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Tractor Semi-Trailer Stability Objective Performance Test Research – Roll Stability

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16. Abstract

This report documents the National Highway Traffic Safety Administration's (NHTSA's) objective performance test development for the evaluation of stability control systems to improve the roll propensity of heavy vehicles. This study was conducted in two phases. Phase I focused on assessing how stability control systems affected the roll propensity of a tractor-semitrailer using three vehicle dynamic maneuvers. Maneuvers included constant radius increasing velocity tests, 150 ft. radius J-turns, and double lane change maneuvers. Tests were performed with two Class 8 tractors and a 53ft. dry box van semitrailer in both a lightly and heavily loaded condition. For the heavily loaded condition, ballast was placed to simulate a high and low center of gravity condition. Both tractors and the trailer were equipped with a stability control system. Performance maneuvers were conducted with and without stability control enabled so that the effects of the technology could be observed.

Overall, both tractor and trailer stability control systems improved the roll stability of the base tractor semi-trailer. For a given maneuver, tractor-based stability systems were able to mitigate trailer wheel lift at the same or higher entrance speeds than trailer only based systems. Trailer-based stability systems were able to mitigate trailer wheel lift at the same or higher maneuver entrance speeds than the base tractor semi-trailer vehicle. For all test maneuvers and conditions performed on the test track, enabling stability control was not observed to degrade the stability of the tractor.

Phase 1 demonstrated that a performance test based on the J-turn is appropriate to evaluate roll stability of tractor and trailer systems. Further study and development of this type of maneuver (Phase II) was necessary to determine the details of such a performance test for truck tractors.

Phase II of this study focused on developing a performance test that challenged the capabilities of a tractor-based stability system designed to mitigate rollover situations for a tractor semi-trailer combination. An automated J-turn type test was developed called the Ramp Steer Maneuver (RSM). The RSM is normalized by a slowly increasing steer (SIS) maneuver so that similar handwheel to lateral acceleration gains are experienced by each test vehicle. Using these maneuvers three tractors (four stability conditions) and six trailers were tested, with and without stability control enabled, loaded either lightly or heavily with a high center of gravity. An additional test series was conducted to understand how mass affected stability interventions. The mass estimation test series used the SIS and RSM to observe how stability interventions changed with loading.

Data from the SIS and RSM are discussed in detail broken down by tractor and trailer type in different loading conditions. Data for these tests are discussed in terms of changes in vehicle dynamics that occur from stability control intervention. These include changes in speed, lateral acceleration, average longitudinal acceleration, average yaw rate, average roll angle, and mean engine torque.

Using these data, several measures of performance (MOP) were identified to have merit in evaluation of heavy vehicle stability control systems. MOP for both engine/power unit control and foundation braking were identified. These included tractor and trailer-based MOP that were wheel lift and ratio based. Wheel lift based metrics were shown to be sensitive to trailer type and load. Ratio based metrics were found to less sensitive to these factors.

The RSM test procedure defined in Phase II challenges the roll dynamics of a tractor semi-trailer. Using this procedure improvements in roll stability were observed for each tractor with all six trailer types in all loading conditions when comparing results with and without stability control. Tractor lateral acceleration ratio was observed to be a repeatable and reliable MOP that quantifies the roll stability performance of stability control.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report documents the results from heavy vehicle stability control (SC) system testing conducted by the National Highway Traffic Safety Administration (NHTSA) Vehicle Research and Test Center (VRTC) from 2006-2009. 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).

The research program was conducted in two phases. Phase I focused on understanding how SC systems could improve the roll propensity of a tractor semi-trailer on a test track. Phase I examined several dynamic maneuvers to evaluate their potential for use as an objective test. Phase II focused on refining the objective tests that were developed during Phase I. During Phase II potential performance criteria were developed that can be used to for assessing the roll stability of tractor semi-trailer combinations.

PHASE I

During Phase I, testing was conducted to meet the following objectives:

1. Understand how trailer-based SC system modifies handling characteristics of a tractor semi-trailer as compared to the base vehicle without SC.
2. Understand how tractor-based SC systems modify the handling characteristics of a tractor semi-trailer as compared to the base vehicle without SC.
3. Understand how semi-trailer loading can influence SC performance.

Two 6x4 tractors (Freightliner and Volvo) and a 53-foot dry box van trailer (Fruehauf) were tested. Both the Freightliner and Volvo were equipped with full electronic stability control (ESC) and the trailer was equipped with roll stability control (RSC). Track testing was conducted to understand how SC changed the combination vehicle's performance compared to the base combination without the technology. All tests were performed on a dry high friction surface. Tests were conducted with and without stability control enabled for each combination. Testing consisted of four SC conditions: (1) No tractor or trailer SC, (2) Tractor SC and no trailer SC, (3) No tractor SC and trailer SC, and (4) Tractor SC and trailer SC.

A variety of dynamic maneuvers were used to test each of the four SC conditions. Test maneuvers included constant radius increasing velocity tests, J-turn tests, and double lane change (DLC) maneuvers. Speed was incremented during testing to increase the maneuver severity. Dynamic maneuvers were conducted using three loading conditions. Loading conditions included a lightly loaded vehicle weight (LLVW), loaded with a low center of gravity (Low CG) load and loaded with a high center of gravity (High CG) load.

For both tractor-based stability systems, changes in the tractor lateral acceleration when the stability systems activated were observed between the LLVW, Low CG, and High CG loads. Maximum lateral accelerations were very similar between the Low and High CG conditions. The trailer-based system exhibited similar changes in tractor lateral acceleration when the stability system intervened but with less range. This suggests that the heavy vehicle stability systems tested were capable of sensing or estimating load but are not estimating the CG height of the load.

For the constant radius circle, increasing velocity tests, both tractor and trailer systems were capable of mitigating trailer wheel lift and limiting maximum tractor lateral acceleration. This maneuver increased lateral acceleration at a moderate rate proportionately with the square of velocity. The maneuver did not produce large peaks (dynamic overshoot) in lateral acceleration. The maneuver demonstrated differences between tests with and without stability control enabled, but was not very effective in demonstrating the differences between a tractor and trailer-based system.

For the J-turn tests, tractor-based systems were able to mitigate trailer wheel lift in all of the test series conducted. The trailer-based RSC system provided some improvement in stability but was overdriven before 50 mph was reached. For the J-turn, lateral acceleration increased at a faster rate than for the constant radius maneuver. At higher speeds, the maneuver generated high levels of lateral acceleration making this a challenging maneuver. The maneuver was able to distinguish between tests with and without stability systems enabled, and demonstrated performance differences between tractor and trailer-based systems.

During DLC testing, tractor-based systems were able to mitigate trailer wheel lift in most of the test series. Regardless, the system performance was better than the base vehicle’s. The trailer-based system provided some improvement in stability but went unstable at lower speeds than the tractor-based systems. Again, its performance was still better than the base vehicle’s performance.

The DLC maneuver was able to demonstrate differences between tests with and without a stability system enabled and between tractor and trailer-based systems; however, these results were not as clear when compared to the other maneuvers. The DLC is a very dynamic maneuver and can generate rapid rates of lateral acceleration, however, the results varied by driver. Since the goal of the maneuver is to navigate the lane change gates, drivers can steer the tractor semi-trailer unit in a variety of ways to success complete the maneuver.

Based on the results of this study, a performance test based on the J-turn appeared to be a suitable maneuver to evaluate tractor and trailer stability control systems. Further study of this type of maneuver was subsequently conducted in Phase II to understand how stability control technology and other factors influence the dynamic response of heavy vehicles. Since Phase I test results indicated that tractor-based SC systems were much more effective than trailer-based SC systems, Phase II research focused on the tractor-based systems.

