occur when a vehicle is in a lightly loaded condition and has a low center of gravity height. Heavy-vehicle rollovers are much more likely to occur when the vehicle is in a fully loaded condition as a result of a high center of gravity height. Cargo that is placed off-center in the trailer will result in the vehicle being less stable in one direction than the other. It is also possible that improperly secured cargo can shift while the vehicle is negotiating a curve, thereby reducing roll or yaw stability. Sloshing can occur in tankers transporting liquid bulk cargoes. This condition is of particular concern when the tank is partially full because the vehicle may experience significantly reduced roll stability during certain maneuvers.

- **Road surface conditions** – The road surface condition can also play a role in the LOC a vehicle experiences. On a dry, high-friction asphalt or concrete surface, a tractor-trailer combination vehicle executing a severe turning maneuver is likely to experience a high lateral acceleration, which may lead to a rollover or LOC. A similar maneuver performed on a wet or slippery road surface may result in LOC.

- **Road design configuration** – Some drivers may misjudge the curvature of ramps and not brake sufficiently to negotiate the curve safely. This includes ramps with decreasing radius curves as well as curves and ramps with improper signage. A decrease in super-elevation (banking) at the end of a ramp where it merges with the roadway causes an increase in vehicle lateral acceleration (and may be accompanied by the driver accelerating in preparation to merge).

- **Braking maneuvers** – Most common heavy-vehicle LOC (jackknife) events occur due to rear wheel lockup during braking. If the rear wheels are locked, they cannot generate any lateral force and only a very small side force (roadway crown or slight trailer angle) is needed to cause the tractor to lose directional control. Also, loss of steering control or "plow-out" can occur due to front wheel lockup, although this is most likely to happen on a heavy vehicle under light loading conditions and slippery road surfaces. Since most jackknife crashes are caused by lockup of the tractor's rear wheels during braking, the requirement for antilock brake systems on truck tractors, effective since 1997, has addressed a portion of the loss-of-control crashes due to wheel lockup during hard braking. SC systems are expected to further reduce crashes while braking in a maneuver.

- **Vehicle factors** – Severely worn tires (tread depth below 2/32 inch) are more likely to contribute to vehicle spinout or plow out under wet slippery conditions. The condition of the vehicle's brakes, including brake adjustment, is critical in enabling the driver to reduce speed for upcoming curves, and also to prevent brake fade from occurring on long downhill grades. Replacing tires that have insufficient tread depth and maintaining the ABS in proper operating condition are critical in preventing jackknife events and trailer swing during panic braking. Both RSC and ESC are enhancements to the ABS platform and for all of these systems to work properly, foundation brake systems and tires must be maintained in proper operating condition.

1.5.1 Determining Factors Contributing to Lateral Instability

A study by UMTRI [9] provides crash analysis regarding rollover and LOC crashes by:

- roadway alignment,
- surface condition,
- trailer cargo weight,
- trailer body style,
- crashes on ramps,
- speed zones, and
- ambient light conditions.

Results from this study were used to support research efforts for identifying potential yaw stability performance maneuvers, maneuver entrance speeds, vehicle mass configurations, and test surfaces.

1.5.2 Potential Maneuvers

The UMTRI study was able to identify, from crash data, the configuration of roads upon which lateral instability occurred. From this analysis they reported 8,674 crashes (over the period 2000 to 2004) on curved sections of roadways and 12,006 crashes on straight sections of roadway. For curves this indicated that drivers were unable to maneuver/negotiate the directional change and the vehicles responded by either understeering or oversteering which may have eventually resulted in a tripped rollover. Maneuvers relating to LOC crashes on straight sections of roadway are open to more interpretation. However, for lateral instability to occur on a straight section of roadway the driver must initiate a directional change in the vehicle (exceptions include vehicle mechanical failures, and high winds, and crashes with other motor vehicles that can initiate unintended directional changes). For straight roads common maneuvers are single and double lane changes, off-road recovery maneuvers, and crash avoidance maneuvers. Generally speaking, these maneuvers require a transient steering input, meaning the steering wheel is turned to change the direction of travel and a second or third input in opposite directions are necessary to redirect the vehicle to remain on the roadway. So a potential yaw performance maneuver should test the ability of a vehicle to negotiate a curve or a transient steering maneuver (straight roadway maneuver). Several test track maneuvers have been developed that replicate these real world maneuvers, including SWD (transient maneuver, HSWD (curve maneuver), NHTSA fishhook (transient maneuver), pulse steer (curve maneuver), J-turn (curve maneuver), RSM (curve maneuver), SISM (curve maneuver), and RWD maneuvers (curve maneuver). VRTC evaluated these types of maneuvers to identify a candidate for a possible yaw stability performance test for truck-tractors.

The UMTRI report also indicates the odds of a crash occurring in a curve are 4.7 times greater than on straight sections of roadway, even though there are 38 percent more crashes on straight roads than curved.

1.5.3 Potential Maneuver Speeds

For these same crash data, the data were sorted into three bins indicating ranges of speed limits for which crashes occurred. For speed limits that ranged from 0-35mph there were 3,966 crashes (again over a 5-year period, 2000 through 2004) related to LOC. For speed limits that ranged from 40 to 55 mph there were 11,387 crashes related to LOC. For speed limits over 55 mph there were 5,326 crashes related to LOC. Though this information was not intended to be used in the selection of a maneuver entrance speed it does correlate well with the range of speeds, 30 to 50 mph, that are currently being evaluated with the potential maneuvers. Maneuvers with speeds greater than 50 mph were not evaluated during our test track research due to driver safety concerns and space limitations.

1.5.4 Vehicle Mass Configurations

Trucks in Fatal Accidents (TIFA) was the only crash database that contained the data needed to perform an analysis regarding vehicle cargo mass and LOC. Thirty-six fatalities were observed when the vehicles in crashes had payloads up to 5,000 lbs. The number of fatalities decreased to 24 when the vehicles had payloads between 5,001 and 20,000 lbs and increased to 100 fatalities for crashes in which the vehicles had a payload of more than 20,000 lbs.

Uniform loading criteria were developed and tested for implementation into a test procedure. The loads evaluated for this research ranged from empty to 60 percent of their gross axle weight rating (GAWR) of the drive and intermediate axles. For the vehicles in VRTC's test fleet this range equates to a payload with a range up to 15,500 lbs. This payload range overlaps the two lower categories for payload from the UMTRI study of the TIFA database.

1.5.5 Potential Test Surfaces

The UMTRI study shows that LOC crashes were recorded with surface conditions that spanned roadways that were dry, wet, and snow- or ice-covered. From the crash databases they were able to bin crashes into 3 categories of roadway surface conditions. 3,466 crashes (again 2000 to 2004) were observed on roadways that were snow- or ice-covered. 3,517 crashes were recorded on wet roadways and 13,696 crashes were recorded on dry roadways. To relate this information to a potential test surface these three categories have generalized surface friction ranges. Snow- and ice-covered asphalt or concrete roadways typically have peak friction coefficients of 0.4 or less. Wet asphalt or concrete roadways typically have peak friction coefficients that range from 0.41 to 0.85 and dry asphalt or concrete roadways typically have peak friction coefficients above 0.86. Four test surfaces that span the friction observed for the crash data surface conditions were considered for the yaw stability research. These surfaces are part of the Vehicle Dynamics Area at TRC Inc. The first is a large asphalt mix pad with a nominal peak friction design of 0.9 when dry and 0.85 when wet. The second is a surface called the Jennite (sealed and polished asphalt sealer) which is used only when wet and has a nominal peak surface friction design of 0.3. The third surface is a wet basalt tile surface it has a nominal peak surface friction design of 0.3. The fourth surface is a wet ceramic tile surface it has a nominal peak surface friction design of 0.2. Though these surfaces were designed to have specific friction coefficients; measurements from 2008 show that each of the surfaces changed over time. Table 1.1 presents the maximum, minimum, average, and standard deviations of measured peak and slide coefficients of friction from 2008 for all four surfaces.

Table 1.1. The table below provides the maximum, minimum, average, and standard deviation of peak and slide coefficients of friction from several test surfaces that include asphalt, Jennite, basalt tile, and ceramic tile surfaces located at TRC from 2008. Additionally it provides the ambient temperature that each measurement was taken.

`	VDA		VDA		VDA	VDA		VDA		VDA		Average ambient temperature over the days of this monitor session (°F)
Pad #	V-5, dry		V-5, wet		V-8	V-9		B-1		C-1		
Pavement	Asphalt		Asphalt		Asphalt	Asphalt		Basalt Tile		Ceramic Tile		
Surface	Untreated		Untreated		Jennite	Jennite		Untreated		Untreated		
Condition	Dry		Wet		Wet	Wet		Wet		Wet		
Peak/Slide	PBC	SN	PBC	SN	PBC	PBC	SN	PBC	SN	PBC	SN	
Nominal #	90	80	85	65	30	30	10	30	10	20	10	
Maximum	103	88	91	64	38	38	16	26	30	25	20	76
Minimum	91	81	64	49	19	18	6	4	13	3	7	27
Average	96	85	81	59	27	30	11	16	19	12	12	59
Standard Deviation	3.1	1.7	6.9	4.1	5.4	6.4	4.1	4.8	4.9	6.3	3.6	16.8

The table shows the standard deviation for both peak and slide coefficients of friction of the dry asphalt surface were lower than the other three surfaces/conditions shown. This indicates that tests conducted on this surface will have better repeatability over time and season changes. Of these four surfaces only two were evaluated for the yaw stability performance test.

The dry asphalt surface was selected for its consistency, frequency of occurrence in the real-world, and size of the test area. This surface provides frictional characteristics similar to dry roadway conditions that were observed in over 13,000 LOC crashes. The wet Jennite was selected for a low-friction surface due to its frequency of occurrence in the real-world and size of the test area. This surface provides frictional characteristics that approximate friction levels associated with snow and ice upon which 3,400 LOC crashes were observed. The basalt and ceramic surfaces were not selected for further research because they are relatively less common and have space and weight limitations that make them infeasible for truck-tractor testing. Wet asphalt was also not selected for further research because it had the largest standard deviation of friction and logistically would have been difficult to consistently apply enough water for a sufficient test maneuver area.

2 HEAVY-VEHICLE STABILITY CONTROL

2.1 Types of Heavy-Vehicle Stability Control Systems

Heavy-vehicle stability systems are being sold in North America in three different configurations. These include:

- Trailer-based roll stability control (RSC).
- Tractor-based RSC.
- Tractor-based electronic stability control (ESC).

Trailer-based RSC is capable of generating torque at the trailer axle brakes only. These systems generally do not improve the stability margin by as much as the tractor-based systems. Stability margin is defined as the ratio between the vehicle's performance with the technology compared to its performance without.

Tractor-based RSC is capable of applying brake torque to the wheels on the tractor drive axles and the trailer axles. Tractor-based RSC systems generally improve the stability margin by a larger amount than do trailer-based systems. This is because they are able to reduce engine torque electronically on the tractor in addition to applying the brakes on the tractor drive axles and the trailer axles, resulting in more total braking torque than trailer-based systems. The tractor will experience lateral forces before the trailer. With a proper understanding of the combination vehicle's dynamics, the stability system can intervene earlier during the event since the tractor-based stability system is sensing tractor lateral acceleration. The stability system can reduce engine torque by electronically removing the driver's throttle input and by activating engine or exhaust braking. Having the ability to control the tractor's drive axle wheels in addition to the trailer axle wheels allows the combination vehicle to decelerate more rapidly. These contributing factors have been observed to increase the combination vehicle's stability margin when compared to a combination vehicle with just trailer-based RSC.

Tractor-based ESC includes the same functionality as tractor-based RSC along with additional performance capabilities. Tractor-based ESC adds the capabilities of braking the steer axle wheels, sensing the steering wheel position, and measuring the tractor's angular yaw rate. With the addition of these capabilities, the ESC system can not only assist drivers in reducing the vehicle dynamics that lead to rollovers but can also reduce or increase the vehicle dynamics that lead to yaw instability events.

Table 2.1 documents the capabilities of the three systems. The table shows the similarities and differences in terms of sensor inputs and control outputs for each type of system.

Table 2.1. Differences between heavy stability control technologies in terms of input and outputs.

Stability Control Technology	Inputs				Outputs				
	Wheel Speed	Lateral Acceleration	Steer Angle	Yaw Rate	Throttle Reduction	Engine Retarder	Trailer Brakes	Drive Axle Brakes	Steer Axle Brakes
Tractor-Based ESC (Roll and Yaw)	X	X	X	X	X	X	X	X	X
Tractor-Based RSC	X	X			X	X	X	X	
Trailer-Based RSC	X	X					X		

3 TEST METHOD

3.1 Test Vehicles

For this research, three truck tractors (one tractor used two SC systems) and four test trailers were used. All testing involved the use of instrumentation and safety equipment on each truck tractor and trailer. The following sections provide descriptions of the truck tractors, trailers, instrumentation, and the test safety equipment used in performing this research. For complete detailed information on each truck tractor and trailer, please refer to Appendix C.

3.1.1 Truck Tractors

Three truck tractors were chosen for research described in this report: a 2006 Freightliner 6x4, a 2006 Volvo 6x4, and a 2008 Sterling 4x2. Each truck tractor had an RSC and/or ESC system installed. In the case of the Freightliner, it had the capability to be tested with either an RSC or ESC system, depending upon which SC module was installed. Table 3.1 documents the truck tractors used in this study.

Table 3.1. Truck tractors tested.

Year	Make	Model	Type	ESC Supplier / Type
2006	Volvo	VNL 64T630	6x4	Bendix ESP
2006	Freightliner	Century Class	6x4	Meritor Wabco ESC or Meritor Wabco RSC
2008	Sterling		4x2	Meritor Wabco RSC

3.1.2 Trailers

Four test trailers were used for the research described in this report: a Fontaine spread- axle flatbed, a Great Dane flatbed, a Strick box van, and a Heil tanker. Each test trailer had air brakes and an air-bag suspension system. Table 3.2 documents the trailers used in this study.

Table 3.2. Trailers tested.

Year	Make	Type	Length (feet)	ESC Supplier / Type
2007	Strick	Dry Box Van	53	None
2007	Fontaine	Flatbed (spread axle)	48	None
2007	Heil	9200 Gallon Tanker	42	None
2003	Great Dane	Flatbed (121-style control trailer)	28	None

3.1.3 Instrumentation

All vehicles evaluated during this research were instrumented with sensors, data acquisition systems, and a programmable steering machine. This section briefly describes the test equipment and instrumentation used. For detailed information, please refer to Appendix B.

Truck Tractor**:** Table 3.3 describes the sensors used by NHTSA to measure the truck tractor's responses. Sensors are listed with the data channel measured in the first column of the table.

Additional columns list the sensor type, sensor range, sensor manufacturer, and sensor model number.

Test Trailer**:** Table 3.4 describes the sensors used by NHTSA to measure the trailer's responses. Sensors are listed with the data channel measured in the first column of the table. Additional columns list the sensor type, sensor range, sensor manufacturer, and sensor model number.

Table 3.3. Truck Tractor Sensor Information.

Data Measured	Type	Range	Manufacturer	Model Number
Steering Wheel Angle	Angle encoder	±720 degrees	Automotive Testing, Inc.	Integral with ATI steering machine
Brake Treadle Application	Switch (normally open)	On/Off	NA	NA
Throttle Position	Direct tap OEM sensor	0-4.5 volts	NA	NA
Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Multi-Axis Inertial Sensing System	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	BEI Technologies Systron Donner Inertial Division	MotionPak Multi-Axis Inertial Sensing System MP-1
Frame Rail Height(L/R) (to determine roll)	Non-contact infrared beam	12-51 inches	Wenglor	HT77MGV80
Rear Axle Height(L/R) (to determine lift)	Non-contact infrared beam	14-35 inches	Wenglor	HT66MGV80
Vehicle Speed	GPS Non-contact 100 Hz speed and distance	0.1-1000 mph	RaceLogic	VBOX III SPS 100HZ GPS speed sensor
Glad Hand Valve Pressure	Volt output pressure transducer	0-200 psi	Transducers Direct.	TDG-AD2F2002GAA0022

Table 3.4. Test Trailer Sensor Information.

Data Measured	Type	Range	Manufacturer	Model Number
Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Multi-Axis Inertial Sensing System	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	Crossbow	VG300CB(DMU-VGX)
Rear Axle Height(L/R) (to determine lift)	Non-contact infrared beam	14-35 inches	Wenglor	HT66MGV80
Frame Rail Height (to determine roll)	Non-contact infrared beam	12-51 inches	Wenglor	HT77MGV80

CAN data from the SAE J1939 [12] and/or SAE J1708 [13] bus were recorded when available. Table 3.5 describes the Suspect Parameter Numbers (SPNs) that were recorded when available. Signals are listed with the data channel measured in the first column of the table. Additional columns list the SPN, data length, resolution, data range, and type of measure.

Table 3.5. J1939 Vehicle Bus Information.

Data Recorded	Suspect Parameter Number	Data length	Resolution	Data Range	Type
Accelerator pedal Position 1	SPN 91	1 byte	0.4%/bit, 0 offset	0 to 100 %	Measured
VDC Fully Operational	SPN 1814	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
VDC Brake Light Request	SPN 1815	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
VDC ROP Engine Control Active	SPN 1816	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
YC Engine Control Active	SPN 1817	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
ROP Brake Control Active	SPN 1818	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
YC Brake Control Active	SPN 1819	2 bits	4 states/ 2 bit, 0 offset	0 to 3	Status
Actual Engine – Percent Torque	SPN 513	1 byte	1%/bit, -125 % offset	-125 to 125 %	Measured
Drivers Demanded Engine – Percent Torque	SPN 512	1 byte	1%/bit, -125 % offset	-125 to 125 %	Measured

3.1.4 Steering Controller

A programmable steering machine produced by Automotive Testing, Inc. (ATI) was used to provide steering inputs for all Phase III test maneuvers. Descriptions of this steering machine, including features and technical specifications, have been previously documented [14] [15].

3.2 Load Conditions

Two load conditions were explored during Phase III testing: the bobtail condition and the 60% GAWR load condition. The bobtail condition was chosen to most closely duplicate the established light vehicle SC test described in FMVSS No. 126, and because it would evaluate the test vehicles' yaw stability and SC effectiveness without any undue influence of a trailer or ballast. The bobtail load condition was comprised of the test tractor, a driver, instrumentation (including a programmable steering machine), and safety equipment (roll bar, aftermarket seat, 5-point safety harness, and outriggers). Each vehicle was tested with its fuel tank at least three-quarters full.

The second loading condition was developed using a 28-foot flatbed trailer that is similar to the test trailer described in FMVSS No. 121 [16]. This loading, referred to as the 60% GAWR condition, places ballast on the trailer, centered over the kingpin. Ballast was added until the tractor's drive axles were loaded to 60 percent of the manufacturer's specified GAWR. This load was selected after reviewing Phase II testing results in which yaw instabilities occurred while testing tractors with 5 of the 6 lightly loaded trailers (payload ~2,500 lbs). Yaw instability was not observed while testing the tractors with the lightly loaded 28-foot flatbed trailer. This trailer is shorter and lighter than the other five trailers evaluated. The 60% GAWR load condition was determined from comparing axle weight distributions and overall mass of the combinations with the five heavier and longer trailers. This methodology resulted in payloads that ranged between

6,800 to 15,500 lbs for combinations with the 28-foot flatbed trailer. Limited crash data were available to determine vehicle mass configurations most associated with loss of yaw stability. Refer to Section 1.5.4 for a brief discussion on payload mass sampled in the crash data.

In addition to the equipment used for the bobtail load condition, the tractor's 60% GAWR condition included the test trailer with its associated instrumentation, ballast load frames, and safety equipment (anti-jackknife brackets, and anti-jackknife cables). Outriggers were removed from the truck-tractors and installed on the trailer. Concrete ballast (water was used for ballast with the tanker) blocks were secured to the deck of the trailer with steel chains. For each tractor, the fifth-wheel was adjusted as close as possible to its middle longitudinal position to be consistent with fifth-wheel position used during the Phase II research. For more information about the loading conditions see Appendix D.

3.3 Testing Surface and Ambient Conditions

All tests were performed on the Transportation Research Center, Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. [Note: The Transportation Research Center, TRC, is "is an independent automotive proving ground providing research and development, and compliance and certification testing for vehicles and components for crash testing, emissions testing, dynamic testing and durability testing," and is not to be confused with NHTSA's Vehicle Research and Test Center, even though both are based in East Liberty.] The VDA is an 1,800- by 1,200-foot flat paved surface with a 1-percent longitudinal grade for drainage. Turn-around loops are provided on each end to facilitate high-speed entry onto the VDA. The surface was paved with an asphalt mix representative of that used on many Ohio highways. Located on the VDA at the south end is a 300- by 550-foot reduced-friction surface (Jennite pad). The Jennite pad consists of wet, sealed asphalt with a peak coefficient of 0.3 to -0.5.

The tests discussed in this study were performed from August 2008 to November 2009. All tests were performed while the VDA high-friction test surface was dry and all tests performed on the Jennite low-friction test surface were wet. Figure 3.1 summarizes the surfaces peak and slide coefficients of friction for the dates relevant to the 2008-09 test seasons. The peak and sliding coefficients of friction were generally monitored twice per month, weather permitting. The peak coefficient was determined with American Society for Testing and Materials (ASTM) procedure E1337 and an E1136 tire [17] [18] . Sliding coefficients were determined with ASTM procedure E274 and an E50 [19] [20].

The ambient temperatures and wind speeds were recorded at the beginning of each test session. The ambient air temperature ranged from 27 to 82 degrees Fahrenheit. The wind speeds ranged from 0 to 30 mph.

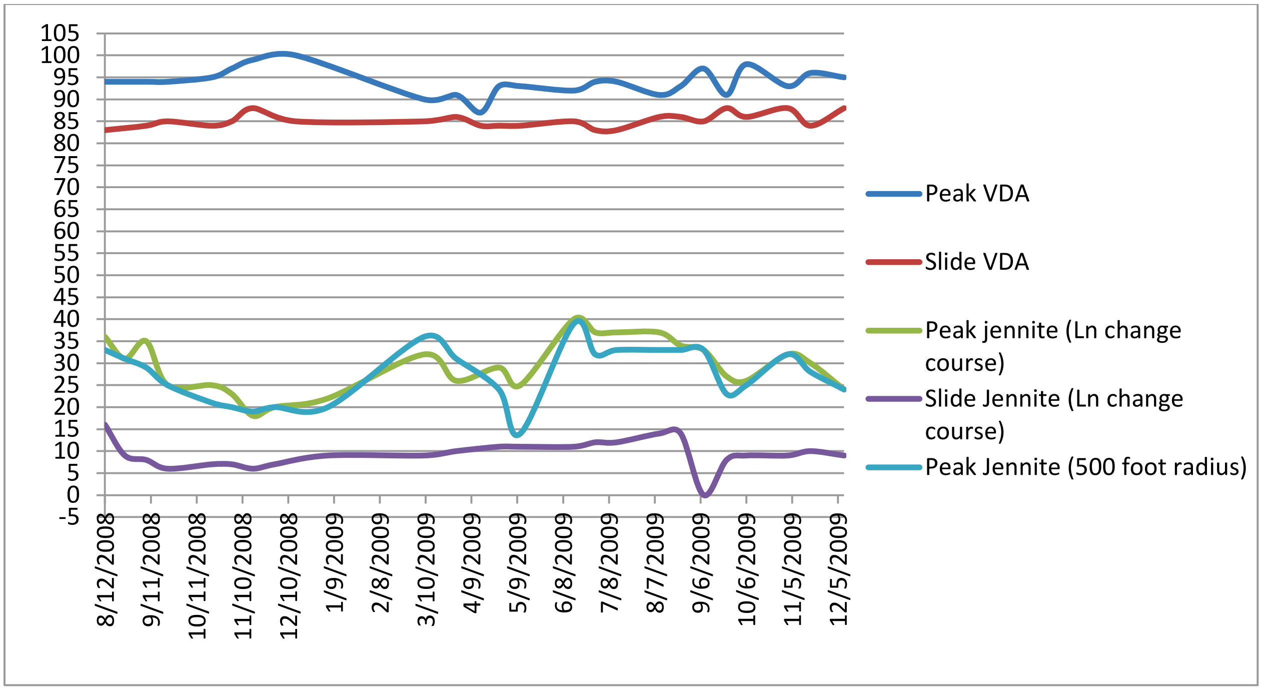

Figure 3.1. TRC VDA dry and Jennite wet peak and slide coefficients of friction for the testing period.

3.4 Test Maneuvers

FMVSS No. 126 [mandates SC for vehicles with a GVWR of 10,000 lbs or less. This rule sets a minimum performance standard for lateral stability of light passenger vehicles. The light vehicle research concluded that the 0.7 Hz sine with a 0.5-second dwell time (Figure 3.2) maneuver was the best candidate maneuver for a vehicle lateral stability assessment. Other performance test candidates were variations of sine steer maneuvers, pulse steers, and an experimental yaw acceleration steering reversal (YASR uses feedback loop to perform steering reversals) maneuvers. Although truck tractor vehicles are very different physically and dynamically, the light vehicle sine with dwell maneuver provided the first dynamic maneuver that was considered for this heavy-vehicle yaw stability research.

Previous research has shown that these types of commercial vehicles can be less responsive to quick transitional (left-right or right-left, like the SWD) steering inputs versus single-direction inputs. This was observed in RSC effectiveness research in which 50-mph lane changes (left then right consecutive steering inputs) were successfully completed before instability was observed with a high-center-of-gravity combination vehicle. When contrasted to the RSM (left or right steer only) test results, roll instabilities were observed at test speeds below 30 mph for the same vehicle and configuration. Therefore, single-direction steering inputs like the pulse steer, or J-turn-like maneuvers, or half-cycle sine steer (Figure 3.3) were also potential maneuvers.

Based on these observations and past lateral stability research several candidate maneuvers were identified with the potential capability of assessing truck-tractor yaw stability. Those maneuvers are the Slowly Increasing Steer (SIS), Sine With Dwell (SWD), Half-Sine With Dwell (HSWD), 150 ft. Radius Brake-in-Curve Maneuver (BIC), Ramp Steer Maneuver (RSM), and Ramp With

Dwell maneuver (RWD). These maneuvers were performed on either high-friction (dry asphalt) and/or reduced-friction surfaces (Jennite).

Maneuver Profiles

SWD and HSWD Maneuvers

The SWD maneuver was based on a single-cycle sinusoidal steering input with a given frequency. Although the peak magnitudes of the first and second half cycles were identical, the SWD maneuver included a pause or "dwell" after completion of the third quarter-cycle of the sinusoid. A generic steering wheel angle profile is shown in Figure 3.2.

The HSWD maneuver was based on half of a single-cycle sinusoidal steering input. The HSWD maneuver included a dwell after completion of the first quarter-cycle of the sinusoid. A generic steering wheel angle profile is shown in Figure 3.3 for the HSWD maneuver.

SWD and HSWD maneuvers were performed at multiple frequencies between 0.3 and 0.7 Hz. Dwell times of 0.5 and 1.0 seconds were also used in conjunction with the multiple frequencies. The amplitudes were based on the average steering wheel angle required to achieve 0.5g (SWA05) of lateral acceleration in series of SIS maneuvers. This methodology was the same as that used to determine the steering magnitude for the RSM. In a SWD or HSWD test series the first test was started at 30 percent of SWA05 and increased in 10 percent increments to 130 percent of SWA05. An automated steering robot was used to get precision steering amplitudes and frequencies.

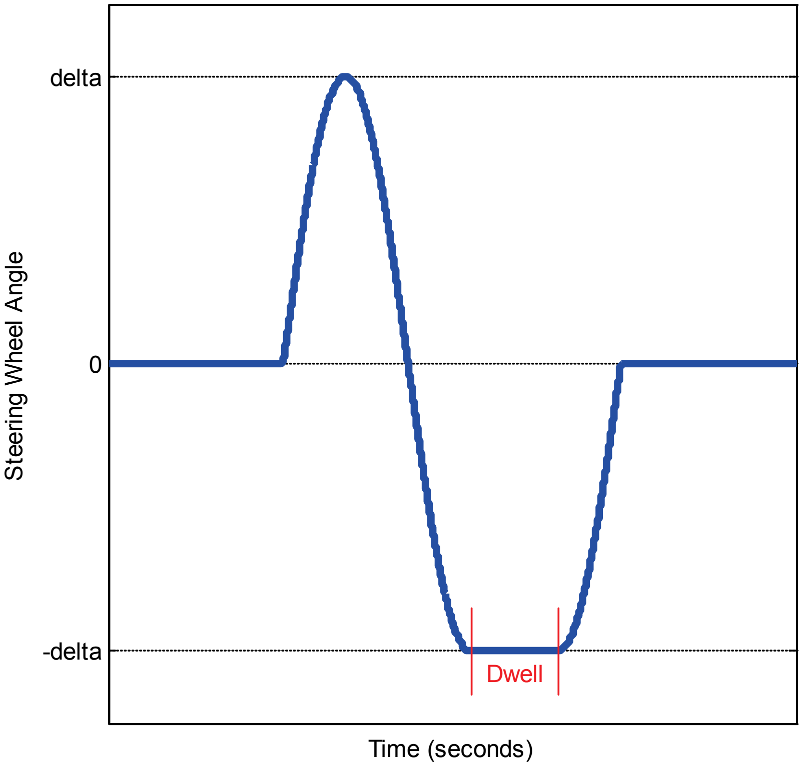

Figure 3.2. Sine With Dwell profile

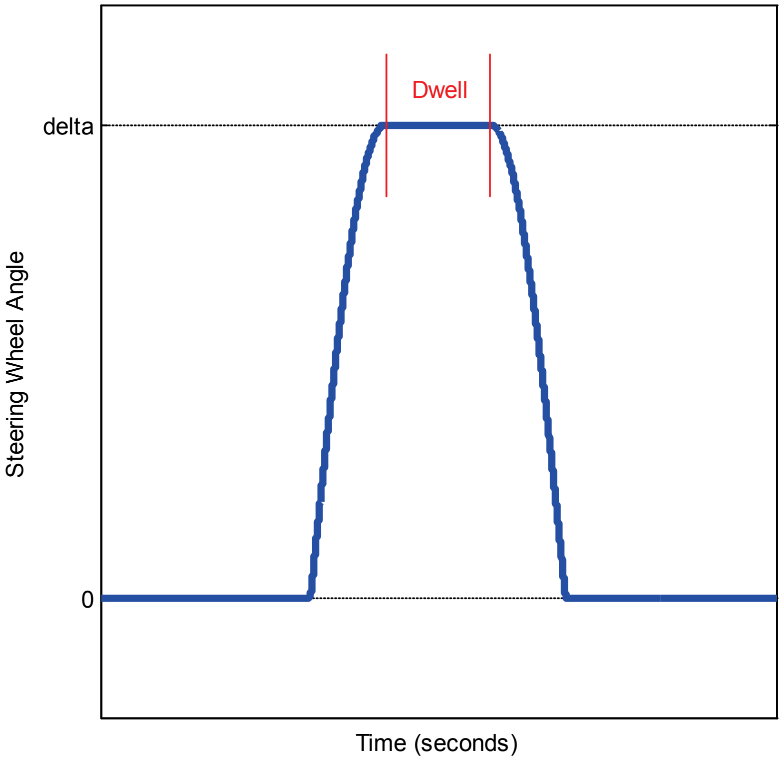

Figure 3.3. Half-Cycle Sine With Dwell profile

150-Foot Radius Brake-In-Curve Maneuver

For the 150-foot BIC maneuver, the tractor semitrailer combinations were driven at a constant speed tangentially entering the left-turn radius. Traffic cones (marker pylons) were placed on the radius depicting two index locations: the turn-entrance-point and the brake-application-point, which was 100 feet into the arc. At the second cone, a full treadle brake application was made and the driver steered, attempting to maintain close proximity to the radius line. Figure 3.4 depicts the course layout for this maneuver. During testing the combination was driven so the inside wheels were adjacent to the outside of the radius line. This allowed the driver to navigate the radius without crossing the lower coefficient-of-friction painted radius line. Steering inputs were controlled by the test driver in this path-following maneuver.

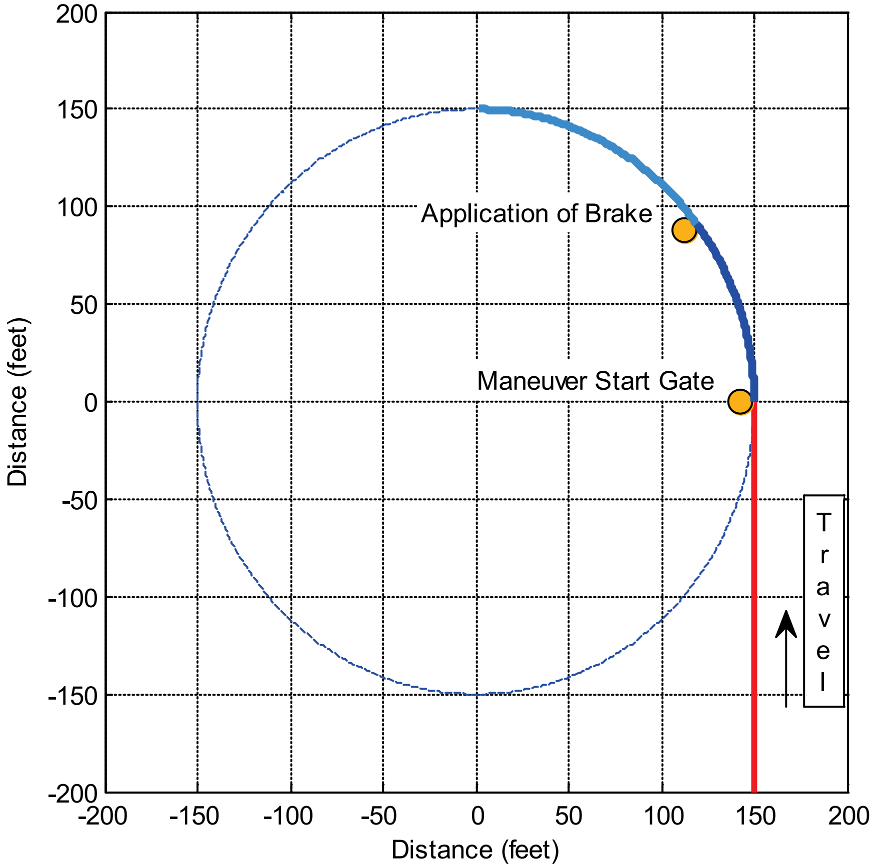

Figure 3.4. 150 ft. Brake-In-Curve maneuver course layout.

Slowly Increasing Steer Maneuver

The SIS test maneuver, used in Phase II, was derived from Society of Automotive Engineers (SAE) Surface Vehicle Recommended Practice J266. It is also described as the Constant Speed Tests – Variable Radius or Variable Steer Angle maneuver [22]. The maneuver is specifically recommended to characterize steady-state directional control properties for light passenger vehicles and has been adapted to normalize steering inputs for maneuvers[1] used by the agency to evaluate dynamic stability. Like light passenger vehicles, various truck tractor configurations have different lateral acceleration to steering wheel angle gains that can be characterized using the SIS maneuver. From SIS test results extrapolation was used to determine the average steering wheel angle needed to produce 0.5 g of lateral acceleration. That steering wheel angle was then used as the steering input magnitude for the RSM. This same angle was also scaled from 10 percent to 130 percent for use with the SWD, and HSWD maneuvers. Figure 3.5 shows an example of the steering wheel profile used to perform the SIS maneuver.

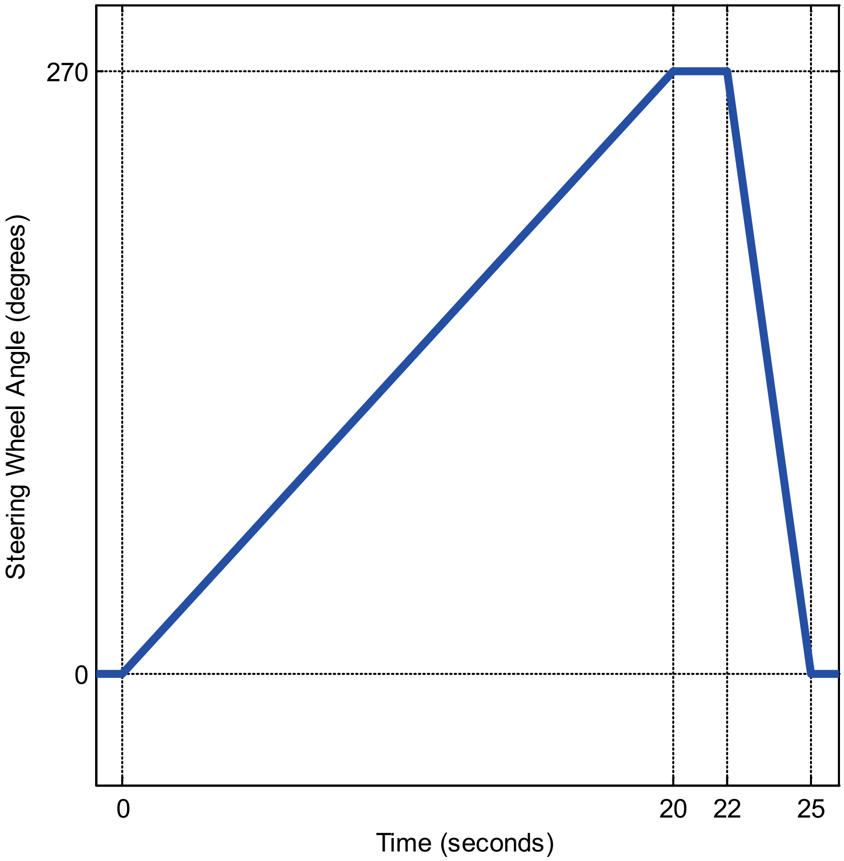

Figure 3.5. Example of the steering wheel profile used for SIS tests.

Ramp Steer Maneuver

The Ramp Steer Maneuver, developed in Phase II, is similar to a path-following J-turn maneuver. The RSM is based on a steering wheel input at a constant rate of 175 deg/sec until the peak steering magnitude is achieved. The definition of the RSM is shown graphically in Figure 3.6 that shows the steering wheel profile and specific timing marks of interest. Where zero marks the initiation of the maneuver, the magnitude is equal to δ^{Test} and "t" is equal to δ^{Test}/175 deg/sec.

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[1] Similar steering wheel input normalization methodology was developed for the NCAP Fishhook Test [23] [24] and for the 0.5 Hz Sine With Dwell maneuver documented in [25].

δ^{Test} is the average steering wheel angle needed to achieve 0.5 g of lateral acceleration in a 30 mph SIS test.

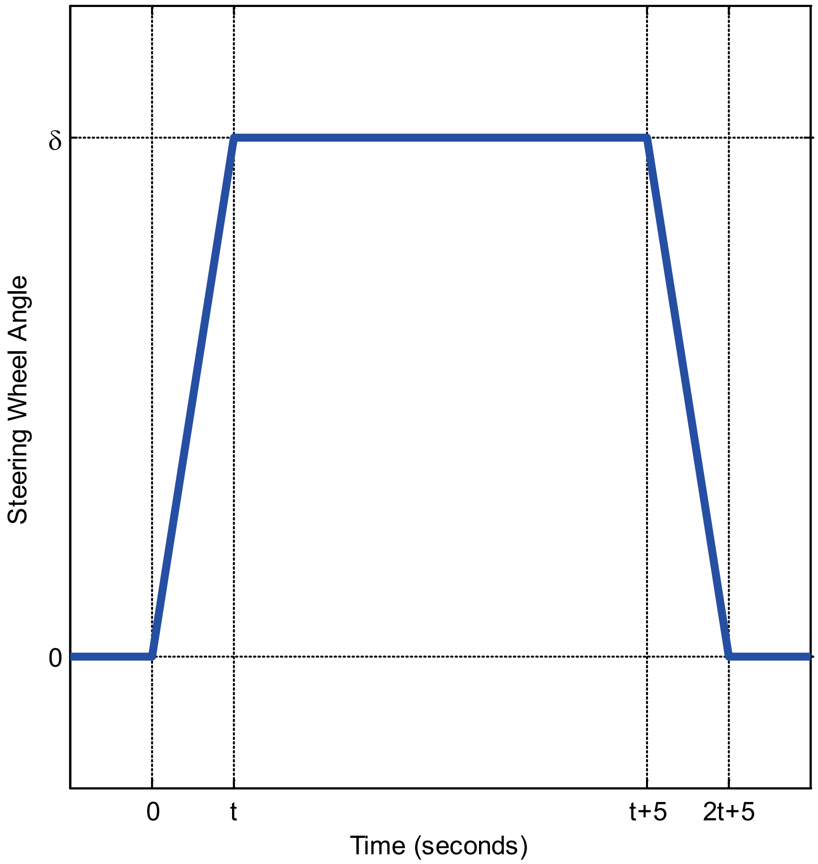

Figure 3.6. Steering wheel profile used for RSM tests.

Ramp With Dwell Maneuver

The Ramp With Dwell maneuver developed by the commercial vehicle industry was considered for evaluating tractors equipped with SC systems. The maneuver was designed to use the wet Jennite surface also used for FMVSS No. 121 [16] testing, and was focused on isolating yaw control. The RWD maneuver steering profile is based on starting with a small constant steering input, then increasing the steering wheel magnitude over a 1.0-second interval, holding that magnitude for 3.0 seconds, and then returning the steering wheel back to zero over a 1.0-second interval. In general the steering profile is similar to the RSM in example Figure 3.6. Different from the RSM, the steering angle is not at zero degrees when the maneuver is executed. In Figure 3.7, δdt is the drive through angle needed to negotiate a 500 ft. radius on the Jennite surface at the maximum drive through speed. The maneuver amplitudes were determined by multiplying a constant (K) integer with a value from 2 to 6 times the characterization drive through angle rounded to the nearest 90 degrees. For each test K is increased by 1 until SC activation occurs.

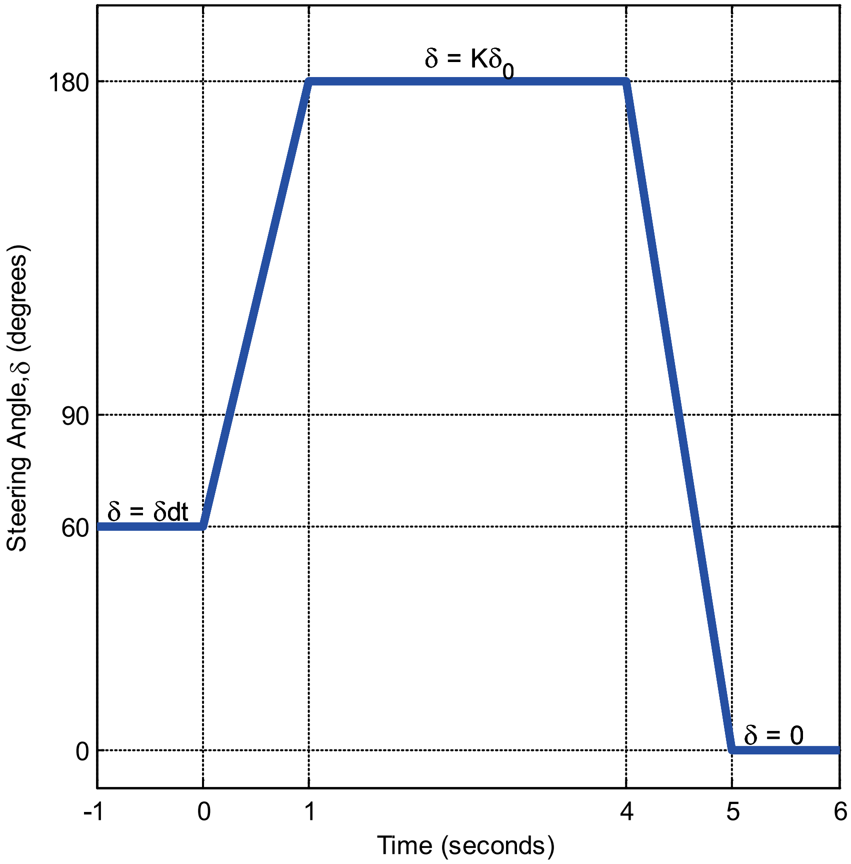

Figure 3.7. Example of steering wheel profile used for RWD tests.