Phase I data was analyzed to determine the optimum steering angle, steering rate, and test maneuver. Amalgamating all of this data, the Ramp Steer Maneuver (RSM) was developed. The RSM is just like a J-turn except the maneuver is performed with a programmable steering controller instead of a driver following a set radius. Since the maneuver is controlled by a robot, effects of the test driver are minimized. This maneuver was used for Phase II testing.

PHASE II

Phase II was initiated to further understand how tractor-based stability control technology and other factors influence the dynamic response of heavy vehicles. This phase focused on developing an optimized performance test that challenged the capabilities of a tractor-based stability system to mitigate rollover situations for a tractor semi-trailer combination. The objectives of Phase II were:

1. Develop an objective test that can produce repeatable test results.
2. Develop an objective test that can discriminate between a tractor with and without SC technology.
3. Develop an objective test that is valid in terms of a “real-world” maneuver that drivers of truck semi-trailers may perform.
4. Develop a metric that ensures the SC system’s ability to mitigate rollovers.

Using the proposed ramp steer maneuver (RSM) objective test procedure developed in Phase I, three tractors (four SC systems) with six semi-trailers were tested. The power units consisted of the same two 6X4 tractors (Freightliner and Volvo) from Phase I, plus a short wheel base 4x2 tractor (Sterling). Both the Freightliner and Volvo were equipped with ESC (roll and yaw stability) and the Sterling was equipped with RSC (roll stability control only). Additionally, an original equipment (OE) RSC electronic control unit was purchased for the Freightliner effectively allowing us to test four tractor-based stability control systems.

A total of six semi-trailers were tested with each of the tractors. The trailer fleet consisted of two 53-foot dry box van trailers (Fruehauf and Strick), two 48-foot flatbed trailers (Fruehauf and Fontaine), a 9200 gallon Heil fuel tanker trailer, and a 28-foot Great Dane flatbed trailer.

The slowly increasing steer (SIS) maneuver was conducted in a bobtail configuration for each tractor. The SIS maneuver was based on the characterization maneuver as described in FMVSS 126. The maneuver is used to characterize each vehicles steering wheel angle to lateral acceleration relationship. Using the steering wheel angle (SWA) calculated from this test, a steering controller was programmed to conduct the ramp steer maneuvers (RSMs). All combinations of the tractors and semi-trailers were tested using the RSM. Tests were conducted with and without SC enabled, with and without trailer brakes, and in the LLVW and High CG load conditions.

SIS Tests

The tractor-based SC systems all responded similarly in the bobtail SIS test maneuver regardless of vehicle or type of SC system installed. As the steering input was increased in a slow linear manner at a 30-mph constant speed, the SC system eventually activated and reduced engine torque output. This in turn reduced the vehicle speed so that lateral acceleration was limited even as the radius of the vehicle was observed to continue to decrease. None of the SIS tests with the SC enabled resulted in understeer, oversteer or roll instability. Four seconds after activation, the input speed was observed to be reduced from the target maneuver entrance speed (MES) of 30 mph by 12.4-27.2 percent. On average, lateral acceleration increased by no more than 6.2 percent and yaw rate no more than 20.0 percent. In comparison, during the SC disabled tests, lateral acceleration was observed to increase by a minimum of 9.9% and yaw rate 12.3%, and the tractors went into an understeer condition. These vehicle dynamics changes were a direct result of SC activation and were correlated in time to the SC systems' command to reduce engine output even though the driver was demanding more engine power to attempt to maintain 30 mph. At a minimum, the engine output torque was observed to be decreased by 38%, versus a minimum 19 percent increase in engine output torque when the SC systems were disabled.

SIS test results were used to determine the steering wheel angle that would generate 0.5 g of lateral acceleration for each vehicle traveling at 30 mph. The angles were calculated on a per vehicle basis. The linear range of lateral acceleration (0.05-0.3 g) was used to extrapolate the steering wheel angle at 0.5 g. The average steering wheel angle at 0.5 g for the Volvo 6x4 was 199 degrees. For the Freightliner 6x4 it was 193 degrees, and for the Sterling 4x2 it was 162 degrees. These steering wheel angles were used as the amplitudes for the RSM.

Results from the SIS test series confirmed the ability of the maneuver to characterize the linear dynamics of Class 8 tractors. The test results confirmed the maneuver's ability to normalize the steering inputs for the RSM. The test results confirmed the linearity of the range of data selected for extrapolation. From the range of speeds observed from SIS testing a target entrance speed of 30 mph with a ±1.0 mph tolerance can be used for future SIS tests conducted to normalize the RSM steering magnitude.

RSM High CG Tests

The RSM results from testing with the High CG load conditions show that all 24 combinations and SC conditions (enabled, enabled without trailer brakes, and disabled) had instances of observed wheel lift. Overall, with SC (ESC and RSC equipped vehicles) enabled without trailer brakes, the net increase in MES at which wheel lift was observed increased by 0-10 mph over the disabled test condition. With SC enabled, the net increase in MES at which wheel lift was observed to increase by 0-12 mph over the disabled test condition.

Differences were observed when comparing ESC and RSC equipped tractors. The net increase in MES at which wheel lift was observed increased by 2-10 mph (over disabled test conditions) for the ESC enabled without trailer brakes test condition. This range improved to 4-12 mph for ESC enabled test series. RSC enabled without trailer brakes series were observe to be increased by 0-6 mph and RSC enabled were increased by 0-8 mph.

The improvements in wheel lift speeds for each tractor, compared to the SC disabled test condition were as follows. The Freightliner 6x4 with ESC, without trailer brakes, resulted in a 2-8 mph increase, and with ESC enabled it ranged from 5-12 mph. The Freightliner 6x4 with RSC, without trailer brakes, resulted in a 4-6 mph increase, and with RSC enabled it ranged from 5-8 mph. The Volvo 6x4 with ESC, without trailer brakes, resulted in a 3-8 mph increase, and with ESC enabled it ranged from 5-11 mph. The Sterling 4x2 with RSC, without trailer brakes, resulted in a 0-3 mph increase, and with RSC enabled it ranged from 0-4 mph.

RSM LLVW Tests

Testing with this load condition was performed at only one SC test condition, SC enabled without trailer brakes. The RSM test results from the LLVW load condition show that only one of the 24 combinations tested resulted in two inches or more of wheel lift. The Volvo 6x4 (ESC) combined with the tanker was observed to produce just over two inches of wheel lift in the RSM when tested with an MES of 47.4 mph.

Nine of the 24 combinations were terminated after the tractors went into an oversteer condition and engaged the safety cables that limited the articulation angles between the tractor and trailer combinations. These nine combinations were observed to engage the safety cables at MESs that ranged from 34.3-41.5 mph. All nine combinations were with RSC equipped vehicles (see Table 5.21). The researchers believe that the additional benefit of allowing the trailer brakes to be utilized by the SC system would increase the yaw and roll stability of the tractor/trailer system. The additional braking provided by the trailer would act like an anchor and would slow the combination down which in turn would reduce the articulation angle and would extend the MES at which instabilities were observed upward.

Results for each tractor show that the Freightliner 6x4 with ESC completed each RSM test series with the six different trailers to an MES of 50 mph without an observed instance of instability. The Freightliner 6x4 with RSC was observed to experience tractor oversteer and engage the safety cables in four of the six combinations at MESs that ranged 35.4-39.4 mph. The remaining two combinations completed the RSM test series to an MES of 50 mph without an observed instance of instability. Five of the six combinations tested with the Volvo 6x4 ESC completed the RSM test series to an MES of 50 mph without an observed instance of instability. Approximately two inches of wheel lift were observed in the RSM at a MES of 47.4 mph with the remaining combination. The Sterling 4x2 RSC was observed to experience oversteer and engage the safety cables in five of the six combinations at MESs that ranged from 34.3-41.5 mph. The remaining combination completed the RSM test series to an MES of 50 mph without an observed instance of instability.

Comparing trailers, the RSM test results from combinations with box vans and long flatbeds were different depending on whether the tractor was equipped with RSC or ESC. All LLVW RSM series conducted with ESC tractors achieved an MES of 50 mph without an observed instance of roll or yaw instability, while all LLVW RSM series conducted with RSC tractors experienced an oversteering yaw instability condition. All tractor combinations with the short 28-foot Great Dane flatbed trailer completed the RSM test series to 50 mph without an observed instance of instability. Two Tanker combinations were observed to complete the RSM test series to 50 mph without an observed instance of instability. The other two resulted in one instance of roll instability at 47.4 mph and the other had yaw instability at 40.4 mph.

Mass Estimation

Test series (SIS and RSM) were performed to observe SC responses to changes in vehicle mass. From the test results it was concluded that all SC systems adjust activation thresholds based on a mass estimation process. Lateral acceleration thresholds were the highest in the unloaded condition for each platform tested. As the load was increased, each system reached a mass where the lateral acceleration intervention level stabilized (approximately 42k to 52k lbs).

Given that higher mass often equates to a higher CG, lowering the activation threshold as the mass increases was deemed appropriate. All systems tested by different manufactures and different types (RSC or ESC) were observed to operate in a similar manner under the given load conditions.

Measures of Performance

The development of a set of lateral performance measures would not only ensure that a Class 8 tractor is equipped with a stability control (SC) system but would also be correlated to some minimum desired effectiveness. Observations of test results from Phase I and II have shown that SC is able to improve the stability of the vehicles in which it is installed by exerting control over the power unit (engine) and\or foundation brakes installed on the tractor and trailer. Measures of performance (MOP) were developed for both.

Engine/Power Unit Control MOP

Engine torque reductions by SC systems were observed to mitigate roll instability in both the constant radius increasing velocity tests and the SIS maneuvers. Since the

SIS maneuver is automated and highly controlled, several measures from this data were chosen to be investigated. They were as follows:

- tractor speed
- tractor lateral acceleration
- tractor longitudinal acceleration
- engine torque/driver requested engine torque

From data collected off the J1939 CAN bus, the “driver requested torque” and “engine torque” output measures were concluded to be potential MOP candidates that warranted further analysis. Tractor forward speed also exhibited potential to be used in conjunction with a primary measure. Review of the torque differences between “driver requested torque” and actual engine torque output were confirmed for SIS tests with SC enabled. This observation led researchers to conclude that the SIS maneuver and torque measures were good MOP candidates to determine if an SC system exhibited engine/power unit control. While this data shows that the respective changes in the torque signals were quite large, it was concluded that a small (5-20 percent) change would be sufficient to establish that engine torque reduction occurred. It is also conceivable that vehicles with low power to weight ratios may not need as much reduction in torque output to limit the dynamic responses of the truck tractor.

Foundation Braking MOP

SC was observed to improve the combination’s roll stability by applying foundation brakes on the vehicle. Measures were assessed according to how well they discriminated between SC and non-SC equipped vehicles and their correlation to the speed at which tractor or trailer wheel lift occurred. After an initial review of the data researchers found six dynamic measurements that merited further analysis and development. Those measures were the following:

- tractor wheel height
- trailer wheel height
- tractor lateral acceleration
- trailer lateral acceleration
- tractor roll angle
- trailer roll angle

Prior to assessing roll stability MOP, a logistical regression model was developed to identify the RSM test data with which to analyze the lateral acceleration and roll angle measures. For this analysis a roll stability threshold definition was needed to make an assessment of stability. The threshold used was 2.00 inches of wheel lift. If a test resulted in the production of 2.00 or more inches of wheel lift at any of the wheel ends, the series was terminated and the resulting MES reported. From this data a model was developed that produced the probability of wheel lift at different MES for the tested SC conditions. For the given load and maneuver, for MES between 29 – 32 mph the probability of wheel lift occurring without stability control was between 0.79 – 0.99. Probability dropped to 0.11 – 0.33 with the “SC enabled unbraked trailer” test condition and dropped further to 0.04 – 0.19 with the enabled test condition. From this analysis, it was concluded that an RSM performed at ~30 mph (tolerance ±1 mph) would be appropriate to assess performance. At this MES the probability of generating two or more inches of wheel lift was 0.91 without SC, with SC the probability dropped to 0.07. Increasing the MES to assess performance would make the test more challenging for the SC system, however, it would only marginally increase the probability of wheel lift without the technology.

Wheel Lift Metric

Wheel lift was considered as a MOP since it has good face validity; it precedes a rollover event, is well understood by researchers and the public, is easily observable on the test track, and has been previously documented and applied in NHTSA NCAP Tests [11]. However, wheel lift results from the High CG RSM tests indicate that the MOP is dependent on the design of the trailer. More specifically, the results changed as a function of geometric, suspension, and torsional rigidity differences that exist between the trailers. Should wheel height be used as a MOP, tight specifications would also be required for the test trailer, location of the load, and corrections to the measured data. In addition, a characterization test could be conducted to determine the precise MES that produces wheel lift for a particular tractor-trailer combination with the SC system disabled.

Ratio Metrics

The ratio metrics, lateral acceleration ratio (LAR), trailer lateral acceleration ratio (Trailer LAR), and trailer roll angle ratio (Trailer RAR), were found to be less dependent on the test trailers and location of the load. The measures were found to correlate well with wheel lift and are considered easily measurable. From the analysis of variance for the three ratios, it was concluded that each has a range of potential time increments from which performance could be assessed. Designating time zero as the end of ramp input (ERI) during the RSM test, for LAR that range was 2.0 – 5.0 seconds, for Trailer LAR it was 2.5 – 5.0 seconds, and for Trailer RAR it was 2.5 seconds. Combining the statistical result with wheel lift results for instability, the time increments between 2.0 and 3.0 seconds after ERI were concluded to be the most suitable candidates for possible performance criteria. Though the ratios were found to be less dependent on the trailer type, trailer and load influences were still present in the Trailer LAR and RAR measures given that standard deviations were larger than Tractor LAR. Therefore, it was concluded that Tractor LAR has the most potential to be developed into a MOP.

The authors recommend that additional data be collected and statistically analyzed to determine/refine the LAR limits and times to assess performance from those presented in this research. Additionally, assessing performance through a reduction in LAR at a given time would indicate that the lateral forces were reduced on the lead unit. Testing of certain load conditions and vehicle combinations have shown that some instances of roll instability (wheel lift) still occurs at the trailer even though substantial reductions to

LAR were present. Therefore, the performance metric developed from lead unit lateral acceleration will indicate it has ESC with some given level of intervention but does not necessarily indicate that the trailer remained roll stable throughout the RSM test.

Regarding Directional (Yaw) Stability: The research presented in this report was performed in support of efforts to develop roll stability tests and potential MOPs. However, several instances of loss of directional control were observed under light load conditions with several types of trailers during RSM testing. The authors recommend that additional research be performed with the truck-tractors and trailers under light and low CG loading conditions in conjunction with maneuvers and test surfaces focused at assessing yaw stability.