Maneuver Control of Severity and Test Series Termination Conditions

For SWD and HSWD Maneuvers

For both the SWD and the HSWD the maneuver entrance speed was fixed and the steering magnitude was incrementally increased up in steps (steering scalars) to control the test severity. If the vehicle achieved the maximum amplitude without yaw or roll instability, the series was terminated. If any of the following were observed during a test series then the testing was terminated:

1. Articulation angle was approximately 45 degrees or higher
2. Wheel lift greater than 2 inches of the tractor drive axles
3. Wheel lift greater than 2 inches of the trailer axles

For 150-foot BIC and RSMs

For both the 150-foot BIC and RSM maneuvers severity was controlled by incrementally increasing the maneuver entrance speed (MES) from an initial speed of 20 mph in 2 mph increments. If the vehicle achieved a maneuver entrance speed of 50 mph without observing one of the following conditions the series was deemed complete. Below are the conditions for test series termination.

1. Articulation angle was approximately 45 degrees or higher
2. Wheel lift greater than 2 inches of the tractor drive axles
3. Wheel lift greater than 2 inches of the trailer axles

Steering amplitude and rate were controlled by the test driver for the 150-foot BIC maneuvers, while an automated steering robot was used for the RSM.

For SIS Maneuvers

SIS tests were conducted at a constant speed of 30 mph. Using the steering controller, the test increased the steering wheel angle at 13.5 degrees/second until reaching a magnitude of 270[2] degrees. Using this maneuver a total of 6 tests were performed per test series. First, 3 were conducted with a left steering input followed by 3 with a right steering input. Tests concluded when the maximum hand wheel angle was achieved, SC intervened, or the vehicle experienced wheel lift.

For RWD Maneuver

For the RWD maneuver, the maneuver entrance speed was always fixed at 90 percent of the maximum drive through speed for a 500-foot radius curve on the wet Jennite, not exceeding 35 mph. The initial steering magnitude was always equal to the drive-through steering angle, and was then increased to 180 degrees (270 degrees and then 360 degrees in subsequent tests). A test series was considered to be completed upon completing a test at each steering angle increment for the left and right steering directions for each test condition evaluated.

For more information regarding test procedures: See Appendix A.

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[2] To make comparisons between SC-enabled and disabled SIS tests, larger steering amplitudes were used for some test series to obtain stability control activation levels.

4 PERFORMANCE MANEUVER RESEARCH AND DEVELOPMENT

To develop an effective maneuver capable of evaluating vehicle lateral dynamic stability many of the parameters used to define the test were manipulated. Table 4.1 and Table 4.2 show the test matrices used to explore parameters such as frequency, amplitude, speed, load, and dwell time. Maneuvers shown in Table 4.1 were conducted on dry high-friction asphalt. Maneuvers shown in Table 4.2 were conducted on the reduced-friction wet Jennite test surface.

Table 4.1. Maneuvers and parameters used on dry asphalt (0.96 peak friction co-efficient) test surface.

Maneuver	Frequencies/Rates	Dwell Time (sec)	Load Condition	Entrance Speed (mph)
SIS	13.5 deg/sec	2.0	Bobtail, 60% GAWR	30
SWD	0.3,0.4,0.5,0.6,0.7 Hz	0.5,1.0	Bobtail, 60% GAWR	50,45
HSWD	0.3,0.4,0.5,0.6 Hz	0.5,1.0	Bobtail, 60% GAWR	50,45
BIC	Driver	Driver	60% GAWR	20-50

Table 4.2. Maneuvers and parameters used on wet Jennite (0.3 peak friction co-efficient) test surface.

Maneuver	Frequencies/Rates	Dwell Time (sec)	Load Condition	Entrance Speed (mph)
SIS	27 deg/sec	2.0	Bobtail	30
SWD	0.2,0.3,0.4,0.5	0.5	Bobtail, 60% GAWR	30
RSM	175 deg/sec	5.0	Bobtail, 60% GAWR	20-40
RWD	1.0 sec to Amplitude	3.0	Bobtail, 60% GAWR	20-35

The maneuvers shown in the test matrices were performed with each tractor and SC system. The matrices were completed with the SC systems disabled, enabled, and (when connected to the trailer) enabled with the trailer brakes disabled (unbraked trailer). This last condition was used to quantify the tractor and SC systems' performance without the added performance of the trailer brakes. For this test condition, the trailer service brake line was disconnected which disabled the trailer bakes.

4.1 SIS Test Results

This section presents the SIS test results conducted on high- and reduced-friction surfaces.

4.1.1 High Surface Friction – Dry Asphalt

The bobtail SIS test data from each vehicle were processed to determine the steering angle required to produce 0.5g of lateral acceleration at 30 mph. This value was then used as the magnitude for the RSM, SWD, and HSWD maneuvers. Given the dependence on these steering wheel angles (SWA), additional SIS series were performed to observe the maneuver's ability to capture changes in lateral performance due to vehicle and environmental factors. As such, SIS test series were performed for each vehicle with SC enabled at the start of each day of testing. Figure 4.1 presents the average steering angle (values extrapolated) needed to produce 0.5g of lateral acceleration at 30 mph for each SIS test series and tractor.

Figure 4.1 shows the average of the angles extrapolated (L/R) at 0.5 g for the Volvo ranged from 200 to 233 degrees, for the Freightliner ESC 199 to 241 degrees, for the Freightliner RSC 186 to 207 degrees, and for the Sterling 155 to 193 degrees.

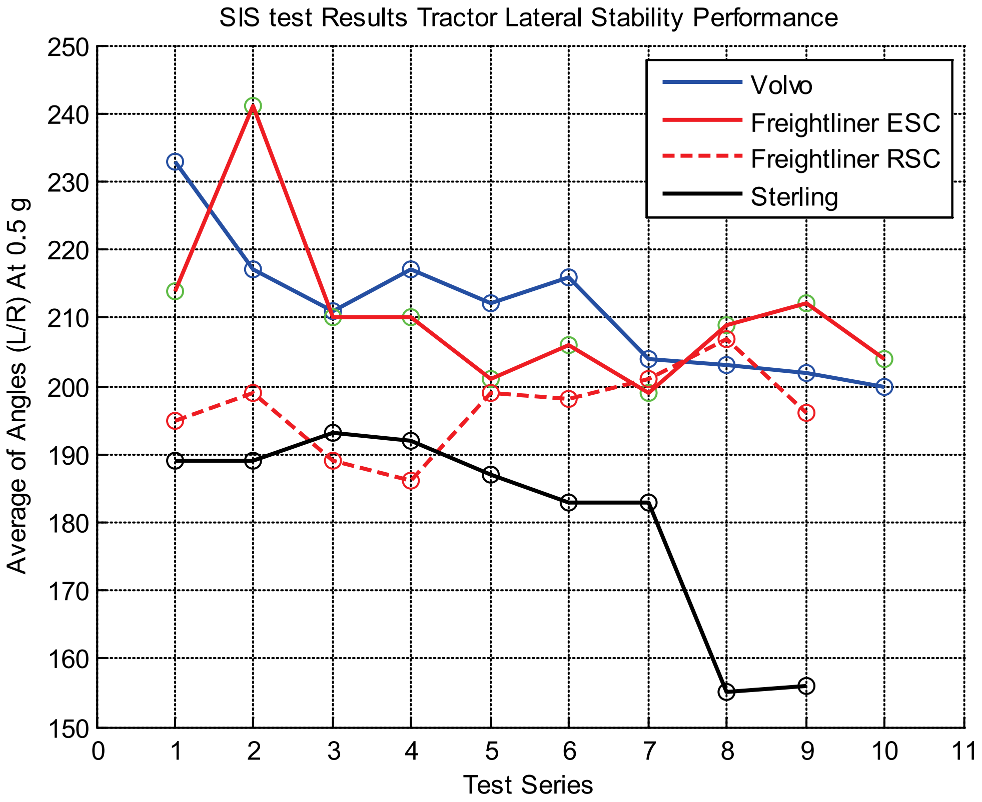


Figure 4.1. Average extrapolated steering wheel angles needed to achieve 0.5 g of lateral acceleration at 30 mph versus the daily test series.

Table 4.3 through Table 4.6 present the SIS test results from 10 test series with the Volvo, 10 series with the Freightliner ESC, 9 series with the Freightliner RSC, and 9 series with the Sterling. Each table presents the range of input speeds observed, the average extrapolated steering angle at 0.5 g for each series, and the R^2 statistics that were obtained from the linear regression analyses.

Table 4.3. Bobtail SIS tests results from the Volvo 6x4.

Vehicle: Volvo 6x4 SIS Test Series Number	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (From linear regression)**
1 (5 tests)	30.1 – 30.5	233	0.996 – 0.997
2 (6 tests)	30.3 – 30.8	217	0.997 – 0.998
3 (6 tests	30.1 – 30.7	211	0.998 – 0.999
4 (6 tests)	29.8 – 30.9	217	0.998 – 0.999
5 (6 tests)*	30.0 – 30.8	212	0.998 – 0.999
6 (6 tests)	29.9 – 30.6	216	0.997 – 0.998
7 (6 tests)*	30.8 – 31.4	204	0.997 – 0.999
8 (6 tests)*	30.3 – 30.9	203	0.997 – 0.998
9 (6 tests)*	30.2 – 30.8	202	0.998 – 0.999
10 (6 tests)*	30.8 – 30.9	200	0.997 – 0.998

*Cruise control was used to maintain speed.

Table 4.4. Bobtail SIS tests results from the Freightliner ESC 6x4.

Vehicle: Freightliner ESC 6x4 SIS Test Series Number	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (From linear regression)**
1 (6 tests)	29.3 – 31.2	214	0.997 – 0.999
2 (6 tests)*	29.0 – 30.1	241	0.931 – 0.990
3 (6 tests)	28.9 – 30.9	210	0.996 – 0.999
4 (6 tests)*	29.9 – 30.2	210	0.983 – 0.995
5 (6 tests)*	30.3 – 30.4	201	0.995 – 0.998
6 (6 tests)*	29.5 – 29.8	206	0.988 – 0.998
7 (6 tests)*	30.0 – 30.2	199	0.994 – 0.999
8 (6 tests) *	29.5 – 29.5	209	0.981- 0.995
9 (6 tests)*	29.2 – 30.2	212	0.962 – 0.998
10 (6 tests)*	29.5 – 30.4	204	0.983 – 0.998

*Cruise control was used to maintain speed.

Table 4.5. Bobtail SIS tests results from the Freightliner RSC 6x4.

Vehicle: Freightliner RSC 6x4 SIS Test Series Number	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (From linear regression)**
1 (6 tests)	30.2 – 31.5	195	0.996 – 0.999
2 (6 tests)	29.6 – 31.1	199	0.997 – 0.999
3 (6 tests)	30.2 – 31.7	189	0.994 – 0.998
4 (6 tests)	29.3 – 31.2	186	0.997 – 0.999
5 (6 tests)	29.6 – 31.6	199	0.998 – 0.999
6 (6 tests)	29.9 – 30.3	198	0.993 – 0.999
7 (6 tests)	29.3 – 30.5	201	0.995 – 0.998
8 (6 tests)	28.9 – 30.2	207	0.997 – 0.999
9 (6 tests)	30.1 – 30.4	196	0.997 – 0.999

Table 4.6. Bobtail SIS tests results from the Sterling 4x2.

Vehicle: Sterling 4x2 SIS Test Series Number	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (From linear regression)**
1 (6 tests)*	30.1 – 30.4	189	0.976 – 0.998
2 (6 tests)*	30.3 – 30.6	189	0.996 – 0.998
3 (6 tests)*	30.0 – 30.3	193	0.996 – 0.998
4 (6 tests)*	29.8 – 30.3	192	0.996 – 0.998
5 (6 tests)*	29.4 – 30.2	187	0.997 – 0.999
6 (6 tests)*	29.7 – 30.1	183	0.997 – 0.998
7 (6 tests)*	29.8 – 30.3	183	0.997 – 0.998
8 (6 tests)*	30.2 – 30.7	155	0.997 – 0.998
9 (6 tests)*	30.0 – 30.6	156	0.994 – 0.998

*Cruise control was used to maintain speed.

4.1.2 Low-Surface Friction Results

The SIS maneuver test procedure on the Jennite was similar to the SIS maneuver conducted on the high-friction surface at 30 mph. The only change to the maneuver for testing on the Jennite was the steering rate. For a SIS maneuver conducted on high-friction surface where space was not an issue a steering rate of 13.5 degrees/second was used. For testing on the Jennite where space is limited the steering rate was doubled to 27 degrees/second. By doubling the steering rate the vehicle would approach its lateral limit faster while still on the test surface.

Table 4.7 documents the results of the bobtail SIS tests on the Jennite surface. The table shows that the Volvo and the Freightliner were observed to complete the SIS maneuvers without observing a yaw stability event regardless of the SC test condition (denoted with TC for test complete). The Sterling with SC enabled, also completed the SIS maneuvers: however, the data show that traction control, not SC, was activating during the tests. SIS tests conducted with the Sterling with SC disabled resulted in loss of yaw stability (spinout). Disabling SC in the Sterling also disabled traction control which allowed the driver to apply more torque to the rear drive wheels and resulted in a throttle induced spinout. With exception to one test condition with the Sterling 4x2, each tractor was observed to understeer with SC disabled. With the SC system disabled, the tractors were observed to reach their lateral limits on the Jennite surface (both yaw rate and lateral acceleration responses were saturated).

Table 4.7. SIS Test Results Jennite

Tractor	**SIS Test Results 3(L\R) Jennite** **SC Condition** **Enabled**	 **Disabled**
2006 Volvo 6X4 ESC	TC	TC
2006 Freightliner 6x4 ESC	TC	TC
2006 Freightliner 6x4 RSC	TC	TC
2008 Sterling 4x2 RSC	TC[1]	Spinout

[1]-Test was completed because traction control activated not SC

Figure 4.2 displays the lateral acceleration versus steering angle for each tractor bobtail for a single SIS maneuver on the Jennite. Included in the figure is an example of a tractor's lateral acceleration vs. steering wheel angle for a SIS maneuver conducted on a high-friction surface For the Volvo and the Freightliner ESC, SC activation was observed in all tests. For the Freightliner RSC and Sterling, no SC activation was observed.

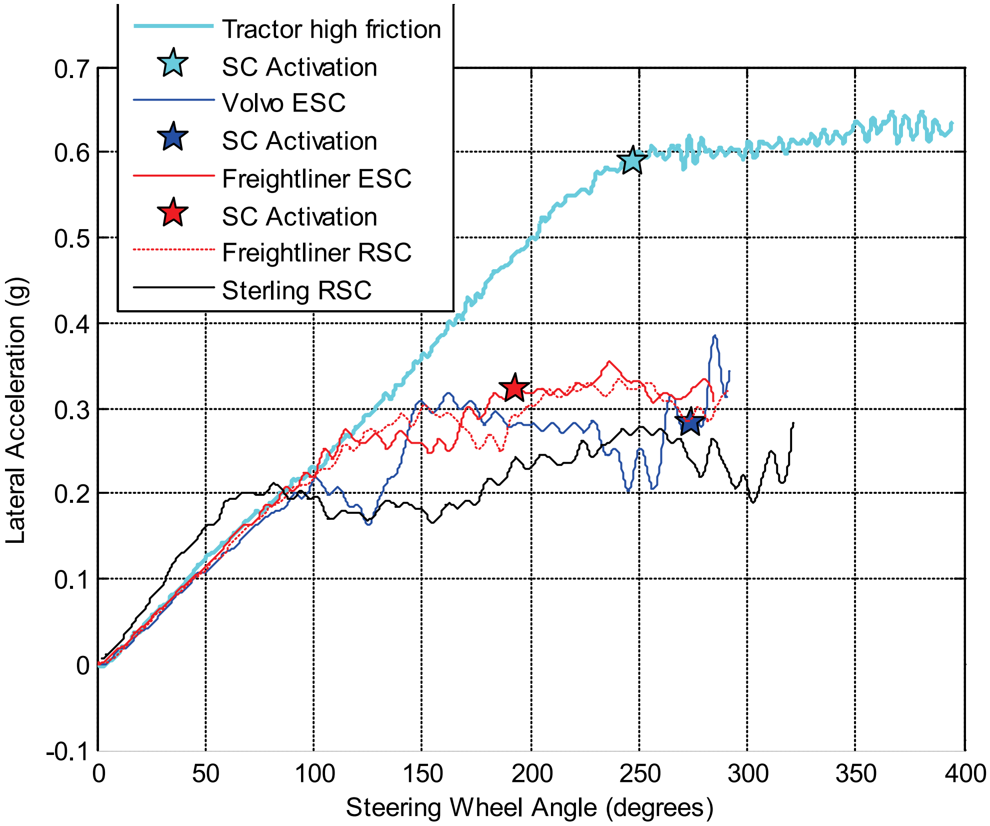


Figure 4.2. Steering angle to lateral acceleration gain for SIS maneuvers on low-and high-friction surfaces.

During the conduct of these tests, researchers observed several anomalies in the data. From the data in Figure 4.2, all three tractors produced linear lateral acceleration until about 0.2 g. However, in between 0.2 and 0.3 g, there are some differences. The Freightliner was observed to continue to increase lateral acceleration to 0.3 g at which point saturation was reached. The Volvo and Sterling tractors saw reductions to lateral acceleration for steering angles ranging from 90 degrees to 150 degrees. Then the lateral acceleration for those two vehicles began to build again to similar levels as observed with the Freightliner. Given that each test is performed at the same speed and with a repeatable steering input from the robot, researchers questioned the validity of the data in this region.

Similar atypical changes were observed in the yaw rate measure that lead to additional data analysis of the geo spatial data. In Figure 4.3, the top plot shows position data from a bobtail tractor during three SIS maneuvers which were overlaid on a GPS survey of the 500-foot radius course on the Jennite. During the maneuvers, speed was held constant at 30 mph and the steering rate used was 27 degrees/second. The blue trace in the position plot is the path of the tractor "CG" during the SIS maneuver. The green highlighted portion of the path represents when the tractor crossed over the 12-foot-wide, 500-foot radius lane. Below the position plot is the tractors steering angle, yaw rate, and lateral acceleration data for the same tests. Disturbances in the data can been seen when the vehicle crosses these sections that are shown in green on the traces. A change in the tractor yaw rate and lateral acceleration can be observed. Researchers concluded that the observed change in the tractor measures could be correlated to a change in surface friction when crossing over this region. Due to the amount of testing that takes place using the 500-foot radius, over time the surface inside the lanes becomes more polished than the surrounding surface. The polished areas have a reduced friction compared to the surrounding areas. Figure 4.4 is an aerial photograph of TRC's Jennite surface. As can be seen in this figure, the darker regions show visually the polished sections of the 500-foot radius and of a similarly heavily-used straight section.

These test results show that the test anomalies and repeatability were dependent on where the maneuver started. Maneuvers for different tractors that are shown in Figure 4.2 were started at different locations on the Jennite. Comparing maneuvers that were conducted in about the same location, results were reproducible but still created atypical nonlinear results (as shown in Figure 4.3).

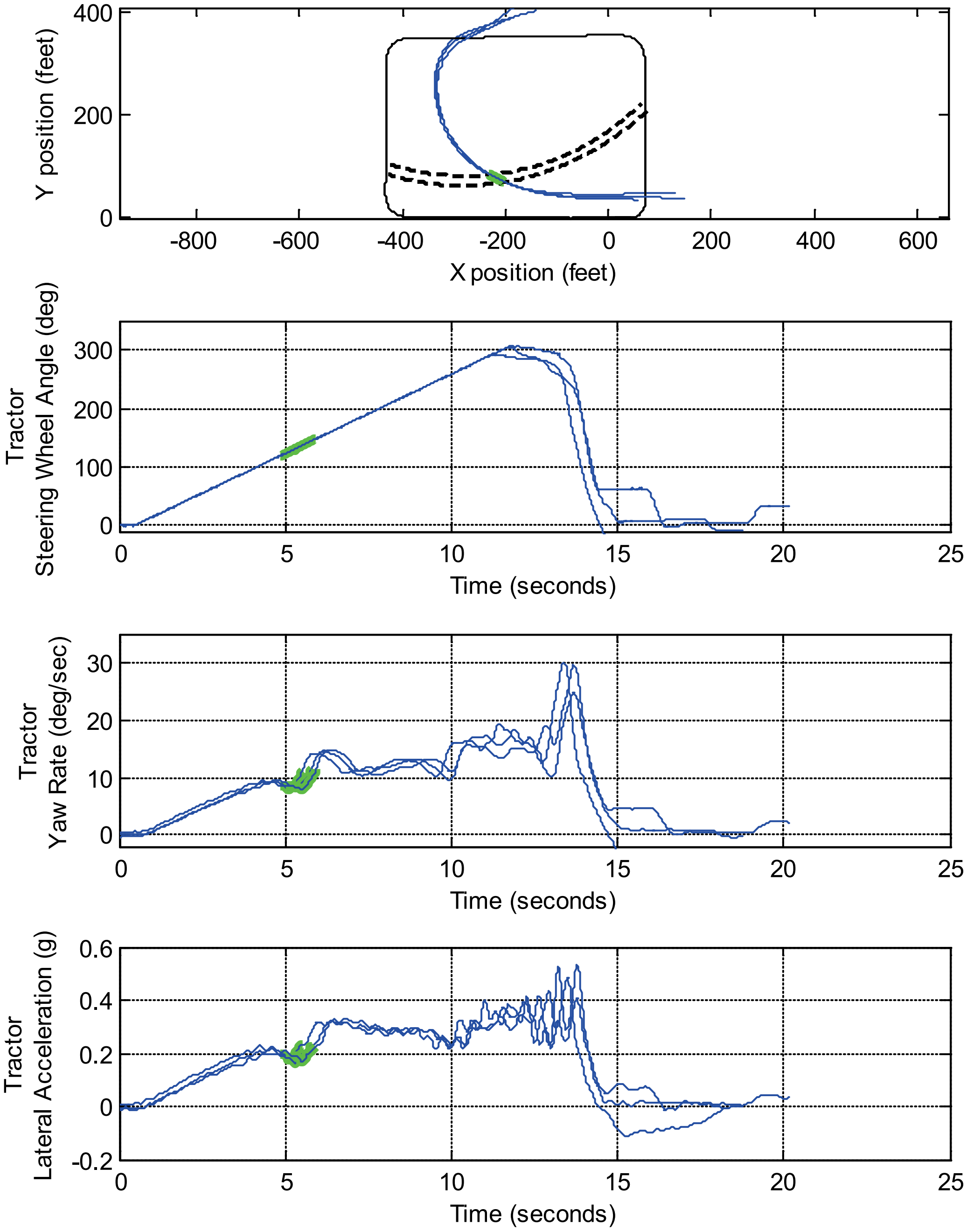


Figure 4.3. Position plot with vehicle measures of 3 SIS maneuvers on the Jennite.

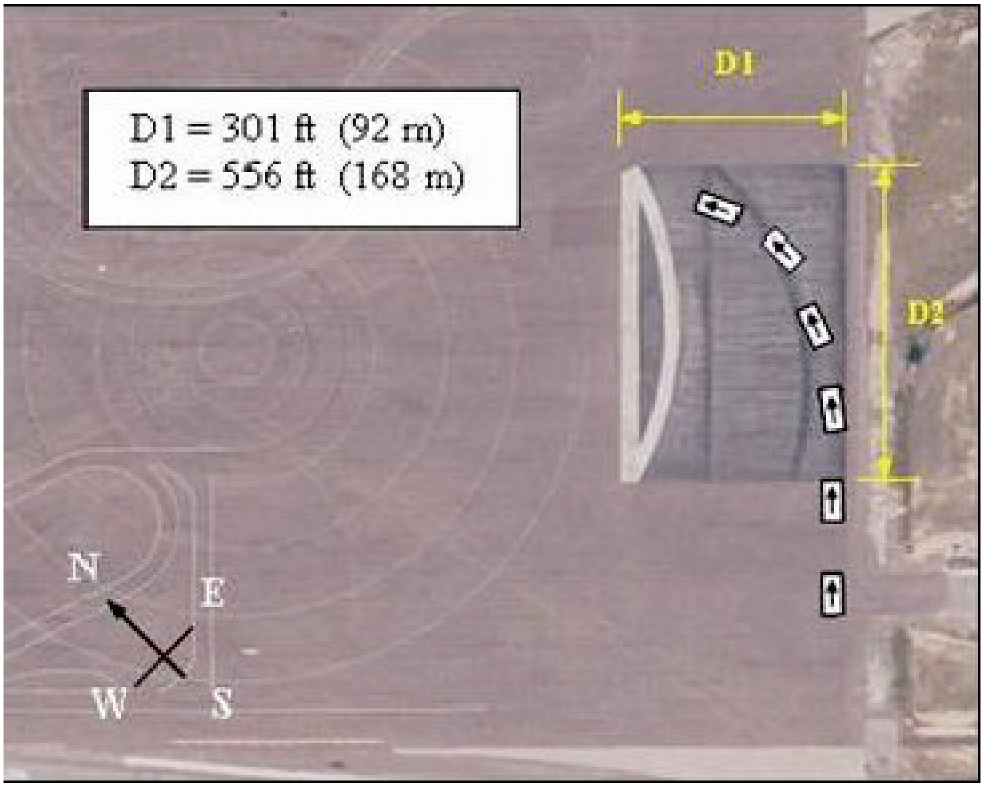


Figure 4.4. TRC's Jennite surface

4.2 150-Foot BIC Test Results

With ESC enabled, the Volvo and the Freightliner completed the 150-foot BIC test series (reaching 50 mph without instability) under certain conditions. The Volvo completed the series with both ESC-enabled test conditions. The Freightliner completed the series for the ESC-enabled condition with the unbraked trailer (see the following paragraph regarding trailer braking). Overall test results from the three tractors with the 28-foot flatbed trailer and 60% GAWR load condition are shown in Table 4.8. The table shows the lowest test speed at which an instability (jackknife or trailer swing) event was observed for each SC test condition. If the combination was observed to be stable up to the maximum test speed of 50 mph then it was denoted as "TC" in the table.

For all tractors and test conditions, the trailer's axle was unloaded. Without significant weight over this axle, the trailer's brakes experienced lock-up when driver-induced or ESC/RSC induced brake pressure was applied during test maneuvers. In some cases, this increased the frequency of trailer jackknife and trailer swing. Anti-jackknife cables were used in all maneuvers conducted with a trailer. In the context of this report a jackknife event indicates those safety devices were engaged. Allowing actual jackknife that would at minimum cause property damage.

For certain test conditions, each of the combinations was observed to experience jackknife with the resulting articulation angle exceeded the 30-degree definitional threshold. Tests series were terminated after jackknifes were observed for the Volvo with ESC disabled test at 48 mph. Two jackknife events were observed with the Freightliner. With RSC enabled and the unbraked trailer, jackknife was observed at 46 mph. With the systems disabled and the unbraked trailer, jackknife was observed at 44 mph. When testing the Sterling, jackknife was observed with RSC enabled at 48 mph when tested with a braked trailer, and with RSC enabled with the unbraked trailer condition at 47 mph.

The Freightliner experienced trailer swing (with the articulation angle greater than 30 degrees) for all test conditions where the trailer axle's brakes were enabled. It was observed at MESs of 42 mph with ESC and RSC enabled. With the systems disabled a similar event was observed at 38 mph. The commanded braking pressure to the trailer's axle caused the lightly loaded trailer (that was not equipped with ABS) to lock up the wheels. This lead to trailer swing despite the truck-tractor being in a stable condition.

In order to disable SC in the Sterling, the ABS fuse was pulled, thus also disabling ABS. The driver was unable to perform the test maneuver without complete brake lock-up as test speeds increased. Thus, the test series with SC disabled was terminated at 40 mph.

Table 4.8. 150-foot Brake in a Curve maneuver test series results

	Test Results (mph)		
	SC Condition		
Tractor	**Enabled**	**Enabled, Unbraked Trailer**	**Disabled**
2006 Volvo 6X4 ESC	TC	TC	48[2] unbraked trailer
2006 Freightliner 6x4 ESC	42[1]	TC	38[1] braked trailer 44[2] unbraked trailer
2006 Freightliner 6x4 RSC	42[1]	46[2]	38[1] braked trailer 44[2] unbraked trailer
2008 Sterling 4x2 RSC	48[2]	47[2]	40*

* Test series terminated due to excessive brake lock-up – Disabling SC also disables ABS.

[1] Trailer swing.

[2] Jackknife, tractor/trailer articulation angle greater than 30 degrees.

For the Volvo and Freightliner, this test maneuver does show how stability control allowed the test vehicles to perform with more stability to higher test speeds than with ABS alone. The Volvo with ESC disabled and the unbraked trailer experienced a jackknife at 48 mph. However, with ESC enabled with and without the unbraked trailer, the Volvo completed the maneuver without losing stability up to 50 mph. The Freightliner had similar results. With the systems disabled and the braked trailer the Freightliner had instability at 38 mph. With the ESC and RSC systems enabled the combinations did not experience instability until 42 mph. With the systems disabled and the unbraked trailer, the Freightliner had instability at 44 mph. With RSC enabled and the unbraked trailer instability was observed at 46 mph and performance was extended to 50 mph with the ESC system and unbraked trailer.

Time history data comparing vehicle kinematic data for a 150-foot BIC test is shown in Figure 4.5. The test was conducted at 44 mph with the Freightliner tractor in the 60% GAWR load condition. The red traces indicate data from the ABS-enabled test and the blue traces represent data from the ESC enabled test. In the subplot, vehicle speed, lateral acceleration, yaw rate, and brake pressures can be observed over time. The brake pressure plot shows brake pressures for all tractor brakes and the brake treadle pressed by the driver. The blue and red thick lines indicate when the driver pressed the brake treadle. In both tests, the driver activates the brakes just after 5.0 seconds into the test. However, in the case where ESC is enabled, it can be observed that braking began about 1 second prior to the driver's input beginning to mitigate the situation. Differences in lateral acceleration and yaw rate can be seen. In the ABS only test condition, the tractor begins to spin and lateral acceleration is sustained at high levels for almost 4 seconds. Yaw rate is also observed to build until about 7.5 seconds when the anti-jackknife cables are engaged, preventing the tractor semitrailer from articulating any further. Comparably, for the test with ESC enabled, the vehicle remains in control.

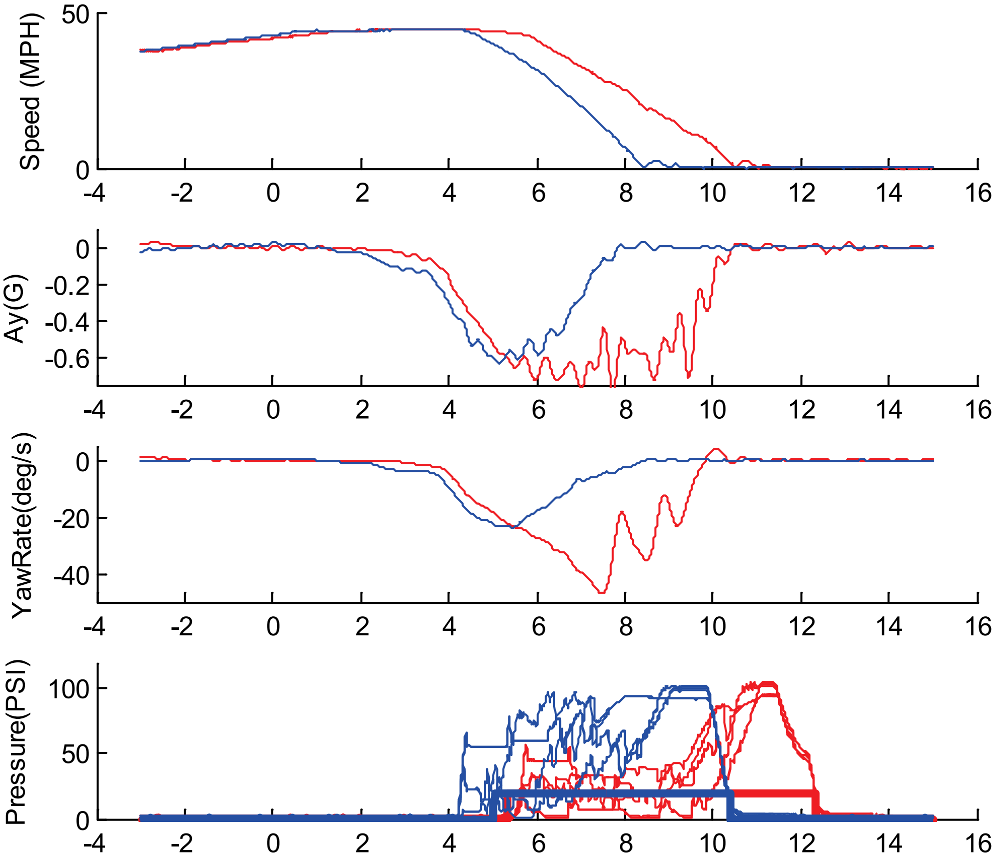


Figure 4.5. Time history data comparing ESC vs. ABS during a 150-foot BIC test.

Figure 4.6 shows geo-spatial test data from those same tests. The white lead vehicle represents the test with the ESC system enabled. The red lead vehicle represents the test without ESC. As previously stated, these BIC tests were performed at 44 mph. The duration of the brake input was represented with the heavy white line. This graphic depicts the dynamic states of the two tests at the same time into the maneuver, approximately 8.2 seconds. The boxes on the left show the measured tractor speed, lateral acceleration (Ay), and tractor semitrailer articulation angle at this time for both ESC-enabled and disabled test conditions. For the disabled test (with ABS), the combination experienced an articulation angle greater than 30 degrees (47.3 degrees in the example). The same combination with ESC enabled experienced no instability and an articulation angle of only 8.5 degrees.

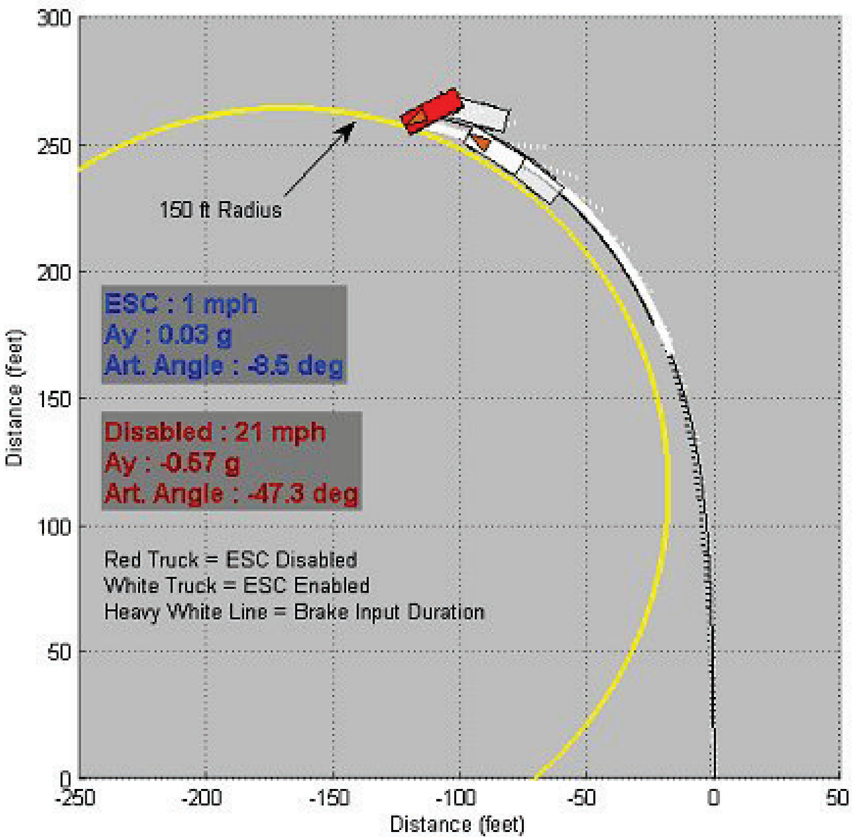


Figure 4.6. Example of a 150-foot BIC maneuver with and without ESC enabled. Combination was tested with the 60% GVWR load condition at 44 mph.

Although ABS has helped reduce jackknife crashes that occur in the real world [27], these tests demonstrated that ABS cannot prevent them all. In a situation where the vehicle speed and lateral forces are high, ABS braking initiated late by the driver is not enough to stop a potential jackknife condition. ESC demonstrated that it can react quickly when speed and lateral forces exceed a given threshold to help further reduce this type of crash.

The accuracy and reproducibility of this maneuver suffered due to inconsistent test driver performance. In order to perform this maneuver, a driver must enter the maneuver at a set speed, steer the vehicle through a prescribed radius while maintaining the set entrance speed, then begin braking at a specific point with maximum pedal force while maintaining the radius as closely as possible. This series of events occurs within a short period of time over a short distance, making it difficult for even an experienced test driver to perform this sequence accurately from test to test. Although this maneuver can show a vehicle's general performance trends, the potential for inconsistent test driver performances reduces this maneuvers objectivity.

4.3 SWD Maneuver Test Results

This section presents the bobtail and 60% GAWR load condition SWD test results from series conducted on the high-and reduced-friction surfaces. The high-level test results from the SWD and HSWD maneuvers were analyzed by steering scalar (expressed as a percentage) rather than the incremental angles used for each vehicle.

Table 4.9 is provided to relate the 30 through 130 percent steering scalars to the target steering wheel amplitude used with each of the tractors for both SWD and HSWD maneuvers. Each scalar represents a steering amplitude used to perform a SWD or HSWD test. Since each tractor has a different steering wheel angle to lateral acceleration gain, scaling the steering angle was necessary to normalize SWD and HSWD test severity. Scaling was based on the steering angles of 212, 204, and 180 degrees for the Volvo, Freightliner, and Sterling tractors, respectively, which were obtained from the SIS test data. For example, the 40-percent steering scalar was calculated by multiplying 212, 204, and 180 degrees by 40 percent, which was equal to 85, 82, and 72 degrees (rounded). For more information regarding scaling see Section 3.4.

Table 4.9. Average steering wheel angle increments used with SWD and HSWD Maneuvers

	Average Steering Wheel Angle Increments (degrees)		
Steering Scalar (percent)	**Volvo 6x4**	**Freightliner 6x4**	**Sterling 4x2**
30%	63	61	54
40%	85	82	72
50%	106	102	90
60%	127	122	108
70%	148	143	127
80%	169	163	145
90%	190	184	163
100%	212*	204*	181*
110%	233	224	199
120%	254	245	217
130%	275	265	235

* Normalized steering wheel angle determined from SIS maneuver data. Value represents angle extrapolated to generate 0.5 g of lateral acceleration at 30mph for each vehicle.

4.3.1 High Surface Friction - Bobtail Load Condition

For SWD test series performed in the bobtail condition on the dry high-friction asphalt, the tractors all produced consistent test results regardless of SC condition, maneuver frequency, or dwell time. SWD test series results for this load condition and surface are presented in Table 4.10. The table presents the lowest steering scalar for each series of SWD maneuvers that resulted in the loss of roll (marked with asterisks) or yaw stability. If neither stability threshold was exceeded then the series were considered test completed and were denoted as “TC” in the table. Series denoted with “NT” were not tested.

Table 4.10. Bobtail SWD test series results for SC-enabled and disabled test conditions.

		Steering Scalar Observed to Produce Instability (SC Disabled, and Enabled)					
	Freq. (Hz)	0.3		0.5		0.7	
Tractor	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4 ESC		TC	TC	TC	TC	TC	NT
Freightliner 6x4 ESC		TC	TC	TC	TC	TC	TC
Freightliner 6x4 RSC		TC	TC	TC	TC	TC	TC
Sterling 4x2 RSC		90%*	90%*	90%*	80%*	90%*	80%*

*** Test series terminated due to loss of roll stability**

As mentioned above the results were consistent between the SC-enabled and disabled test conditions for each tractor and SC system evaluated. The Volvo and Freightliner experienced no instability and completed all test conditions at 50 mph.

The Sterling was unable to complete any test series without experiencing wheel lift for initial series conducted at 45 mph, so SWD series at 50 mph were not performed. Despite RSC being enabled, the Sterling's RSC system did not intervene during any SWD maneuver. Thus, the vehicle's performance was the same whether its RSC system was enabled or disabled. Wheel lift occurred at 80 percent steering scalar for the 0.5Hz and 0.7Hz with 1.0-second dwell maneuvers, and at 90 percent steering scalar for all other SWD maneuvers. The Freightliner's RSC system likewise did not intervene during any SWD maneuver. However, the Freightliner did not experience any instability.

Figure 4.7 shows time history data from the Sterling with RSC enabled and disabled. From top to bottom, and left to right, the figure shows tractor, steering wheel angle, speed, lateral acceleration, deceleration, yaw rate, drive wheel height, angle, and roll angle. The figure shows that there was no SC activity to limit the lateral dynamics and wheel lift was observed for the same set of given inputs with the Sterling.

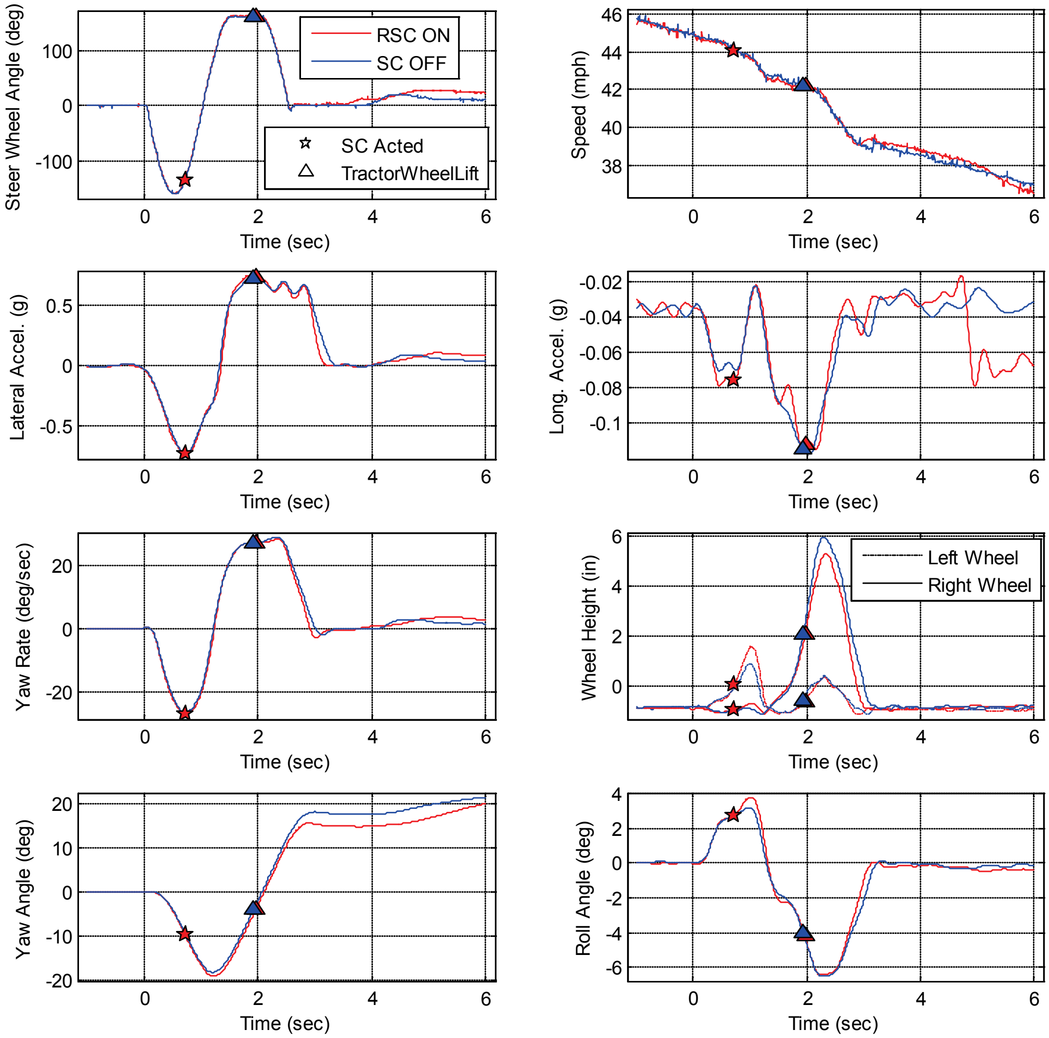


Figure 4.7. Bobtail SWD time history data from Sterling 4x2 with RSC enabled and disabled.

4.3.2 High Surface Friction - 60% GAWR Load Condition

SWD testing with the 28-foot flatbed trailer in the 60% GAWR load condition on high friction dry asphalt at 45 mph emphasized ESC's ability to limit instability. When ESC was disabled, both the Volvo and the Freightliner had cases of instability in 16 out of 20 SWD test series. However, when ESC was enabled on both truck-tractors, there were no instabilities. The RSC system in the Freightliner successfully averted instability in 4 out of 20 test series performed.