1.0 INTRODUCTION

1.1 Background

Electronic stability control (ESC) systems have been available on light vehicles for the past decade. Over this time, NHTSA and others have estimated that this technology has the potential to prevent over 8,000 fatal crashes[1] per year [3]. Recognizing the safety potential of this technology, NHTSA has mandated that all vehicles with a GVWR of 10,000 lbs. or less be equipped with ESC by model year 2012 [4].

More recently, heavy vehicle manufacturers and suppliers have begun offering stability control systems in the North American market on late model truck tractors and trailers. Some manufacturers have made these systems standard equipment. Unlike passenger cars, heavy vehicle stability systems are available in different configurations with different levels of performance. Depending on the application, it can be installed as a tractor-based system or a trailer-based system. Tractor-based systems are available that can mitigate roll only (Roll Stability Control, RSC) or are available that can mitigate roll and yaw instability (ESC). In addition, trailer-based systems are available that can mitigate rollover only.

Since 2006, NHTSA has been conducting heavy truck stability control research on a test track to understand the performance benefits of this technology. This research has been conducted in three phases. The first phase focused on understanding how stability control (SC) systems worked on heavy vehicles. During this phase, both tractor and trailer-based SC systems were tested. For this study two truck tractor stability systems and a trailer-based stability system were tested to understand how stability control modified the base vehicle's performance. A variety of test maneuvers were used to conduct this testing.

Building from the results of Phase I, a second phase was conducted. The second phase focused on developing dynamic tests and measures that could be used to assess SC systems ability to mitigate rollover situations. The third phase of research, which is not included in this report, focused on developing dynamic tests and measures that could be used to assess SC systems ability to mitigate lateral stability situations relating to both rollover and loss of directional control.

1.2 Crash Problem

Tractor trailer combination vehicles are involved in about 74 percent of the fatal crashes involving large trucks, annually. According to the Large Truck Crash Facts 2006, there

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[1] The NHTSA Final Regulatory Impact Analysis for FMVSS 126 states that the Benefits of the rule are measured from a baseline of 71% ESC installation to 100% installation. However, the overall benefits of ESC could be measured from "no ESC" to 100% penetration rate. Overall, ESC would save a total of 5,319 – 9,611 lives and eliminate 155,895 – 238,083 MAIS 1-5 injuries annually. Of these benefits, 4,244– 5,522 lives and 114,522 – 129,390 MAIS 1-5 injuries would be associated with single vehicle rollovers.

were 4,321 fatal crashes involving large trucks during 2006. A total of 220 fatal crashes attributed rollover as the first harmful event [1]. Combination unit trucks had a fatal crash involvement rate of 2.2 crashes per 100 million vehicle miles (VMT) traveled, whereas single unit trucks had a fatal crash involvement rate of 1.5 crashes per 100 million VMT. Combination vehicles represent about 25 percent of large trucks registered but travel 64 percent of the large truck miles, annually. Primarily because of the high crash exposure rate for tractor trailer combination vehicles, the agency is focusing its efforts to evaluate stability control systems for these vehicles.

1.3 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 roll. Described below are several real-world situations where roll or electronic stability control systems may prevent or lessen the severity of crashes [12]:

- **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 maneuver exceeds the vehicle's roll stability threshold, a rollover is initiated. A driver typically cannot recover from the rollover once it begins.

- **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. 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 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 the roll 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 loss of control 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. A similar maneuver performed on a wet or slippery road surface may result in vehicle yaw.

- **Road design configuration** – some drivers may misjudge the curvature of ramps and not brake sufficiently to safely `negotiate the curve. 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) may result in rollover.

- **Braking maneuvers** – most common heavy vehicle yaw (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 (ABS) on truck tractors, effective since 1997, has largely addressed the loss-of-control crashes due to wheel lockup. As a result, ESC systems are expected to reduce crashes other than braking-related jackknife crashes.

- **Vehicle factors** – Severely worn tires (e.g., tread depth below 2/32 inch) are more likely to contribute to vehicle yaw or under-steering 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.

1.4 Study Objectives

For this research, NHTSA performed objective testing of commercially available SC systems. Phase I testing included both tractor and trailer-based technologies. The goal of this testing was to evaluate the performance of SC systems.

During Phase I, testing was conducted to meet the following objectives:

1. Understand how trailer-based SC systems modify handling characteristics of a tractor semi-trailer as compared to the base vehicle without SC.
2. Understand how tractor-based SC systems modify handling characteristics of a tractor semi-trailer as compared to the base vehicle without SC.
3. Understand how semi-trailer loading can influence SC performance.

The second phase focused on developing an optimized performance test that challenged the capabilities of a tractor-based stability system to mitigate rollover situations for a tractor semi-trailer combination. The objectives of phase II were:

1. Develop an objective test that can produce repeatable test results.
2. Develop an objective test that can discriminate between a tractor with and without SC technology.
3. Develop an objective test that is valid in terms of a “real-world” maneuver that drivers of truck semi-trailers may perform.
4. Develop a metric that ensures the SC system’s ability to mitigate rollovers.

2.0 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 are not expected to improve the stability margin by as much as the tractor-based systems. Stability margin is defined as the ratio between the vehicles 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 trailer axles. Tractor-based RSC systems are expected to improve the stability margin by more than trailer-based systems. This is for three reasons. First, they are able to apply both the brakes on the tractor and the trailer, and therefore apply more braking torque than trailer-based systems. Second, temporally 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 stability system is sensing tractor lateral acceleration. Third, 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 platform’s stability margin when compared to a combination vehicle with just trailer-based RSC.

Tractor-based ESC has the same functionality as tractor-based RSC, with additional performance capabilities. Tractor-based ESC adds the capability to brake the steer axle wheels, sense the steering wheel position, and measure the tractor’s angular yaw rate. With the addition of these capabilities, the ESC system can not only assist drivers in mitigating roll events but also 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 Retarder	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		

3.0 METHOD

3.1 Test Vehicles

A total of three test truck tractors (one test truck tractor used two stability control systems) and six test trailers were used for the work described in this report. All testing involved the use of instrumentation and safety equipment on each test truck tractor and test trailer. The following sections provide descriptions of test truck tractors, test trailers, instrumentation, and test safety equipment. For complete detailed information on each truck tractor and trailer, please refer to Appendix B.

3.1.1 Truck Tractors

Three test 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 as standard equipment. In the case of the Freightliner, it had the capability to be tested with either an RSC or ESC system, depending on which stability control 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 (ESC)
2006	Freightliner	Century Class	6x4	Meritor Wabco ESC Meritor Wabco RSC
2008	Sterling		4x2	Meritor Wabco RSC

3.1.2 Trailers

Six test trailers were chosen for research described in this report: a Fruehauf Box Van, a Fontaine Spread Axle Flatbed, a Fruehauf Flatbed, a Great Dane 28-Foot Flatbed, a Strick Box Van, and a Heil Tanker. The Great Dane 28-foot flatbed is also used at VRTC as a control trailer for conducting tractor braking tests as specified in FMVSS No. 121, Air Brake Systems. 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
2000	Freuhauf	Dry Box Van	53	Meritor Wabco RSS (RSC)
2007	Strick	Dry Box Van	53	None
1998	Freuhauf	Flatbed (tandem bogey)	48	None
2007	Fontaine	Flatbed (spread Axle)	48	None
2007	Heil	9200 Gallon Tanker	42	Meritor Wabco RSS (RSC)
2003	Great Dane	Flatbed (121 Style Trailer)	28	None

3.1.3 Instrumentation

All test vehicles were instrumented with sensors and data acquisition systems. In addition, a programmable steering controller was used during many of the tractor test maneuvers. This section briefly describes the test equipment and instrumentation used. For detailed information, please refer to Appendix C.