In contrast to the Freightliner with RSC enabled, the Sterling in its RSC-enabled condition experienced no instabilities, provided the trailer brakes were functioning. With RSC enabled and the trailer brakes disabled, the Sterling experienced instability in 4 of 5 test series performed. These test results are summarized in the tables below.

Table 4.11 through Table 4.13 present the results for each SC condition evaluated. The tables present the lowest steering scalar for each series of SWD maneuvers that resulted in the loss of roll or yaw (jackknife) stability. If neither stability threshold was exceeded then the series were considered test complete and were denoted as “TC” in the table. Series denoted with “NT” were not tested. Series resulting in roll instability were denoted with asterisks.

Table 4.11. 60% tractor GAWR SWD test series results for the SC-disabled test condition at 45 mph.

	Steering Scalar Observed to Produce Instability (SC Disabled)										
	Freq. (Hz)	0.3		0.4		0.5		0.6		0.7	
Tractor	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4		TC	TC	110%	100%	105%	95%	TC	100%	TC	120%
Freightliner 6x4		100%	85%	100%	75%	100%	85%	95%	95%	125%	85%
Sterling 4x2		130%	110%*	NT	NT	110%*	95%*	NT	NT	110%*	100%*

* Test series terminated due to loss of roll stability

These results tables were used to narrow down the SWD frequencies and dwell times evaluated to a single frequency and dwell time that could be further evaluated as a candidate performance maneuver. For each tractor semitrailer combination at each frequency between 0.3 to 0.7 Hz, the test terminating steering scalar was evaluated for the two dwell times of 0.5 and 1.0 seconds. With SC disabled, in every comparison, the maneuver with the 1.0-second dwell time required an equal or lower steering scalar (0 to 40 percent lower) to observe instability. These results were used to narrow the dwell time to 1.0 seconds allowing for a simpler assessment of maneuver input frequency.

For each vehicle at each frequency with a 1.0-second dwell time, the test terminating steering scalar was evaluated. With SC disabled for the Volvo and Sterling, the lowest steering scalar needed to attain a test series terminating condition was observed with the 0.5 Hz frequency. For the Freightliner, 0.4 Hz was the lowest and 0.5 Hz was the second lowest. Between those two frequencies, the ranges of scalars needed to attain a test series terminating condition were 75 to 100 percent for the 0.4 Hz SWD and 85 to 95 percent for the 0.5 Hz SWD.

Table 4.12. 60% tractor GAWR SWD test series results for the SC enabled with an unbraked trailer test condition at 45 mph.

	Steering Scalar Observed to Produce Instability (SC Enabled, Unbraked Trailer)										
	Freq. (Hz)	0.3		0.4		0.5		0.6		0.7	
Tractor	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4 ESC		TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 ESC		TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 RSC		TC	TC	120%	120%	105%	120%	110%	100%	120%*	100%
Sterling 4x2 RSC		TC	130%*	NT	NT	125%	130%*	NT	NT	NT	125%*

* Test series terminated due to loss of roll stability

Table 4.13. 60% tractor GAWR SWD test series results for the SC-enabled test condition with a braked trailer at 45 mph.

Tractor		**Steering Scalar Observed to Produce Instability (SC Enabled)**									
	Freq. (Hz)	0.3		0.4		0.5		0.6		0.7	
	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4 ESC		TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 ESC		TC	TC	TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 RSC		TC	TC	115%	105%	120%	95%	105%	95%	120%	100%
Sterling 4x2 RSC		TC	TC	NT	NT	TC	TC	NT	NT	TC	TC

These tables show SC's effectiveness in mitigating instability. Unlike the bobtail condition evaluated, each SC system intervened with foundation braking for a majority of the steering scalars performed for each SWD test series with this load condition. Due to SC commanded foundation braking, large differences in time history data were observed between the enabled and disabled test conditions. Figure 4.8 through Figure 4.10 show a graphical example of these differences that were observed. From top to bottom and left to right the figures show tractor: steering wheel angle, speed, lateral acceleration, deceleration, yaw rate, drive axles wheel heights, tractor semitrailer articulation angle, and roll angle.

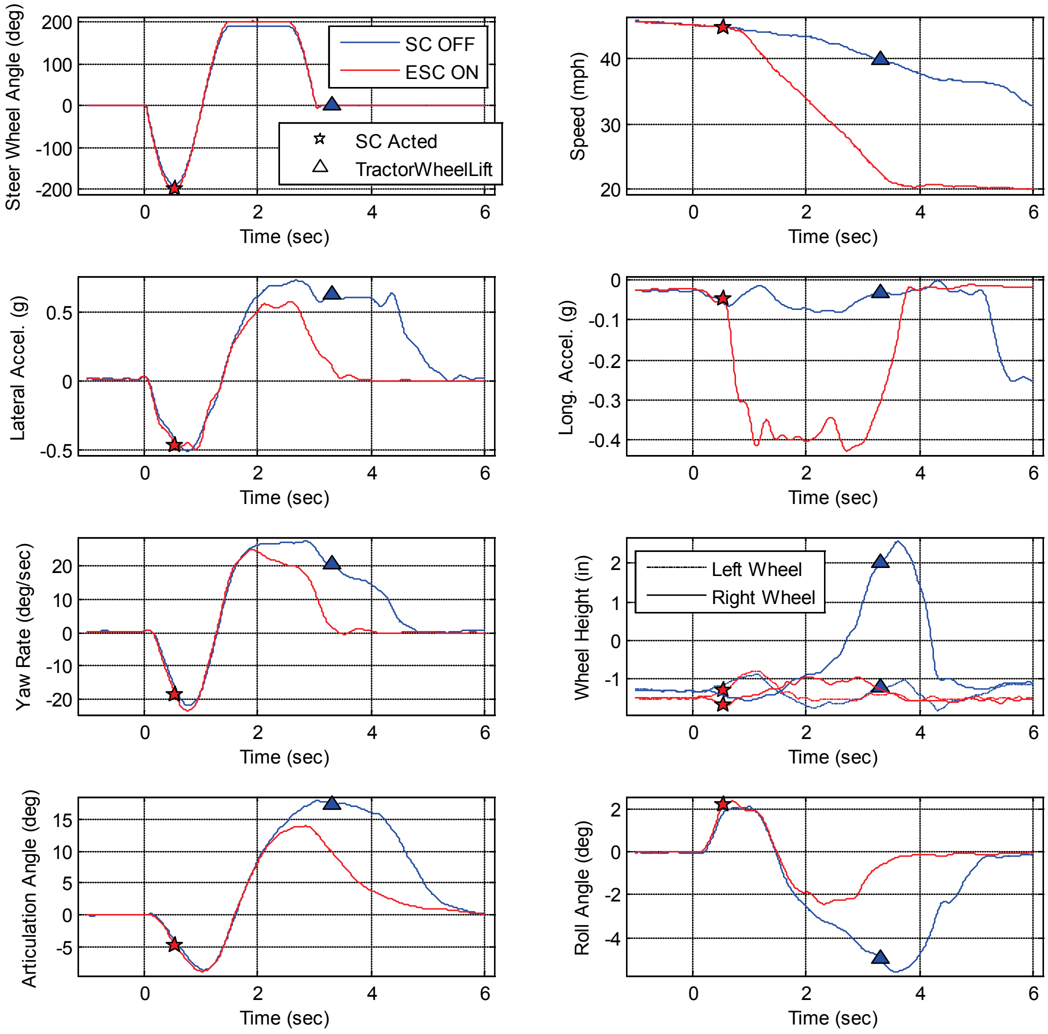


Figure 4.8. Shows that ESC activated the foundation brakes approximately at the peak of the initial steering input, reducing vehicle speed, lateral acceleration, yaw rate, and roll angle. Without these reductions in lateral dynamics, wheel lift was observed for the same set of given inputs with SC disabled.

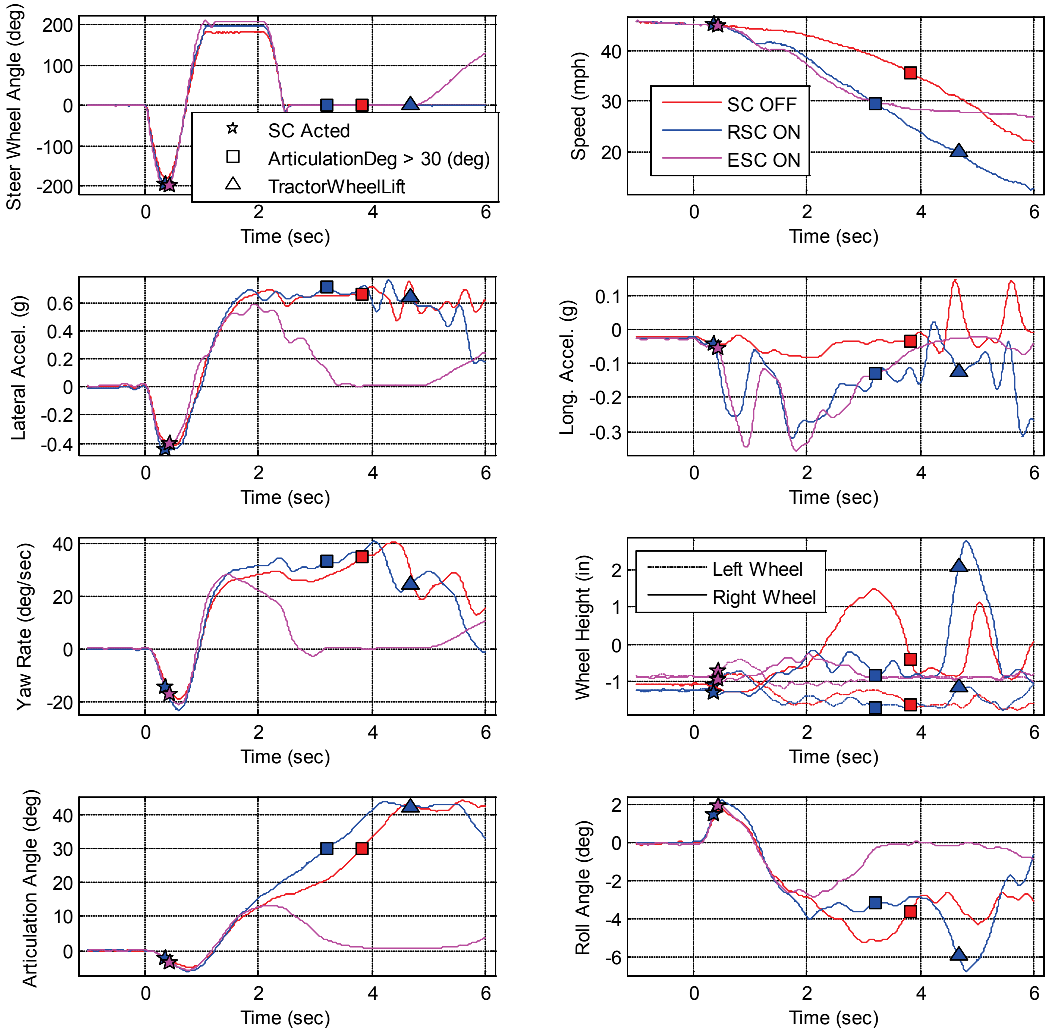


Figure 4.9. Time history data from SWD maneuvers with SC disabled, RSC enabled and ESC enabled. Data markers indicate when SC activated, when articulation angle was 30 degrees and wheel height was 2.0 inches.

Figure 4.9 shows that ESC and RSC activated the foundation brakes at approximately the peak of the initial steering input, reducing vehicle speed. ESC was also reducing lateral acceleration, yaw rate, and roll angle, which prevented wheel lift and kept the articulation angle below 15 degrees. However, RSC was not able to reduce yaw rate and lateral acceleration sufficiently, resulting in wheel lift and an articulation angle greater than 30 degrees for the same set of given inputs.

While these time history plots show there were large differences between SC test conditions they were difficult to put into perspective the resulting differences in position and orientation. To show these differences the time history data for position and yaw angle were combined with vehicle dimensional data produce the image shown in Figure 4.10.

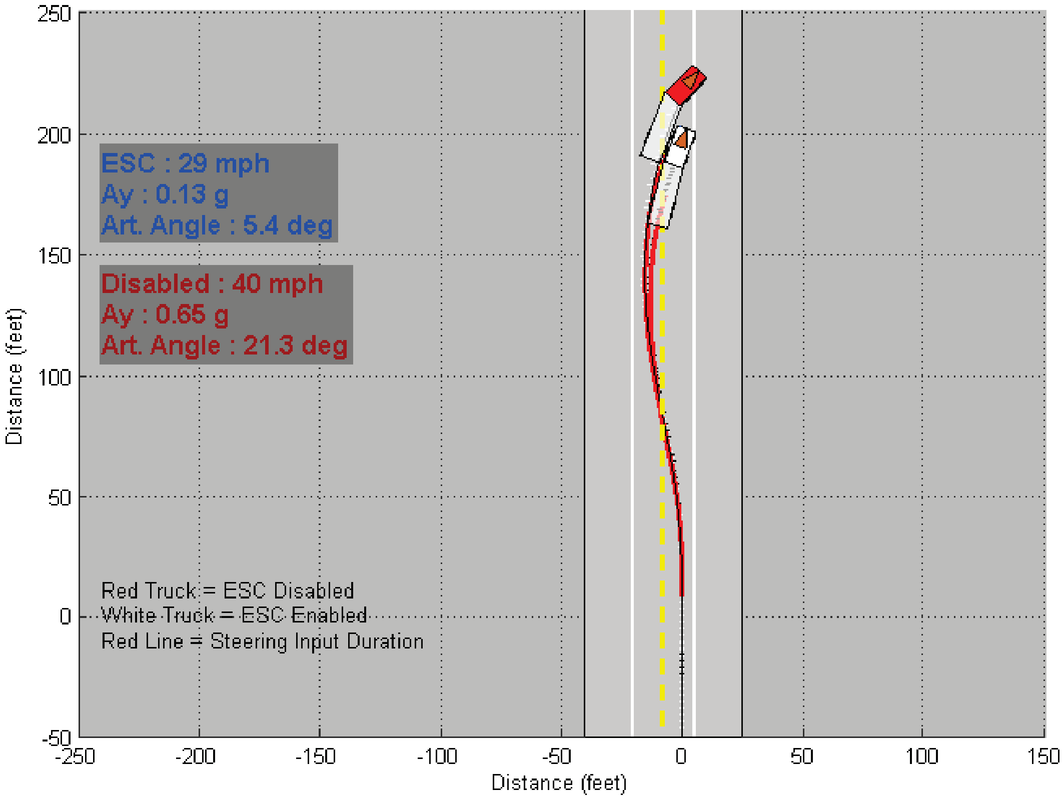


Figure 4.10. Example of a 45 mph 0.5 Hz sine with 1.0-second dwell maneuver with and without ESC enabled. This combination was tested with the 60% GAWR Load at the 80 percent steering scalar.

This figure shows two SWD tests with the same vehicle, test inputs, and 60% GAWR load condition. The white lead vehicle represents the SWD test with the ESC system enabled. The red lead vehicle represents the same test with the SC system disabled. These SWD tests were performed at 45 mph at a steering scalar of 80 percent. The black lines represent the path of the tractor and the heavy red line indicates the duration of the SWD maneuver. This graphic depicts the dynamic states of the two tests at the same time into the maneuver, approximately 4.4 seconds. The boxes on the left show the measured tractor speed, lateral acceleration (Ay), and tractor semitrailer articulation angle at this time for both ESC-enabled and disabled conditions. The roadway lanes were added to provide space and roadway alignment perspective. The lane widths depicted were 13 ft across.

This figure shows that the two tests were observed to have the same initial path and move from the center of the hypothetical right lane to near the center of the left lane. At that point, the paths begin to separate, and the SWD test conducted with ESC enabled returns into the original lane with less longitudinal displacement and with a lesser articulation angle. From this graphic the vehicle with ESC is clearly observed to have a better chance of recovering its original path and heading.

4.3.3 Low Surface Friction - Bobtail

For SWD test series performed in the bobtail condition at 30 mph on the wet Jennite, the tractors were all able to consistently perform each series in a stable manner regardless of SC condition, maneuver frequency (0.2 to 0.5 Hz), or dwell time (0.5 seconds) evaluated. SWD test series results for this load condition and surface are presented in Table 4.14. The table presents the lowest steering scalar for each series of SWD maneuvers that resulted in the loss of yaw stability. If the vehicle was stable then the series was considered test complete and was denoted as "TC" in the table. Series denoted with "NT" were not tested.

Table 4.14. Bobtail low-surface friction SWD test series results with SC disabled and enabled at 30 mph.

Tractor		**Steering Scalar Observed to Produce Instability (SC Enabled and Disabled)**			
	Freq. (Hz)	0.2	0.3	0.4	0.5
	Dwell (sec)	0.5	0.5	0.5	0.5
Volvo 6X4 ESC		TC	TC	TC	TC
Freightliner 6x4 ESC		TC	TC	TC	TC
Freightliner 6x4 RSC		TC	TC	TC	TC
Sterling 4x2 RSC		TC	TC	TC	TC

The Freightliner tested with SC enabled did not have any SC activations and displayed no instabilities. Therefore, the Freightliner was not tested in the SC-disabled condition, because observed changes would not have been attributable to SC.

Similarly, when testing the Sterling with RSC enabled at the 0.4 and 0.5 Hz frequencies, SC was not observed to activate or lose stability. Therefore, the Sterling was not tested in the SC-disabled condition because changes in vehicle performance would not have been attributable to RSC. The Sterling was tested with the SC disabled for the 0.2 and 0.3 Hz maneuvers, and there were no instabilities. Again, the truck-tractor was not tested in those maneuvers for the SC-enabled condition.

Figure 4.11 shows from top to bottom, and left to right, the tractor: steering wheel angle, speed, lateral acceleration, deceleration, yaw rate, drive axle side slip angle, yaw angle, and roll angle. This figure shows that two runs with the same set of given inputs were nearly identical regardless of SC condition; SC did not activate, and the vehicle did not experience instability.

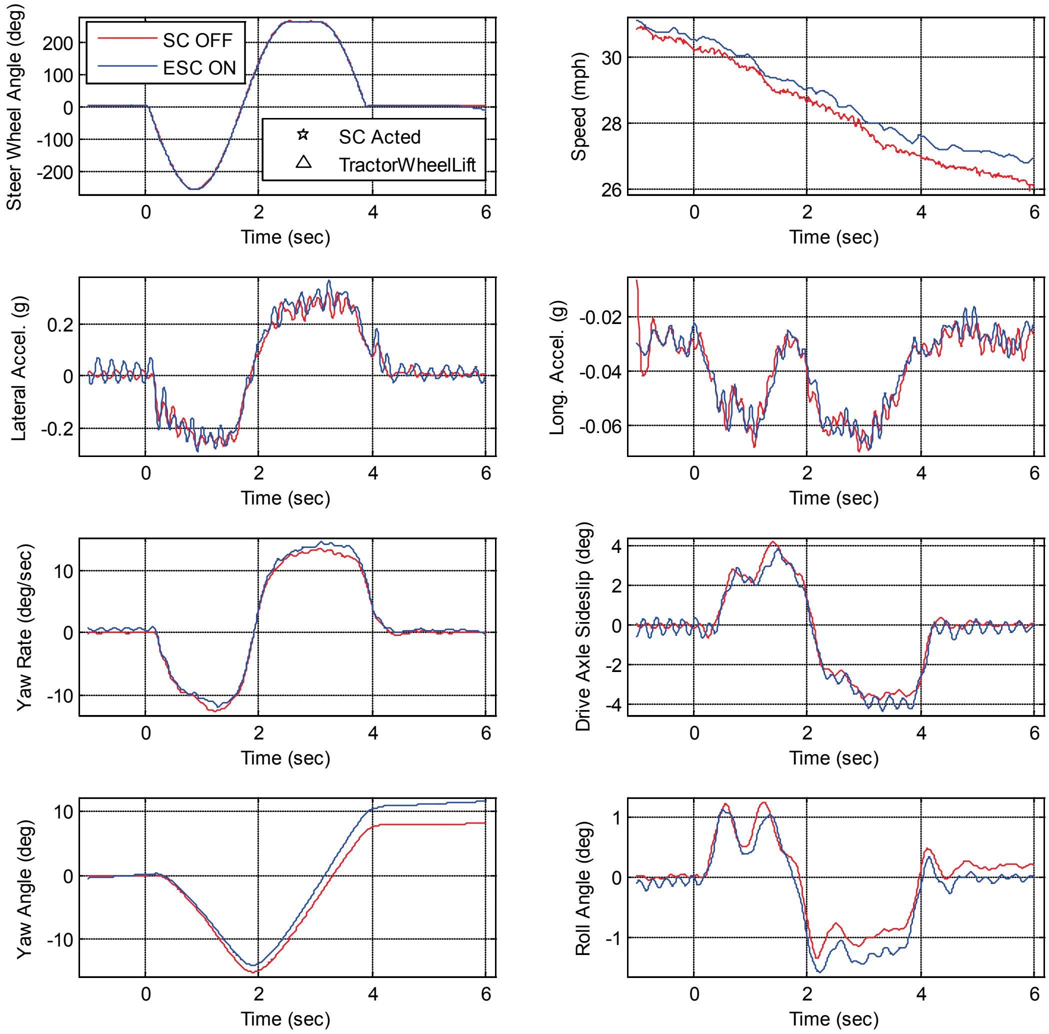


Figure 4.11. SWD Time history data from testing on a reduced-friction surface with SC disabled and enabled.

4.3.4 Low Surface Friction – 60% GAWR Load Condition

Table 4.15 and Table 4.16 present SWD test results from the three tractors in combination with the 28-foot flatbed trailer and 60% GAWR load condition that were performed on the reduced-friction wet Jennite surface. These maneuver series were performed at 30 mph at frequencies ranging between 0.2 to 0.5 Hz with the 0.5-second dwell time. The table presents the lowest steering scalar for each series of SWD maneuvers that resulted in the loss of yaw stability. If the combination was stable then the series was considered test complete and was denoted as “TC” in the table. Series denoted with “NT” were not tested.

The tables show test outcomes regarding overall stability for the Volvo and Freightliner were similar regardless of ESC test condition evaluated. These two vehicles were observed to be stable across all SC conditions and test maneuver frequencies evaluated at 30 mph.

time for both ESC-enabled and disabled conditions. The roadway lanes were added to provide space and roadway alignment prospective. The lane widths depicted were 13 ft.

This figure shows that the two tests were observed to have the same initial path and track the initial portion of the curve in a similar fashion. Towards the end of the curve, the red tractor keeps spinning even though it has been commanded to track straight (steering returns to zero - end of red line).

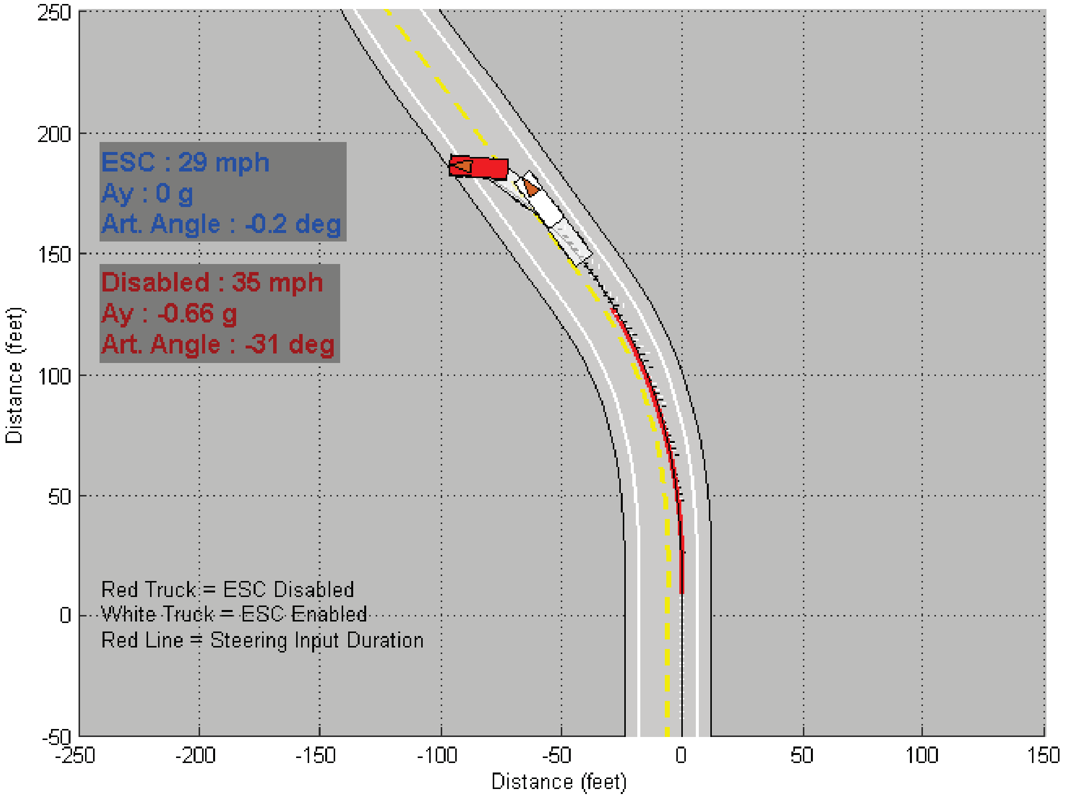


Figure 4.14. Example of a HSWD maneuver with and without ESC enabled. Combination was tested with the 60% GAWR load condition at the 80 percent steering scalar at 45 mph.

4.5 Ramp With Dwell

This section presents the bobtail and 60% GAWR load condition RWD test results conducted on a wet Jennite surface. The RWD maneuver was developed to identify deviation between the driver intended course and the actual vehicle course and to observe if SC intervenes.

To normalize each vehicle tested, a drive through speed and steering angle was determined by finding the maximum speed, not to exceed 35 mph, that the driver could maintain on the 500-foot radius curve without exiting the lane. All vehicles tested reached 35 mph during the drive through tests without exiting the lane. The speed used to conduct the RWD maneuver was 90 percent of the drive through speed. The speed at which RWD maneuver was conducted for the Volvo, Freightliner, and the Sterling bobtail and in combination with the 28-foot control trailer and 60% GAWR load condition was 32 mph.

Table 4.24. 60% GAWR load condition RWD test that resulted in SC activation at 32 mph

Tractor	**Lowest Target Steering Angle That SC Activation Was Observed (deg)**
2006 Volvo 6X4 ESC	180
2006 Freightliner 6x4 ESC	180
2006 Freightliner 6x4 RSC	N/A[1]
2008 Sterling 4x2 RSC	N/A[2]

1 No SC activation.
2 Not Tested

Table 4.25. 60% GAWR load condition RWD test that resulted in instability at 32 mph

Tractor	**Lowest Target Steering Angle That Instability Was Observed (deg)**	
	Enabled	**Disabled**
2006 Volvo 6X4 ESC	TC	TC
2006 Freightliner 6x4 ESC	TC	TC
2006 Freightliner 6x4 RSC	TC[1]	TC
2008 Sterling 4x2 RSC	N/A[2]	N/A[2]

1 No SC activation.
2 Not Tested

Figure 4.19 shows RWD time history data for the Volvo in combination with the 28-foot control trailer and 60% GAWR load condition with ESC enabled and disabled. This figure shows the tests with the target 180-degree steering wheel angle magnitude performed at 32 mph. From top to bottom, and left to right, the figure shows tractor, steering wheel angle, speed, yaw rate, lateral acceleration, torque, and brake pressure at each wheel. For the enabled tests, both engine torque reduction and brake pressure at both rear drive axles were observed during the maneuver with ESC activation. Engine torque reduction for the ESC-enabled test is shown, when the driver requested torque (the blue trace) and engine torque (the green trace) separate. For the SC-disabled tests both driver torque and engine torque remain equal.

The Freightliner with the RSC system enabled was observed to be actively applying the foundation brakes during this maneuver. In this test condition the Freightliner was observed to be stable at each frequency tested. The Sterling was tested only with RSC enabled, and each test series resulted in a jackknife with an articulation angle greater than 30 degrees, at steering scalars between 60 and 100 percent. Despite the RSC being enabled, the RSC activations observed with this tractor occurred after the tractor had jackknifed. Therefore, the Sterling was not tested in the SC-disabled condition because observed improvements to yaw stability would not have been attributable to SC.

Low-surface friction testing was not explored further due to several factors. In the bobtail condition, none of the vehicles displayed instability, regardless of SC condition. In the 60% GAWR load condition, neither the Volvo nor the Freightliner displayed any instability. The Sterling displayed instability (in the 60% GAWR load condition), and its RSC did not activate prior to instability.

Table 4.15. 60% GAWR, low surface friction, SWD test series results with SC disabled at 30 mph.

		Steering Scalar Observed to Produce Instability (SC Disabled)			
	Freq. (Hz)	0.2	0.3	0.4	0.5
Tractor	Dwell (sec)	0.5	0.5	0.5	0.5
Freightliner 6x4		TC	TC	TC	TC
Volvo 6X4		TC	NT	TC	TC
Sterling 4x2		NT	NT	NT	NT

Table 4.16. 60% GAWR, low surface friction, SWD test series results with SC enabled at 30 mph.

		Steering Scalar Observed to Produce Instability (SC)			
	Freq. (Hz)	0.2	0.3	0.4	0.5
Tractor	Dwell (sec)	0.5	0.5	0.5	0.5
2006 Volvo 6X4 ESC		TC	TC	TC	TC
2006 Freightliner 6x4 ESC		TC	TC	TC	TC
2006 Freightliner 6x4 RSC		TC	TC	TC	TC
2008 Sterling 4x2 RSC		60%	90%	100%	65%

Figure 4.12 shows from top to bottom, and left to right tractor, the steering wheel angle, speed, lateral acceleration, longitudinal acceleration, yaw rate, drive axle side slip angle, articulation angle, and roll angle. These data from the Freightliner shows that the vehicle performed slightly differently with ESC enabled and disabled, while the test with RSC enabled was observed to have larger differences. RSC applied more braking, shown in the plot of deceleration. This was observed to increase or extend the responses depicted in the plots of lateral acceleration, yaw rate, and drive axle side slip angle.

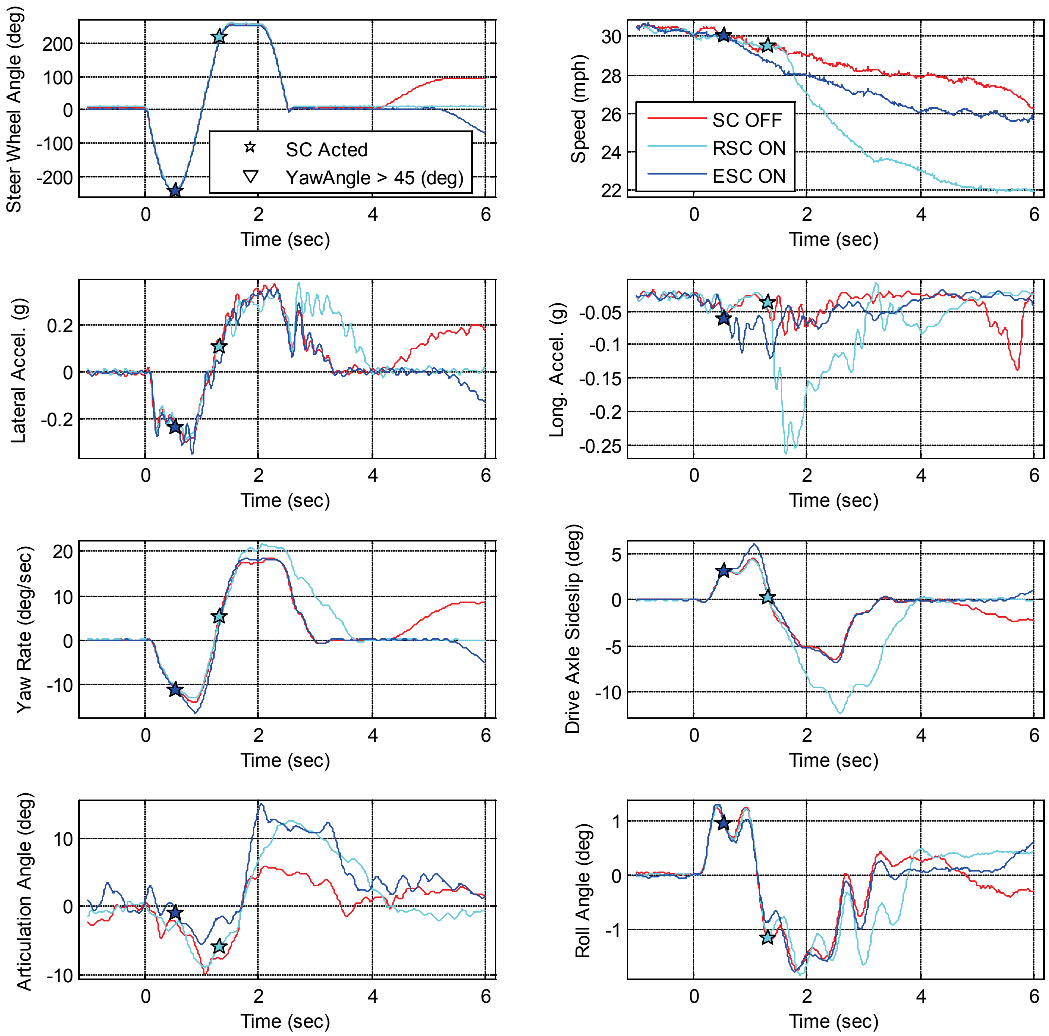


Figure 4.12. Time history data from loaded SWD test series conducted on a reduced-friction surface. Test data are from the Freightliner ESC, RSC and disabled test conditions.

Figure 4.13 shows from top to bottom, and left to right for the Sterling tractor: steering wheel angle, speed, lateral acceleration, longitudinal acceleration, yaw rate, yaw angle, articulation angle, and roll angle. This figure shows that the Sterling's RSC did not activate during the dynamic portion of the maneuver. As shown in the figure, this combination was observed to experience extended responses in lateral acceleration, yaw rate, yaw angle, and articulation angle that lead to a jackknife. Scalar values shown in the legend were divided by 100.

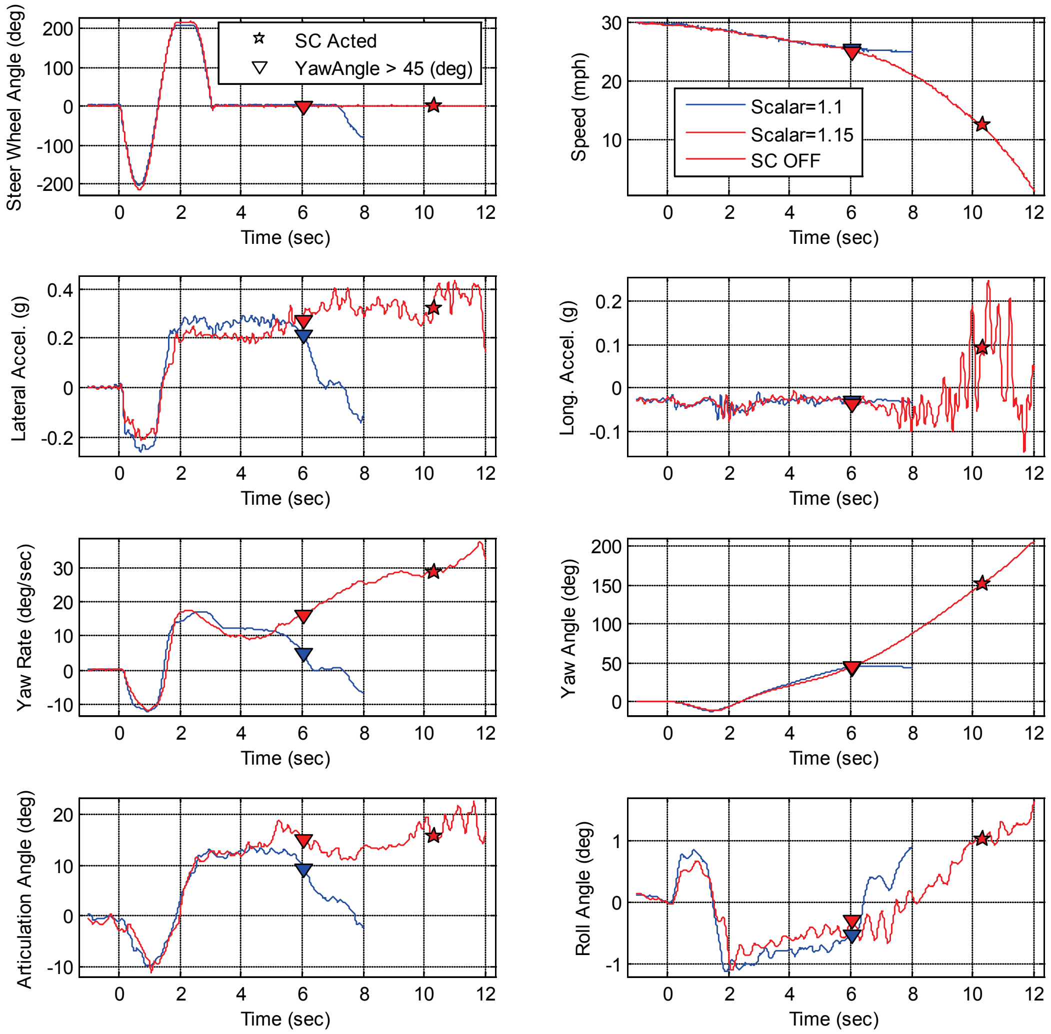


Figure 4.13. Sterling 4x2 time history data from loaded SWD test series conducted on a reduced-friction surface.

4.4 HSWD Test Results

This section presents HSWD test results from the bobtail and 60% GAWR load conditions that were conducted on dry asphalt.

4.4.1 High Surface Friction - Bobtail Load Condition

HSWD test results for all tractors in the bobtail load condition were observed to perform consistently regardless of SC condition, maneuver frequency, or dwell time evaluated. Table 4.17 and Table 4.18 present test series results observed at the different frequencies and dwell times for the SC-enabled and disabled test conditions. These series of maneuvers were performed at 50 mph with the Volvo and Freightliner 6x4 tractors and at 45 mph with the Sterling 4x2. They were conducted at frequencies of 0.3 and 0.5 Hz, with 0.5 and 1.0-second dwell times. The values in the table represent the lowest steering scalar at which loss of stability was observed. TC indicates the series was completed to the maximum steering scalar of 130 percent without losing stability. Series with observed loss of roll stability (wheel lift) were denoted with asterisks.

The Volvo and Freightliner experienced no instability and completed all test conditions at 50 mph. As was seen during the SWD test maneuvers, the Sterling was unable to complete any test series without experiencing wheel lift, regardless of SC condition at 45 mph. The Sterling's RSC system did not intervene during any HSWD maneuver. Thus, the vehicle's performance was nearly the same whether its RSC system was in the enabled or disabled. With the Sterling, wheel lift was observed between 80 and 90 percent steering scalars for all HSWD test series, regardless of RSC test condition.

Identical to the SWD testing, the Freightliner's RSC system did not intervene during any HSWD maneuver and was not observed to experience instability.

Table 4.17. Bobtail HSWD test series results for the SC-disabled test condition.

Tractor		**Steering Scalar Observed to Produce Instability (SC Disabled)**			
	Freq. (Hz)	0.3		0.5	
	Dwell (sec)	0.5	1.0	0.5	1.0
Freightliner 6x4 (50 mph)		TC	TC	TC	TC
Volvo 6X4 (50 mph)		TC	TC	TC	TC
Sterling 4x2 (45 mph)		90%*	90%*	90%*	90%*

* Test series terminated due to roll instability

Table 4.18. Bobtail HSWD test series results for the SC-enabled test condition.

Tractor		**Steering Scalar Observed to Produce Instability (SC Enabled)**			
	Freq. (Hz)	0.3		0.5	
	Dwell (sec)	0.5	1.0	0.5	1.0
Volvo 6X4 ESC (50 mph)		TC	TC	TC	TC
Freightliner 6x4 ESC (50 mph)		TC	TC	TC	TC
Freightliner 6x4 RSC (50 mph)		TC	TC	TC	TC
Sterling 4x2 RSC (45 mph)		90%*	80%*	80%*	80%*

* Test series terminated due to roll instability

4.4.2 High Surface Friction - 60% GAWR Load Condition

HSWD testing in the 60% GAWR load condition emphasized ESC's ability to limit instability. HSWD overall test results from this load condition are presented in Table 4.19 through Table 4.21 for the SC-disabled, SC-enabled with the unbraked trailer, and SC-enabled with braked trailer test conditions. These series of maneuvers were performed at 45 mph at frequencies of 0.3 to 0.6 Hz with 0.5- and 1.0-second dwell times. The values in the table represent the steering scalar at which loss of stability was observed. TC indicates the maneuver the series was completed to the maximum steering scalar of 130 percent without losing stability. Test series with roll instability were denoted with asterisks.

When ESC was disabled, both the Volvo and the Freightliner had cases of instability in all 16test series performed. These high-level test results shown in the tables for the HSWD were used to determine a frequency and dwell time for a candidate performance maneuver. For each combination, at each frequency between 0.3 to 0.6 Hz the test terminating steering scalar was evaluated for the two dwell times of 0.5 and 1.0 seconds. With SC disabled, in nearly every single comparison, the maneuver with the 1.0-second dwell time required equal or lower steering scalar (10 to 45% lower) to observe instability (observed in Table 4.19). Like the SWD, these results indicated the longer dwell time was more challenging to stability. These observations were used to narrow the maneuver dwell time to 1.0 second.

For each vehicle, at each frequency with a 1.0-second dwell time the test terminating steering scalar was evaluated. With SC disabled, the lowest steering scalar needed to attain test instability was observed at a different frequency for each vehicle. Those frequencies were 0.5, 0.4, and 0.3 Hz for the Volvo, the Freightliner, and the Sterling tractors. For all three vehicles, the 0.5 Hz test series was observed to have the lowest or second lowest steering scalar need to achieve a test series terminating condition. Between those three frequencies the ranges of scalars needed to attain a test series terminating condition were 75 to 115 percent for the 0.3 Hz, 70 to 90 percent for the 0.4 Hz, and 75 to 95 percent for the 0.5 Hz HSWD.

Table 4.19. HSWD test series results with SC disabled at 45 mph.

Tractor	**Steering Scalar Observed to Produce Instability**								
	Freq. (Hz)	0.3		0.4		0.5		0.6	
	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4		100%	115%	100%*	90%	130%	85%	130%	95%
Freightliner 6x4		85%	75%	90%	70%	100%	75%	95%	75%
Sterling 4x2		100%*	90%*	NT	NT	110%*	95%*	NT	NT

* Test series terminated due to wheel lift

As shown in Table 4.20, when ESC was enabled with the unbraked trailer, the Volvo and Freightliner tractors completed 15 of the 16 test series without loss of stability. The lone instance of instability was observed with the Freightliner at a scalar of 130 percent while performing the 0.4 Hz, 1.0-second HSWD maneuver. With the unbraked trailer the Freightliner's RSC system was able to extend the vehicles performance beyond that observed when the SC systems were disabled. However, instability was still observed in all eight test series performed in this test condition. This table shows a similar trend with the Sterling 4x2 with RSC enabled and the unbraked trailer. The Sterling's RSC system was able to extend the vehicle's performance to a larger steering scalar before observing instability (compare enabled to disabled test series with the same frequency and dwell time).

Table 4.20. HSWD test series results with SC-enabled and unbraked trailer at 45 mph.

Tractor	Steering Scalar Observed to Produce Instability (SC Unbraked Trailer)								
	Freq. (Hz)	0.3		0.4		0.5		0.6	
	Dwell (sec)	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Volvo 6X4 ESC		TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 ESC		TC	TC	TC	130%	TC	TC	TC	TC
Freightliner 6x4 RSC		110%*	80%*	100%	95%	100%*	80%*	125%	90%
Sterling 4x2 RSC		130%*	120%	NT	NT	120%*	125%	NT	NT

* Test series terminated due to wheel lift

Table 4.21 documents the results from the same HSWD testing with trailer brakes enabled. With the ESC systems enabled with the braked trailer the Volvo and Freightliner were observed to be stable in each of the test series performed. The Freightliner with the RSC enabled was observed to improve the performance over the disabled test condition in all eight test series performed but each series was still terminated due to instability. Comparing the braked versus unbraked trailer test series with the Freightliner and RSC enabled shows that the braked trailer extended the vehicles' performance to a larger steering scalar in three of the eight test series performed. The Sterling with RSC enabled and the braked trailer was observed to improve the performance over the disabled test condition in all test series performed. Compared to the RSC enabled unbraked trailer test condition, the Sterling was able to improve the performance in three of the four test series performed. The lone exception was observed at the 0.5 Hz frequency with the 1.0-second dwell time.

Table 4.21. HSWD test series with SC-enabled and braked trailer at 45 mph.

Tractor	Steering Scalar Observed to Produce Instability (SC ON)								
	Freq. (Hz)	0.3		0.4		0.5		0.6	
	Dwell (sec)	0.5		1.0		0.5		1.0	
Volvo 6X4 ESC		TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 ESC		TC	TC	TC	TC	TC	TC	TC	TC
Freightliner 6x4 RSC		95%	90%	95%	85%	110%	90%	105%	85%
2008 Sterling 4x2 RSC		TC	TC	NT	NT	TC	110%	NT	NT

Figure 4.14 shows two HSWD tests with the same vehicle, test inputs, and 60% GAWR load condition. The white lead vehicle represents the HSWD test with the ESC system enabled. The red lead vehicle represents the same test with the SC system disabled. These HSWD tests were performed at 45 mph at a steering scalar of 80 percent. The black lines represent the path of the tractor and the heavy red line indicates the duration of the maneuver. This graphic depicts the dynamic states of the two tests at the same time into the maneuver, approximately 4.4 seconds. The boxes on the left show the measured speed, lateral acceleration, and articulation angle at this

4.5.1 Bobtail

To conduct the bobtail RWD maneuver, the vehicle was navigated through the 500-foot radius curve at 32 mph. At the appropriate time, the driver would initiate the first steering increment to the left. The bobtail drive through steering angle at 35 mph for the Volvo was 60 degrees, for the Freightliner 50 degrees, and for the Sterling 40 degrees. From the drive through angle the steering controller was programmed to steer to the second target steering angle of 180 degrees for the Volvo, Freightliner, and Sterling tractors. Unless instability was observed, tests were also performed with target steering angles of 270 and 360 degrees. Due to differences in initial drive through steering angles needed to negotiate the 500-foot radius curve, the actual magnitudes achieved were typically 0 - 30 degrees lower than the targets. This was due to adjustments made by the driver to maintain lane position just prior to activating the steering controller. The steering controller was programmed to increase the steering angle from the initial input used by the driver to get to the target of 180, 270, or 360 degrees. Preprogrammed angles of 120, 130, and 140 degrees were used for the Volvo, Freightliner, and Sterling tractors to get to the target steering wheel input of 180 degrees.

For the Volvo and Freightliner with ESC enabled, ESC activation was observed on the first initial test with a target steering angle of 180 degrees. SC was not observed to activate during the Freightliner and Sterling RSC enabled test series. These results are summarized in two tables. Table 4.22 presents the lowest target steering angle that SC activation was observed with the SC-enabled test condition. Table 4.23 presents the lowest target steering angle that instability was observed with each SC test condition. SC activation was observed with the both the Volvo and Freightliner ESC systems in the first test with the target 180-degree steering angle. SC activation was not observed with either RSC system installed in the Freightliner or Sterling tractors.

From Table 4.23, the Volvo and Freightliner ESC\RSC experienced no instability for the first 180-degree increment and for additional increments of 270 and 360 degrees. There were no instabilities observed for any of the tests independent of SC condition with either 6x4 tractor. The 6x4 tractors with SC disabled were observed to understeer and reached their lateral limits on the Jennite surface (both yaw rate and lateral acceleration responses were saturated). However, the Sterling was unable to complete the first increment regardless of SC condition. The maneuver was terminated because the vehicle experienced engine torque induced spinout.

Table 4.22. Bobtail RWD tests that resulted in SC activation at 32 mph

Tractor	Lowest Target Steering Angle That SC Activation Was Observed (deg)
2006 Volvo 6X4 ESC	180
2006 Freightliner 6x4 ESC	180
2006 Freightliner 6x4 RSC	N/A[1]
2008 Sterling 4x2 RSC	N/A[1,2]

[1] No SC activation.

[2] Vehicle experienced engine torque-induced spinout (drive wheel longitudinal slip caused spinout).

Table 4.23. Bobtail RWD tests that resulted in instability at 32 mph

Tractor	**Lowest Target Steering Angle That Instability Was Observed (deg)**	
	Enabled	Disabled
2006 Volvo 6X4 ESC	TC	TC
2006 Freightliner 6x4 ESC	TC	TC
2006 Freightliner 6x4 RSC	TC[1]	TC
2008 Sterling 4x2 RSC	180[1,2]	180[1,2]

[1] No SC activation.

[2] Vehicle experienced engine torque-induced spinout (drive wheel longitudinal slip caused spinout).

Figure 4.15 shows RWD time history data from the Volvo bobtail with ESC-enabled and disabled tests at 32 mph. For the tests shown, the target steering wheel input was 180 degrees. From top to bottom, and left to right, the figure shows tractor steering wheel angle, speed, yaw rate, lateral acceleration, torque, and brake pressure at each wheel. For the enabled tests both engine torque reduction and brake pressure at the left rear drive axles were observed during the maneuver with SC activation. Engine torque reduction for the ESC-enabled test is shown when the driver requested torque (the blue trace) and engine torque (the green trace) separate. For the SC-disabled tests both driver torque and engine torque remained equal.

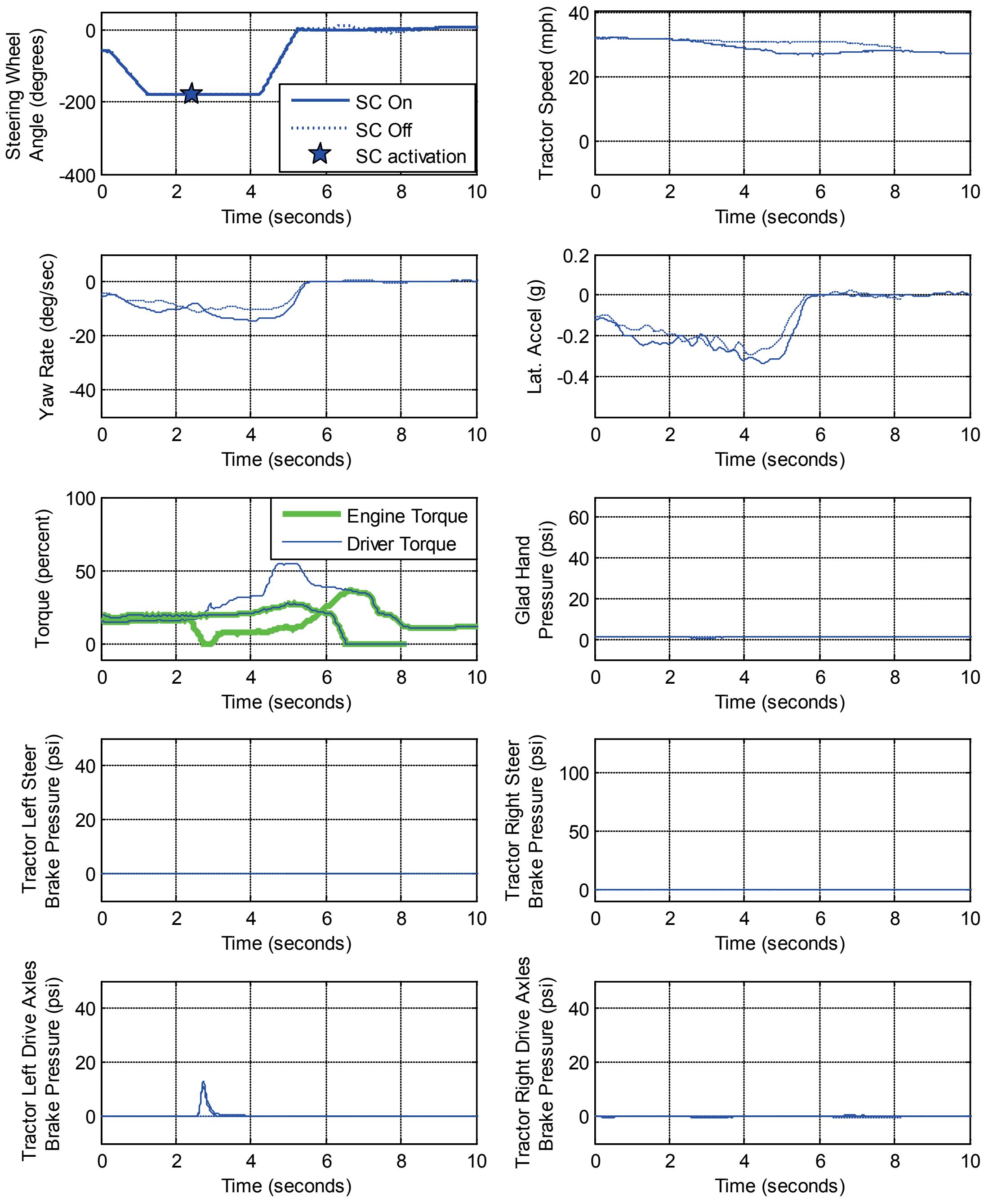


Figure 4.15. RWD time history data for ESC-enabled and disabled tests for the Volvo bobtail conducting an RWD maneuver at 32 mph.

Figure 4.16 is a position plot showing the path of the vehicle for SC-enabled and disabled tests. The green dot indicates the beginning of steering input for the portion of the maneuver where the steering controller increments the steering angle to 180 degrees. The blue star represents when SC activation occurred during the maneuver and the red dot indicates the completion of steering input by the steering controller. Comparing ESC enabled versus disabled, a small deviation in path was observed.

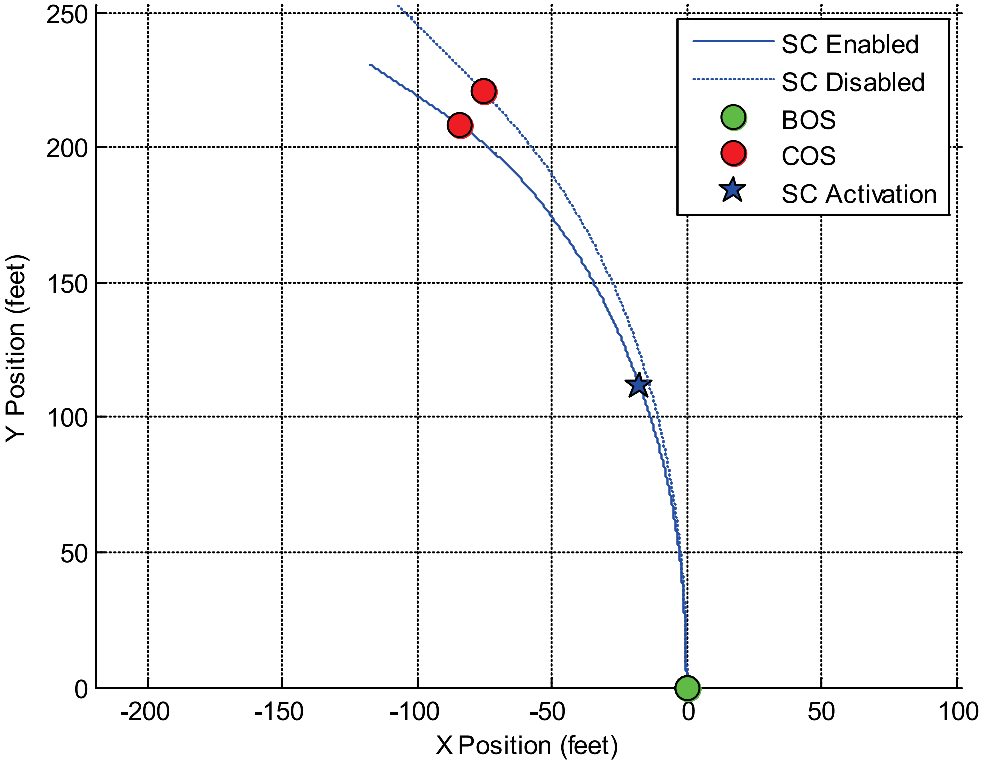


Figure 4.16. Position plot for ESC-enabled and disabled tests for the Volvo bobtail. Time history data for these tests were also shown in Figure 4.15.

Figure 4.17 shows RWD time history data from the Freightliner bobtail with ESC enabled and disabled at 32 mph. The target steering wheel input was 180 degrees. For the enabled tests, only engine torque reduction was observed during the maneuver at ESC activation. Engine torque reduction for the ESC-enabled test can be observed where the driver requested torque (the blue trace) and engine torque (the green trace) separate. For the ESC-disabled tests, both driver torque and engine torque remain equal.

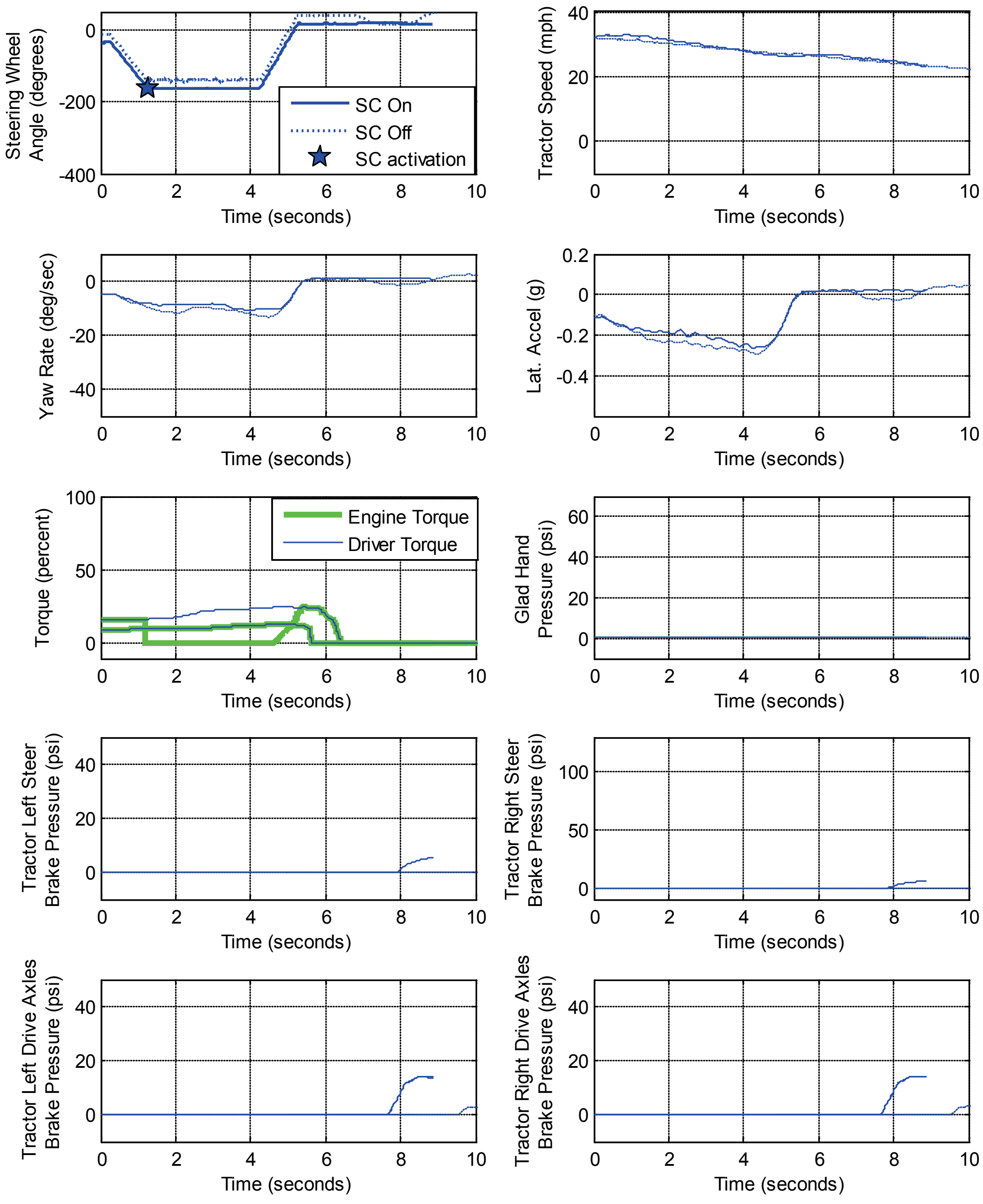


Figure 4.17. Time history data for ESC-enabled and disabled tests for the Freightliner ESC bobtail conducting an RWD maneuver.

Figure 4.18 is a position plot showing the path of the Freightliner for ESC-enabled and disabled tests. The green dot indicates the beginning of steering input for the portion of the maneuver where the steering controller increments the steering angle to 180 degrees. The blue star represents where ESC activation occurred during the maneuver and the red dot is indicates the completion of the steering input by the steering controller. Comparing ESC enabled versus disabled a small deviation in path can be observed. These bobtail data sets show that the ESC systems were active, but position data show conflicting and inconclusive changes to performance on the Jennite test surface.

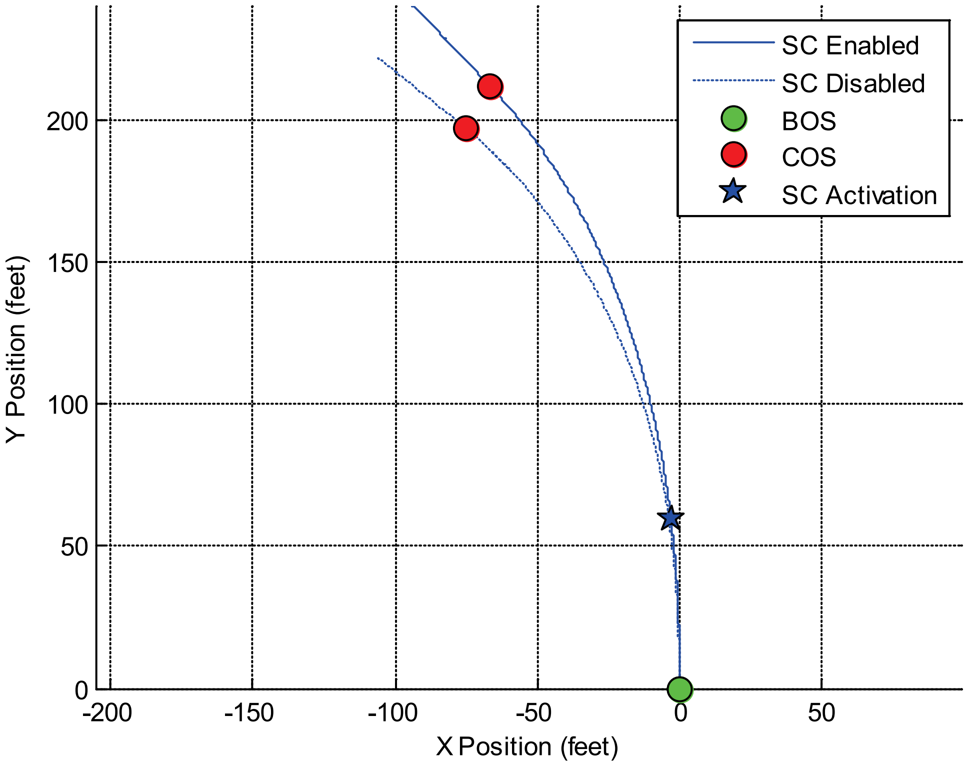


Figure 4.18 Example shows a position plot for SC-enabled and disabled tests for the Freightliner ESC bobtail. Time history data for these tests were shown in Figure 4.17.

4.5.2 60% GAWR Load Condition

Table 4.24 presents the lowest target steering angle that SC activation with was observed with each tractor in the RWD with the 60% GAWR load condition. ESC activation was observed with the initial 180-degree steering wheel angle for the Volvo and Freightliner with ESC enabled. No SC activation occurred during the Freightliner or Sterling RSC test series.

Table 4.25 presents the lowest target steering angle that instability was observed with each tractor in the RWD with the 60% GAWR load condition. The Volvo and Freightliner were observed to be stable for the 180-, 270-, and 360-degree steering inputs for SC enabled and disabled test conditions. The Sterling was not tested in this condition because it experienced a torque-induced spinout when tested in the bobtail condition.

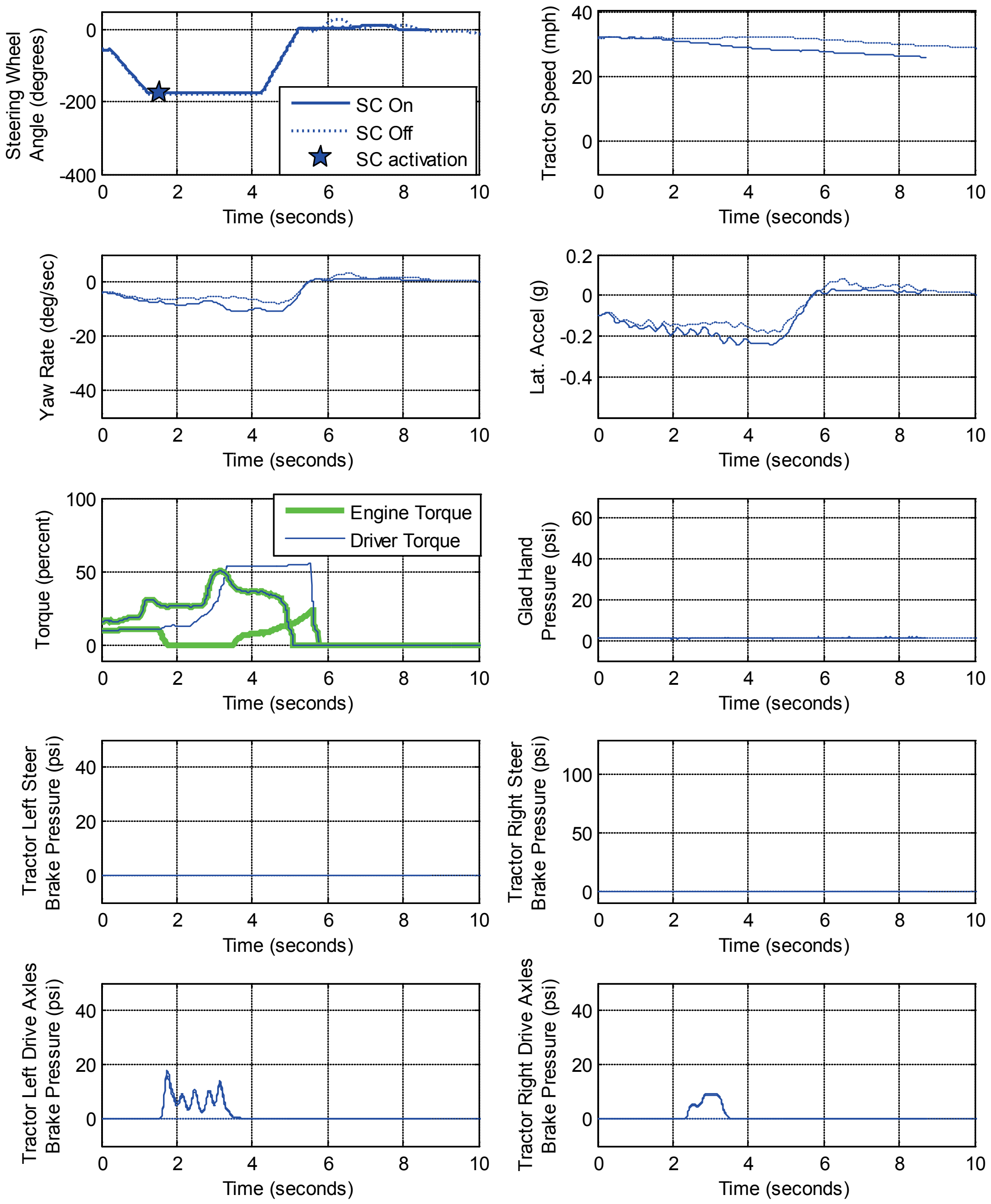


Figure 4.19. Example shows test data for SC-enabled and disabled tests for the Volvo ESC in combination with the 28-foot control trailer 60% GAWR conducting an RWD maneuver.

Figure 4.20 is a position plot showing the vehicle path for the ESC-enabled and disabled tests. The green dot indicates the beginning of steering input for the portion of the maneuver where the controller increments the steering angle to 180 degrees from the initial drive through angle. The blue star represents where ESC activation occurred during the maneuver and the red dot is indicates the completion of steering input by the steering controller. Comparing ESC enabled versus disabled a small change in path was observed.

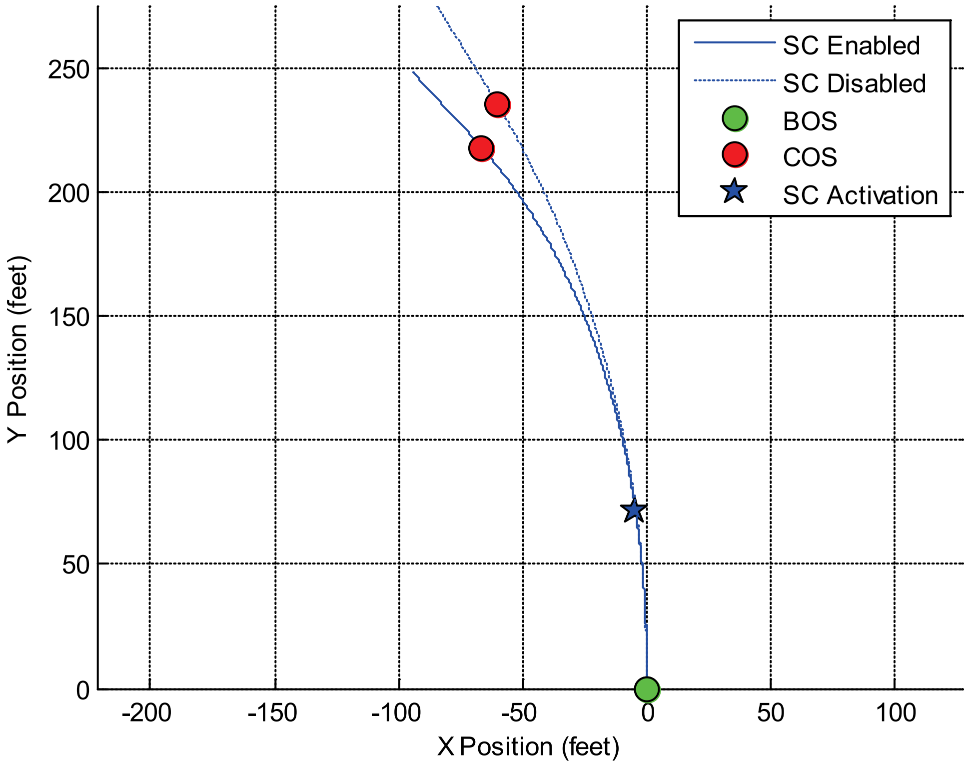


Figure 4.20. Position plot of RWD maneuvers for the Volvo ESC enabled and disabled in combination with the 28-foot control trailer and 60%GAWR load condition. Time history data for these tests were shown in Figure 4.19.

Figure 4.21 shows time history data for the Freightliner in combination with the 28-foot control trailer loaded with ESC enabled and disabled at 32 mph. The target steering wheel input was 180 degrees. For the enabled tests ESC commanded engine torque reduction, brake pressure at the left rear drive axles, and gladhand pressure (which indicated the trailer was also braked).

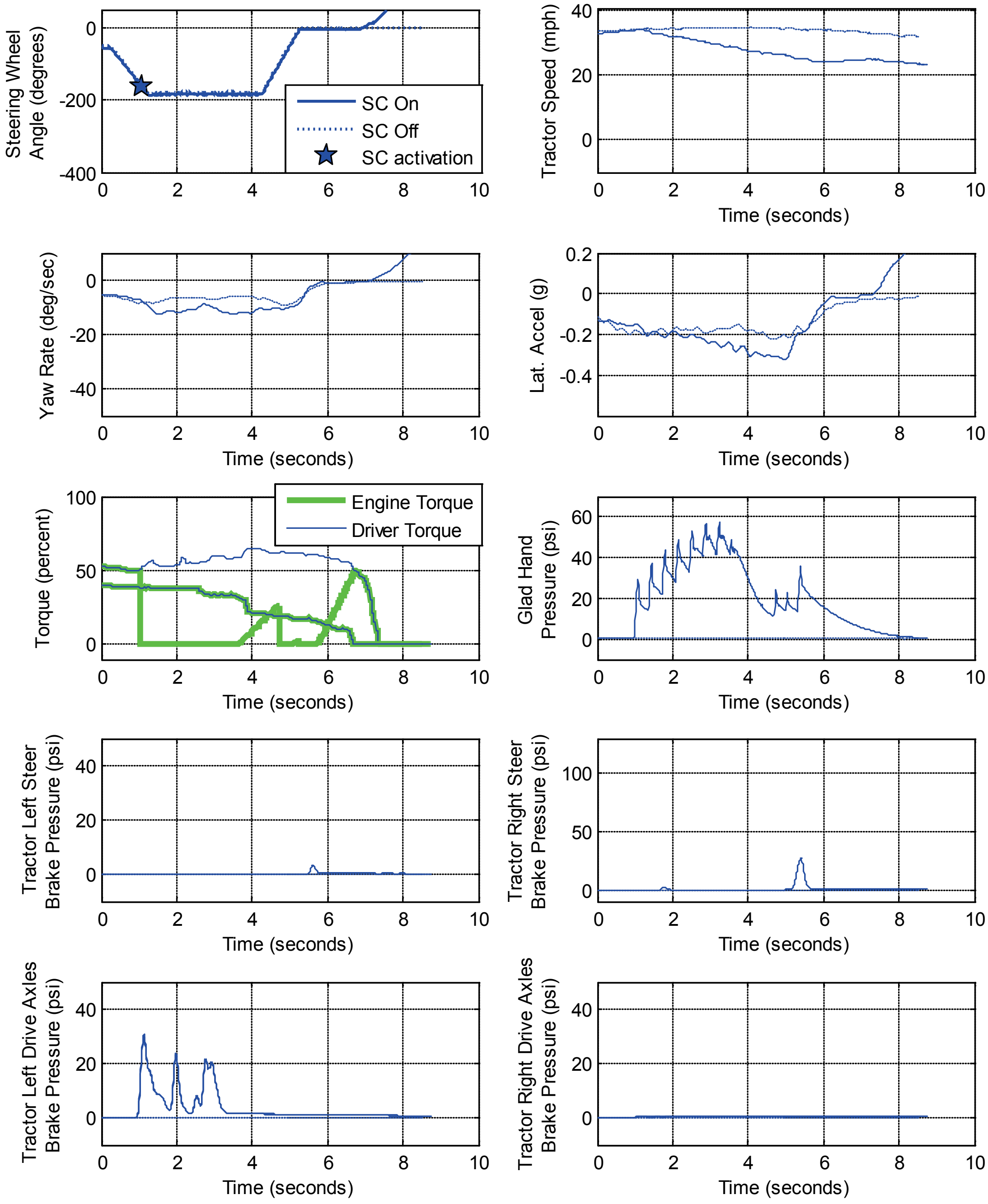


Figure 4.21. Example shows test data for ESC-enabled and disabled tests for the Freightliner ESC in combination with the 28-foot control trailer and 60% GAWR load condition while conducting an RWD maneuver at 32 mph.

Figure 4.22 is a position plot showing the vehicle path for ESC-enabled and disabled tests. The green dot indicates the beginning of steering input for the portion of the maneuver where the steering controller increments the steering angle to 180 degrees from the initial drive through angle. The blue star represents where SC activation occurred during the maneuver and the red dot indicates the completion of steering input by the steering controller. Comparing SC enabled versus disabled a change in path was observed.

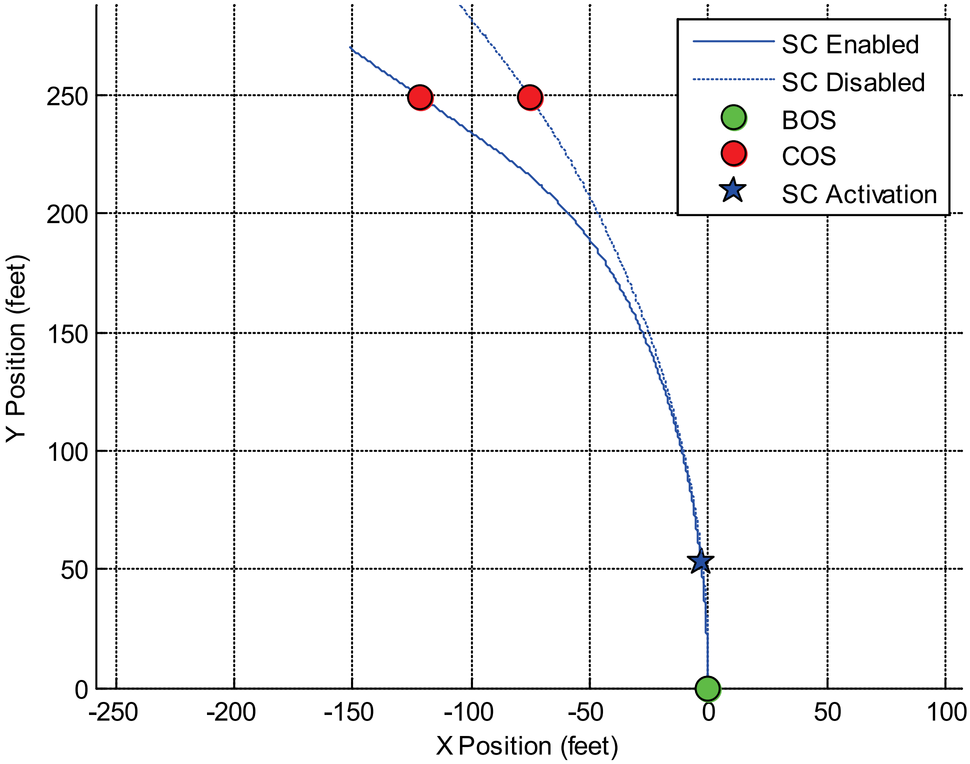


Figure 4.22. Position plot of RWD maneuvers for the Freightliner ESC in combination with the 28-foot control trailer 60% GAWR load condition. Time history data for these tests were shown in Figure 4.21.

4.6 RSM

This section presents the bobtail and 60% GAWR load condition RSM test results conducted on the wet Jennite surface. The RSM maneuver was conducted using the same test procedure used for high-surface friction testing in Phase II [1]. The steering wheel inputs were based on the average extrapolated steering wheel angle required to achieve 0.5g (SWA05) of lateral acceleration at a speed of 30 mph, determined from a series of SIS maneuvers. RSM steering magnitudes of 199 degrees for the Volvo, 193 degrees for the Freightliner, and 162 degrees for the Sterling were used for all tests conducted with both load conditions on the Jennite. For safety reasons, test speeds did not exceed 40 mph. For speeds greater than 40 mph, researchers concluded that there would not be enough space on the low-friction surface for the driver to recover if the vehicle were to spinout or jackknife without transitioning to a much higher friction surface. For all RSM maneuvers conducted on the Jennite, there were no roll instabilities observed.

4.6.1 Bobtail - Low Surface Friction

Table 4.26 and Table 4.27 documents the lowest speed that resulted in SC activation and the speed at which the maneuver was terminated for the RSM test series on the wet Jennite surface. For the Volvo ESC enabled condition, activation was first observed at 30 mph and the maneuver was terminated at 36 mph because the vehicle was plowing through the desired path. For the ESC-disabled condition, the test series was terminated at 32 mph because of plow out conditions. During testing with this maneuver, a test series were terminated by the experimenter subjectively determining from visual observation that the vehicle was experiencing plow.

For the Freightliner with ESC enabled, activation was first observed at 30 mph and the test series was terminated at 40 mph. For the Freightliner RSC tests series, RSC was not observed to activate and the maneuver was terminated at 40 mph. In this condition at the higher speeds the Freightliner was observed to understeer and reached its lateral limits on the Jennite surface (both yaw rate and lateral acceleration responses were saturated). Since RSC did not activate, the test series with the system disabled was not conducted because the results would have been the same.

For the Sterling RSC enabled test series, there were no RSC activations observed regardless of SC test condition. The test series was terminated at 34 mph because the vehicle experienced plow out conditions.

Table 4.26. Lowest speed that resulted in SC activation in bobtail RSM tests performed on the Jennite.

Tractor	**Lowest Speed That Resulted in SC Activation (mph)**
2006 Volvo 6X4 ESC	30
2006 Freightliner 6x4 ESC	30
2006 Freightliner 6x4 RSC	No Activation (test terminated at 40 mph)
2008 Sterling 4x2 RSC	No Activation (test terminated at 34 mph)

Table 4.27. Entrance Speed at which the RSM maneuver was terminated.

Tractor	**Speed That Resulted in Maneuver Termination (mph)**	
	Enabled	Disabled
2006 Volvo 6X4 ESC	36[2]	32[2]
2006 Freightliner 6x4 ESC	TC	TC
2006 Freightliner 6x4 RSC	TC	TC
2008 Sterling 4x2 RSC	34[2]	34[2]

TC- Test completed up to 40 mph

[2]- Test series terminated due to excessive plow

4.6.2 60% GAWR Load Condition – Low Surface Friction

Table 4.28 and Table 4.29 documents the lowest speed that resulted in SC activation and the speed at which the maneuver was terminated for the RSM test series on the Jennite surface. For the Volvo ESC-enabled condition, activation was first observed at 28 mph and the maneuver was terminated at 34 mph because the vehicle experienced plow out conditions. For the ESC-disabled condition, the test series was also terminated at 34 mph because the vehicle experienced plow out conditions. Testing was not conducted with the unbraked trailer condition.

For the Freightliner ESC-enabled test series, activation was first observed at 28 mph, and the series was terminated at 36 mph because of excessive trailer swing. For the unbraked test series, ESC activation was first observed at 26 mph and the series was terminated at 40 mph. When testing the Freightliner with the RSC system, RSC was not observed to activate in any of the tests in this series. In this condition at the higher speeds the Freightliner was observed to understeer and reached its lateral limits on the Jennite surface (both yaw rate and lateral acceleration responses were saturated). Testing with the RSC was terminated at 40 mph. Since the RSC system did not activate in this maneuver, additional test series with the unbraked trailer and the system disabled were not performed because the results would have been similar.

For the Sterling RSC-enabled test series, RSC was not observed to activate and the series was terminated at 33 mph after engaging the anti-jackknife cables. Since the RSC system did not activate in this maneuver and the vehicle experienced a jackknife event at 33 mph, additional test series with the unbraked trailer and the system disabled were not performed because the results would have been similar.

Table 4.28. 60% GAWR load condition RSM test that resulted in SC activation.

Tractor	**Lowest Speed That Resulted in SC Activation (mph)**	
	Enabled	Unbraked Trailer
2006 Volvo 6X4 ESC	28	NT
2006 Freightliner 6x4 ESC	28	26
2006 Freightliner 6x4 RSC	--	--
2008 Sterling 4x2 RSC	--	--

NT- Not Tested

Table 4.29. 60% GAWR load condition RSM test series stability summary.

Tractor	**Speed That Resulted in Maneuver Termination (mph)**		
	Enabled	Unbraked Trailer	Disabled
2006 Volvo 6X4 ESC	34[2]	NT	34[2]
2006 Freightliner 6x4 ESC	36[4]	TC	NT
2006 Freightliner 6x4 RSC	TC	NT	NT
2008 Sterling 4x2 RSC	33[3*]	NT	NT

TC- Test completed up to 40 mph
NT- Not tested
[2]- Test series terminated due to excessive plow
[3]- Test series terminated due to jackknife.
[4]- Test series terminated due to trailer swing.
*- Test series with SC showed no SC activation.

4.7 Maneuver Discussion and Evaluation Summary

One of the objectives of this research was to determine which maneuver and surface pairs were capable of assessing tractor semitrailer combination lateral yaw stability. A process of elimination was used to assess the different maneuvers and test conditions evaluated in this chapter. The two surface types were compared first. Selecting a surface first narrowed candidate maneuvers and conditions by nearly half. After selecting the surface for continued research, the two load conditions were compared and one was selected for further analysis. This again halved the maneuvers and conditions to analyze. The following subsections provide discussion and rationale for selecting the surface, load condition, and specific dynamic maneuvers for continued research and development.

4.7.1 Discussion on Surface Friction

Test results were compared between the two surfaces used in this phase of maneuver development. Test results from the maneuvers conducted on the reduced-friction Jennite surfaces show that there were few instabilities observed. Considering all maneuvers on this surface, 9 of the 77 (12%) test series were terminated due to instability. On this surface, SWD test results show that 4 of 43 test series were stopped due to a test series terminating condition. When conducting the RSM, 3 of 20 test series were stopped due to a test series terminating condition. When conducting the RWD, 2 of 14 test series were stopped due to power spinout condition.

There was a noticeable increase in the number of instabilities observed on high-friction dry asphalt in comparison to the reduced-friction test surface. 63 of the 140 (45%) combined SWD and HSWD test series were stopped due to roll or yaw instability on this surface. The SWD test results show that 35 of 84 test series were stopped due to lateral instability. When conducting the HSWD, 28 of the 56 series were stopped due to lateral instability.

Regarding the reduced-friction Jennite surface, the test results did show that ESC could improve the stability of these vehicles. The improvements in performance were noticeable when comparing an individual vehicles performance with and without ESC for maneuvers with the same given inputs. Measures of performance that were investigated worked for one vehicle, but were not replicated by the performance of another vehicle and ESC system. The test results with the RWD did show that there was potential to validate ESC's engine torque reduction function. However, the SIS conducted on high-friction surfaces was equally capable of evaluating ESC's engine torque reduction function. This would make the RWD maneuver redundant of the SIS maneuver (used for characterization). The remaining discussion regarding maneuver test results will be focused on the series conducted on dry asphalt (high-friction surface). This decision is supported by the increased number of test track instabilities observed on the high-friction surface, and the surface's reproducibility and availability. If objective performance tests for ESC using a low-friction surface were to be pursued, additional data analysis and maneuver design and development testing would likely be needed.

4.7.2 Discussion on Load Conditions

Results were compared between the two load conditions evaluated. During dry asphalt testing of the tractors in the bobtail condition, there were no yaw instabilities when performing the test maneuvers for any of the tractors. The Volvo and Freightliner 6x4 tractors were stable regardless of the state of the SC systems. The 4x2 Sterling did produce roll instability observations in both the SWD and HWSD maneuvers. Between the two maneuvers and three tractors, 70 series of tests were performed. Twenty of the 70 series were terminated due to roll instability with the Sterling. When these series were repeated with the 60% GAWR load condition, 43 of the 70 series were stopped due to observances of a test terminating condition for either roll or yaw stability. Of the 43 observances, 15 were terminated due to roll instability, and 28 due to yaw instability. The remaining discussion regarding the maneuver test results will be focused on the series conducted with the 60% GAWR load condition due to these increased frequency of instabilities.

4.7.3 Selecting a Candidate Performance Maneuver

When comparing the test results from the SWD and HSWD maneuvers, both appeared capable of being developed into an objective performance maneuver. The large differences in test results indicated that each would challenge a vehicle's lateral stability and (for the tractors tested) discriminate whether or not it was equipped with SC. The lowest steering scalar needed to attain a test series terminating condition was observed at frequencies that ranged from 0.4 to 0.5 Hz for the SWD and from 0.3 to 0.5 Hz for the HSWD. For two of the three series at these frequencies (0.3 to 0.5 Hz) the spread in the steering scalars needed to achieve instability was smaller for the SWD. This indicated that the vehicles were more sensitive to changes in frequency and steering amplitude when performing the SWD versus the HSWD. Based on these results from the maneuver development research, the 0.5 Hz sine with 1.0-second dwell was selected for continued objective performance maneuver development. While the test results indicated that it was the best candidate, there were also several tangible reasons to support its selection. It is representative of crash avoidance or lane change maneuvers, and its previous use in FMVSS No. 126 accelerated the measure of performance research. Since researchers had little experience with the selected SWD parameters and load conditions, supplementary test series were performed with additional trailers to refine the testing methodology and to verify the results presented in this section that were obtained with a low-production, low-usage trailer. The additional research performed conducting the SWD maneuvers with other trailers is discussed in the following section of this report

5 TEST MANEUVER REFINEMENT

Maneuver development discussed in the previous section were limited to a low-production, low-usage, and short 28-foot single axle flatbed trailer. That trailer was used for two reasons. First, Phase II roll stability research conducted with this trailer (when loaded) were concluded to produce very similar test results to combinations that were tested with two 53-foot box vans, two 48-foot flatbeds and a 42.5-foot tanker. Second, this trailer was selected to limit the size of the test matrix used to evaluate potential maneuvers, loads, and surfaces. Once these variables were reduced, a larger number of combinations with different trailers could then be evaluated. Table 5.1 shows the added trailers that were used to refine the testing methodology and further evaluate the candidate performance maneuvers.