Truck Tractor: Table 3.3 describes the sensors used by NHTSA to measure tractor 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	Switch (normally open)	On/Off	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, Inc. 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

Test Trailer: Table 3.4 describes the sensors used by NHTSA to measure trailer 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 3.4. 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
Outrigger Height (to determine roll)	Non-contact infrared beam	12-51 inches	Wenglor	HT77MGV80

CAN Data: CAN data from the SAE J1939 [14] and/or SAE J1708 [15] bus was 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	SPN	Data length	Resolution	Data Range	Type
Accelerator pedal Position 1	SPN 91	1 byte	0.4%/bit, 0 offset	0 to 100 %	Measured
VDC 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

Steering Controller: A programmable steering controller produced by Automotive Testing, Inc. (ATI) was used to provide steering inputs for all Phase II test maneuvers. Descriptions of the steering machine, including features and technical specifications, have been previously documented and are available in [5],[6].

3.2 Load Conditions

A total of four load conditions were used for the work described in this report:

- Bobtail – Tractor without a trailer
- Lightly Loaded Vehicle Weight (LLVW) - Tractor connected to a trailer with a ballast load frame installed, but otherwise unloaded (except the tanker used no load frame).
- High CG – Tractor connected to a trailer and loaded to typical highway weight, with the ballast load blocks spaced 24 inches above the trailer deck. Also, the standard tanker trailer loading condition.
- Low CG – Tractor connected to a trailer and loaded to typical highway weight, with the ballast load blocks placed directly on the trailer deck.

For detailed information about loading conditions and the rationale behind their selection, please 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. The VDA is an 1800 by 1200 foot flat paved surface with a one 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.

The tests discussed in this study were performed between January 2006 and August 2009. All tests were performed while the VDA high-friction test surface was dry. Figure 3.1 summarizes the VDA's dry peak and slide coefficients of friction for the dates relevant to the 2006-09 test seasons. The VDA's peak and sliding coefficients of friction were generally monitored twice per month, weather-permitting, using American Society for Testing and Materials (ASTM) procedures. The peak coefficient was determined with ASTM procedure E1337 and an E1136 tire [[7],[8]]. Sliding coefficients were determined with ASTM procedure E274 and an E501 tire [[9],[10]].

The ambient temperatures and wind speeds were recorded at the beginning of each test session. The ambient air temperature ranged between 30 to 95 degrees Fahrenheit. The wind speeds ranged from 0 to 30 mph.

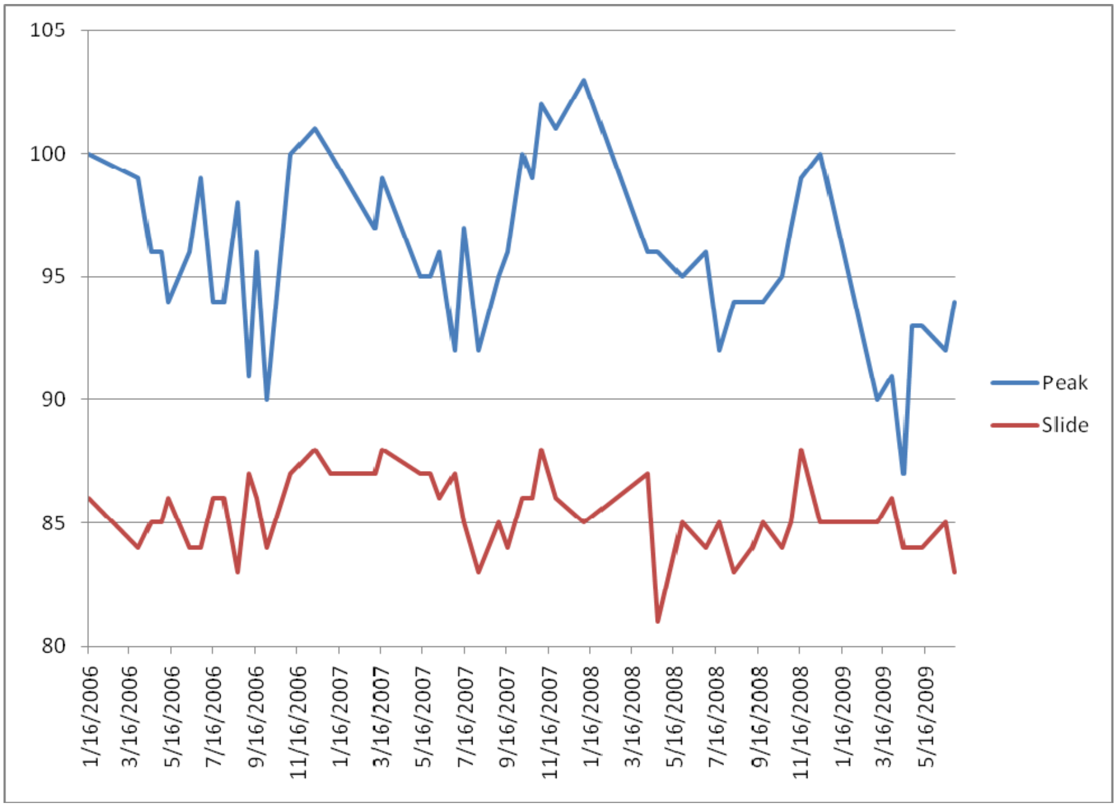

Figure 3.1. TRC VDA peak and slide coefficients of friction for the testing period.

3.4 Test Maneuvers

3.4.1 Constant Radius Circle with Increasing Velocity

Constant radius circles with increasing velocity tests were conducted on the 150-foot and 200-foot radius circles located on the center of the VDA. For both of these maneuvers, the test driver followed the radius with either the passenger side steer tire (clockwise) or the driver side steer tire (counter-clockwise) while slowly increasing the vehicle's speed. As speed increased, the driver steered the vehicle to maintain the radius as the vehicle tended to understeer. The test was complete when the driver was no longer able to follow the radius (vehicle plows out), no longer increase velocity (drive axles lose traction), and/or the trailer wheels lifted more than 2 inches off the ground (outriggers making contact with the test surface).

3.4.2 J- Turn with Constant Radius

J-turn tests with a constant radius were conducted using a 150-foot and 200-foot radius located on the center of the VDA. For purposes of this paper, only the 150-foot data will be discussed.

To conduct this maneuver, the driver entered a start gate delineated by pylons and then followed the radius with either the passenger side steer tire (clockwise) or the driver side steer tire (counter-clockwise) at a given test entrance speed. When the driver entered the start gate (cones at the point tangent to the radius), they were instructed to drop-throttle, and complete the maneuver following the radius as best they were able. Test entrance speeds started at 20 mph and were incremented by 2 mph to increase severity until the test termination condition was met. The test termination condition was satisfied when either the outriggers made contact with the ground, the combination vehicle was noticeably under-steering, stability control brake activation was observed, or when the test entrance speed of 50 mph was achieved. 50 mph was chosen for a maximum test entrance speed based on available test area and design of the safety support equipment (outriggers, roll bar, etc.)