The test refinement research was centered on a characterization issue dealing with how vehicles were to be loaded for the SIS test procedure. This issue revolved around tractors with liftable axles. Specifically, in the bobtail condition they are in the lifted position, but when the vehicle is loaded the liftable axles are typically down carrying a portion of the combination’s weight. By lowering and loading this additional axle the vehicle’s steady-state and dynamic performance can be altered. The first section in this chapter presents SIS maneuver results conducted with the tractors and four different trailers in the 60% GAWR load condition. While the tractors used in this study did not have liftable axles, it was desired to see how the trailer and load would alter the characterization process used to determine the SWA needed to produce 0.5 g of lateral acceleration. Depending on the effects, the SWA scaling used for the SWD would have to be adjusted or altered or the loaded condition could potentially replace the bobtail test condition in the SIS characterization procedure.

The second section in this chapter presents face validity research with the candidate 0.5 Hz SWD maneuver, the prescribed 60% load condition, and three vastly different, high-production, high-usage trailer types. Table 5.2 below presents the test matrix used for this stage of the performance test research and development. The table shows the HSWD was also evaluated in this phase as it was considered the next best candidate.

Table 5.1. Trailers tested.

Year	Make	Type	Length (feet)
2007	Strick	Dry Box Van	53
2007	Fontaine	Flatbed (spread Axle)	48
2007	Heil	9200 Gallon Tanker	42
2003	Great Dane	Flatbed (121 Style Trailer)	28

Table 5.2. Refinement and face validity test matrix.

Maneuver	Frequency/Rates	Dwell Time	Loads Condition	Entrance Speed
SIS	13.5	2.0	60% GAWR	30
SWD	0.5	1.0	60% GAWR	45
HSWD	0.5	1.0	60% GAWR	45

5.1 SIS Test Results

SIS tests were conducted with three tractors and four different trailers in the 60% GAWR load condition at 30 mph. These test series were performed to compare SIS test results with the two load conditions and to assess if the loaded condition could replace the bobtail test condition in the SIS characterization procedure.

Table 5.3 through Table 5.6 present for the SIS test series, the load condition the vehicle was tested in; the range of input speeds; the average extrapolated SWA at 0.5 g for each series; and the R^2 statistics that were obtained from the linear regression analyses. Before the SIS maneuver was conducted with a trailer and load, the bobtail test series was performed so test results could be compared.

For the Volvo (Table 5.3) the calculated average of angles for bobtail tests ranged between 214 and 221 degrees. When connected to the loaded trailers the calculated average of angles ranged between 200 and 226 degrees.

For the Freightliner ESC (Table 5.4) the calculated average of angles for bobtail tests ranged between 204 and 212 degrees. When connected to the loaded trailers the calculated average of angles ranged between 183 and 197 degrees.

Table 5.3. SIS tests results for the Volvo 6x4. Table shows the test series range of input speeds, average steering angle extrapolated at 0.5 g, and the R^2 statistic.

Vehicle Tested	**Test Series (number of tests)**	**Load Conditions**	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range**
Volvo	1 (6 Tests)	Bobtail	30.0 – 30.1	221	0.996 – 0.998
Volvo	2 (6 Tests)	Bobtail	29.6 – 30.4	216	0.996 – 0.998
Volvo	3 (6 Tests)	Bobtail	30.1 – 30.5	214	0.997 – 0.998
Volvo with					
Box Van	1 (6 Tests)	60% GAWR	30.1 – 30.6	226	0.994 – 0.998
Flatbed	2 (6 Tests)	60% GAWR	30.0 – 30.6	206	0.997 – 0.998
Tanker	3 (6 Tests)	60% GAWR	29.7 – 30.3	207	0.994 – 0.998
28-Foot Flatbed	4 (6 Tests)	60% GAWR	30.1 – 30.5	200	0.995 – 0.998

For the Freightliner RSC (Table 5.5) the calculated average of angles for bobtail tests ranged between 196 to 201 degrees. When connected to the loaded trailers the calculated average of angles ranged between 187 and 200 degrees.

For the Sterling (Table 5.6) the calculated average of angles for bobtail tests ranged between 152 and 156 degrees. When connected to the loaded trailers the calculated average of angles ranged between 144 and 156 degrees.

Table 5.4. SIS tests results from the Freightliner 6x4 ESC.

Vehicle Tested	**Test Series (number of tests)**	**Load conditions**	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (from linear regression)**
Freightliner ESC	1 (6 Tests)	Bobtail	29.6 – 29.9	209	0.981 – 0.995
Freightliner ESC	2 (6 Tests)	Bobtail	29.2 – 30.2	212	0.962 – 0.998
Freightliner ESC	3 (6 Tests)	Bobtail	29.5 – 30.4	204	0.983 – 0.998
Freightliner with					
Box Van*	1 (6 Tests)	60% GAWR	30.3	189	0.998 – 0.999
Flatbed	2 (6 Tests)	60% GAWR	28.8 – 30.2	193	0.988 – 0.998
Tanker*	3 (6 Tests)	60% GAWR	30.1	183	0.997 – 0.998
28-Foot Flatbed	4 (6 Tests)	60% GAWR	30.5 - 31	197	0.996 – 0.998

*Cruise control was used to maintain speed.

Table 5.5. SIS tests results from the Freightliner 6x4 RSC.

Vehicle Tested	**Test Series (number of tests)**	**Load conditions**	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (from linear regression)**
Freightliner RSC	1 (6 Tests)	Bobtail	29.9 – 30.7	198	0.993 – 0.999
Freightliner RSC	2 (6 Tests)	Bobtail	29.3 – 30.5	201	0.995 – 0.998
Freightliner RSC	3 (6 Tests)	Bobtail	30.1 – 30.4	196	0.997 – 0.999
Freightliner with					
Box Van	1 (6 Tests)	60% GAWR	29.7 – 31.9	188	0.997 – 0.998
Flatbed	2 (6 Tests)	60% GAWR	29.6 - 30	191	0.991 – 0.998
Tanker	3 (6 Tests)	60% GAWR	29.3 – 30.4	187	0.994 – 0.998
28-Foot Flatbed	4 (6 Tests)	60% GAWR	30.4 – 30.9	200	0.996 – 0.997

Table 5.6. SIS tests results from the Sterling 4x2 RSC.

Vehicle Tested	**Test Series (number of tests)**	**Load Conditions**	**Input Speed Range (mph)**	**Average of Angles (L/R) at 0.5 g**	**R^2 Range (From linear Regression)**
Sterling RSC	1 (6 Tests)	Bobtail	30.0 – 30.6	156	0.994 – 0.998
Sterling RSC	2 (6 Tests)	Bobtail	30.3 – 30.7	152	0.992 – 0.997
Sterling RSC	3 (6 Tests)	Bobtail	30.2 – 30.7	155	0.997 – 0.998
Sterling with					
Box Van	1 (6 Tests)	60% GAWR	30.1 – 30.6	154	0.996 – 0.998
Flatbed	2 (6 Tests)	60% GAWR	30 – 30.8	144	0.995 – 0.998
Tanker	3 (6 Tests)	60% GAWR	30.2 – 30.7	156	0.990 – 0.998
28-foot flatbed	4 (6 Tests)	60% GAWR	29.9 – 30.6	153	0.995 – 0.998

5.2 Sine With Dwell Results

In addition to testing with the 28-foot flatbed trailer, SWD testing using the 0.5 Hz frequency and 1.0-second dwell time was conducted with the tractors and three other trailers at an entrance speed of 45 mph. These trailers were a spread-axle flatbed, a 53-foot box van, and a 9,200-gallon tanker. They were loaded per the 60% GAWR loading condition (the loading details are included in Appendix D). These tests were performed to compare test results with the 28-foot control trailer to results with the same tractors combined with common over-the-road trailers.

Table 5.7 shows the lowest steering scalar at which the articulation angle exceeded 30 degrees (loss of yaw stability) for each tractor with the two flatbeds and the single box van trailers, and SC test conditions. Series denoted with "TC" indicate that the SWD maneuver was completed up to the steering scalar of 130 percent without the observation of a loss of stability. The table shows, in general, that each tractor semitrailer combination performed similarly when comparing the same SC test conditions (i.e., Volvo/28-foot flatbed trailer to Volvo/box van to Volvo/spread axle with the SC-enabled test condition).

Table 5.7. SWD test results with 28-foot flatbed, spread axle flatbed, and box van trailers, at 45 mph.

Tractor	Steering Scalar Observed to Produce Instability								
	28-Foot Flatbed Trailer			Spread Axle Trailer			Box Van Trailer		
	SC Enabled	SC Enabled Unbraked Trailer	SC Disabled	SC Enabled	SC Enabled Unbraked Trailer	SC Disabled	SC Enabled	SC Enabled Unbraked Trailer	SC Disabled
Volvo 6X4 ESC	TC	TC	95%	TC	TC	100%	TC	TC	110%
Freightliner 6x4 ESC	TC	TC	85%	TC	TC	65%	TC	TC	95%
Freightliner 6x4 RSC	95%	120%	85%	TC	75%	65%	TC	95%	95%
Sterling 4x2 RSC	TC	130%	95%	110%	100%	95%	TC	110%	105%

From Table 5.7, with SC disabled, loss of yaw stability was observed at steering scalars of 95, 100, and 110 percent for the 28-foot flatbed, spread axle, and box van trailers, respectively, when combined with the Volvo. When that SWD series were repeated with the two ESC-enabled test conditions the loss of yaw stability events were no longer observed.

Similar results were observed with the Freightliner equipped with the ESC system. With the two ESC-enabled test conditions (with trailer brake, and without trailer brakes), the systems remained stable. With the SC systems disabled loss of yaw stability was observed at steering scalars of 85, 65, and 95 percent when combined with the 28-foot flatbed, spread axle, and box van trailers. When the Freightliner was tested with the RSC system enabled, only the SWD series with the 28-foot flatbed was observed to experience loss of yaw stability. That loss of yaw stability was observed at a steering scalar of 95 percent. When tested in the RSC-enabled with the unbraked trailer test condition, SWD test series were terminated at the 120, 75, and 95 percent steering scalars when combined with the 28-foot flatbed, spread axle, and box van trailers.

The Sterling with RSC enabled completed SWD series conducted with the 28-foot flatbed and box van trailers. However, it was observed to lose yaw stability at the 110 percent steering scalar with the spread axle trailer. With the SC system enabled with the unbraked trailer, loss of yaw stability was observed at the 130, 100, and 110 percent steering scalars with three different trailers. With the SC system disabled, loss of stability was observed at steering scalars of 95, 95, and 105 percent when combined with the three different trailers shown in the table.

Comparing results with the spread axle trailer, the SC-disabled test series experienced yaw instability in all four test series at steering scalars between 65 to 100 percent. The truck-tractors with ESC enabled were able to complete every test series (with trailer brakes and without trailer brakes) without loss of stability. Those vehicles with RSC systems did show a performance improvement over the SC-disabled test condition. However, three of the four series tested with RSC equipped vehicles were observed to attain instability at the 75 to 110 percent steering scalars.

Similar to testing with the spread-axle flatbed trailer, when testing with the box van trailer with SC disabled loss of yaw stability was observed in all four test series at steering scalars between 95 to 110 percent. The tractors with ESC enabled were able to complete every test series (with trailer brakes and without trailer brakes) without loss of stability. Those vehicles with RSC systems did show a performance improvement over the SC-disabled test condition. Test series conducted with RSC enabled were observed to mitigate the yaw instability. However, two series with RSC enabled and the unbraked trailer were observed to lose yaw stability at the 95 and 110 percent steering scalars.

Table 5.8 presents the lowest steering scalar for each SWD test series that wheel lift was observed to exceed 2.0 inches (loss of roll stability) for each combination with the tanker trailer. Testing with the tanker resulted in test terminating conditions (specifically, wheel lift) for all truck tractors regardless of SC configuration (ESC, RSC, enabled or disabled). The water ballast movement (sloshing) during the test maneuvers produced a roll-inducing condition. This factor kept SC systems from improving performance to a similar level as observed with the fixed-ballast trailers. Nevertheless, the two 6x4 tractors equipped with ESC systems had significant increases in steering scalars at which instability was observed, which indicated a better stability margin. Roll instability was observed at the 50 percent steering scalar with ESC disabled (both Volvo and Freightliner), and between 60-95 percent with the two ESC-enabled test conditions. RSC showed improvement from 50 percent steering scalar (RSC disabled) to as much as 65 percent with RSC enabled on the Freightliner, but showed no improvement in the Sterling.

Table 5.8. SWD test results with tanker trailer, at 45 mph.

Tractor	**Steering Scalar Observed to Produce Instability**		
	SC Enabled	**SC Enabled With Unbraked Trailer**	**SC Disabled**
Volvo 6X4 ESC	95%*	90%*	50%*
Freightliner 6x4 ESC	65%*	60%*	50%*
Freightliner 6x4 RSC	65%*	55%*	50%*
Sterling 4x2 RSC	60%*	60%*	60%*

* Test series terminated due to roll instability

5.3 Half-Sine With Dwell Results

Table 5.9 presents the lowest steering scalar at which a loss of either roll (denoted with asterisks) or yaw instability was observed during HSWD testing with the tractors and the 28-foot flatbed, spread axle, and box van trailers. Series denoted with "TC" indicate that the HSWD maneuver was completed up to the steering scalar of 130 percent without the observation of a loss of stability. In general, the results show that ESC and RSC were able to improve stability from the SC-disabled test condition for the given HSWD steering inputs and entrance speed of 45 mph. The largest improvements were observed with the vehicles equipped with the ESC systems.

Table 5.9. HSWD test results with 28-foot flatbed, spread axle flatbed, and box van trailers, at 45 mph.

Tractor	**Steering Scalar Observed to Produce Instability**								
	28-Foot Flatbed Trailer			**Spread Axle Trailer**			**Box Van Trailer**		
	SC Enabled	**SC Enabled Unbraked Trailer**	**SC Disabled**	**SC Enabled**	**SC Enabled Unbraked Trailer**	**SC Disabled**	**SC Enabled**	**SC Enabled Unbraked Trailer**	**SC Disabled**
Volvo 6X4 ESC	TC	TC	85%	TC	100%	80%	TC	TC	85%
Freightliner 6x4 ESC	TC	TC	75%	TC	TC	60%	TC	TC	70%
Freightliner 6x4 RSC	90%	80%*	75%	110%	70%	60%	85%	80%	70%
Sterling 4x2 RSC	110%	125%	95%*	85%	80%	85%	85%	85%	90%

* Test series terminated due to roll instability

From Table 5.9, ESC was observed to improve the stability of the Volvo over the disabled test condition. The Volvo with ESC enabled was observed to complete each series with the three different trailers without a loss of stability event. When the enabled series were repeated with the unbraked spread axle trailer, loss of yaw control was observed at the 100 percent steering scalar.

When ESC was disabled in the Volvo, loss of stability was observed at the 80, 85, and 85 percent steering scalars with the three different trailers.

Similarly, the Freightliner's stability margin was improved with ESC compared to the disabled test conditions. When tested with ESC enabled and the unbraked trailer, the Freightliner was observed to complete each HSWD series with the three different trailers. When repeating the series with the ESC system disabled, the three combinations were observed to lose stability at steering scalars of 75, 60, and 70 percent. With the RSC system enabled and with trailer braking enabled, the steering scalar at which loss of stability was observed improved to 90, 110, and 85 percent for the combinations with the 28-foot flatbed, spread axle, and box van trailers. With RSC enabled and the unbraked trailer those scalars fell to 80, 70, and 80 percent with the three different trailers.

From the table, the Sterling tested in the RSC-enabled conditions was able to improve the steering scalar at which loss of stability was observed compared to the SC-disabled condition with the 28-foot flatbed trailer. Loss of stability with this trailer and SC condition was observed at the 95 percent steering scalar. With the RSC-enabled conditions instability was observed at 125 percent with the unbraked trailer condition and at 110 percent for the SC-enabled condition. When combined with the spread axle and box van trailers, loss of stability was observed between the 80 to 90 percent steering scalars regardless of the RSC-enabled/disabled test conditions.

During testing with the spread-axle flatbed trailer, the tractors with SC disabled experienced a test series terminating condition in all four test series at steering scalars between 60 to 85 percent. The truck-tractors with ESC enabled were able to complete three out of four test series (with the trailer brakes enabled or disabled) without loss of stability. The Freightliner with RSC did show a performance improvement over the disabled test condition, with instability moving from 60 percent to 70 percent with RSC enabled with unbraked trailer, and increasing to 110% in the RSC-enabled condition with trailer brakes. The Sterling saw no improvement with RSC enabled.

Testing with the box van trailer and SC disabled, test terminating conditions were observed in all four series at steering scalars between 70 to 90 percent. The tractors with ESC enabled were able to complete every test series (with the trailer brakes enabled and disabled) without loss of stability. The Freightliner with RSC did show a performance improvement over the disabled condition, with instability moving from 70 percent to 80 percent with unbraked trailer, and increasing to 85 percent in the RSC-enabled condition with trailer brakes. The Sterling saw no improvement with RSC enabled.

Table 5.10 presents results from HSWD testing from combinations with the tanker trailer. Much like SWD testing, HSWD test series with the tanker resulted in loss of roll stability for all tractor semitrailer combinations regardless of SC condition (ESC, RSC, enabled or disabled). The water ballast movement (sloshing) during the test maneuvers produced a roll-inducing condition. Still, the Volvo and Freightliner with ESC enabled were observed to improve the scalar at which wheel lift events were observed. With the Volvo both ESC enabled and enabled with the unbraked trailer, the steering scalars were improved to 70 percent, versus a steering scalar of 50 percent observed when ESC was disabled. With the Freightliner ESC enabled, wheel lift events were observed at the 50 percent steering scalar versus the 45 percent scalar when it was disabled. This same change in performance was also observed with the Freightliner equipped with the RSC system. With the Sterling wheel lift events were observed at the same steering scalars regardless of the SC condition tested with the tanker trailer.

Table 5.10. HSWD test results with the tanker trailer, at 45 mph.

Tractor	**Steering Scalar Observed to Produce Instability**		
	SC Enabled	**SC Enabled With Unbraked Trailer**	**SC Disabled**
Volvo 6X4 ESC	70%*	70%*	50%*
Freightliner 6x4 ESC	50%*	50%*	45%*
Freightliner 6x4 RSC	50%*	50%*	45%*
Sterling 4x2 RSC	60%*	60%*	60%*

* Test series terminated due to wheel lift

5.4 Maneuver Refinement Discussion

The SIS test track results with the four different trailers and 60% GAWR load condition were observed to produce overlapping steering scalar ranges in the bobtail condition. From these test results the loaded condition could potentially replace the bobtail test condition in the characterization maneuver and normalization test procedures. Analysis of the loaded SIS engine torque data revealed that SC's engine torque reduction function was active earlier in the maneuver (versus when compared to SIS data from bobtail tractors). When engine torque was reduced, the forward speed was observed to decrease.

Research with the candidate 0.5 Hz SWD maneuver, the 60% GAWR load condition, and the three different trailer combinations produced test track results that supported the selection of the SWD maneuver and load condition. Overall, with SC disabled, each combination's SWD test series were terminated for either roll or yaw instabilities prior to reaching the 130 percent steering scalar. When enabling the SC systems and repeating the SWD test series, the systems were concluded to improve both roll and yaw stability. RSC was concluded to improve roll and yaw stability of the vehicles in which it was installed, but not to the extent that was observed from ESC equipped vehicles for these trailers.

6 POTENTIAL MEASURES OF PERFORMANCE

Observations of test track results from Phases I through III have shown that SC was able to improve the stability of the vehicles in which it was installed by exerting control over the power unit (engine) and\or foundation brakes installed on the tractor. Depending on the maneuver and the vehicle's response to the speed and steering inputs different combinations of power unit control and/or foundation braking by SC intervention were needed to improve stability.

Phase II test results showed that the SIS maneuver was capable of challenging the engine/power unit control to maintain stability. Phase III test results showed that the SWD was the best candidate for evaluating dynamic lateral stability and that to remain stable in this maneuver required the SC systems to use foundation braking. With these findings several measures of performance were explored that were determined to be effective in maintaining tractor semitrailer stability. Measures were explored that would indicate SC systems were capable of exerting control over the engine/power unit (SIS test data) and foundation braking control (SWD test data) while maintaining the same level of maneuverability or responsiveness.

6.1 Engine Torque Reduction

Engine/power unit control measures of performance were evaluated in Phase II with SIS test data obtained from the bobtail load condition. That research found that the time at which SC actively reduced the engine power output could accurately be determined from engine torque and driver demanded torque signals. These signals were found to be equal and would separate upon the SC activation. Upon this event, the speed of the tractor was observed to be decreased and was determined to be a potential measure of performance. This section investigates the SIS test data collected from the loaded test condition to verify the previously determined methodology and measure were still valid.

Using loaded combination test data from the SIS maneuver, torque data collected from each vehicle's communication bus were analyzed. Driver requested torque and engine torque output measures were concluded to be potential measures to indicate engine torque was reduced. The tractor forward speed could additionally be used to show a reduction in the dynamics of the vehicle took place. During normal operation the "driver requested torque" and "engine torque" measures were observed to be equal to each other. During SIS maneuvers, once SC activated and invoked engine control the two measures were observed to separate. In all cases, the "engine requested torque was much less than the "driver requested torque," example shown in Figure 6.1. Originally, to quantify the change in the torque signals the difference using both torque values at the reduction event was calculated and expressed as a percentage change over time for each test in an SIS test series. As discussed earlier, after SC activates and the reduction event takes place, the speed of the maneuver was reduced which also limited the lateral dynamic response of the vehicles.

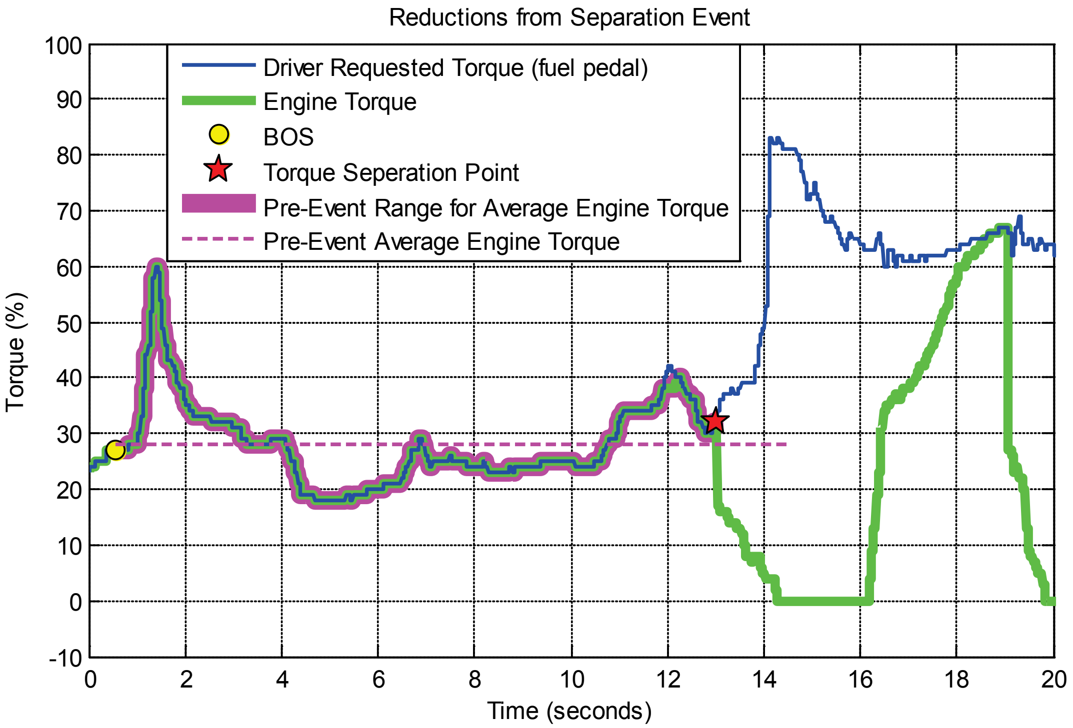


Figure 6.1. Engine torque data and the SC torque reduction event. Figure shows regions of time history data used to determine average engine torque output.

To quantify the change in the torque signals, the difference using both torque signals at the reduction event was calculated and expressed as a percentage change over time for each test in an SIS test series. Using only engine torque, an average value is found from BOS to the observed point of separation between the two torque signals (denoted as time “0”) and is used to calculate the percent difference in engine torque only for each test in a SIS test series. Further analysis supported using an average engine torque value versus the instantaneous value at the torque reduction event because the average helped mitigate the modulation effect from the driver trying to maintain 30 mph during the maneuver. During the assessment, it was observed that following the torque reduction event, the driver demanded torque should remain above the pre-event average value for at least 4 to 5 seconds. This translates to the driver recognizing when SC activates and continuing to try and maintain the desired speed of 30 mph.

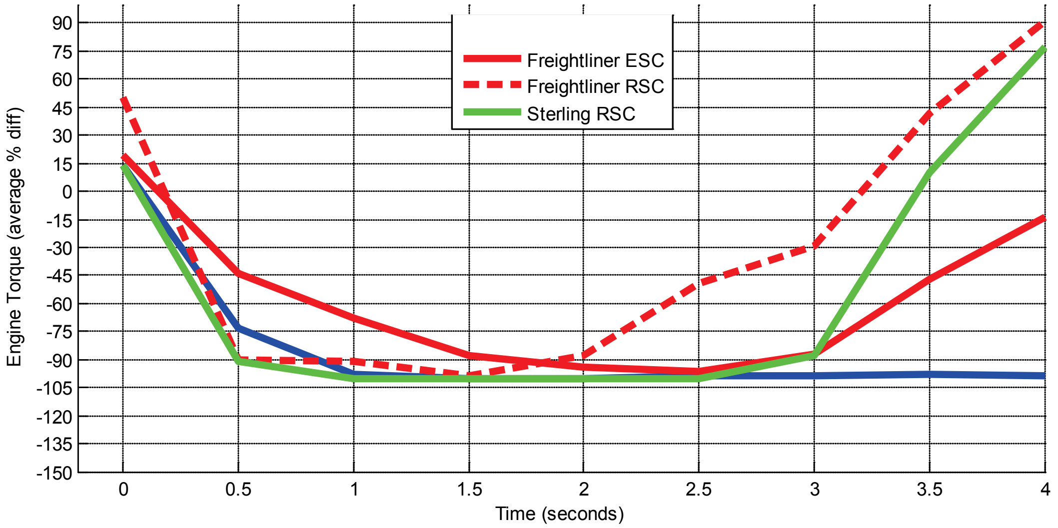


Figure 6.2. Average engine torque reduction for each tractor tested in combination with four different trailers (2 flatbeds, box van and a tanker) and 60% GAWR load condition.

In Figure 6.2, each trace represents the average of the percent difference in the engine torque over half-second intervals from the torque reduction event for each tractor tested in combination with four different trailers. From the figure, the average change shows that a good region for assessing performance lies between 0.5 and 2 seconds after intervention. The smallest deviations in the average torque signals were observed between the vehicles in this region. While these data show that the respective changes in engine torques were quite large, a small (5 to 20%) change would be sufficient to identify the torque reduction event. Once these events were determined, speed could also be assessed as a measure of performance. Table 6.1 presents the average speed measured at time increments from the torque reduction event.

Table 6.1. Average tractor speed reduction for each tractor tested in combination with four different trailers in the 60% GAWR load condition.

Vehicle	**Condition**	**Average Tractor Speed (mph) at Given Time Increments (Event Point = 0.0 s)**								
		0.0	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Volvo	ESC Enabled	29.99	29.82	29.29	28.59	27.98	27.45	26.80	26.12	25.47
Freightliner	ESC Enabled	29.80	29.46	28.92	28.26	27.52	26.53	25.66	25.02	24.63
Freightliner	RSC Enabled	29.55	29.11	28.47	27.62	26.20	24.63	23.48	22.92	22.82
Sterling	RSC Enabled	30.00	29.55	28.67	26.53	23.59	20.87	19.33	18.85	19.38

Table 6.1 shows the average speed reduction for each tractor with four trailers tested. At the torque reduction event (time 0) speed ranged between 29.5 and 30.0 mph. At 4 seconds following the torque reduction event the average speed for the Volvo was 25.4 mph, 24.6 mph for the Freightliner ESC, 22.8 mph for the Freightliner RSC, and 19.3 mph for the Sterling.

6.2 Foundation Braking

While researching, developing, and validating the SWD maneuver, the test results were also being explored to determine potential measures of performance. The SC systems, when enabled, commanded foundation braking in every 0.5Hz SWD (1.0-second dwell) test track series with the each of the trailers evaluated. When compared to the SC-disabled test series it was found that the foundation braking improved the roll and yaw stability in each of those comparisons. The SWD test data were used to investigate several potential measures of performance for use in assessing the lateral stability of tractor-trailer combinations equipped with SC. Previously documented and used lateral acceleration ratio (LAR) and yaw rate ratio (YRR) measures were studied first. These measures were preferred because they were easy to measure, filter, correct, and calculate versus more involved measures such as yaw angle, articulation angle and wheel height. If they proved to be impracticable or unpredictable then other measures would be considered. For more information regarding LAR see [1] and for more information regarding YRR see [21] and [25]. While LAR was not specifically developed to assess stability in the SWD maneuver it was easily adapted and applied. The definitions for LAR and YRR as they were used for this research are shown below, both are expressed as percentages.

LAR Definition: $$\text{LAR} = \frac{Ay_{Tractor}\left(COS + 1.0, +1.5 \ldots + 3.0\,\text{sec}\right)}{MAX(Ay_{Tractor})\big]_{t=1.0}^{COS}} x100$$

Where:
$Ay_{Tractor}$ = Lateral Acceleration of the tractor
COS = Completion Of Steer

YRR Definition: $$\text{YRR} = \frac{\Psi_{Tractor}\left(COS + 1.0, +1.5 \ldots + 3.0\,\text{sec}\right)}{MAX(\Psi_{Tractor})\big]_{t=1.0}^{COS}} x100$$

Where:
Ψ = Yaw Rate of the tractor

Examples of these definitions are shown graphically in Figure 6.3. From top to bottom in the figure are SWD time history examples of tractor steering wheel angle, lateral acceleration, LAR, yaw rate, and YRR. These measures were then combined with definitions for stability of a tractor semitrailer system to create statistical models that could then be used to predict the stability of a combination based on its residual LAR and/or YRR from a SWD maneuver.

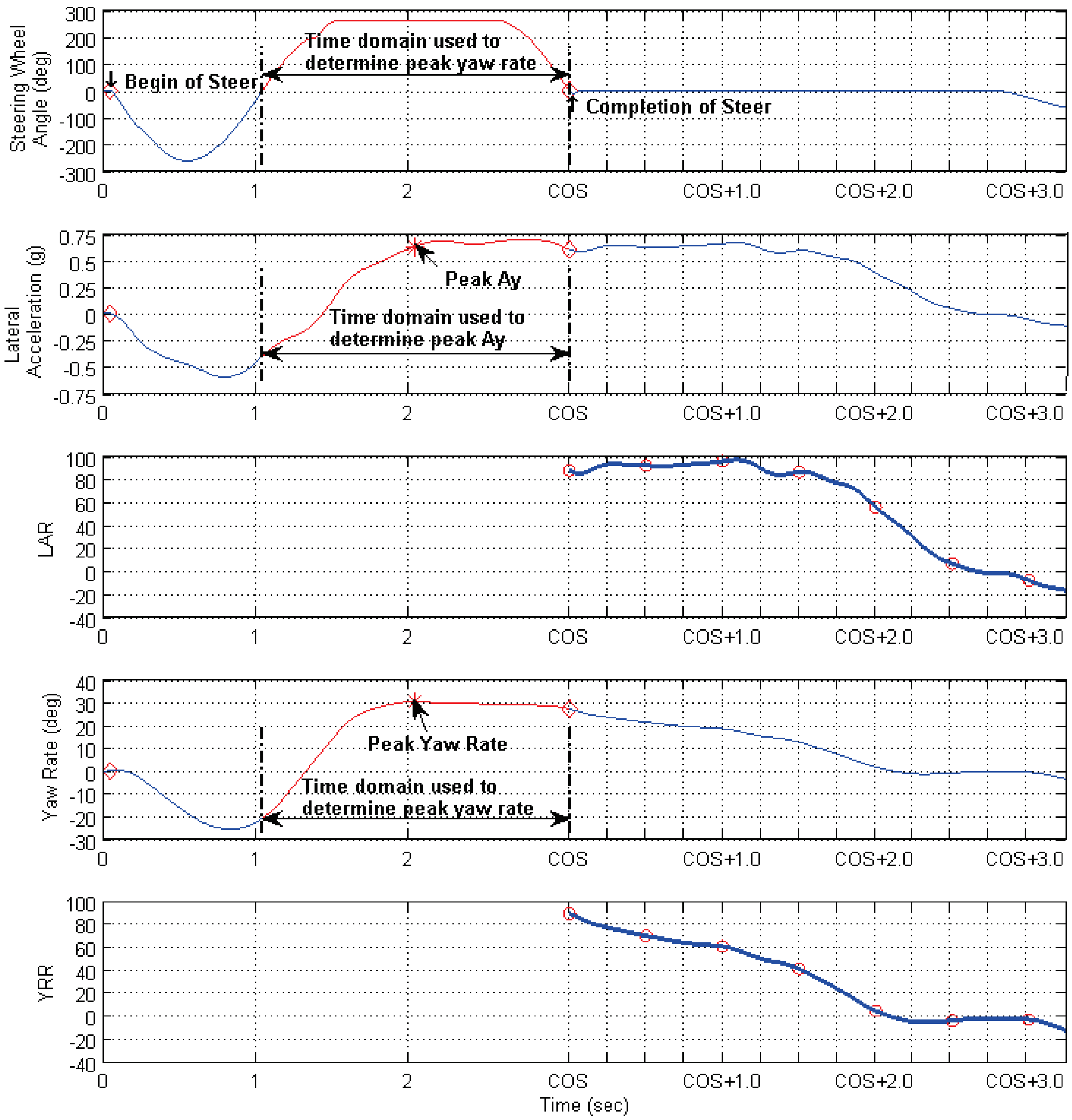


Figure 6.3. Key events in the SWD maneuver's steering input, measured lateral acceleration, and yaw rate that were used to calculate the LAR and YRR measures.

Prior sections of this report used articulation angle, and wheel height measurements to assess given stability thresholds during maneuver research and development. For loss of roll stability, 2.00 or more inches of wheel height was defined as the stability threshold, while an articulation angle that exceeded 30 degrees defined loss of yaw stability. These thresholds were used for their ease of collection and ability to be verified visually in the field. These definitions worked for maneuver development, refinement, and selection. Measure of performance research and development was conducted to define the states of stability in terms of vehicle kinematics. The roll stability definition and threshold was found to be suitable, however, an alternate yaw stability definitions and thresholds was developed.

The tractor's yaw angle measure was preferred over the articulation angle measure between the tractor and the trailer. This was primarily due to the fact that the articulation angle between the tractor and trailer was limited through safety cables while tractor yaw angle was unlimited. The articulation angle was typically limited to ±45 degrees; however, a few combinations were restricted to less than 45 degrees due to clearance issues. Additionally, the tractor's yaw angle was calculated by integrating the tractor's measured yaw rate. This was considered easier to obtain and required less instrumentation versus articulation angle which was calculated by subtracting the integrated tractor and trailer yaw rate measures. For this measure of performance research, any SWD test that resulted in the tractors yaw angle exceeding 45 degrees was determined to be yaw unstable. Two example SWD tests are shown in Figure 6.4.

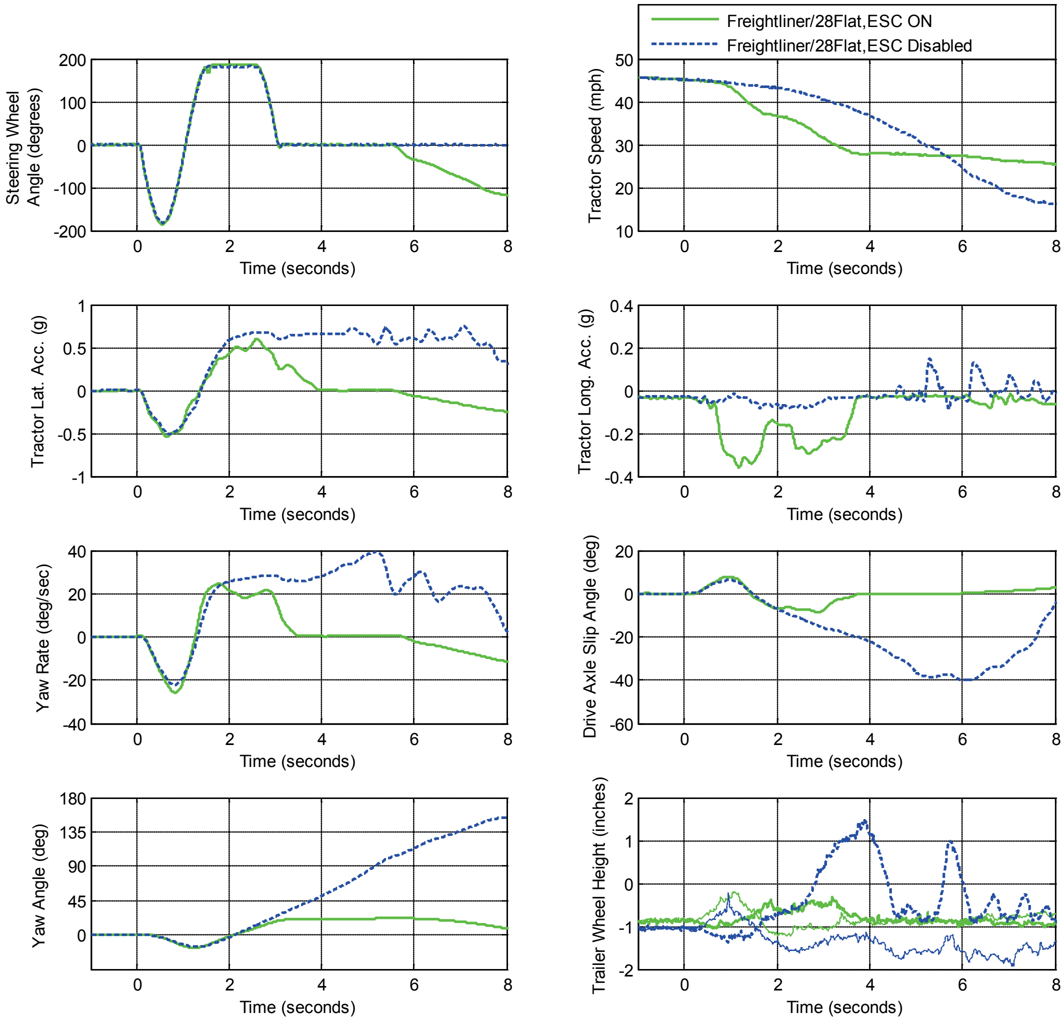


Figure 6.4. Example shows test data in which the tractor's yaw angle has exceeded 45 degrees in the disabled SWD test and is under the threshold for the enabled test.

The figure shows test data in which the ESC system uses foundation braking to reduce lateral acceleration and yaw rate. This results in a final yaw angle that is much less than 45 degrees. The second test shows a SWD test in which ESC is disabled and results in a final yaw angle that is greater than 45 degrees. From top to bottom and left to right in the figure are tractor steering wheel angle, speed, lateral acceleration, longitudinal acceleration, yaw rate, drive axle side slip angle, yaw angle and wheel height. Note that the figure shows these two tests were conducted with the same vehicle combination and load, and with the same speed and steering inputs.

Figure 6.5 shows the time history data of the brake pressures that were applied by the ESC system during the SWD example shown in Figure 6.4. The figure shows that the ESC system was commanding brake applications from just less than 1.0 second into the maneuver and maintained some pressure until nearly 4.0 seconds. Figure 6.6 presents, from that same test data, the LAR and YRR measures. The figure highlights the region of the measures that were used to assess the stability of the combinations.

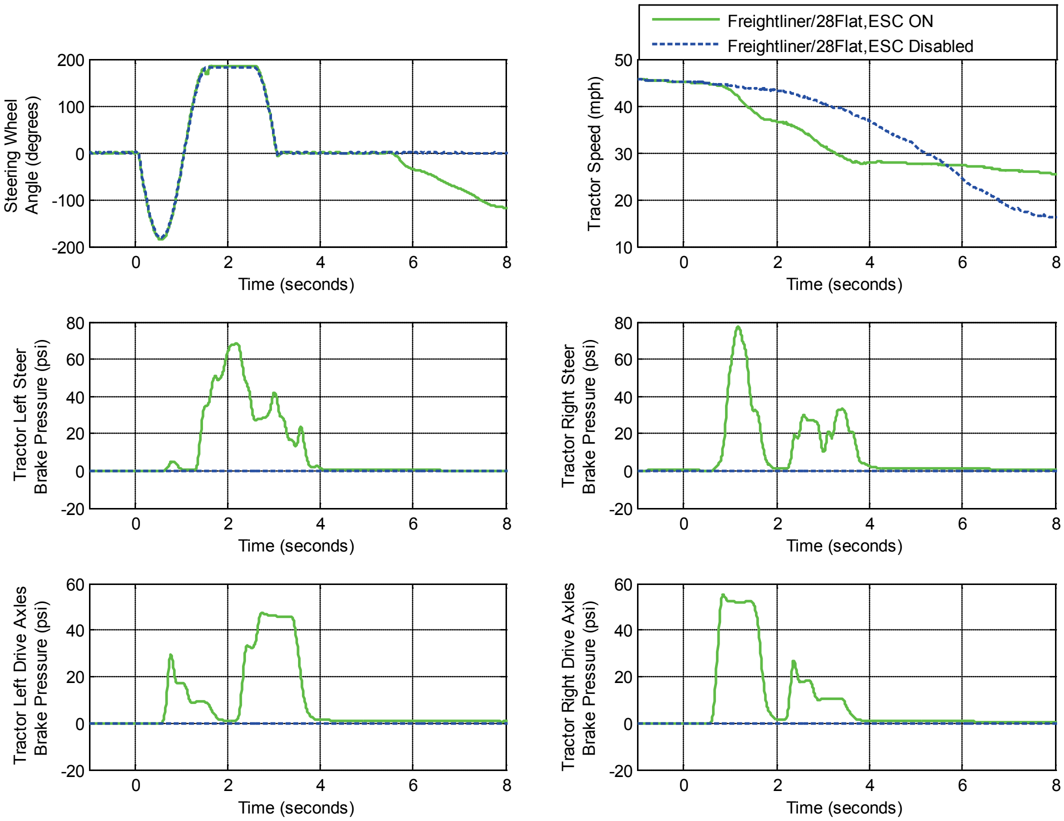


Figure 6.5. Brake pressure data from the same example SWD tests shown in Figure 6.4.

Lastly, Figure 6.7 shows the position and orientation of the combination at approximately 3.75 seconds into the maneuver. While this maneuver was conducted on a large asphalt test pad, the roadway lanes were added to the graphic to provide the reader with space perspective. Each lane shown was 13 ft. wide and the heavy red line indicates the duration of the maneuver, while the black curves show the vehicle's paths.

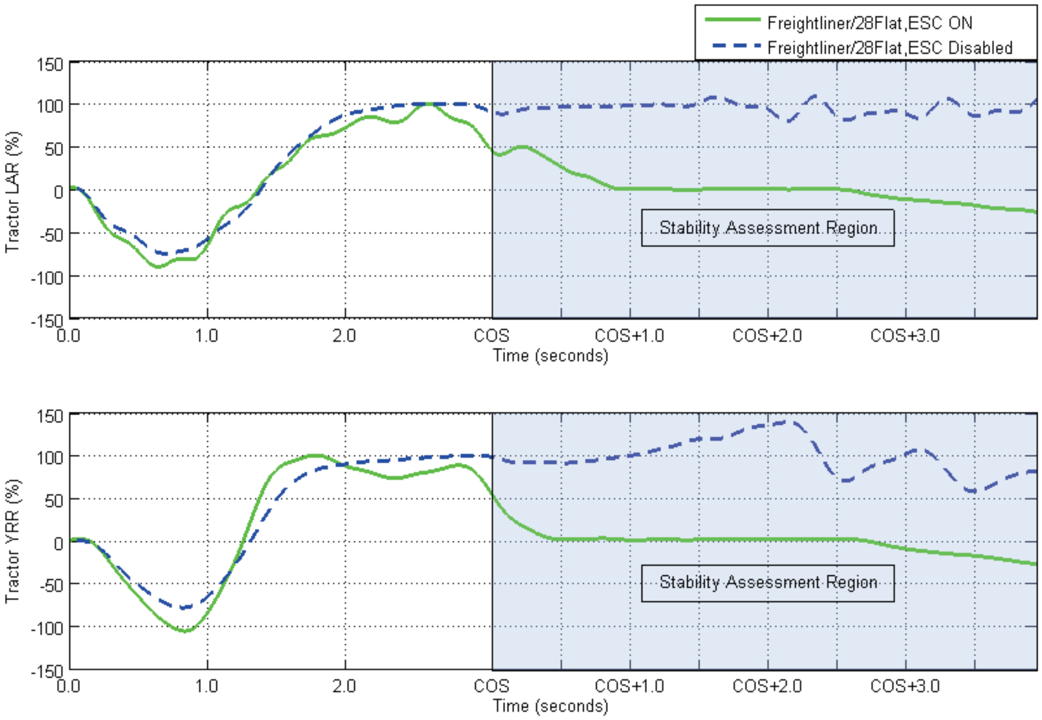


Figure 6.6. LAR and YRR measures from the same example SWD tests shown in Figure 6.4.

The test data show that the wheel height did not exceed 2 inches for either test represented in the figures. The disabled test does show minor amounts of wheel lift of just over one inch however, it did not meet the roll threshold so both tests were coded as roll stable. The following section presents SWD test results for LAR and YRR measures that indicate if the yaw and/or roll thresholds were exceeded.

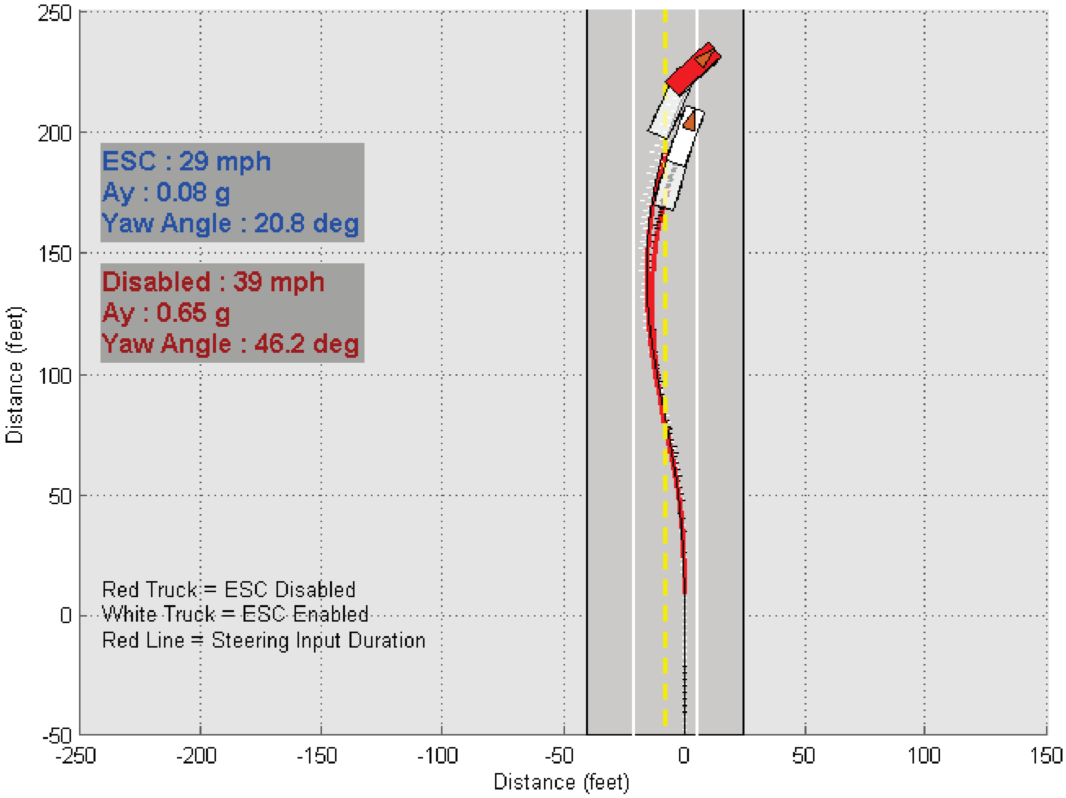


Figure 6.7. Position and orientation figure from the same example SWD tests shown in Figure 6.4. The graphic depicts the data from ~3.75 seconds into the maneuver.

6.2.1 LAR and YRR

Figure 6.8 through Figure 6.15 present LAR and YRR for a 0.5 Hz SWD (1.0-second dwell) maneuver for the Volvo 6x4, Freightliner 6x4 and Sterling 4x2 tractors. All data were from series conducted with the 60% GAWR load condition and 28-foot flatbed trailer. Each figures time history represents 0 to 2.5 seconds after the completion of steer (COS) event (the highlighted stability assessment region shown in Figure 6.6). For each vehicle, SC-enabled and SC-disabled data were presented. The SC-enabled data shown were from series in which the trailer brakes were disabled (unbraked trailer test condition). For the figures in this section, the numbers appearing directly on the data traces indicated the value of the steering scalar divided by 10 (i.e., 9 = 90% scalar). To simplify the plots, only the larger steering scalars were shown. In general, the lower steering scalars were less dynamic for all these series and to include them would have cluttered the figures. WL and YA stand for wheel lift and yaw angle. The thin solid blue lines represent SC-enabled series tests which were coded as both roll and yaw stable. For these tests WL was less than 2.0 inches, and YA was less than 45 degrees. The thin dotted lines represent SC-disabled tests which were coded as either roll and/or yaw unstable. The heavy dotted lines represent SC-enabled tests that were coded as either roll and/or yaw unstable, i.e., WL was observed to be greater than 2.0 inches and/or YA was greater than 45 degrees.

Black, red, and purple line colors were used to show which stability threshold was exceeded. If only the roll stability threshold was exceeded, then the dotted line was assigned purple. If only the yaw stability threshold was observed to be exceeded, then the dotted line was assigned red. And if both thresholds were observed to be exceeded, then the dotted line was assigned Black.

Data from the Volvo 6x4 in Figure 6.8 and Figure 6.9 show that with ESC enabled the residual LAR and YRR measures were approaching zero and were settled out between 1.00 to 1.25 seconds after COS. These series also show that each successive increase in steering scalar resulted in a larger amount of LAR and YRR. Even though the ratio values increased at the higher scalars with ESC enabled, neither roll nor yaw instability were observed. The two SC-disabled tests shown were at the 90 and 95 percent steering scalars (testing was terminated at the 95 percent scalar). Both tests resulted in the observance of roll and yaw instability. Note that for the two tests with ESC disabled, a small 5-percent increase in steering scalar had a large effect on the YRR measure. This indicated that the vehicle was spinning faster even though the steering wheel input was in the zero position.

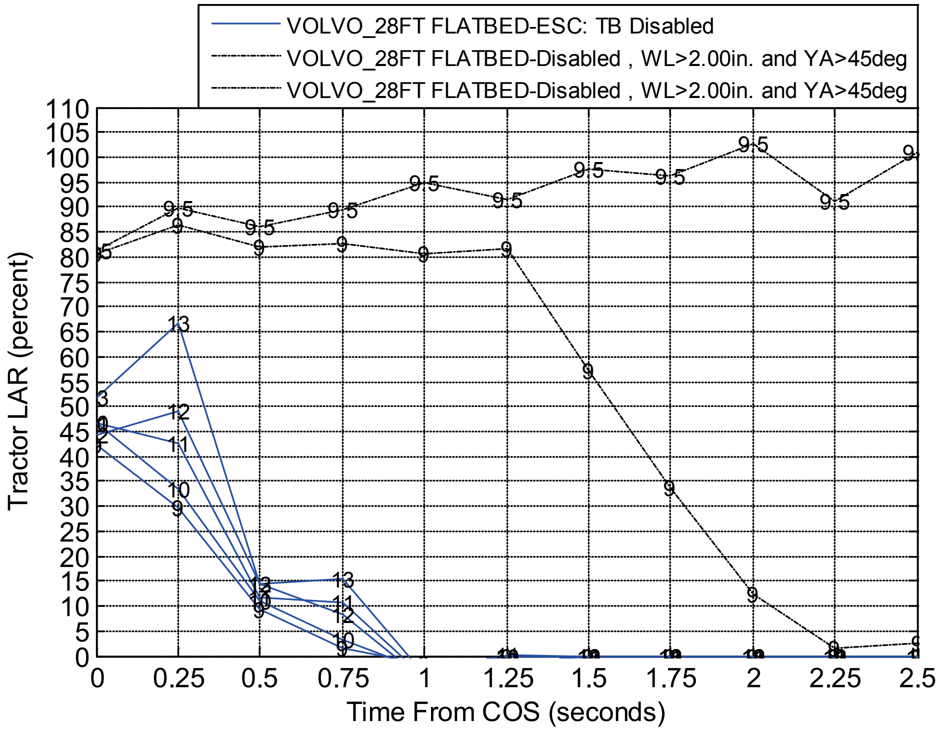


Figure 6.8. SWD LAR data from the Volvo 6x4 with and without ESC. For the figures in this section; the numbers for data traces indicated steering scalar divided by 10 (i.e. 9 = 90% scalar). WL and YA stand for wheel lift and yaw angle.

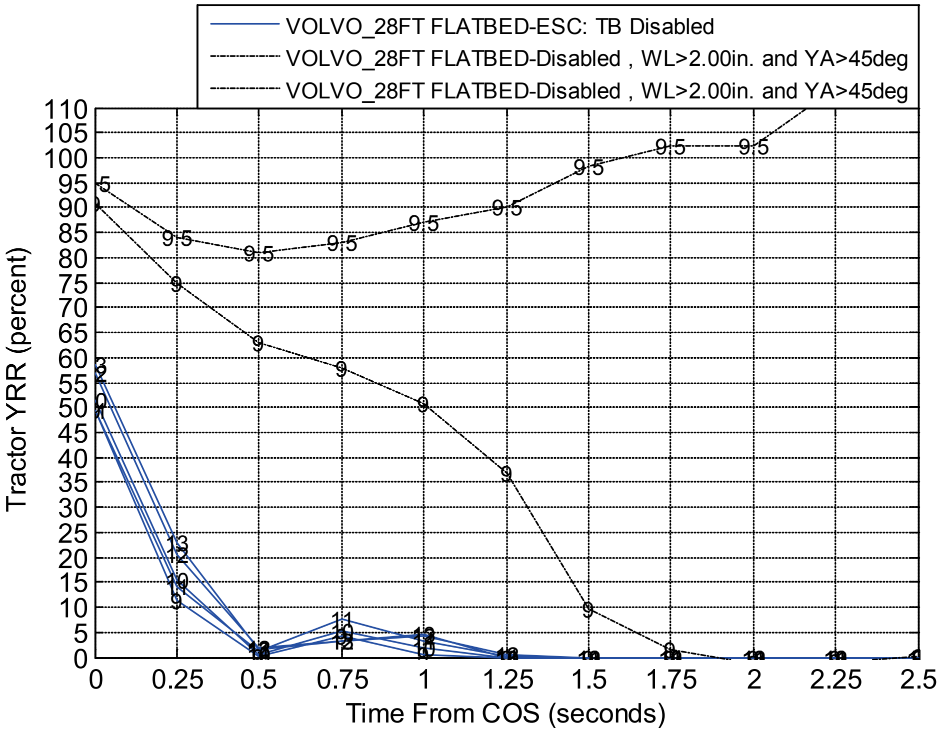


Figure 6.9. SWD YRR data from the Volvo 6x4 with and without ESC.

Data from the Freightliner 6x4 equipped with the ESC system are shown in Figure 6.10 and Figure 6.11. The figures show that with ESC enabled, the residual LAR and YRR measures were approaching zero and were settled out between 0.25 to 1.00 seconds after COS. These series show that each successive increase in steering scalar resulted in a larger reduction to LAR and YRR, which was opposite of what was observed with the Volvo. The one SC-disabled test that is shown was conducted at a steering scalar of 85 percent (testing was stopped the 85 percent scalar). This test resulted in the observance of yaw instability only. Like the Volvo's disabled test at 95 percent, the Freightliner's disabled test at the 85 percent steering scalar was showing the vehicle's rate of spin was increasing though the steering wheel was in the zero position.

LAR and YRR data from the Freightliner 6x4 equipped with the RSC system are shown in Figure 6.12 and Figure 6.13. With RSC enabled, the residual LAR and YRR measured responses were increasing with each successive increase in steering scalar. With RSC enabled, scalars of 90 and 105 percent were coded as stable in both roll and yaw, but scalars of 100, 110, and 115 percent were coded as yaw unstable, since YA exceeded 45 degrees. The 120 percent scalar was coded as yaw and roll unstable (testing was terminated at the 120 percent scalar for the RSC-enabled test series). Though the RSC equipped Freightliner was unable to complete the test series through the maximum steering scalar of 130 percent due to instability, it did improve the performance of the vehicle as compared to the SC-disabled test condition. With RSC, a 120 percent steering scalar was observed to produce similar LAR and YRR data as the SC-disabled test at the 85 percent scalar.

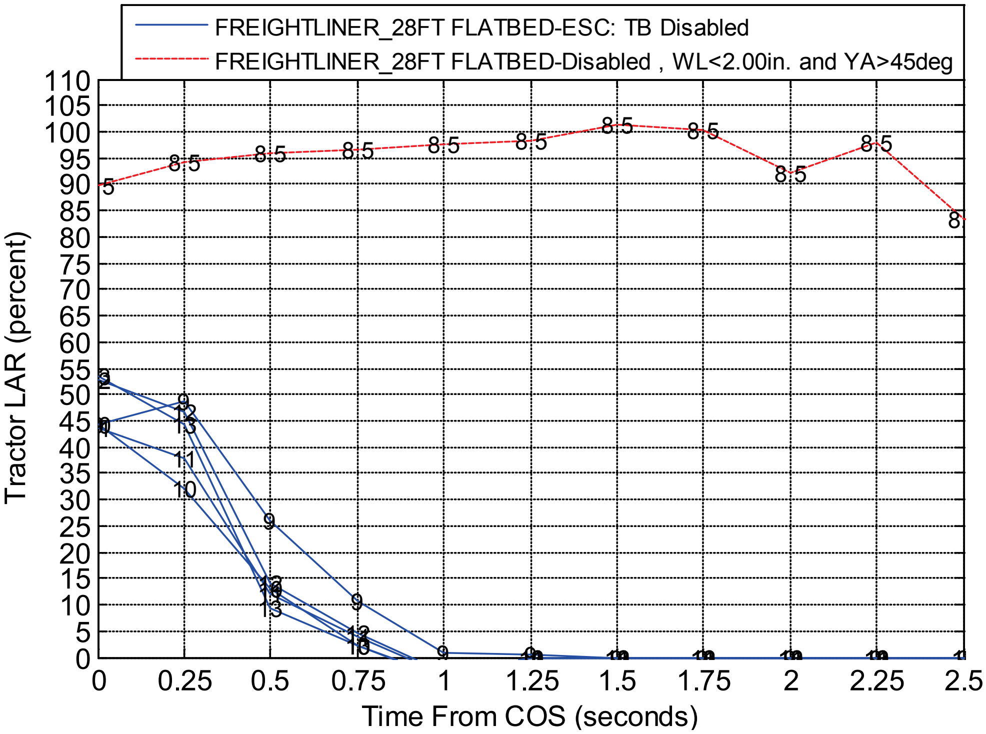


Figure 6.10. SWD LAR test data from the Freightliner 6x4 with and without ESC.

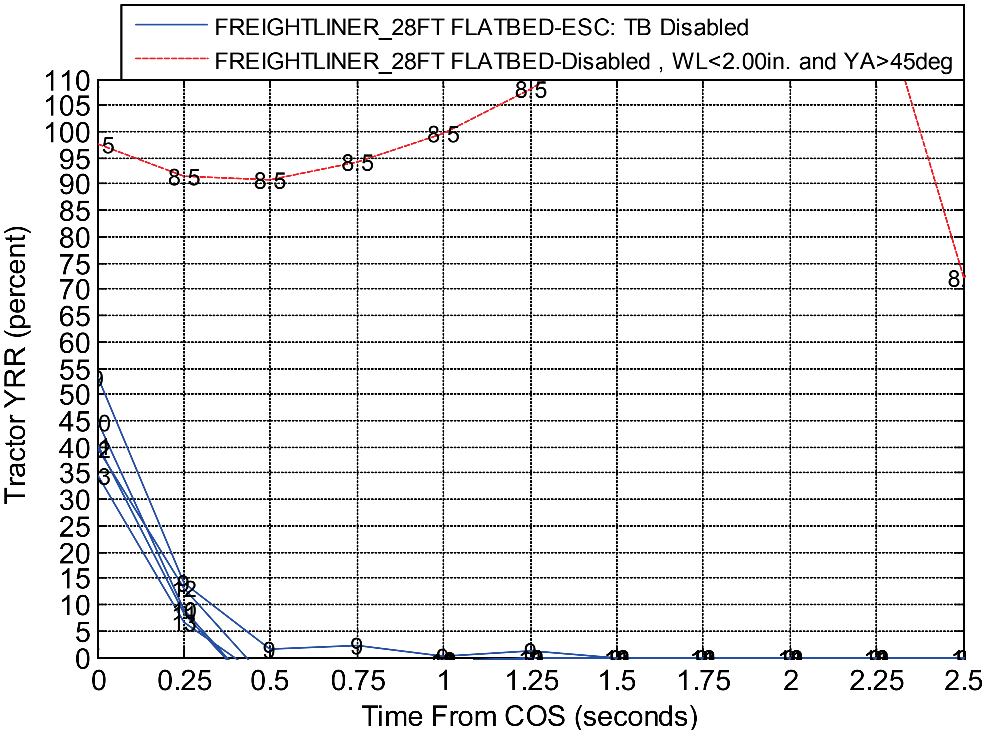


Figure 6.11. SWD YRR test data from the Freightliner 6x4 with and without ESC.

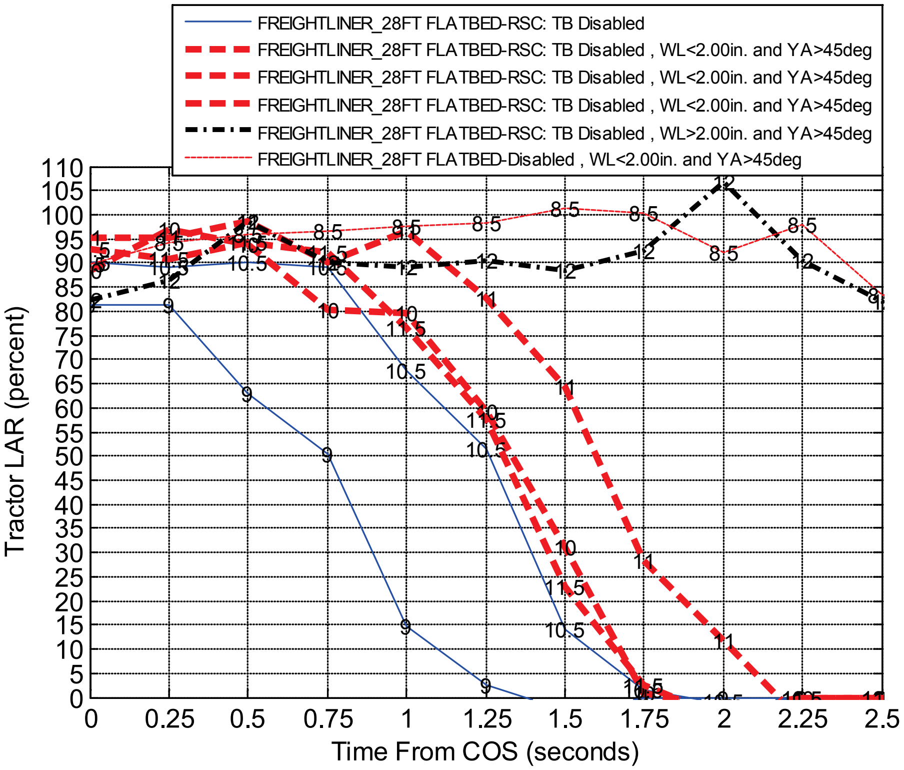


Figure 6.12. SWD LAR test data from the Freightliner 6x4 with and without RSC.

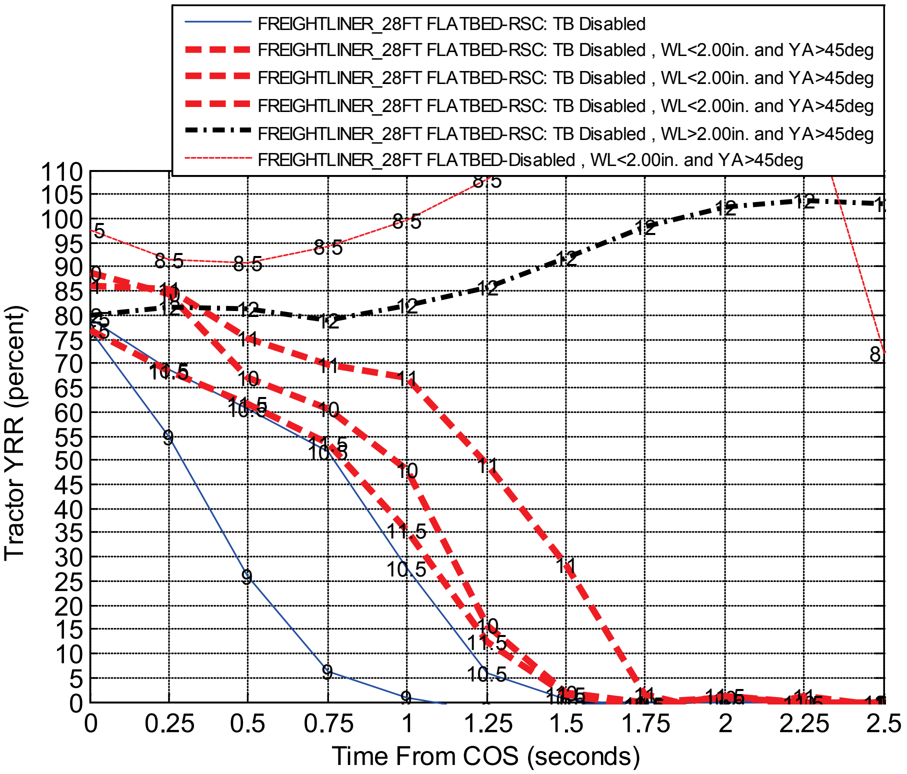


Figure 6.13. SWD YRR test data from the Freightliner 6x4 with and without RSC.

LAR and YRR data from the Sterling 4x2 equipped with the RSC system are shown in Figure 6.14 and Figure 6.15. With RSC enabled, the residual LAR and YRR measured responses were increasing with each successive increase in steering scalar. With RSC enabled, the scalar at 100 percent was observed to be stable. The next scalar of 110 percent was observed to be roll unstable. Successive scalars of 120 and 130 percent were coded as yaw unstable. Like the RSC equipped Freightliner, the Sterling's RSC system did improve the performance of the vehicle over the disabled test condition. With RSC, a 110 percent steering scalar was observed to produce similar LAR and YRR as the disabled test at the 100 percent scalar.

Generally speaking, these figures show that the LAR and YRR measures were able to discriminate stable from unstable tests. The graphical trends presented in each figure show that the instances of observed instability coincided with LAR and YRR that were observed to extend towards the upper right hand corner of the figures. This was expected since these measures indicate the residual lateral acceleration and yaw rate from the SWD maneuver. As the magnitude and duration of the LAR and YRR measure increased so did the likelihood that the test resulted in roll and/or yaw instability. Also graphically depicted were the large differences SC had on the LAR and YRR measures and the separation in the test data between the series conditions. While these trends were observed, the small number of SWD tests with instability does not offer a graphically clear region of LAR or YRR which was classifiable as either likely stable or likely unstable.

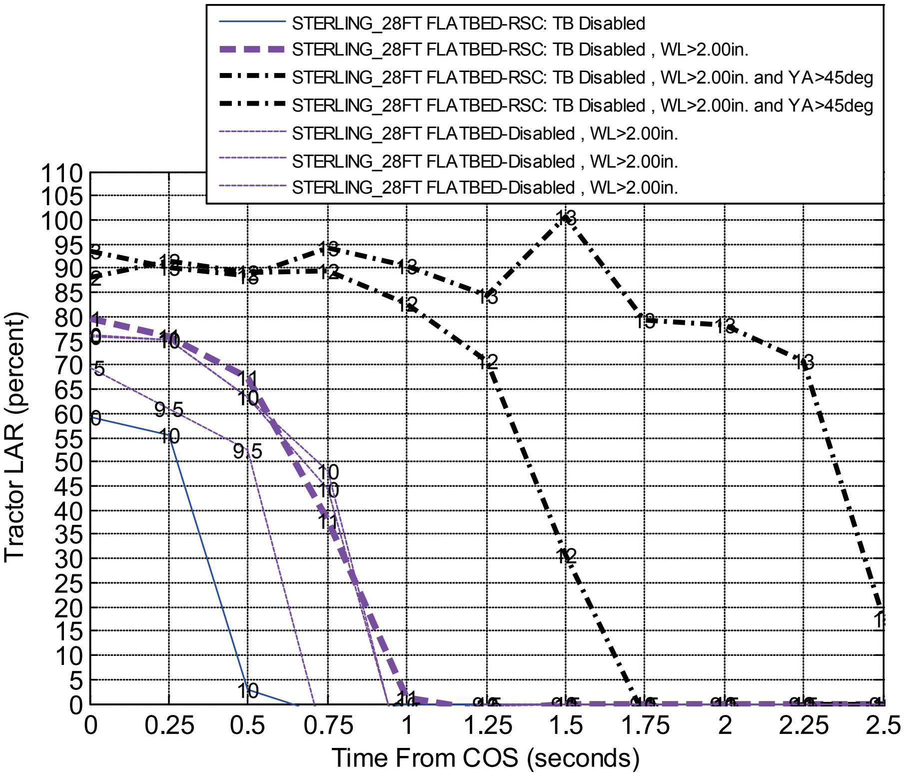


Figure 6.14. SWD LAR data from the Sterling 4x2 with and without RSC.

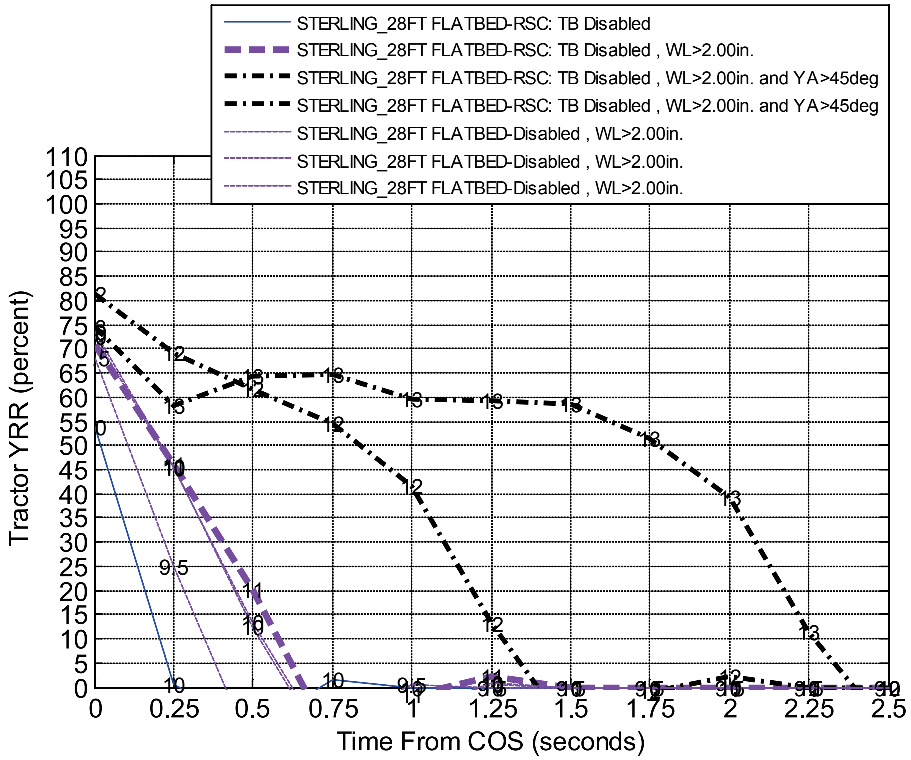


Figure 6.15. SWD YRR data from the Sterling 4x2 with and without RSC.

6.2.2 Statistical Analysis of LAR and YRR

Logistical regression was used to gain statistical insight into LAR and YRR's capability of discriminating tractor yaw and roll stability from the 0.5Hz SWD (1.0-second dwell) data sets. This was accomplished by investigating the relationship between the stability definitions and the potential measures. If a relationship was found then their ability to predict a vehicle's state of stability from SWD test data were assessed.

Using the previously discussed stability definitions, the outcome of each completed SWD maneuver was assessed in a binary classification. Using these definitions, the outcome from the maneuver was determined to be either stable (0) or unstable (1). The entire data set was assessed in this manner using three analysis methods shown below.

- Binary stability assessed using roll stability definition.
- Binary stability assessed using yaw stability definition.
- Binary stability assessed using roll and/or yaw stability definitions.

The data sets were then organized and binned according to the amount of residual LAR or YRR at quarter-second time increments after the COS event. Then the number of tests in each bin was divided by the total number of samples within the bin to determine the proportion of tests that experienced instability. Binned data sets were then used to perform a logistical regression analysis. The results from that analysis are shown below.

6.2.3 Stability Model for LAR

A logistic regression model was developed at each quarter of a second after COS up to COS + 3.5 seconds. For each of these time increments the model predicts the probability that the vehicle was unstable based on the amount of LAR observed at that time.

Examples of the logistical regression input data sets for each model (roll, yaw and combined roll and yaw) are presented in Table 6.2 through Table 6.4. Table 6.2 shows the input data for the roll only model developed at 0.75 seconds after COS. From left to right in the table are the columned LAR bins, the number of samples observed with wheel lift greater than 2.0 inches, the total number of samples in the bin, the proportion of samples in the bin that had wheel lift, and the binomial fit through the proportion data. For this analysis coarse LAR bins were stepped in 20 percent increments about the bin centers for LAR values between 10 to 130 percent.

At 0.75 seconds after COS, the table shows in the first bin, LAR 10 percent bin, there was one test out of the 85 tests in the bin that was observed to have wheel lift greater than 2.0 inches. For this bin the proportion was 1/85 or 0.012. Moving down through the table, the frequency of wheel lift increases to a maximum at the 90 percent bin, where six of the 14 tests were observed to have wheel lift, which resulted in a proportion of 0.43. Relative to the number of tests that were considered stable, there were few tests that were coded as roll unstable and had LAR values greater than 90 percent. Thus, the 110 and 130 percent bins were empty. A similar result was found when binning the input data for the yaw only model developed at 0.75 seconds after COS. Table 6.3 uses the previously described format for Table 6.2.

For the yaw only model at this time increment, 0 out of 85 tests were observed to have a yaw angle greater than 45 degrees in the first bin (10%). Similar to the model described above, moving down through the table the frequency of tests observed to exceed the yaw threshold increases to a maximum at the 90 percent bin, where 12 of the 14 tests in the bin exceeded the threshold. This resulted in a proportion of 12/14 or 0.86. Combining Table 6.2 and Table 6.3 resulted in the data set presented in Table 6.4.

Table 6.2. Data set used to assess the roll stability model at COS + 0.75-second time increment. Samples with wheel lift greater than 2.00 inches were used to define roll stability.

LAR Bins	Number of Samples Wheel Lift>2.00 inches	Total Samples	Proportion	Binomial Fit of Proportion
10	1	85	0.0118	0.0174
30	1	7	0.1429	0.1875
50	2	6	0.3333	0.3571
70	0	2	0.0000	0.1667
90	6	14	0.4286	0.4333
110	0	0	--	--
130	0	0	--	--

Table 6.3. Data set used to assess the yaw stability model at COS + 0.75-second time increment. Samples with tractor yaw angle greater than 45 degrees were used to define roll stability.

LAR Bins	Samples Yaw Angle>45 degrees	Total Samples	Proportion	Binomial Fit of Proportion
10	0	85	0.0000	0.0058
30	0	7	0.0000	0.0625
50	0	6	0.0000	0.0714
70	2	2	1.0000	0.8333
90	12	14	0.8571	0.8333
110	0	0	--	--
130	0	0	--	--

Table 6.4 uses the same format that was presented for Table 6.2 and Table 6.3. Combining the tables allowed utilization of refined LAR bin increments. LAR bins were stepped in 5 percent increments about the bin centers for LAR values between 5 and 110 percent. Note that five of the six LAR bins (that contain data) over the 60 percent bin had proportions of 1.0. Figure 6.16 presents a graphical representation of the proportion data for all the time increments and bins statistically analyzed (includes the data shown in Table 6.4). LAR is shown on the y-axis and time is shown on the x-axis. The graph shows the instabilities to total samples ratio as a fraction for each bin. The logistical regression was then performed on these input data sets.

Table 6.4. Refined data used to build the stability model at COS + 0.75-second time increment. Samples in which yaw angle was greater than 45 degrees or wheel lift exceeded 2.00 inches were summed to define stability model.

LAR Bins	Number Samples YA>45 or Wheel Lift>2.00 inches	Total Samples	Proportion	Binomial Fit of Proportion
5	1	62	0.0161	0.0238
10	0	17	0.0000	0.0278
15	0	6	0.0000	0.0714
20	0	0	--	--
25	0	4	0.0000	0.1000
30	0	1	0.0000	0.2500
35	0	0	--	--
40	1	2	0.5000	0.5000
45	1	2	0.5000	0.5000
50	1	4	0.2500	0.3000
55	0	0	--	--
60	0	0	--	--
65	1	1	1.0000	0.7500
70	0	0	--	--
75	1	1	1.0000	0.7500
80	1	1	1.0000	0.7500
85	3	5	0.6000	0.5833
90	3	3	1.0000	0.8750
95	5	5	1.0000	0.9167
100	0	0	--	--
105	0	0	--	--
110	0	0	--	--

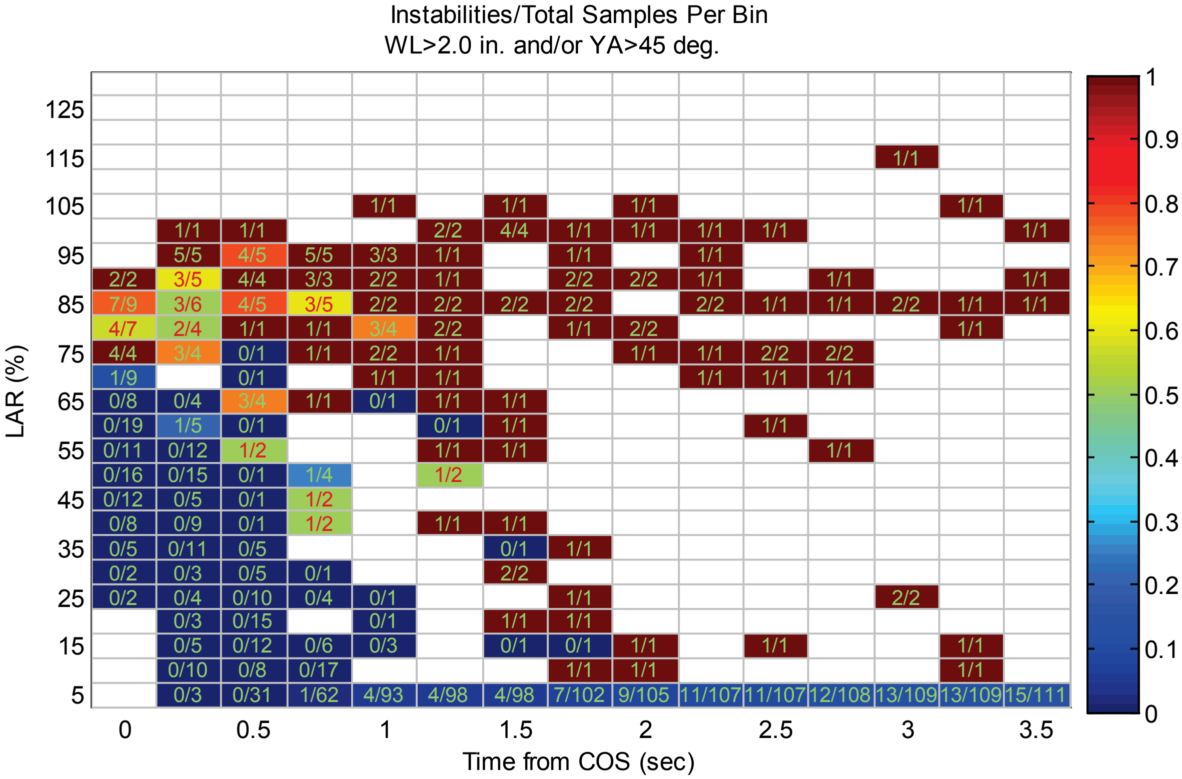


Figure 6.16. Graphical representation of the proportion data at each time increment which includes the data shown in Table 6.4. Color bar indicates proportionate value.

The results from the regression analysis at the COS + 0.75-second time increment are shown in Figure 6.17. These individual and combined logistic regression models predict the probability of exceeding the wheel lift and/or yaw angle threshold limits at COS + 0.75-seconds. In the figure, probability is shown on the y-axis and the LAR value is shown on the x-axis. LAR in this figure is expressed as a percentage. The proportions shown in Table 6.2 through Table 6.4 were represented with square, circle, and pentagram data point markers for the roll, yaw and combined data sets. Red dotted, black dashed, and purple lines represent the logistic regression results for the roll, yaw and combined models. Figure 6.18 presents another example of the logistic regression solution that was returned from the 0.75 seconds after COS time increment.

For this time increment the logistic regression data shows that for larger values of LAR the probability of observing either roll stability or yaw stability increases. For the roll model, as increased levels of LAR were observed the probability that wheel lift greater than 2.0 inches was also observed to increase to over 0.5 for LAR levels near 100 percent. Similar to the roll model, the yaw only model shows that the probability of observing yaw instability was low for LAR less than 40 percent. As LAR approaches 100 percent the probability of observing yaw instability increases to over 0.9. For this example, the combined model shows that for LAR less than 35 percent, the probability of observing either roll and/or yaw instability were small. Moving towards the right in the figure, the probability of observing instability increased to over 0.9 by the 90 percent LAR level.

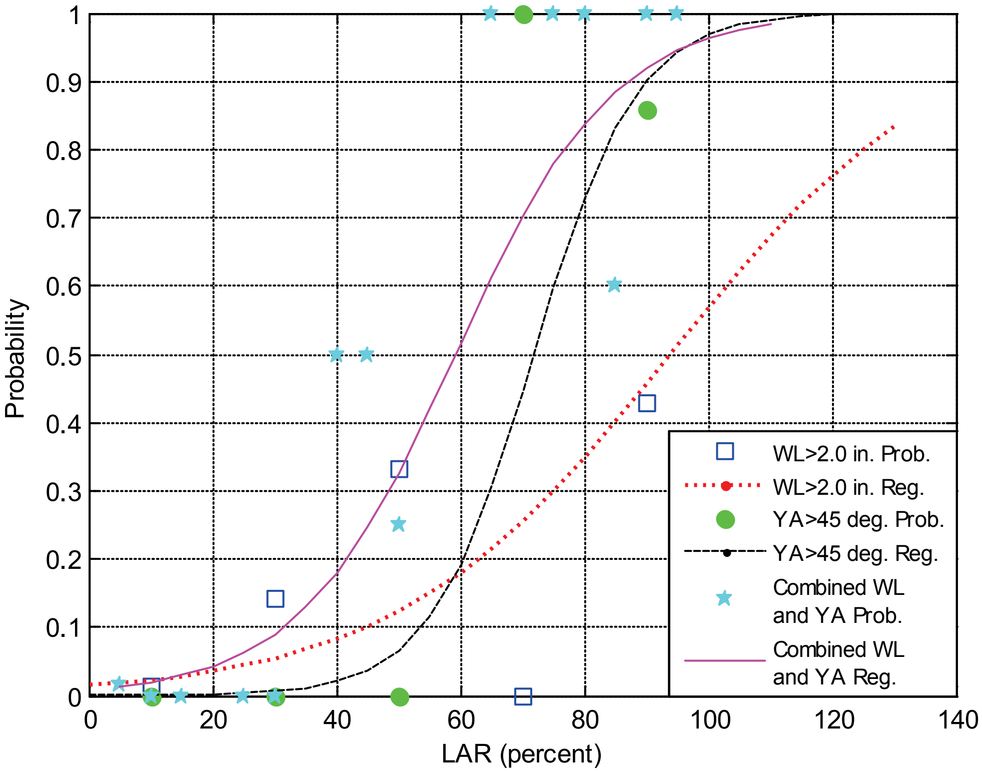


Figure 6.17. Individual and combined logistic regression models predict the probability of exceeding the wheel lift and/or yaw angle threshold limits from LAR at COS + 0.75 sec.

Table 6.5 shows the logistic regression output in tabular form for the combined model at COS + 0.75 seconds. From left to right are the LAR bins, number of tests observed with instabilities, total number of tests represented, proportion of instabilities, binomial fit of proportion, log estimate of the previous column, standard error of the log estimate, Phat (predicted probability), lower 95th confidence interval, and upper 95th confidence interval.

The last two columns of data were used to create the LAR stability map:

- LAR bins in which Phat's 95th confidence intervals were both below 0.05 were assigned the color green. A SWD test with a LAR observed in this bin did not exceed either stability threshold.

- LAR bins in which only the lower 95th confidence interval remains below 0.05 were assigned the color yellow. A SWD test with a LAR observed in this bin likely did not exceed either stability threshold.

- LAR bins in which both of the Phat confidence intervals were over the 0.05 and both remain below 0.95 were assigned the color blue. A SWD test with a LAR observed in this bin was considered equally likely to be either stable or unstable (region of uncertainty).

- LAR bins in which upper 95th confidence intervals were above 0.95 were assigned the color red. A SWD test with a LAR observed in this bin likely exceeded one or both stability thresholds.

- LAR bins in which Phat's 95th confidence intervals were both 0.95 were assigned the color dark red. A SWD test with a LAR observed in this bin exceeded one or both stability thresholds.

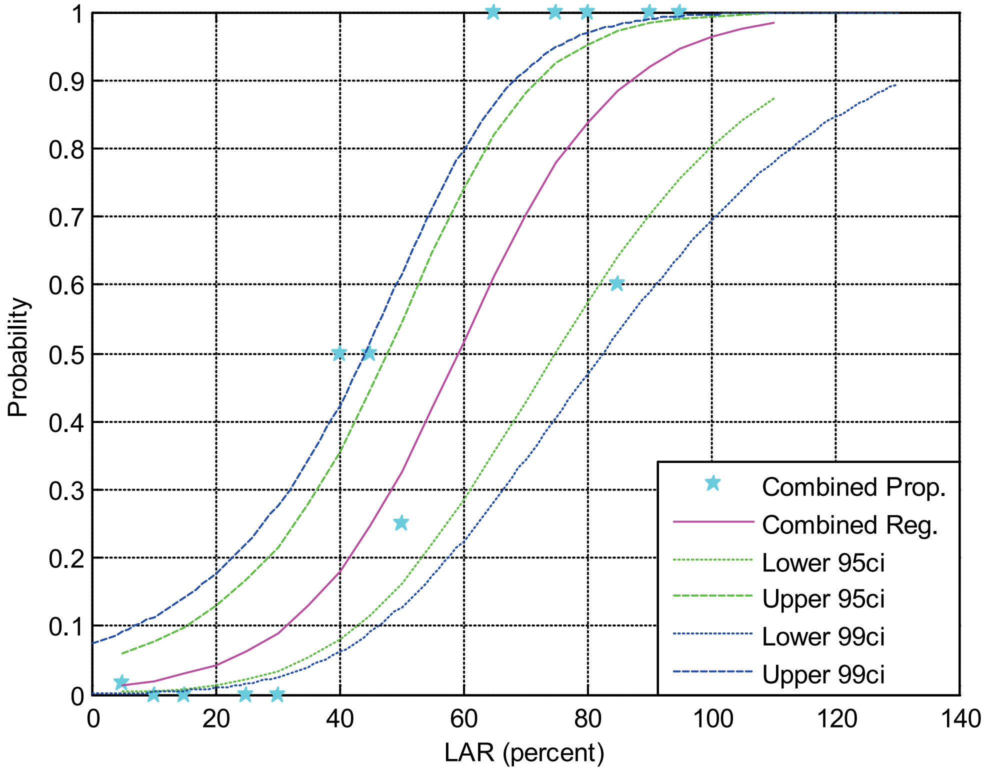


Figure 6.18. Combined model logistic regression solution for LAR and probability with 95th and 99th confidence intervals shown.