3.4.3 Double Lane Change Maneuver

Double lane change tests were performed on the VDA. Gates were set up as detailed in Figure 1. The test driver was instructed to enter the starting gate a given test entrance speed, drop throttle, and then to steer the combination vehicle through the gates, as best they were able without hitting any of the pylons delineating the course. Test entrance speeds started at 20 mph and were incremented by 2 mph to increase severity until the test termination condition was met. The test termination condition was satisfied when either the outriggers made contact with the ground, the combination vehicle was grossly under or over-steering, stability control brake activation was observed, or when the test entrance speed of 50 mph was achieved.

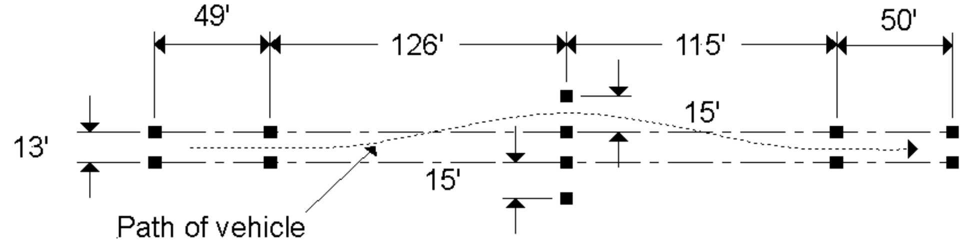

Figure 3.2. Double lane change maneuver.

3.4.4 Slowly Increasing Steer Maneuver (SIS)

The SIS test maneuver was derived from Society of Automotive Engineers (SAE) Surface Vehicle Recommended Practice J266, Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks. It is also described as the Constant Speed Tests – Variable Radius or Variable Steer Angle maneuver [13]. 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[2] used by the Agency to evaluate dynamic stability. Like light passenger vehicles, various truck-tractor configurations have different lateral acceleration to

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[2] Similar steering wheel input normalization methodology was developed for the NCAP Fishhook Test [3], [11] and for the 0.5 Hz Sine with Dwell Maneuver documented in [2].

steering wheel gains that can be characterized using the SIS maneuver. From the SIS test results, extrapolation was used to determine the magnitude of steering input for the RSM. The SIS test series documented in this report were conducted as follows.

The SIS tests were conducted at a constant speed of 30 mph. Using the steering controller, the hand wheel angle was increased at 13.5 degrees/second until a magnitude of 270[3] degrees was reached. Using the maneuver, a total of 6 tests were performed per test series. First, three were conducted with a left steering input, followed by three with a right steering input. Tests were concluded when the maximum hand wheel angle was achieved, or the vehicle experienced wheel lift. Figure 3.3 shows an example of the steering wheel profile used to perform the SIS maneuver.

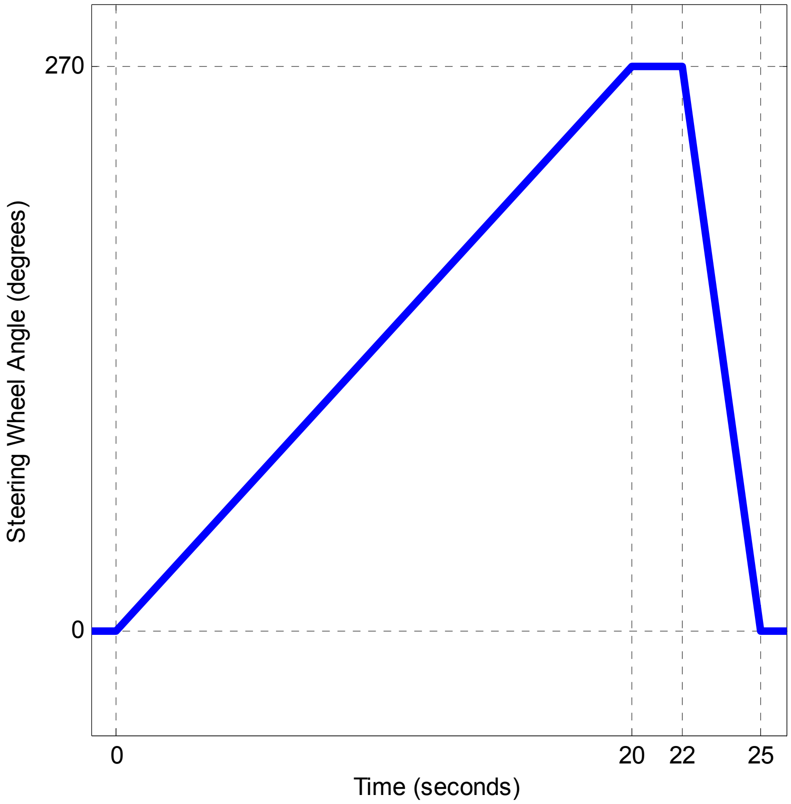

Figure 3.3. Example of the steering wheel profile used for SIS tests.

3.4.5 Ramp Steer Maneuver (RSM)

The Ramp Steer Maneuver is similar to a path-following J-Turn maneuver. The RSM is based on a steering wheel input at a constant rate until a steering magnitude is achieved. To achieve precise steering wheel amplitudes and rates, automated steering controllers were employed. The RSM can be manipulated by either changing the rate

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[3] To make comparisons between SC enabled and disabled SIS tests, larger steering amplitudes of up to 400 degrees were used for some test series to evaluate vehicle handling and SC characteristics at higher steering wheel angles.

or the magnitude of the steering controlled maneuver. The RSMs documented in this report utilized fixed steering wheel amplitude (from SIS data) and a fixed rate (175 deg/sec). Test severity was controlled by incrementally increasing maneuver entrance speed (MES) from 20 mph by 2 mph increments. The definition of the RSM is shown graphically in Figure 3.4 which shows the steering wheel profile and specific timing marks of interest. Zero marks the initiation of the maneuver. The steering magnitude (handwheel angle, delta) is equal to δ^{Test} and "t" is equal to δ^{Test}/175 deg/sec. Table 3.6 provides a summary of the RSM maneuver as it was performed for the research documented in this report. It summarizes the speed and steering inputs and provides the test series termination criteria. Flow charts for testing procedures that were used to perform the RSM are provided in Appendix F. Some background development work with regards δ^{Test} and the steering rate utilized with the RSM is detailed in the following paragraphs.