Three of these stability map regions are shown in Table 6.5. LAR bins between 5 and 30 percent were assigned yellow and were considered to be likely stable. LAR bins between 35 and 75 percent were assigned blue were considered equally likely to be either stable or unstable. LAR bins between 80 and 110 percent assigned red and were considered likely to be unstable for the analysis at this 0.75-second time increment.

Table 6.5. Inputs and outputs from the logistic regression of LAR using the combined instability model

Bins	Instability Observed	Total Samples	Proportion	Binomial Proportion	Log Estimate	Log Est. Standard Error	Phat	Phat Standard Error	Phat lower 95th	Phat upper 95th
5	1	72	0.0161	0.0238	-4.2869	0.7734	0.0136	0.0103	0.0030	0.0589
10	0	9	0.0000	0.0278	-3.8910	0.7139	0.0200	0.0140	0.0050	0.0764
15	0	4	0.0000	0.0714	-3.4952	0.6577	0.0294	0.0188	0.0083	0.0992
20	0	0	--	--	-3.0993	0.6059	0.0431	0.0250	0.0136	0.1288
25	0	4	0.0000	0.1000	-2.7035	0.5595	0.0628	0.0329	0.0219	0.1670
30	0	1	0.0000	0.2500	-2.3076	0.5200	0.0905	0.0428	0.0347	0.2161
35	0	0	--	--	-1.9118	0.4892	0.1288	0.0549	0.0536	0.2783
40	1	2	0.5000	0.5000	-1.5159	0.4688	0.1801	0.0692	0.0806	0.3550
45	1	2	0.5000	0.5000	-1.1201	0.4600	0.2460	0.0853	0.1169	0.4456
50	1	4	0.2500	0.3000	-0.7242	0.4637	0.3265	0.1020	0.1634	0.5460
55	0	0	--	--	-0.3284	0.4794	0.4186	0.1167	0.2196	0.6482
60	0	0	--	--	0.0675	0.5062	0.5169	0.1264	0.2840	0.7426
65	1	1	1.0000	0.7500	0.4633	0.5422	0.6138	0.1285	0.3545	0.8214
70	0	0	--	--	0.8592	0.5860	0.7025	0.1225	0.4282	0.8816
75	1	1	1.0000	0.7500	1.2550	0.6357	0.7782	0.1097	0.5023	0.9242
80	1	1	1.0000	0.7500	1.6509	0.6903	0.8390	0.0932	0.5740	0.9527
85	3	5	0.6000	0.5833	2.0467	0.7485	0.8856	0.0758	0.6410	0.9711
90	3	3	1.0000	0.8750	2.4426	0.8096	0.9200	0.0596	0.7018	0.9825
95	5	5	1.0000	0.9167	2.8384	0.8731	0.9447	0.0456	0.7553	0.9895
100	0	0	--	--	3.2343	0.9383	0.9621	0.0342	0.8014	0.9938
1.05	0	0	--	--	3.6301	1.0051	0.9742	0.0253	0.8403	0.9963
1.10	0	0	--	--	4.0260	1.0730	0.9825	0.0185	0.8725	0.9978

This analysis at 0.75 seconds after COS confirms the observation from the graphs in the previous section that LAR and roll and yaw stability were strongly correlated for these vehicles, this maneuver, and these test conditions. So the combined model and stability mapping methodology were selected to analyze the prior and remaining time increments after COS. The resulting stability map from this overall analysis is shown in Figure 6.19.

Figure 6.19 shows time after COS on the x-axis and LAR on the y-axis. As mentioned earlier the map confirms the observation that the probability of observing instability increases towards the upper right corner of the figure. Note that there are small amounts of dark red areas near the top of the map. This region was believed to actually extend down and to the right further however insufficient data in these regions reduced the confidence in the probability estimate and resulted in the large light red area. Although these red regions lacked sufficient data, the lower left corner made up of the green and yellow areas were observed to be well defined and contained a bulk the data.

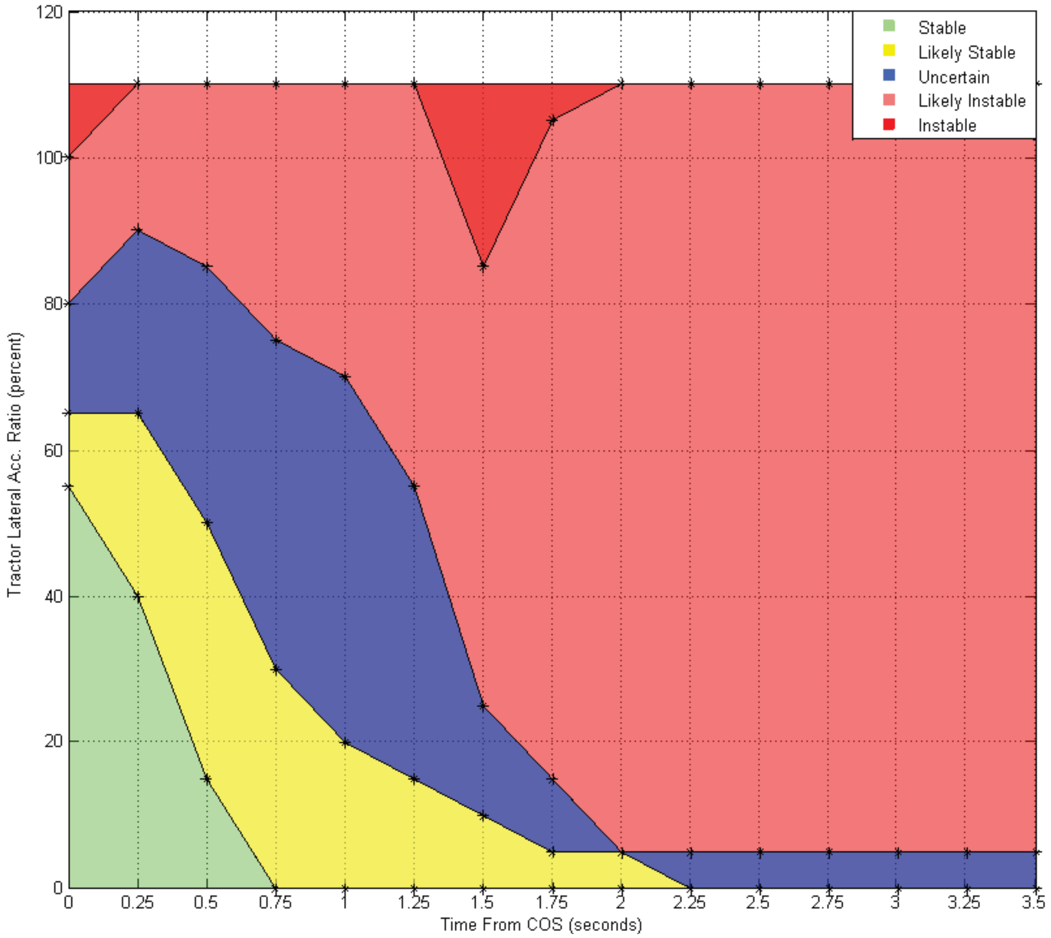


Figure 6.19. Graphical results showing regions of stability from the logistic regression analysis of LAR.

6.2.4 Stability Model for YRR

After developing and performing the logistical regression on the SWD LAR data sets a similar analysis was performed on the YRR measure. A logistic regression model was developed at each quarter of a second after COS up to COS + 3.5 sec. For each of these time increments the model predicts the probability that the vehicle was unstable based on the amount of YRR observed at that time.

Examples of the logistical regression input data sets for each model (roll, yaw and combined roll and yaw) were presented in Table 6.2 through Table 6.4. Similar tables were produced and input into the YRR logistic regression. Figure 6.20 shows the input proportions from those tables and the regression output from each of the models. This figure was observed to be similar to the previous one shown for LAR. However, there were notable subtle differences in the models.

In this figure, the individual and combined logistic regression models show the probability of exceeding the wheel lift and/or yaw angle threshold limits at COS + 0.75 seconds based on the residual YRR measure. For this time increment, the logistic regression data show that for larger values of YRR the probability of observing either roll stability or yaw stability increases.

For the roll model shown in Figure 6.20, the probability of observing roll instability was low for YRR less than 15 percent. Increased levels of YRR were observed to increase the probability of roll instability to over 0.5 for YRR levels near 100 percent, which is very similar to LAR.

The yaw-only model shows that the probability of observing yaw instability was low for YRR less than 35 percent. As YRR approaches 60 percent the probability of observing yaw instability increases to over 0.9.

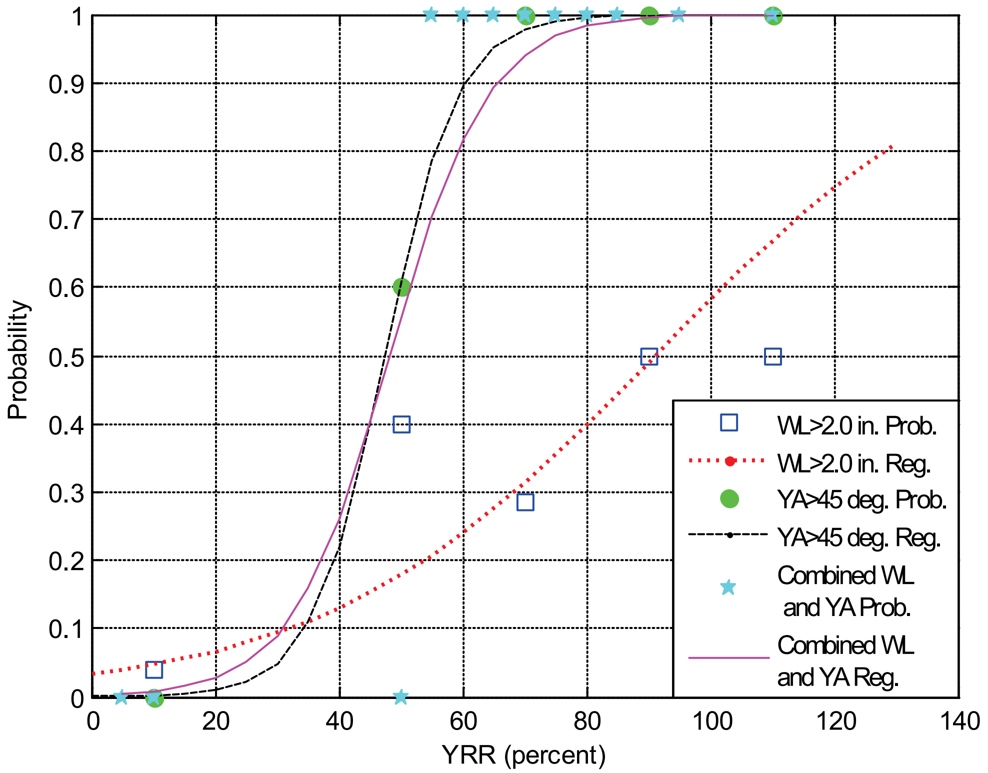
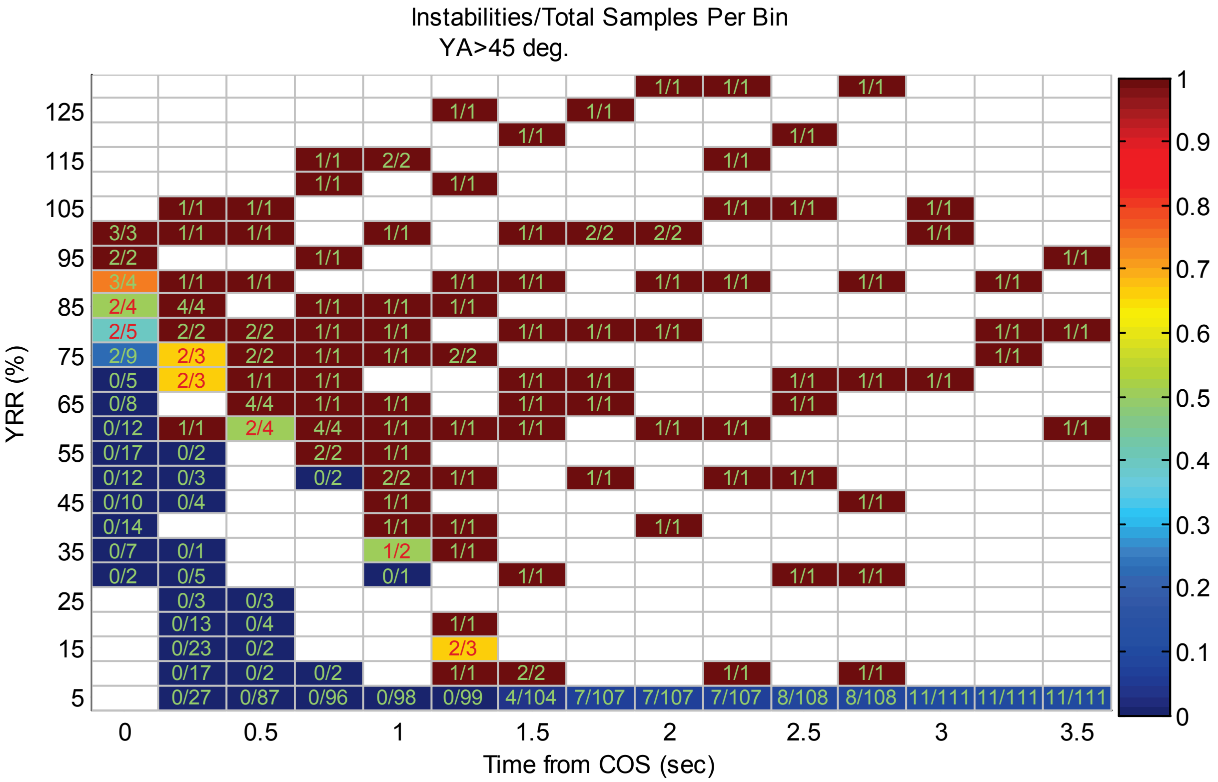


Figure 6.20. Individual and combined logistic regression models predict the probability of exceeding the wheel lift and/or yaw angle threshold limits from YRR at COS + 0.75 sec. Yaw and Combined models were iteration limited solutions.

The combined model in Figure 6.20 shows that for YRR less than 30 percent the probability of observing either roll and/or yaw instability was small and the probability increased to over 0.9 by the 70 percent YRR level.

The yaw-only model was favored for creating an YRR stability map similar to the one created for LAR. This was primarily due to the domination of the roll model at low levels of YRR. For this time increment, low levels of YRR between 15 and 40 percent show the combined model has a shallow slope which leads to a large region of uncertainty. This especially true when compared to the steep slope of the yaw-only stability model. This also led to the conclusion that YRR was not as good a discriminator of roll stability compared to LAR. The yaw stability model was used to create a stability map similar to the one created for LAR. Figure 6.21 shows the instabilities to total samples (each sample represents a single SWD test) ratio as a fraction for each YRR bin and time increment. The logistical regression was then performed on these input data sets.

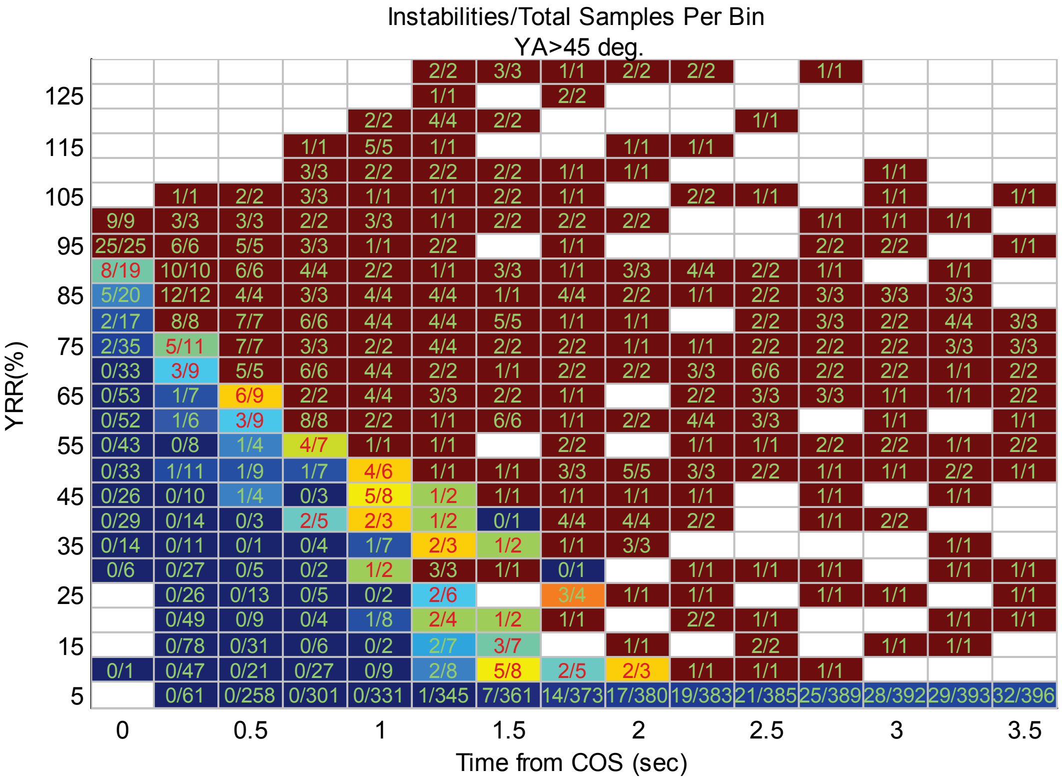


YRR (%)	0		0.5		1		1.5		2		2.5		3		3.5
									1/1	1/1		1/1			
125						1/1		1/1							
							1/1				1/1				
115				1/1	2/2					1/1					
				1/1		1/1									
105		1/1	1/1							1/1	1/1		1/1		
	3/3	1/1	1/1		1/1		1/1	2/2	2/2				1/1		
95	2/2			1/1											1/1
	3/4	1/1	1/1			1/1	1/1		1/1	1/1		1/1		1/1	
85	2/4	4/4		1/1	1/1	1/1									
	2/5	2/2	2/2	1/1	1/1		1/1	1/1	1/1					1/1	1/1
75	2/9	2/3	2/2	1/1	1/1	2/2								1/1	
	0/5	2/3	1/1	1/1			1/1	1/1			1/1	1/1	1/1		
65	0/8		4/4	1/1	1/1		1/1	1/1			1/1				
	0/12	1/1	2/4	4/4	1/1	1/1	1/1		1/1	1/1					1/1
55	0/17	0/2		2/2	1/1										
	0/12	0/3		0/2	2/2	1/1		1/1		1/1	1/1				
45	0/10	0/4			1/1							1/1			
	0/14				1/1	1/1			1/1						
35	0/7	0/1			1/2	1/1									
	0/2	0/5			0/1		1/1				1/1	1/1			
25		0/3	0/3												
		0/13	0/4			1/1									
15		0/23	0/2			2/3									
		0/17	0/2	0/2		1/1	2/2			1/1		1/1			
5		0/27	0/87	0/96	0/98	0/99	4/104	7/107	7/107	7/107	8/108	8/108	11/111	11/111	11/111

Figure 6.21. YRR proportion data used to create yaw only model from SWD series performed with the 28-foot flatbed trailer and 60% GAWR load condition. Color bar indicates proportionate value.

The logistic regression performed on the data set shown in Figure 6.21 returned a solution with very low confidence due to a separation/quasi-separation of the proportion data. This was attributed to the lack of proportion data around the stability transition zone. To reduce the separation phenomenon, more SWD test data were added from the face validity SWD tests performed with the box van, long flatbed, and tanker trailers.

Figure 6.22 shows the resulting proportion data set from analysis of the four different trailers. The added SWD data sets have vastly increased the amount of data in the transition zone up to about 2.0 seconds after COS where the zone diminishes into the 5 percent YRR bin. This larger data set was then used to perform the logistic regression on YRR. Figure 6.23 presents an example of the logistic regression solution that was returned from the 0.75 seconds after COS time increment.



YRR(%)	0		0.5		1		1.5		2		2.5		3		3.5
						2/2	3/3	1/1	2/2	2/2		1/1			
125						1/1		2/2							
					2/2	4/4	2/2				1/1				
115				1/1	5/5	1/1			1/1	1/1					
				3/3	2/2	2/2	2/2	1/1	1/1				1/1		
105		1/1	2/2	3/3	1/1	1/1	2/2	1/1		2/2	1/1		1/1		1/1
	9/9	3/3	3/3	2/2	3/3	1/1	2/2	2/2	2/2			1/1	1/1	1/1	
95	25/25	6/6	5/5	3/3	1/1	2/2		1/1				2/2	2/2		1/1
	8/19	10/10	6/6	4/4	2/2	1/1	3/3	1/1	3/3	4/4	2/2	1/1		1/1	
85	5/20	12/12	4/4	3/3	4/4	4/4	1/1	4/4	2/2	1/1	2/2	3/3	3/3	3/3	
	2/17	8/8	7/7	6/6	4/4	4/4	5/5	1/1	1/1		2/2	3/3	2/2	4/4	3/3
75	2/35	5/11	7/7	3/3	2/2	4/4	2/2	2/2	1/1	1/1	2/2	2/2	2/2	3/3	3/3
	0/33	3/9	5/5	6/6	4/4	2/2	1/1	2/2	2/2	3/3	6/6	2/2	2/2	1/1	2/2
65	0/53	1/7	6/9	2/2	4/4	3/3	2/2	1/1		2/2	3/3	3/3	1/1	1/1	2/2
	0/52	1/6	3/9	8/8	2/2	1/1	6/6	1/1	2/2	4/4	3/3		1/1		1/1
55	0/43	0/8	1/4	4/7	1/1	1/1		2/2		1/1	1/1	2/2	2/2	1/1	2/2
	0/33	1/11	1/9	1/7	4/6	1/1	1/1	3/3	5/5	3/3	2/2	1/1	1/1	2/2	1/1
45	0/26	0/10	1/4	0/3	5/8	1/2	1/1	1/1	1/1	1/1		1/1		1/1	
	0/29	0/14	0/3	2/5	2/3	1/2	0/1	4/4	4/4	2/2		1/1	2/2		
35	0/14	0/11	0/1	0/4	1/7	2/3	1/2	1/1	3/3					1/1	
	0/6	0/27	0/5	0/2	1/2	3/3	1/1	0/1		1/1	1/1	1/1		1/1	1/1
25		0/26	0/13	0/5	0/2	2/6		3/4	1/1	1/1		1/1	1/1		1/1
		0/49	0/9	0/4	1/8	2/4	1/2	1/1		2/2	1/1			1/1	1/1
15		0/78	0/31	0/6	0/2	2/7	3/7		1/1		2/2		1/1	1/1	
	0/1	0/47	0/21	0/27	0/9	2/8	5/8	2/5	2/3	1/1	1/1	1/1			
5		0/61	0/258	0/301	0/331	1/345	7/361	14/373	17/380	19/383	21/385	25/389	28/392	29/393	32/396

Figure 6.22. YRR Proportion data used to create yaw only model from SWD series performed with the All the trailers and 60% GAWR load condition.

Table 6.6 shows the logistic regression output in tabular form for the yaw model and YRR at the COS + 0.75-second time increment. From left to right are the YRR bins, number of tests observed with instabilities, total number of tests represented, proportion of instabilities, binomial fit of proportion, log estimate of the previous column, standard error of the log estimate, Phat (predicted probability), lower 95th confidence interval, and upper 95th confidence interval.

Like the analysis of LAR, the last two columns of data were used to create the YRR yaw stability map:

- YRR bins in which Phat's 95th confidence intervals were both below 0.05 were assigned the color green. A SWD test with an YRR observed in this bin did not exceed the yaw stability threshold.

- YRR bins in which only the lower 95th confidence interval remains below 0.05 were assigned the color yellow. A SWD test with an YRR observed in this bin likely did not exceed the yaw stability threshold.

- YRR bins in which both of the Phat confidence intervals were over the 0.05 and both remain below 0.95 were assigned the color blue. A SWD test with a YRR observed in this bin was considered equally likely to be either yaw stable or unstable (region of uncertainty).

- YRR bins in which upper 95th confidence intervals were above 0.95 were assigned the color red. A SWD test with an YRR observed in this bin likely exceeded the yaw stability threshold.

- YRR bins in which Phat's 95th confidence intervals were both 0.95 were assigned the color dark red. A SWD test with an YRR observed in this bin exceeded the yaw stability threshold.

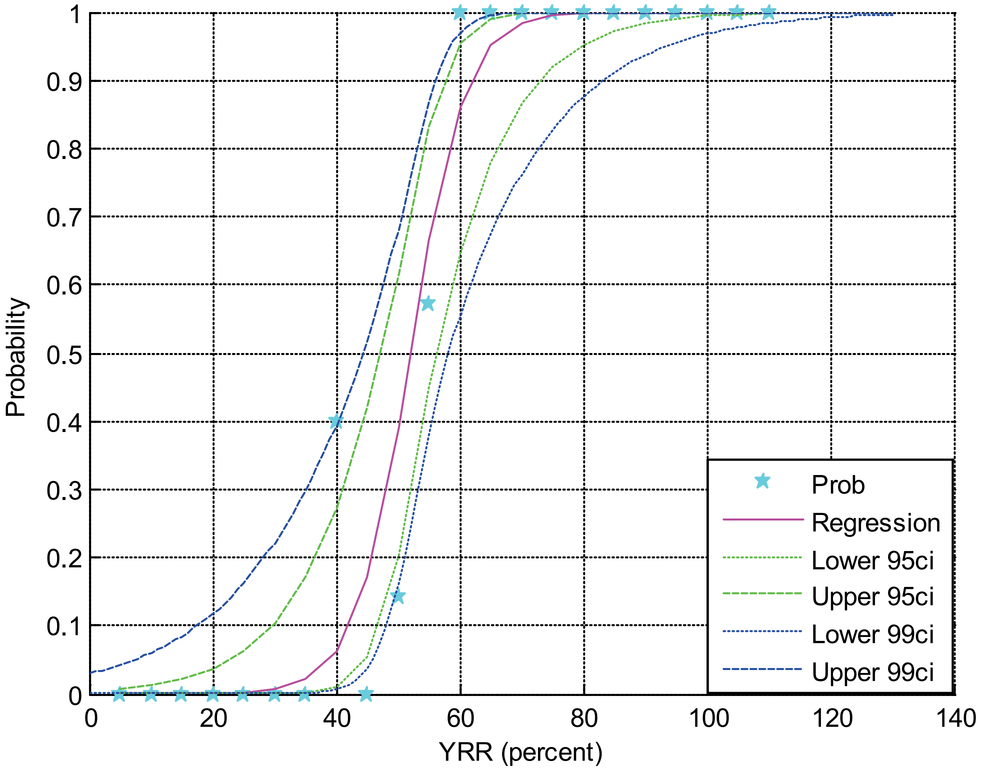


Figure 6.23. Yaw stability model logistic regression solution for YRR and probability of yaw instability with 95th and 99th confidence intervals shown.

Table 6.6. Inputs and outputs from the logistic regression of YRR at 0.75 seconds after COS.

Bins	Instability Observed	Total Samples	Proportion	Binomial Proportion	Log Estimate	Log Est. Standard Error	Phat	Phat Standard Error	Phat lower 95th	Phat upper 95th
5	0	301	0.0000	0.0017	-10.669	2.9352	0.0000	0.0001	0.0000	0.0073
10	0	27	0.0000	0.0179	-9.5333	2.6348	0.0001	0.0002	0.0000	0.0125
15	0	6	0.0000	0.0714	-8.3974	2.3354	0.0002	0.0005	0.0000	0.0215
20	0	4	0.0000	0.1000	-7.2615	2.0374	0.0007	0.0014	0.0000	0.0367
25	0	5	0.0000	0.0833	-6.1256	1.7415	0.0022	0.0038	0.0001	0.0623
30	0	2	0.0000	0.1667	-4.9897	1.4491	0.0068	0.0097	0.0004	0.1044
35	0	4	0.0000	0.1000	-3.8538	1.1627	0.0208	0.0236	0.0022	0.1715
40	2	5	0.4000	0.4167	-2.7179	0.8882	0.0619	0.0516	0.0114	0.2735
45	0	3	0.0000	0.1250	-1.5820	0.6412	0.1705	0.0907	0.0553	0.4194
50	1	7	0.1429	0.1875	-0.4461	0.4672	0.3903	0.1112	0.2039	0.6153
55	4	7	0.5714	0.5625	0.6898	0.4589	0.6659	0.1021	0.4478	0.8305
60	8	8	1.0000	0.9444	1.8257	0.6229	0.8612	0.0744	0.6468	0.9546
65	2	2	1.0000	0.8333	2.9616	0.8662	0.9508	0.0405	0.7797	0.9906
70	6	6	1.0000	0.9286	4.0975	1.1392	0.9837	0.0183	0.8658	0.9982
75	3	3	1.0000	0.8750	5.2334	1.4249	0.9947	0.0075	0.9199	0.9997
80	6	6	1.0000	0.9286	6.3693	1.7170	0.9983	0.0029	0.9528	0.9999
85	3	3	1.0000	0.8750	7.5052	2.0126	0.9995	0.0011	0.9724	1.0000
90	4	4	1.0000	0.9000	8.6411	2.3105	0.9998	0.0004	0.9839	1.0000
95	3	3	1.0000	0.8750	9.7770	2.6098	0.9999	0.0001	0.9906	1.0000
100	2	2	1.0000	0.8333	10.9129	2.9102	1.0000	0.0001	0.9946	1.0000
105	3	3	1.0000	0.8750	12.0487	3.2112	1.0000	0.0000	0.9968	1.0000
110	4	4	1.0000	0.9000	13.1846	3.5128	1.0000	0.0000	0.9982	1.0000

All five of these stability map regions are shown in Table 6.6. YRR bins between 5 and 20 percent were assigned green and were considered to be stable. YRR bins between 25 and 40 percent were assigned yellow and were considered to be likely stable. YRR bins between 45 and 55 percent were assigned blue and were considered equally likely to be either stable or unstable. YRR bins between 60 and 75 percent were assigned red and were considered likely to be unstable. Finally, YRR bins between 80 and 110 percent assigned dark red and were considered to be unstable for the analysis at this 0.75-second time increment. This analysis at 0.75 seconds after COS confirms the observation from the graphs in the previous section that YRR and yaw stability were strongly correlated. The yaw model and stability mapping methodology were selected to analyze the prior and remaining time increments after COS. The resulting stability map from this overall analysis is shown in Figure 6.24.

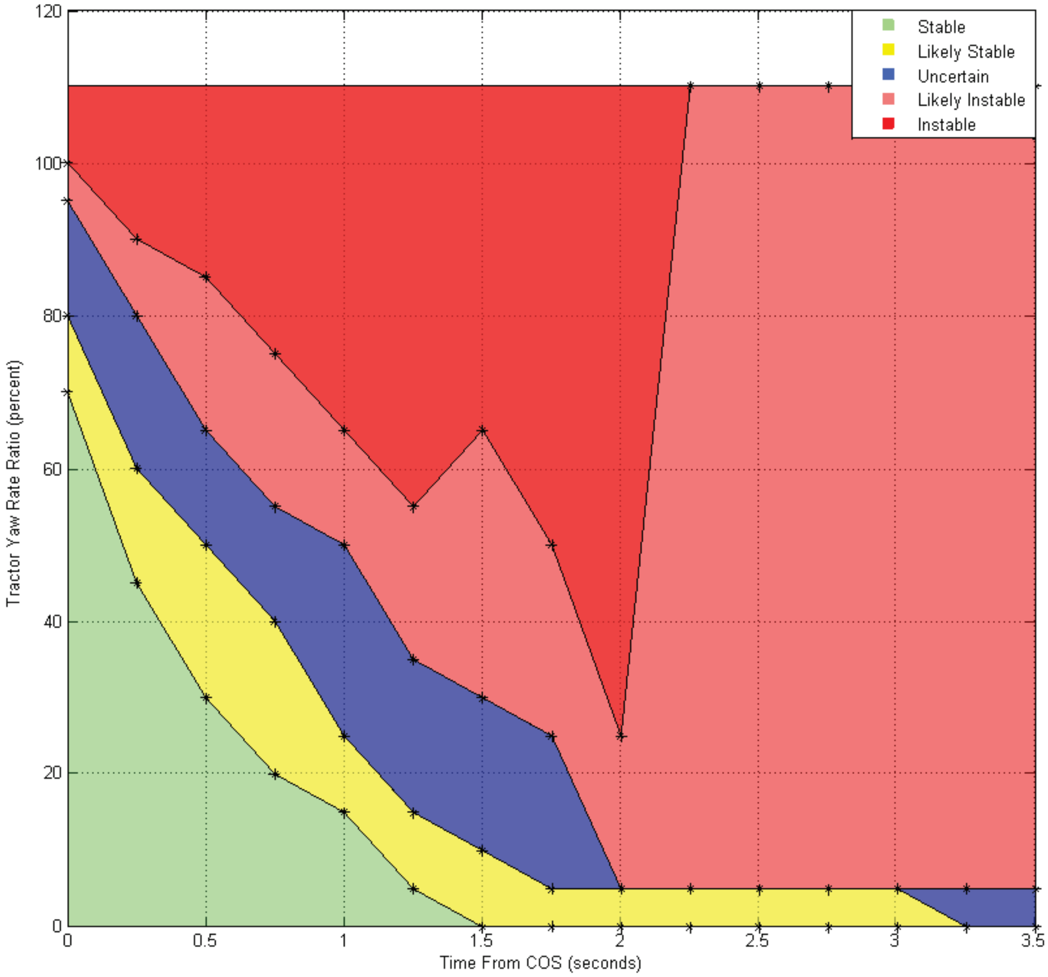


Figure 6.24. Graphical results showing regions of stability from the generalized linear regression of YRR data. SWD data with additional trailer types were added to reduce model failures due to lack of convergence.

Figure 6.24 shows time after COS on the x-axis and YRR on the y-axis. As mentioned earlier with LAR, the map confirms the observation that the probability of observing instability increases towards the upper right corner of the figure. Note the dark red areas near the top of the map. This region was believed to actually extend further to the right. However, the confidence in the probability estimate in the 2.0 to 3.0-second region was reduced and resulted in the large light red area. Though this region lacked confidence, the lower left corner made up of the green and yellow areas were observed to be well defined and contained a bulk of the data and were observed to have very good confidence.

6.3 Responsiveness

Stability control intervention has the potential to significantly increase the stability of the vehicle in which it is installed. A hypothetical way to improve stability control would be to either make the base vehicle or its stability control system intervention such that the vehicle is unresponsive to the speed and steering inputs commanded by a driver. This would degrade the maneuverability required to avoid an obstacle. This hypothetical situation was addressed in "Development Criteria for Electronic Stability Control Performance Evaluation" [25]. That report details a “responsiveness” measure that was developed to assure that a balance between lateral stability and the ability of the vehicle to respond to the driver’s inputs was preserved. Though the test results presented in that report do not show any of the vehicles tested were out of balance with respect to stability or responsiveness, the rationale presented for a responsiveness assessment also was warranted for heavy vehicles. Therefore, a similar responsiveness measure based on the lateral displacement of the vehicle was studied. It was found easy to measure\calculate, had good discriminatory capability for the vehicles tested, and had a direct relation to obstacle avoidance. Based on those observations, researchers decided to investigate lateral displacement measures to quantify the responsiveness of SC equipped class 8 tractors.

For this phase of research the lateral displacement measure was determined the same way as prescribed by FMVSS No. 126. Lateral displacement is calculated by double integrating and zeroing the corrected lateral acceleration measure. For tractor semitrailers, the responsiveness would be measured at 1.5 seconds after the initialization of the maneuver. This time coincides with the end of the 3rd quarter cycle for a 0.5 Hz sine with 1.0-second dwell maneuver. This portion of the maneuver was considered to be the obstacle avoidance portion, while execution of the maneuver’s dwell and 4th quarter cycles were considered the recovery portion of the maneuver. An example of this is provided in Figure 6.25.

From top to bottom, this figure presents examples of time history data for steering wheel angle, lateral acceleration and calculated lateral displacement. Eight steering scalars are overlaid in plots to show how lateral displacement grows with each successive increase in steering input. Each plot has diamond, circle, and pentagram data markers denoting BOS, the 1.5-second responsiveness measure, and COS. The plot of steering wheel angle has the avoidance and recovery regions of the SWD maneuver highlighted. The figure shows that the responsiveness measure was taken at the end of the avoidance portion of the maneuver.

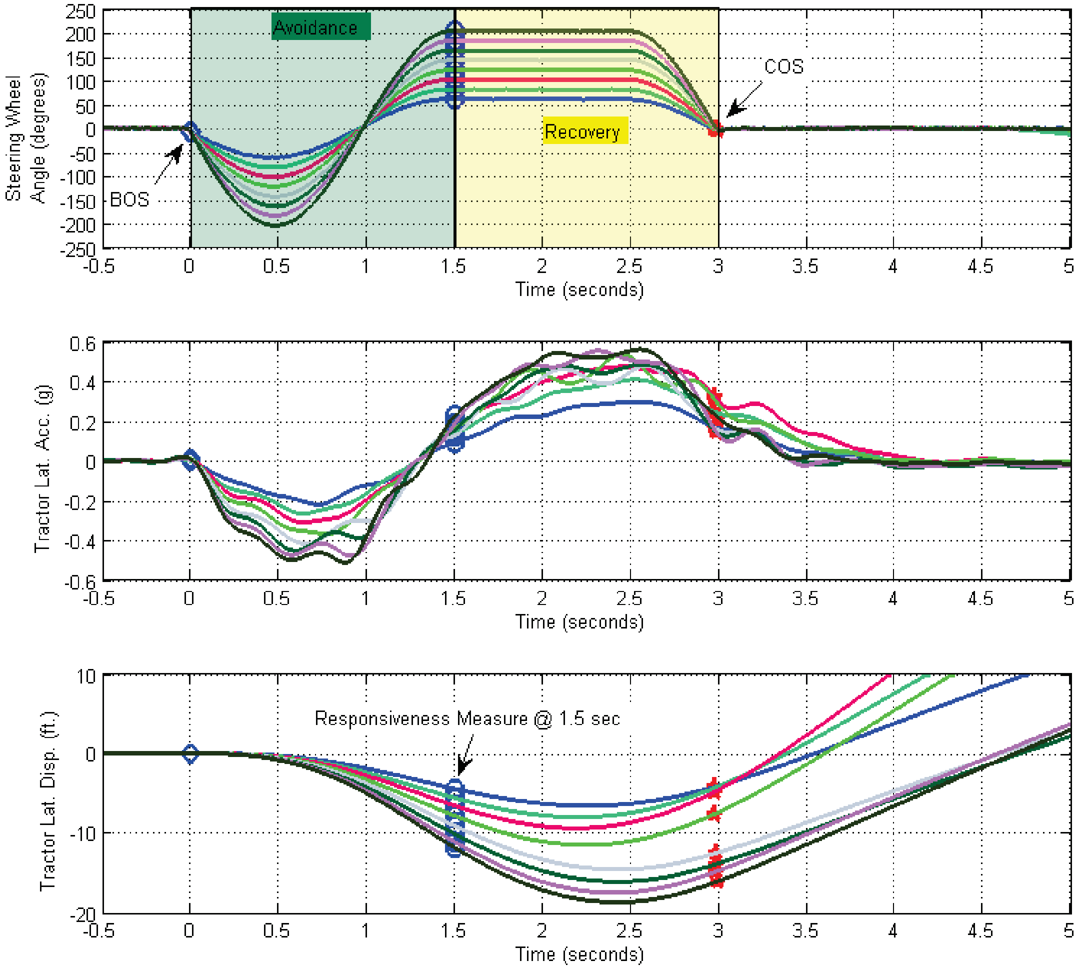


Figure 6.25. Time history data from the SWD denotes BOS, responsiveness measure, COS and the maneuver avoidance and recovery regions.

This lateral displacement measure was calculated and assessed for each 0.5 Hz SWD maneuver conducted with the 28-foot flatbed trailer in the 60% GAWR load condition. Figure 6.26 shows the lateral displacement achieved 1.5 seconds into the SWD maneuver for each vehicle, SC condition (enabled and disabled) and steering scalar condition tested. This figure shows that as the test severity was increased with steering scalar the lateral displacement measure also increased. Note that the SC-enabled test series were not much different than the SC-disabled series and this indicates that the systems were not sacrificing maneuverability to increase stability.

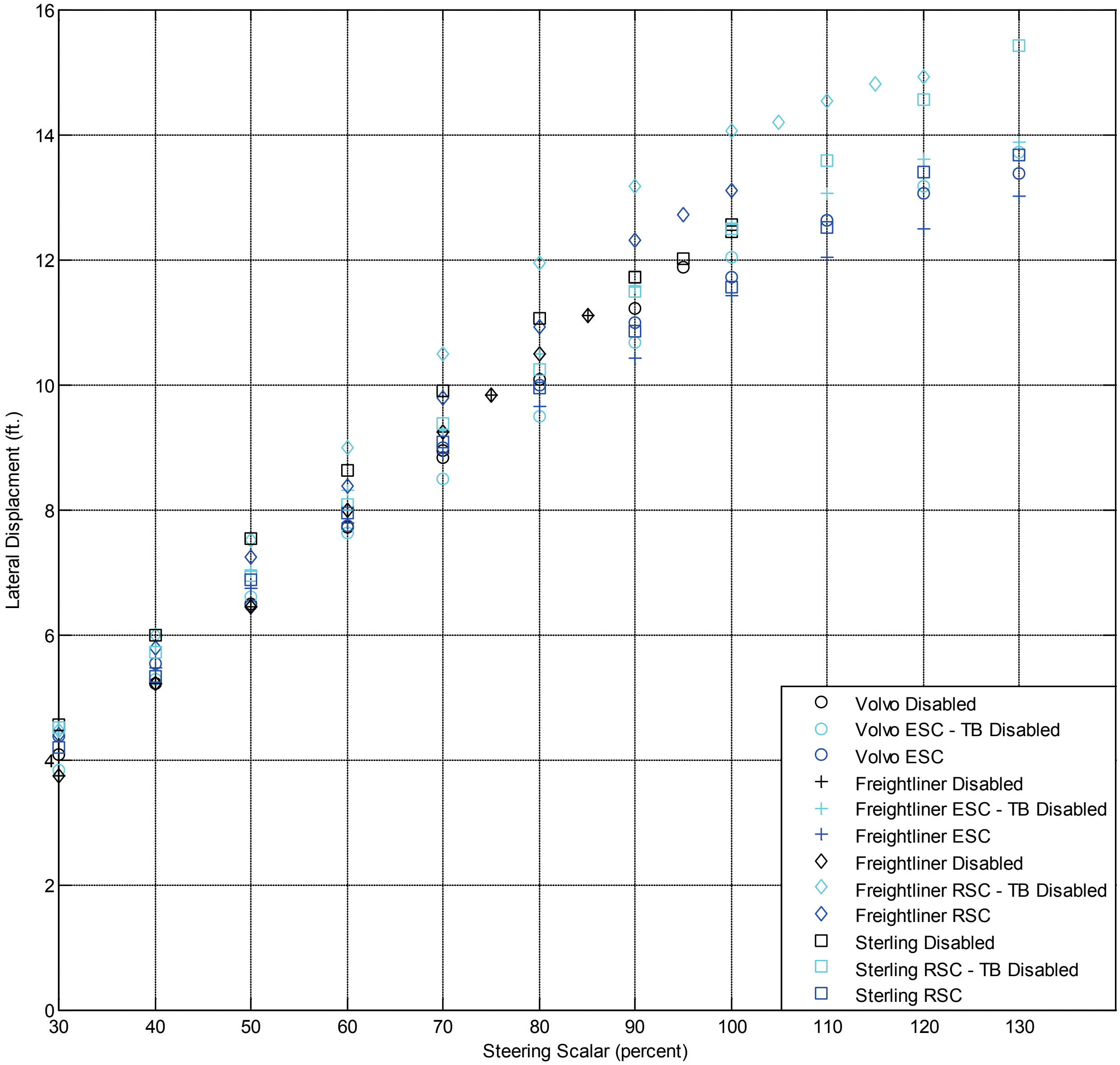


Figure 6.26. Figure shows the lateral displacement achieved 1.5 seconds into the SWD performance maneuver for each steering scalar, vehicle, and SC test condition.