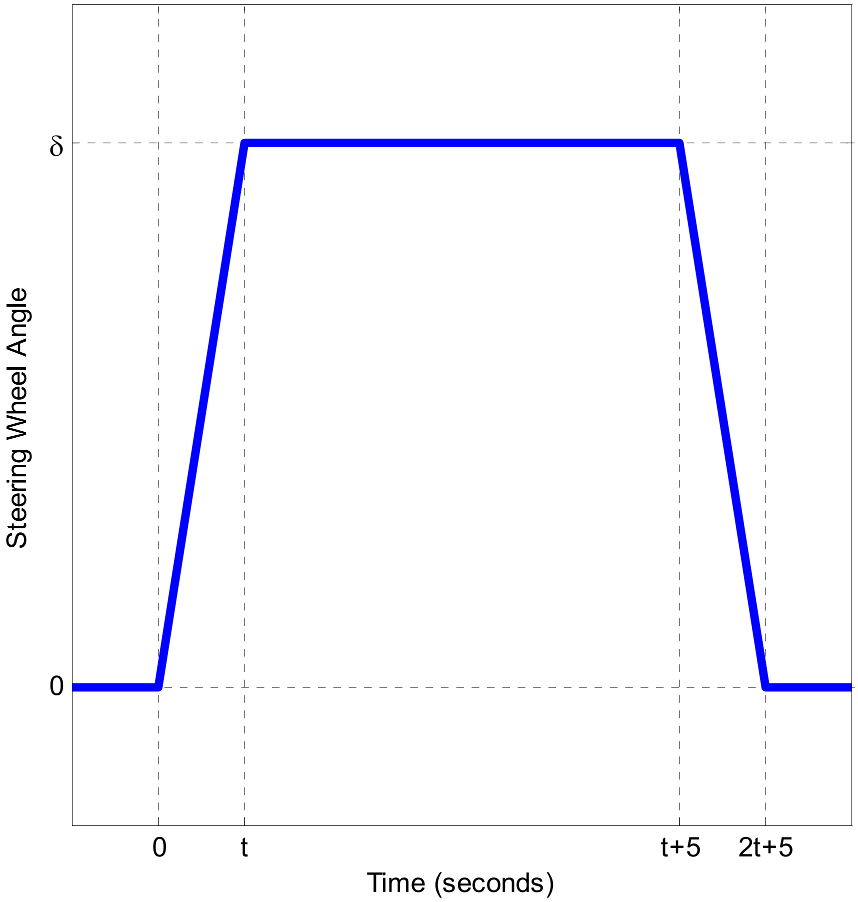

Figure 3.4. Steering wheel profile used for RSM tests.

From previous truck tractor stability control research, δ^{Test} and a steering rate of 175 deg/sec were determined to be near the middle of the range of steering wheel inputs used for driver controlled 150-foot J-Turn tests. The overall range for those tests was found to vary between 108 and 224 degrees for magnitude and 53 and 482 deg/sec for steering rates.

The specific steering magnitude for the RSM was decided upon after collaboration with industry and a review of 150-foot J-turn test data revealed that similar strategies were being developed to normalize steering magnitude on a per vehicle basis. The strategies involved calculating magnitude based on a vehicle's wheelbase or from a characterization maneuver such as the SIS maneuver. Ultimately, the experimenters chose to determine the RSM magnitude from the SIS test data since it would account for different wheelbases, steering ratios, suspensions, tires, test surfaces, and other differences that exist between truck-tractors.

The level of lateral acceleration for deriving the steering wheel angle was determined after several SIS test series were completed and the data analysis performed. Two levels of lateral acceleration were considered. VRTC was experimenting with the steering wheel angle at 0.3 g from 25 mph SIS tests (with a combination vehicle) and Industry was recommending 0.5 g from 30 mph SIS tests (with a bobtail truck tractor). Data analysis from both methodologies revealed similar (170 degrees versus 193 degrees) projected δ^{Test} steering inputs for the RSM. Given the similarities of test results from the two methodologies, the bobtail 30-mph SIS test was selected to normalize the δ^{Test} input into the RSM. It was believed that testing bobtail would eliminate possible negative characterization effects from including different types of trailers in the test. In addition, a methodology was developed to extrapolate the steering wheel angle needed to produce 0.5 g from SIS testing in the linear handling range of 0.05 to 0.30 g of lateral acceleration, again using a 30-mph speed and a bobtail tractor. While one tractor could obtain 0.5 g of lateral acceleration in the SIS test prior to SC intervention, the other tractors had SC interventions just under 0.45 g.

To determine the steering rate for the RSM, experimenters used the precise control offered by the automated steering controllers to experiment with multiple steering rates for the RSM. Six steering wheel rates were chosen for evaluation that was in the range observed for 150-foot J-turn maneuvers (53 - 482 deg/sec). The rates were 50, 60, 75, 110, 175 and 450 deg/sec. Results from those experiments revealed larger performance benefits at slower steering rates versus those greater than 110 deg/sec. The slower steering rates were concluded to be less dynamic requiring milder amounts of SC intervention at a given speed to maintain stability in the system. Based on those results 175 deg/sec was selected for the RSM steering rate documented in this report. A summary of the RSM parameters as it has been performed for the research detailed in this report is shown in Table 3.6.

Table 3.6. Summary of RSM maneuver.

Number of Tests	14 test runs (maximum)
Test Throttle Condition	Drop throttle (clutch-in)
Test Speed	20 mph start; increment each test by 2 mph
HW Angle	δ^{Test}, determined by SIS maneuver
HW Rate	175 deg/sec, ("t" = δ^{Test}/175 deg/sec shown in Figure 3.4)
Automated Steering Controller	Yes
Surface	Dry Asphalt; high mu
Test Termination Criteria (observance of one of the following terminated a test series)	1. Wheel lift of one or more axles in excess of 2.00 inches 2. Articulation angle limited by safety cables 3. Test speed of 50 mph completed

3.4.6 Industry Maneuvers

Based on discussions with industry, several additional maneuvers were considered. These Industry maneuvers were:

1. Decreasing Radius Test
2. Roll Stability Control Test

These maneuvers are further discussed in aNHTSA white paper (see Appendix E).

4.0 PHASE I

Based on the experience from previous NHTSA light vehicle research, several maneuvers were chosen in Phase I to evaluate combination unit truck stability control performance on a high coefficient of friction surface [3]. These maneuvers included the following:

- Constant Radius Test
- J- turn with a 150-foot Constant Radius
- Double Lane Change Maneuver

4.1 Test Matrices

For each vehicle and loading combination, three handling maneuvers were performed. The matrix displayed in Table 4.1 was completed for each of the three maneuvers. This matrix was designed to allow a performance comparison of the combinations with and without stability control at the three different load conditions. This methodology also allowed the observance of interactions between the tractor and trailer stability control systems. Phase I testing was conducted using the Freightliner and Volvo 6x4 tractors, both equipped with ESC, and the Fruehauf van trailer equipped with a trailer-based RSC system.

Table 4.1. Test matrix conducted for each test maneuver.

	Speed (MPH) at Critical Event					
	LLVW		~GVWR			
			Low CG		High CG	
	Trailer RSC		Trailer RSC		Trailer RSC	
	OFF	ON	OFF	ON	OFF	ON
Freightliner						
ESC OFF	X	X	X	X	X	X
ESC ON	X	X	X	X	X	X
Volvo						
ESC OFF	X	X	X	X	X	X
ESC ON	X	X	X	X	X	X

4.2 Constant Radius Test Results

Tests were conducted following a 150-foot constant radius (CR) circle using slowly increasing vehicle speed to evaluate the SC's ability to mitigate roll instability in a steady state maneuver. Tests were conducted with and without SC enabled and in various loading conditions. The following sections document the results from these tests.

4.2.1 Speed at Trailer Wheel Lift

Table 4.2 summarizes the results in terms of speed at the critical event during the maneuver. The speed is representative of all runs in a series including both left and right conditions. The speed that wheel lift greater than 2.0 inches occurred is reported.

Test results show that truck tractor ESC as well as trailer-based RSC were capable of mitigating wheel lift in this maneuver. When any of the SC systems were enabled, wheel lift was not observed. SC interventions limited the speed of the vehicle combination and did not allow the unit to continue to accelerate. These tests are indicated in Table 4.2 as "TC".

With ESC completely disabled, both the LLVW and Low CG conditions resulted in the vehicles severely under-steering and no wheel lift occurred. The speeds at which this occurred were very similar for each of the truck tractor combinations tested. For the High CG load condition, each test resulted in wheel lift at the same speed for each tractor.

The test trailer RSC condition was tested with only the Volvo tractor since it is independent of the power unit. Again, with the trailer-based SC enabled, no instabilities were observed.

Table 4.2. Speed where wheel lift was observed during the constant radius increasing velocity tests.