For the three SC conditions tested, all three tractors demonstrated good lateral displacement response to the range of steering inputs up to 100 percent of SWA found at 0.5g. For the SC-enabled and disabled test conditions, this means that the systems demonstrated a good balance between lateral stability and the ability of the vehicle to respond to the maneuver inputs.

7 CONCLUSIONS

7.1 Potential Objective Performance Maneuvers

Regarding the reduced-friction Jennite surface, in general the test results from this surface did show that ESC could improve the stability of these vehicles on this surface. The improvements in performance were most noticeable when comparing an individual vehicle's performance with and without ESC for maneuvers with the same given inputs. Data analysis indicated that ESC systems made improvements that either reduced plow or spinout situations but the differences in the data were small, compared to the data from the high-friction dry asphalt surface. Pursuing a performance test on the Jennite surface will require further data analysis and additional maneuver design and development testing. For this phase of research the maneuvers conducted on dry asphalt (high-friction surface) were selected to continue maneuver development and metric research. This decision was also supported by the increased number of test track instabilities observed on the high-friction surface, and the surface's consistency, size, and availability.

In this study, two load conditions were evaluated; bobtail and the 60% GAWR[3] at the tractor's drive axles. Instabilities were observed on the high-friction surface for both load conditions. However, the instabilities with the bobtail condition were only observed on the 4x2 configured Sterling, and those instabilities were limited to roll only (wheel lift was greater than 2.0 inches). Because the 60% GAWR load condition was found to produce both roll and yaw instabilities for the three tractors tested, it was selected for continued research and development.

Narrowing the choices between loads and surfaces to high-friction dry asphalt and the 60% load condition also narrowed the maneuver profiles to the SIS, SWD and HSWD maneuvers. The SIS was prescribed in the SWD and HSWD testing methodology, and of the three maneuvers it was the only one performed at a constant speed and considered quasi-steady state. The SIS maneuver was determined to have the potential to evaluate SC's engine torque reduction function.

Comparing the test results from the SWD and HSWD maneuvers, it was concluded that both were capable of being developed into an objective performance test maneuver. The large differences in test results between SC-enabled and disabled test series indicated that each would challenge/discriminate a vehicle's lateral stability. For both maneuvers, the longer 1.0-second dwell time was selected because it was determined to be more challenging than 0.5 seconds of dwell at 45 mph. 0.5 Hz was selected as the steering wheel sinusoidal input frequency because it was determined to be the common (first or second) frequency at which instabilities were observed for a narrow range of speed and steering inputs for the two maneuvers. The spread in the steering scalars needed to achieve instability was smaller for the SWD than the HSWD. This indicated that the vehicles were more sensitive to changes in frequency and steering amplitude when performing the SWD versus the HSWD. Based on those results, the 0.5 Hz sine with 1.0-

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[3] The 60% Tractor GAWR, was chosen because crash data indicated that loss-of-control crashes were occurring with payloads as low as 5,000 lbs. For this load condition, between 6,800 and 15,500 lbs of ballast was placed onto the 28-foot flatbed trailer to achieve the desired 60% GAWR on the tractor's drive axles.

second dwell was determined to be the best candidate for an objective performance maneuver capable of assessing stability of a combination at its dynamic lateral limit.

Note that this phase of research was begun to develop a performance tests to evaluate yaw stability that would complement a roll stability performance tests documented in the previous phases of SC research. The initial test results were analyzed and the selected maneuver was observed to be capable of challenging a tractor semitrailer combination's roll and yaw propensity at the dynamic limit with the 60% GAWR loading condition.

7.2 Test Refinement Research

The test refinement research was centered on a characterization issue addressing how the vehicles were to be loaded for the SIS test procedure. The SIS test track results with the four different trailers and 60% GAWR load condition were observed to produce overlapping steering scalar ranges in the bobtail condition. From these test results, the loaded condition could potentially replace the bobtail test condition in the characterization maneuver and normalization test procedures. This would make the prescribed load condition for the characterization test the same as the candidate performance test and capable of addressing vehicles equipped with liftable axles. Additional analysis of the loaded SIS engine torque data revealed that SC's engine torque reduction function was active earlier in the maneuver (versus when compared to SIS data from bobtail tractors). When engine torque was reduced the forward speed began to drop and a subsequent reduction in the dynamics of the vehicle took place.

Research with the candidate 0.5 Hz SWD maneuver, the 60% GAWR load condition, and three different trailer combinations produced test track results that supported the selection of the SWD maneuver and load condition. Overall, with SC disabled, each combination's SWD test series were terminated for either roll or yaw instabilities prior to reaching the 130 percent steering scalar. When enabling the SC systems and repeating the SWD test series, the systems were concluded to improve both roll and yaw stability. RSC was concluded to improve roll and yaw stability of the vehicles in which it was installed, but not to the extent that was observed from ESC equipped vehicles for these trailers. The results from the tanker trailer highlighted the added control issues with a sloshing load. Due to the sloshing load none of the test series with this trailer were completed without observing roll instability. Nevertheless, RSC marginally improved roll stability over the disabled state, and ESC significantly improved roll stability even with the partially filled tanker.

7.3 Measures of Performance

Phase II's methodology for assessing the engine torque reduction event was determined to be valid for the SIS test data collected with the 60% GAWR loaded combinations. Review of the time history data from those series verified that the measured speed was consistently reduced after the torque reduction event. This research showed that SC's engine torque reduction function can be accessed from test data collected from the SIS maneuver with either the bobtail or the loaded test condition equally as well.

Phase II research also identified LAR as a potential measure of performance for indicating whether a tractor was equipped with an SC system and had some measureable increase in stability. Although LAR was determined for a different load condition and test maneuver, and was meant to assess roll stability, the current Phase III research shows that the LAR measure was applicable and versatile for accessing stability from SWD lateral acceleration data. The YRR measure was also found to be applicable and accelerated the measure of performance research due its previous development for the SWD and use for evaluating stability of vehicles with GVWR under 10,000 lbs.

From the figures presented in Section 6.2.1, it was graphically concluded that the LAR and YRR measures were able to discriminate stable from unstable SWD test results. As the magnitude and duration of the residual LAR and YRR measures increased, so did the frequency of tests that resulted in roll and/or yaw instability. Also, the results show that there were large differences in the LAR and YRR measures between SC-enabled and disabled test conditions. To gain more insight with the limited data sets, statistical analyses were performed.

Logistical regressions of LAR and YRR using study definitions for stability showed that there were clear relationships and that LAR and YRR both could be used to predict the stability outcome from performing a SWD maneuver with a loaded combination. Individually, the statistical results show that LAR was able to predict both roll and yaw stability. While YRR was also, it was better at predicting the yaw stability than roll stability. Comparing the two measures against each other, LAR was observed to be a better predictor of roll stability while YRR was observed to be a better predictor of yaw stability. Stability maps for LAR and YRR, shown in Figure 7.1 and Figure 7.2 (identical to Figure 6.19 and Figure 6.24), were created from the 95th confidence intervals for the logistical regression models at each time increment. This method of assessment was determined to provide a good estimate for boundaries that define the regions of stability. This was especially true for the regions denoted as stable since these regions contained a bulk of the data.

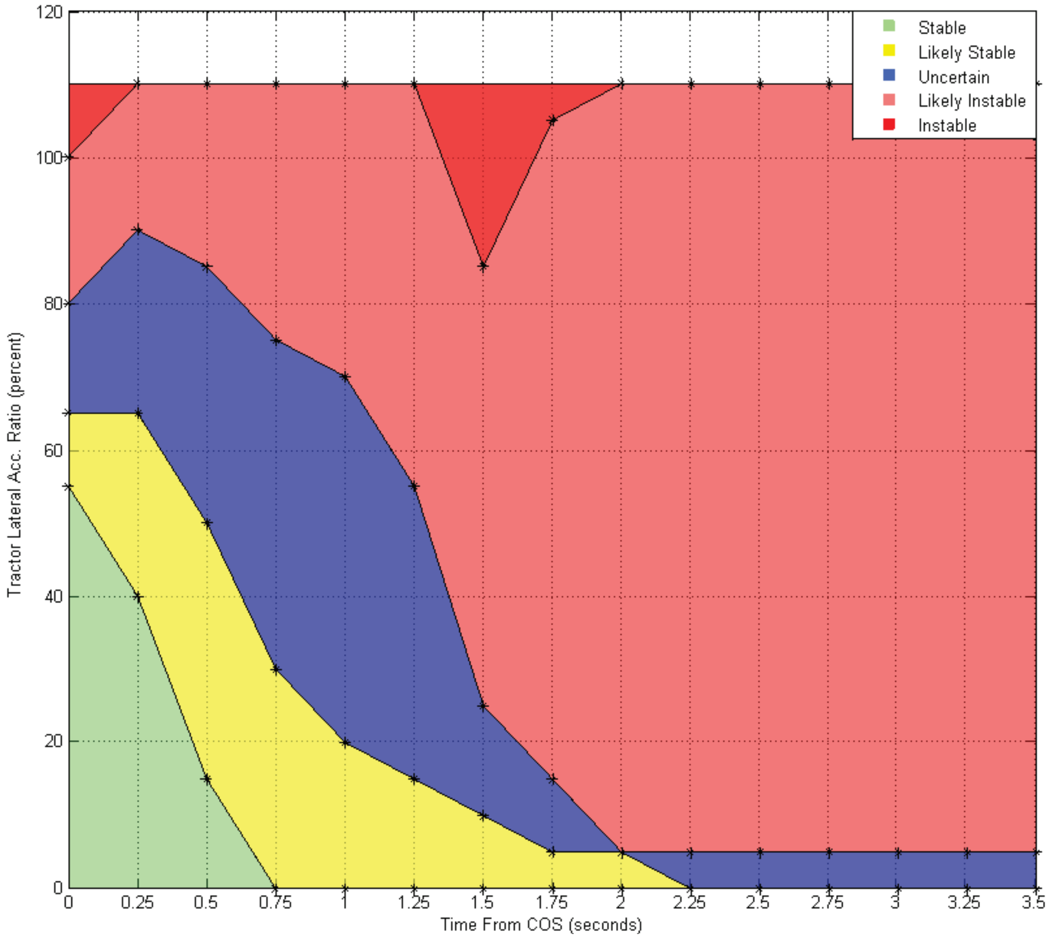

Figure 7.1. Graphical results showing regions of stability from the logistic regression analysis of LAR.

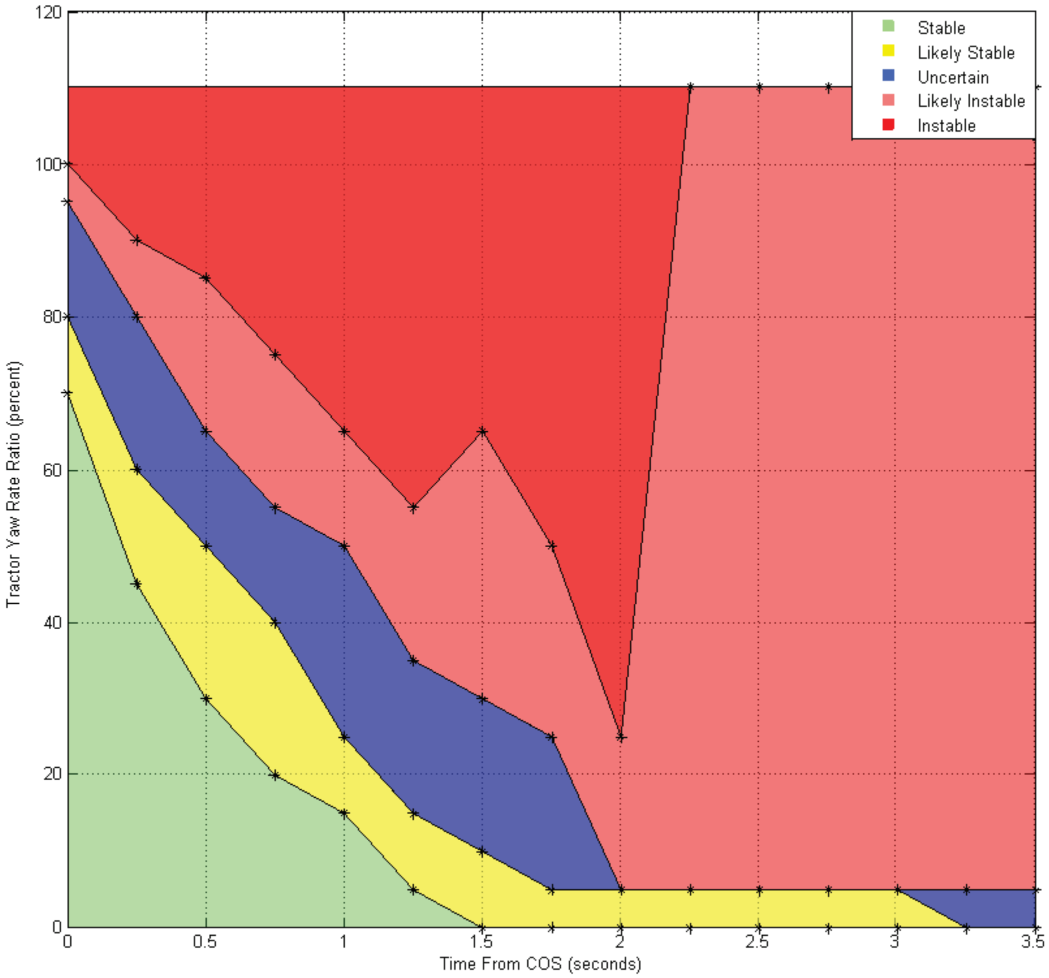

Figure 7.2. Graphical results showing regions of stability from the generalized linear regression of YRR data.

The lateral displacement measure was determined to be useful for assessing the responsiveness of the tractors and SC systems in the SWD maneuver. For the conditions evaluated, all three tractors and four stability control systems were observed to have good lateral displacement responses for the range of steering inputs used. For SC-enabled and disabled test conditions, the systems had good balance between lateral stability and the ability for the vehicle to respond to the maneuver inputs. This was concluded from Figure 7.3 (Figure 6.26 with means and confidence intervals added) that shows the lateral displacement performance. This figure has the average shown with the lower second and third multiples of standard deviation. While there are no responsiveness issues shown with these test tractors, the rationale for the use of the responsiveness metric is still relevant for evaluating SC equipped heavy vehicles. This was concluded because responsiveness or maneuverability of the vehicle can be sacrificed or manipulated to increase the stability of these vehicles.

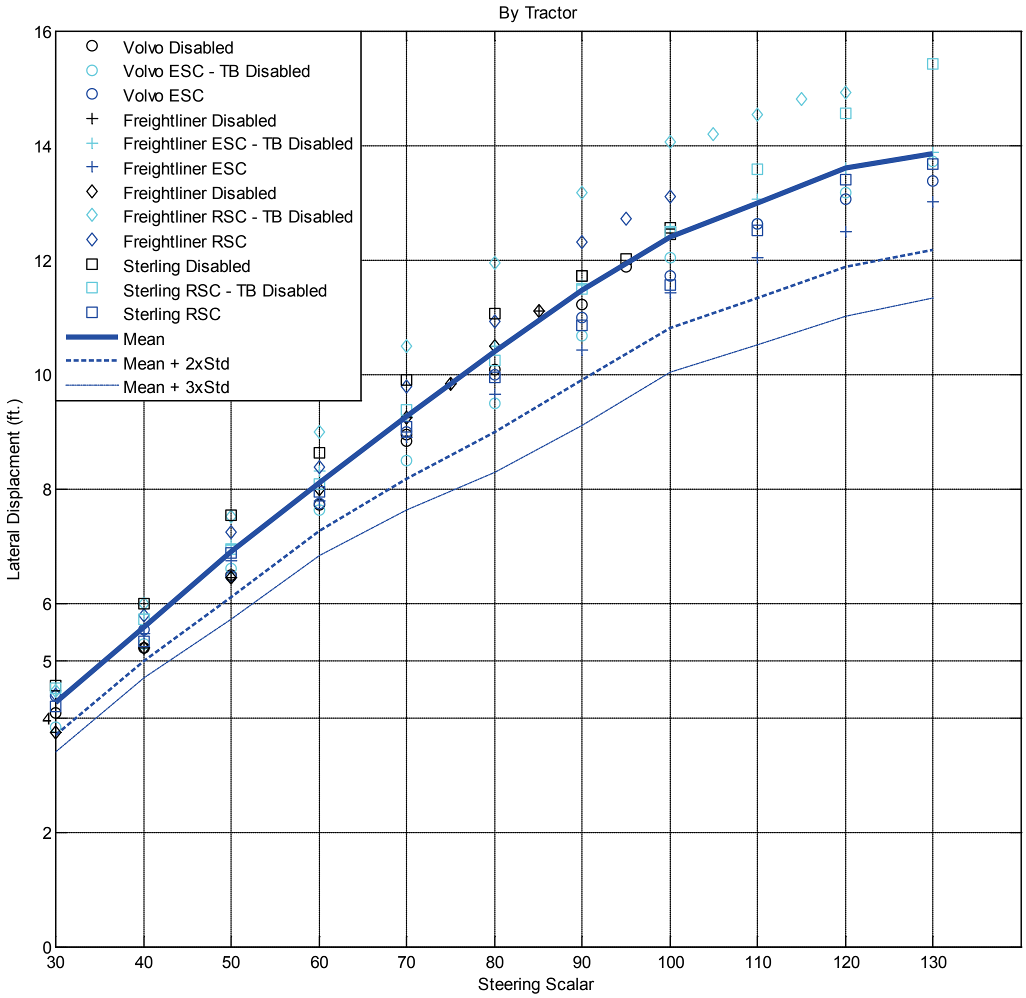

Figure 7.3. SWD Responsiveness measure versus steering scalar. Lines were added to show data mean and standard deviation information.

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APPENDIX A

A. TEST PROCEDURES

Vehicle Pre-Test Conditioning (For SIS and RSM)

1. Mass Estimation Drive Cycle
   a. Accelerate to 40 mph
   b. Decelerate at 0.3-0.4g to a stop
2. Ignition cycle will require new mass estimation drive cycle
3. Tire warm-up
   Two circles to the left and two circles to the right at a speed that result in 0.1 G lateral acceleration. (Approximate 150 ft radius at 20 MPH.)
4. Brake warm-up
   a. Use 40-20 mph burnish (0.3g decel.) bring tractor brake temperatures to a minimum of 150-200 degrees (FMVSS 121)

SIS Characterization Test Procedure

1. Perform Vehicle Pre-Test Conditioning
2. Perform SIS
   a. Test (3 tests in each direction – bobtail)
   b. Speed = 30 mph
   c. Steering = steering increases from 0 to δ^{SIS} @ 13.5 deg/sec.
3. Test Ends IF
   a. Steering magnitude = δ^{SIS} deg
   b. Tractor wheel lift is observed
   c. Articulation angle is limited by safety cables
4. Calculate SWD and HSWD δ^{Test}

NOTE; Steering magnitude, δ^{SIS}, is selected on a per test vehicle basis such that the steering continues to increase for 5.0 or more seconds after ESC activation has been detected. For Example; ESC activation was detected at 260 degrees, then δ^{SIS} = 260 degrees + 13.5 deg/sec x 5.0 sec = ~328 degrees.

SWD and HSWD Test Procedure

1) Pre-Test Conditioning
2) Test (per each load condition)
   a) steering magnitude start = X%* δ^{Test} [X_{start}= 30%]
   b) steering frequency = 0.3,0.5, or 0.7 Hz
   c) speed = xx mph (this may increase depending on initial test results)
   d) At maneuver start: Drop throttle and clutch in.

   e) Maneuver is triggered automatically by speed passing through the start speed trigger of the controller (simple comparator).

3) Continue testing incrementing amplitude up by increasing X by 10% increments until one of the following conditions occur.
   a) Amplitude = 130%* δ^{Test} degrees – Test Complete
   b) Articulation angle is in excess of 45 degrees or wheel lift occurs
      i) If the test resulted in an articulation angle greater than 45 degrees or wheel lift was visually seen – jump to step 4. - The result will be considered wheel lift if it is visually obvious that any of the tractor or trailer wheels have come off the ground and/or the outriggers hit the ground during any part of the test.
   c) Test Driver feels its unsafe to continue
4) If tractor/trailer articulation angle greater than 45 degrees or wheel lift occurred, steering magnitude should be decremented by (X-10%)* δ^{Test} degrees.
   a) Repeat test at – (X-10%)* δ^{Test} degrees.
   b) Repeat test at – (X-5%)* δ^{Test} degrees.
   c) Repeat test at – (X)* δ^{Test} degrees
   d) If excessive articulation angle or wheel lift has not occurred, continue to increment steering (X)* δ^{Test} up.
   e) Test is complete when excessive articulation angle or wheel lift occurs (jump step 6).
5) Test is complete when excessive articulation angle or wheel lift has occurred 2 times or condition 3a. has been met.
6) Test Complete

Note: For series in which tests are conducted in a single direction. Test drivers should be sensitive to this issue and make opposite turns when returning to the test start point so as not to bias any learning algorithms that a system may have. The number of left turns and right turns should be balanced as much as possible.

Brake-In-Curve Test Procedures

1) Pre-Test Conditioning
2) Test (per each load condition)
   a) steering input = required to stay adjacent to the outside of the 150-foot radius line
   b) speed = 20 mph
   c) At maneuver start (first cone): Drop throttle, shift to neutral and steer to follow the 150-foot radius.
   d) At maneuver end (second cone): Apply full treadle brake application and counter steer if necessary to maintain close proximity of the combination to the radius.
3) Continue testing incrementing speed for each test @ 2 mph until one of the following conditions occur.

    a) Speed = 50 mph – Test Complete
    b) Hit the anti-jackknife cables or major wheel lift.
        i) Cable contact – jump to step 4. - The result will be considered a jackknife if it is visually obvious that the safety cables were hit or feedback from the driver indicates the cables were hit.
        ii) Major Wheel lift - jump to step 4. - The result will be considered wheel lift if it is visually obvious that any of the tractor or trailer wheels have come off the ground and/or the outriggers hit the ground during any part of the test.
    c) Test driver feels its unsafe to continue
4) If cable contact or major wheel lift occurred, test should be decremented by 2 mph.
    a) Repeat test at cable contact or major wheel lift speed – 2 mph.
    b) Repeat test at cable contact or major wheel lift speed – 1 mph.
    c) Repeat test at cable contact or major wheel lift speed.
    d) If safety cables have not been hit and wheel lift has not occurred, continue to increment speed by 1 mph until cable contact or wheel lift occurs.
    e) Test is complete when cable contact or major wheel lift occurs (jump step 6).
5) Test is complete when cable contact or wheel lift has occurred 2 times or condition 3a has been met.
6) Test Complete

Note: For series in which tests are conducted in a single direction. Test drivers should be sensitive to this issue and make opposite turns when returning to the test start point so as not to bias any learning algorithms that a system may have. The number of left turns and right turns should be balanced as much as possible.

Ramp With Dwell (RWD) Test Procedures

1) 500 ft. Steering Calibration/Characterization
    a) Perform on wet Jennite at prescribed load condition
    b) In order to determine a speed and steering profile that will result in the desired vehicle response on a given surface, it is necessary to characterize the test vehicle. Performance of the maneuver described below will provide the characteristic information that is used to normalize the test maneuver to the vehicle and surface conditions.
    c) Enter the Jennite following the 500 ft. radius curve, at a speed of approximately 20 mph, and drive through the entire curve. Repeat the run, adjusting the speed until the vehicle is traveling at the maximum speed possible while remaining in the marked lane, not to exceed 35 mph.
    d) The following are defined based on the test results:
        i) Vdt = Drive through speed
        ii) δdt = Drive through steering angle

2) Ramp With Dwell - Yaw Stability Maneuver
   a) Perform on wet Jennite at prescribed load condition
   b) The steering input can be described as a ramp with dwell that has amplitude directly related to the steering input required for the vehicle to negotiate the Jennite curve at the drive-through speed.
   c) The steering profile is constructed from the following steering amplitudes:
      i) δdt is the drive-through steering input determined during the normalization procedure.
      ii) δ0 is defined as the drive-through steering input, δdt, rounded to the nearest 90-degree increment (e.g., 110 degrees is decreased to 90 degrees). The sole exception is: For all cases when δdt is less than 90 degrees, δ0is defined as 90 degrees.
      iii) δm is defined as the maximum amplitude of the steering input during the maneuver. δm is equal to δ0 multiplied by a scaling factor, K. K is an integer value ranging from 2 to 6.
   d) The steering profile is defined as:
      i) t < 0: δ = δdt
      ii) t = 0 to t = 1: Ramp from δ = δdtto δ = Kδ0
      iii) t = 1 to t = 4: δ = Kδ0
      iv) t = 4 to t = 5: Ramp from δ = δ0to δ = 0
   e) Test Maneuver
      i) The speed at which the maneuver is conducted is at least 0.9 times the drive through speed, or 35 mph, whichever is less.
      ii) Maneuver speed = Vm >= (0.9)(Vdt) Drive the vehicle on the Jennite curve at a speed of Vm, using either constant throttle or cruise control to maintain the vehicle speed.
      iii) For the first test run, execute the steering profile using a steering amplitude scaling factor, K, of 2. Maintain constant throttle or use cruise control.
      iv) Repeat the maneuver using increasing values of K.

APPENDIX B

B. INSTRUMENTATION AND SAFETY EQUIPMENT

Data Acquisition: In-vehicle data acquisition systems comprised of ruggedized industrial computers, recorded outputs from the previously mentioned sensors during the conduct of test maneuvers.

The computers employed the DAS-64 data acquisition software developed by VRTC. Analog Devices Inc. 3B series signal conditioners were used to condition data signals from all transducers listed in Table 3.3 and Table 3.4. Measurement Computing Corporation PCI-DAS6402/16 boards digitized analog signals at a collective rate of 200 kHz. The test drivers armed the trigger for data collection prior to each test; however, actual data collection was automatically initiated the instant the steering machine began to execute its commanded inputs (i.e., at the desired test speed). To provide the initial conditions just prior to execution of each test maneuver, a short period of pre-trigger data were recorded.

A second data acquisition system ADERS (Analog Digital Event Recording System) recorded j1939 signals from the vehicles bus. Table 3.5 listed the signals recorded.

Signal Conditioning: Signal conditioning consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Signals are analog filtered using a 20 Hz; 2 pole; Butterworth filter. Test Safety Equipment

Steering Wheel Angle: Steering wheel angle was recorded from an optical encoder that is part of the programmable steering machine.

Brake Treadle Application: Brake treadle was measured with a normally open switch mounted underneath the dash making contact with the brake pedal. It was important to monitor the driver's braking activity during testing. If the driver applied the brake during the maneuver the test was invalid.

Throttle Position: Throttle position was measured directly from the vehicle's OE throttle position sensor. The signal is buffered with an instrumentation amplifier so not to interfere with its normal operation. In some vehicles the throttle position had to be recorded from the vehicle bus. It was important to monitor the driver's throttle position activity during testing. If the driver was requesting throttle during certain maneuvers, the test was invalid.

Inertial Sensing System: A multi-axis inertial sensing system was used to measure accelerations and roll, pitch, and yaw angular rates. The system was placed near the vehicle's CG so as to minimize roll, pitch, and yaw effects. Since it was not possible to position the accelerometers precisely at the vehicle's CG for each loading condition, sensor outputs were corrected to translate the motion of the vehicle at the measured location to that which occurred at the actual CG during post-processing of the data. The sensing system did not provide inertial stabilization of its accelerometers. Lateral acceleration was also corrected for vehicle roll angle during post processing using ride height data collected from both tractor and trailer.

Frame Rail Height: An infrared distance measurement system was used to collect left and right side vehicle ride heights for the purpose of calculating vehicle roll angle. Vehicle roll angle was computed with data output from the two sensors, used in conjunction with roll rate data measured by the multi-axis inertial sensing system.

Rear Axle Height: An infrared distance measurement system was used to collect left and right side axle ride heights for the purpose of calculating vehicle wheel lift. Wheel lift for each tractor was defined in the lab by doing a static calibration.

Vehicle Speed: Vehicle speed (i.e., longitudinal velocity) was measured with a non-contact speed sensor mounted above the roof of each vehicle. Sensor outputs were transmitted to the data acquisition system, dashboard display unit, and to the steering machine. The steering machine can use vehicle speed to activate.

Glad Hand Valve Pressure: The glad hand valve pressure was measured downstream from the tractor protection valve. From the data, it could be determined if the tractor was applying the trailer brakes during ESC activation.

Trailer Inertial Sensing System: A multi-axis inertial sensing system was used to measure accelerations and roll, pitch, and yaw angular rates. The system was placed near the vehicle's CG so as to minimize roll, pitch, and yaw effects. Since it was not possible to position the accelerometers precisely at the vehicle's CG for each loading condition, sensor outputs were corrected to translate the motion of the vehicle at the measured location to that which occurred at the actual CG during post-processing of the data. The sensing system did not provide inertial stabilization of its accelerometers. Lateral acceleration was also corrected for trailer roll angle during post processing using ride height data collected sensor mounted on the trailer.

Trailer Rear Axle Height: An infrared distance measurement system was used to collect left and right side axle ride heights for the purpose of calculating trailer wheel lift. Wheel lift for each trailer was defined in the lab by doing a static calibration.

Trailer Outrigger Height: An infrared distance measurement system was used to collect left and right side outrigger ride heights for the purpose of calculating vehicle roll angle. Vehicle roll angle was computed with data output from the two sensors, used in conjunction with roll rate data measured by the multi-axis inertial sensing system.

J1939 Communication Bus: See Table 3.5.

Programmable Steering Machine: A programmable steering machine was used to provide steering inputs for all ESC test maneuvers. Descriptions of the steering machine, including features and technical specifications, have been previously documented and are available in [14][15].

Safety Equipment: Before the conduct of any test, safety equipment was installed on each tractor and trailer. These supporting safety devices may not be necessary to safely conduct these tests, however, given the exploratory nature and potential test severity it was decided to error on the side of caution. For all tests conducted during Phase III research, each tractor and trailer tested had the following safety equipment installed.

Safety Outriggers**:** Low inertia outriggers were developed for this testing. The outrigger system adds approximately 1,500 lbs to the trailer (or tractor) but was designed to minimize roll and yaw inertias. When deployed, the outriggers span 270 inches across from wheel to wheel. For testing tractor semi-trailer combinations the outriggers were mounted to the trailer. For testing a bobtail tractor the outriggers can be mounted to the tractor. Further information and detailed specifications of the outriggers can be obtained in DOT HS 811 289 [Elsasser, D. H. (2010, April). National Highway Traffic Safety Administration's class 8 tractor/trailer safety outrigger. Washington, DC: National Highway Traffic Safety Administration].

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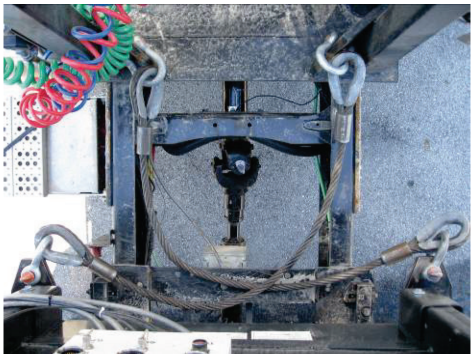
AP Figure 1. Tractor and trailer mounted outriggers.

Anti-Jackknife Safety System: Each tractor semi-trailer combination had an anti-jackknife support system installed. The supports for the tractor were incorporated into the design of the roll bar. For the trailer, supports were fabricated at the bulkhead and welded on to the frame. The tractor supports are shown in the picture on the left and the supports for the trailer are shown in the picture on the right.


AP Figure 2. Anti-jacknife mounts on tractor and trailer.

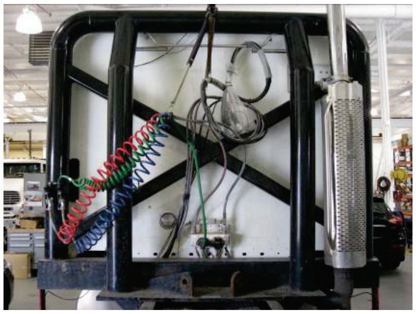
One inch independent wire rope core cables constructed from extra improved plow steel were used to limit the articulation angle and prevent a jackknife. The cables were attached in an "X" configuration to the supports on the tractor and trailer. To accommodate the geometry differences between the various combinations, different cable lengths ranging from 50 to72 inches were used.


AP Figure 3. Anti-jacknife cables connected to mounts.

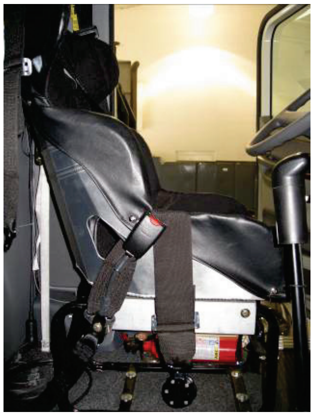
The cable length was selected to allow an articulation angle of up to 45 degrees. Using a dial protractor the angle between the trailer and the tractor frame was measured. At the 45-degree point the distance between the opposite tractor and trailer jackknife support was measured. The final measurement was matched to the closest cable length.


AP Figure 4. Cable length determination.

Tractor Roll Bar: An external roll bar was fabricated and mounted just behind the cab of each test tractor. The purpose of the external roll bar was to protect the driver in the event that the vehicle rolled over. Roll bars were customized based on the vehicle they were installed on, but generally added about 1,500 pounds of weight to the vehicle. The roll bar was constructed from six inch diameter quarter inch thick steel round tubing.


AP Figure 5. Example of a tractor rollbar.

Driver Restraint System: The driver restraint system consists of a racing seat and a 5-point restraint harness. The racing seat allowed the harness to be properly installed in the cab without the risk of compressing the driver in the event of a rollover. Additionally, the racing seat provided stability for the driver when conducting maneuvers that generated high lateral forces.



AP Figure 6. Driver restraint system.

APPENDIX C

C. TRUCK TRACTOR AND TRAILER TEST TRAILER PARAMETERS

The following table documents the general information for each test truck tractor.

AP Table 1. Truck Tractor General Information.

	Model Year	Model	VIN	Date of Manufacture	SC Supplier
Freightliner	2006	Century Class 6x4	1FUJBBCK26LW63660	10/05	Meritor Wabco
Volvo	2006	VNL 64T630 6x4	4V4NC9GH16N441360	10/05	Bendix
Sterling	2008	4x2	2FWBA3CV98AZ79449	10/07	Meritor Wabco

The following table documents the tire specifications for each test truck tractor.

AP Table 2. Truck Tractor Tire Specifications.

	Tire Size	Tire Brand	Tire Model (Front, Rear)	Tire Pressure (psi)
Freightliner	275/80 R24.5	Michelin	XZA3, XDA-HT	110
Volvo	295/75 R22.5	Goodyear	G395 LHS, G182 RSD	110
Sterling	295/75 R22.5	Goodyear	G395 LHS, G395 LHS	110

The following table documents rated axle weights and GVWR for each test truck tractor.

AP Table 3. Truck Tractor GAWRs and GVWRs.

(All weights in pounds)	GAWR Steer Axle	GAWR Intermediate Axle	GAWR Drive Axle	GVWR
Freightliner	12,000	20,000	20,000	52,000
Volvo	12,350	18,739	18,739	49,828
Sterling	12,000	n/a	23,000	35,000

The following table documents the general dimensions of each test truck tractor.

AP Table 4. Truck Tractor Dimensions

(All dimensions in inches)	Total Length	Steer Axle to Front Drive Axle	Front Drive Axle to Rear Drive Axle	Wheelbase	Front Track Width	Drive Track Width (Center of Duals)	Fifth Wheel to Steer Axle
Freightliner	319.0	190.0	51.125	215.5	81.625	73.125	207.0
Volvo	316.0	186.0	51.75	211.875	83.625	72.625	201.5
Sterling	247.0	160.0	n/a	160.0	82.5	72.875	148.0

The following table documents the CG position of each test truck tractor.

AP Table 5. Truck Tractor CG Positions at LLVW and GVWR (inches)

(All dimensions in inches)	Longitudinal CG (from front axle, positive toward rear)	Lateral CG (from centerline, positive to the right)	Vertical CG (from ground plane)
Freightliner	100.03	0.06	35.97
Volvo	95.58	0.18	39.36
Sterling	58.06	-0.25	33.00

AP Table 6. Test Trailer General Information

	Trailer Model	VIN	Date of Manufacture
Fontaine Spread Axle Flatbed	VFT-1-8048WSAWK	13N-14820-9-81547919	8/07
Great Dane 28-Foot Flatbed	GPAR128	1GRDM56124M701484	11/03
Strick Box Van	53-Foot Box Van	1S12E95338E518713	1/07
Heil Tanker	9200-Gallon Fuel Tanker	5HTAB432/9/87H74526	3/08

The following table documents the tire specifications for each test trailer.

AP Table 7. Test Trailer Tire Specifications

	Tire Size	Tire Brand	Tire Model	Tire Pressure (psi)
Fontaine Spread Axle Flatbed	11 R22.5	Hankook	Radial F80	95
Great Dane 28-Foot Flatbed	295/75 R22.5	Bridgestone	R194	100
Strick Box Van	295/75 R22.5	Hankook	Radial F80	105
Heil Tanker	11 R24.5	Michelin	Radial XT-1	105

The following table documents rated axle weights and GVWR for each test trailer.

AP Table 8. Test Trailer GAWRs and GVWRs.

(All dimensions in pounds)	GAWR Front Axle	GAWR Rear Axle	GVWR
Fontaine Spread Axle Flatbed	20,000	20,000	70,543
Great Dane 28-Foot Flatbed	n/a	20,000	39,000
Strick Box Van	17,000	17,000	65,000
Heil Tanker	20,000	20,000	68,000

The following table documents the general dimensions of each test trailer.

AP Table 9. Test Trailer Dimensions.

(All dimensions in inches)	Total Length	Bulkhead to Kingpin	Bulkhead to Landing Gear	Bulkhead to Front Axle	Front Axle to Rear Axle	Deck Height (nominal)	Axle Track (Center of Duals)
Fontaine Spread Axle Flatbed	581.0	33.5	144.0	425.0	123.0	57.0	77.5
Great Dane 28-Foot Flatbed	337.0	34.5	146.0	302.0	n/a	54.0	77.5
Strick Box Van	636.0	36.25	142.5	491.75	49.0	50.0	77.5
Heil Tanker	516.3	34.5	149.0	432.5	49.0	50.0	72.5

The following table documents the CG position of each test trailer.

AP Table 10. Test Trailer CG Positions at LLVW (except as noted)

(All dimensions in inches)	Longitudinal CG (from front bulkhead, positive toward rear)	Lateral CG (from centerline, positive to the right)	Vertical CG at LLVW	Vertical CG at GVWR (Freightliner & Volvo)	Vertical CG at GVWR (Sterling)
Fontaine Spread Axle Flatbed	329.10	-1.06	51.0	87.4	89.5
Great Dane 28-Foot Flatbed	188.53	0.14	49.0	74.7	75.5
Strick Box Van	359.29	1.43	48.0	83.1	83.0
Heil Tanker	316.87	1.40	66.0	77.1	74.1

The following table documents the torsional and roll stiffness of each test trailer.

AP Table 11. Test Trailer Torsional Stiffness and Roll Stiffness (ft-pound per degree)

(All dimensions in ft-pound per degree) (Condition as delivered)	Whole Unit Torsional Stiffness	Torsional Stiffness of Trailer Chassis	Roll Stiffness of Trailer Suspension
Fontaine Spread Axle Flatbed	739	7,979	815
Great Dane 28-Foot Flatbed	1,917	13,034	2,248
Strick Box Van	13,668	15,962	95,080
Heil Tanker	12,031	12,422	381,861

APPENDIX D

D. LOAD CONDITIONS

Two load conditions were used for the work described in this report. The following sections provide descriptions of the load conditions and the rationale behind their selection.

Bobtail: For the SIS maneuver, the bobtail load condition was used. The SIS maneuver was a maneuver used to characterize the truck tractors' sub-limit performance, and it was determined that by testing the tractors without trailers would give the most accurate results. Additionally, because the maneuver was performed with SC enabled and disabled it was determined that additional safety equipment (such as outriggers) were required.

The bobtail load condition was comprised of the test tractor, a driver, instrumentation (including a programmable steering machine), and safety equipment (roll bar, aftermarket seat, and five-point safety harness and outriggers). Each vehicle was at least three-quarters full of fuel. The bobtail load condition was used during SIS testing.

AP Table 12. Bobtail Load Condition Weights.

(All weights in pounds)	Steer Axle Total	Drive Position Total	Total Weight
Freightliner	11,204	10,296	21,500
Volvo	11,178	10,108	21,286
Sterling	9,998	6,704	16,702

Lightly Loaded Vehicle Weight: In addition to the equipment used for the bobtail load condition, the LLVW condition included a test trailer with its associated instrumentation, ballast load frames (except the Heil tanker), and safety equipment (anti-jackknife brackets, anti-jackknife cables, and outriggers). The LLVW load condition was used to find the 60% tractor GAWR load condition.

AP Table 13. LLVW Load Condition Weights.

(All weights in pounds)	Steer Axle Total	Drive Position Total	Trailer Position Total	Total Combination Weight
Freightliner With Fontaine Spread Axle Flatbed	10,800	14,360	9,440	34,600
Freightliner With Great Dane 28-Foot Flatbed	10,960	13,260	6,140	30,360
Freightliner With Strick Box Van	10,890	14,270	10,940	36,100
Freightliner With Heil Tanker	10,820	12,910	7,310	31,040
Volvo With Fontaine Spread Axle Flatbed	10,960	13,860	9,520	34,340
Volvo With Great Dane 28-Foot Flatbed	10,880	12,810	6,140	29,830
Volvo With Strick Box Van	10,930	13,510	10,920	35,360
Volvo With Heil Tanker	10,810	12,310	7,290	30,410
Sterling With Fontaine Spread Axle Flatbed	10,130	10,380	9,890	30,400
Sterling With Great Dane 28-Foot Flatbed	10,010	9,530	6,170	25,710
Sterling With Strick Box Van	10,120	10,560	10,950	31,630
Sterling With Heil Tanker	9,900	9,050	7,470	26,420

60% Tractor GAWR: In addition to the equipment used for the bobtail load condition, the 60% tractor GAWR condition included the test trailer with its associated instrumentation, ballast load frames, and safety equipment (anti-jackknife brackets, anti-jackknife cables). Outriggers were removed from the truck-tractors and a set mounted to the test trailer. Concrete ballast (water was used for ballast with the tanker, the forward compartment was filled volumetrically to: 25.0 percent with the Sterling 4x2: 49.7 percent with the Volvo 6x4: and 57.5 percent with the Freightliner 6x4) blocks were secured to the deck of the trailers with steel chains. Loads were centered (as much as possible) over the test tractor fifth-wheel, and adjusted so that the tractors' drive axles equaled 60 percent of the combined rear GAWRs. For each tractor, the fifth-wheel was adjusted as close as possible to its middle longitudinal position. This was done to be consistent with fifth-wheel position used during Phase II research. We also allowed a +/- 2 percent tolerance on the tractor drive axles final weight. The 60% tractor GAWR condition was used for all maneuvers discussed in phase III.

AP Table 14. 60% Tractor GAWR condition Load Condition Weights.

(All weights in pounds)	Steer Axle Total	Drive Position Total	Trailer Position Total	Total Combination Weight
Freightliner With Fontaine Spread Axle Flatbed	11,410	23,750	8,930	44,090
Freightliner With Great Dane 28-Foot Flatbed	11,440	24,000	6,750	42,190
Freightliner With Strick Box Van	11,400	23,160	11,110	45,670
Freightliner With Heil Tanker	11,290	23,930	8,260	43,480
Volvo With Fontaine Spread Axle Flatbed	10,940	22,300	9,540	42,780
Volvo With Great Dane 28-Foot Flatbed	11,384	21,952	6,628	39,964
Volvo With Strick Box Van	10,980	22,990	12,050	46,020
Volvo With Heil Tanker	11,050	22,340	12,100	45,490
Sterling With Fontaine Spread Axle Flatbed	10,420	13,880	9,230	33,530
Sterling With Great Dane 28-Foot Flatbed	10,348	13,800	5,848	29,996
Sterling With Strick Box Van	10,410	13,790	10,520	34,720
Sterling With Heil Tanker	10,560	13,850	7,760	32,170

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