	Speed (MPH) at Wheel Lift					
	LLVW		**Load Condition**			
			Low CG		**High CG**	
	Trailer RSC		**Trailer RSC**		**Trailer RSC**	
	OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**
Freightliner						
ESC OFF	40^	X	35^	X	30*	TC
ESC ON	TC	TC	TC	TC	TC	TC
Volvo						
ESC OFF	41^	TC	35^	TC	30*	TC
ESC ON	TC	TC	TC	TC	TC	TC

* - Denotes wheel lift.
^ - Denotes no wheel lift, but severe understeer
X - Denotes not tested.
TC – Test Complete

4.2.2 Maximum Tractor Lateral Acceleration

The effects of stability control can be observed by comparing maximum tractor lateral acceleration vs. speed for each load and stability condition. Maximum lateral acceleration (Ay) of the tractor vs. event speed data for the constant radius test is displayed in Figure 4.1 and Figure 4.2, for the Freightliner and Volvo. In each figure, there are three subplots. Each subplot represents one of the loading conditions; they are labeled LLVW, Low CG, and High CG.

No cases of wheel lift were observed under the LLVW or Low CG condition. All test runs with trailer wheel lift occurred without stability control active and in the High CG load condition. Under these load conditions, both tractors would understeer and could not reach a velocity much greater than 40 and 34 mph for their respective loading conditions. When loaded in the High CG condition, wheel lift occurs in every test that results in a lateral acceleration greater than 0.45 g.

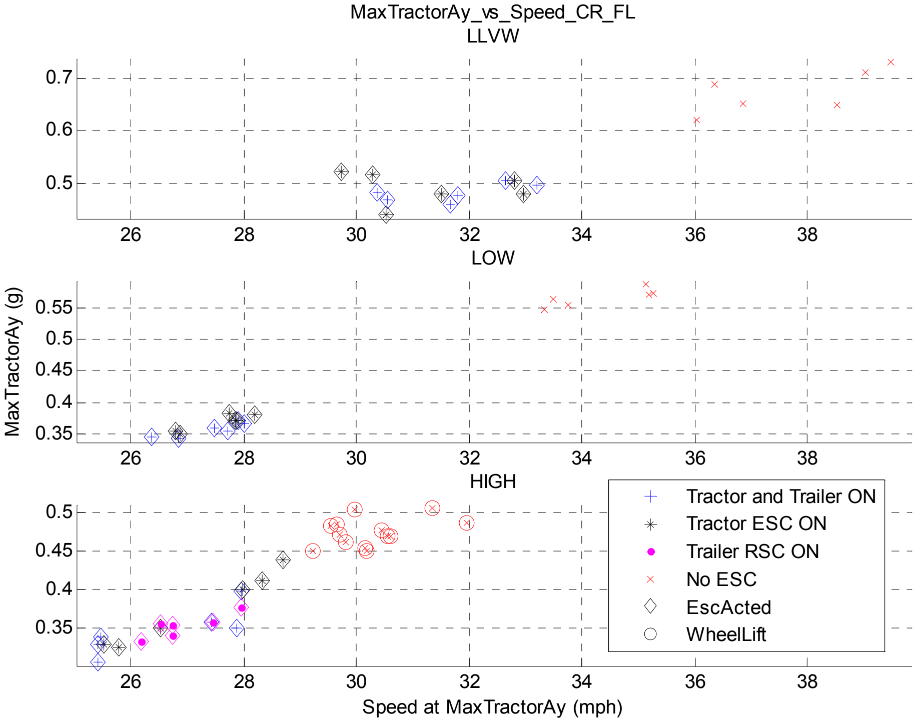

Figure 4.1. Maxima of the Freightliner tractor Ay vs. speed for the different stability control conditions during constant radius increasing velocity test.

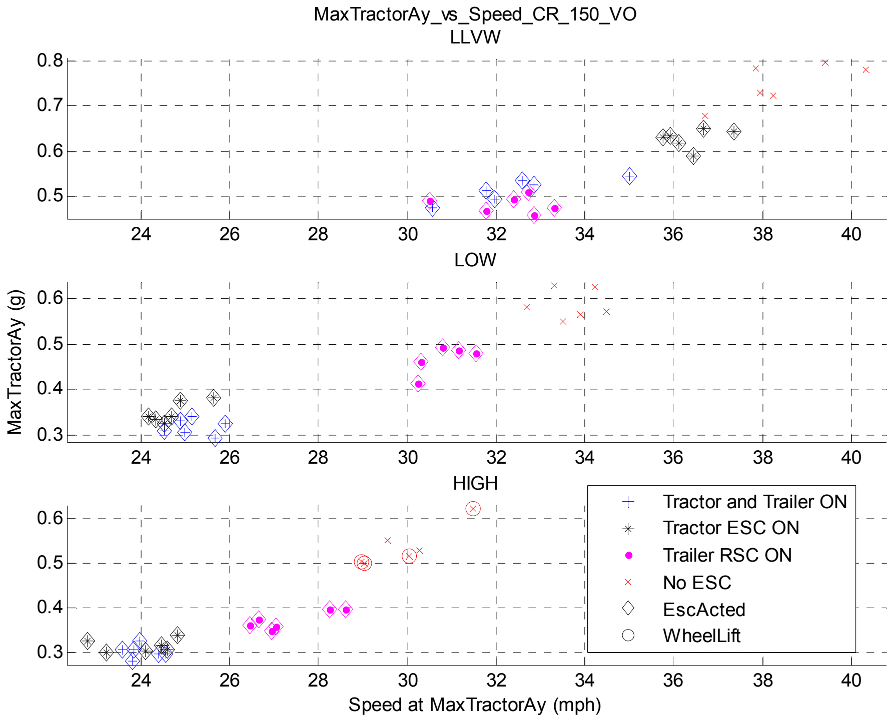

Figure 4.2. Maxima of the Volvo tractor Ay vs. speed for the different stability control conditions during constant radius increasing velocity tests.

Truck tractor-based stability control was capable of limiting the maximum lateral acceleration of the tractor and preventing wheel lift with the different loads tested. Both tractors function in a similar manner, allowing higher maximum lateral accelerations for the LLVW as compared to the Low CG and High CG conditions. There was little difference in peak lateral acceleration under the Low CG and High CG conditions.

Trailer-based RSC was observed to limit maximum lateral acceleration and mitigate wheel lift with the different loads tested. Truck tractor maximum lateral acceleration was limited by the trailer to under 0.5 g for LLVW, 0.4 g to 0.5 g for Low CG, and 0.35 to 0.4 g for the High CG condition.

When both truck tractor and trailer-based stability control were enabled, results were similar to the tractor-based stability control system for the Low CG and High CG conditions and closer to the trailer only RSC condition under the LLVW load. This might be expected as the trailer-based system has a more conservative approach to adjust the allowable maximum lateral acceleration based on loading condition, while the truck tractor-based systems were observed to be more adaptive as the load increases.

4.2.3 Maximum Trailer Lateral Acceleration

In service, a truck tractor forms a combined vehicle unit when connected to a semi-trailer. In many cases, a tractor will handle differently bobtail than when connected to a trailer. For a SC system to be effective, it must also manage the lateral dynamics of the trailer. The effects of SC can be observed by comparing maximum trailer lateral acceleration vs. tractor speed for each load and stability condition.

Maximum lateral acceleration (Ay) of the trailer vs. tractor speed data for the constant radius test is displayed in Figure 4.3 and Figure 4.4, for the Freightliner and Volvo. In each figure there are three subplots. Each subplot represents one of the loading conditions; they are labeled LLVW, Low and High.

The results show that the maximum trailer Ay is typically 0.05 g lower than the maximum tractor Ay.

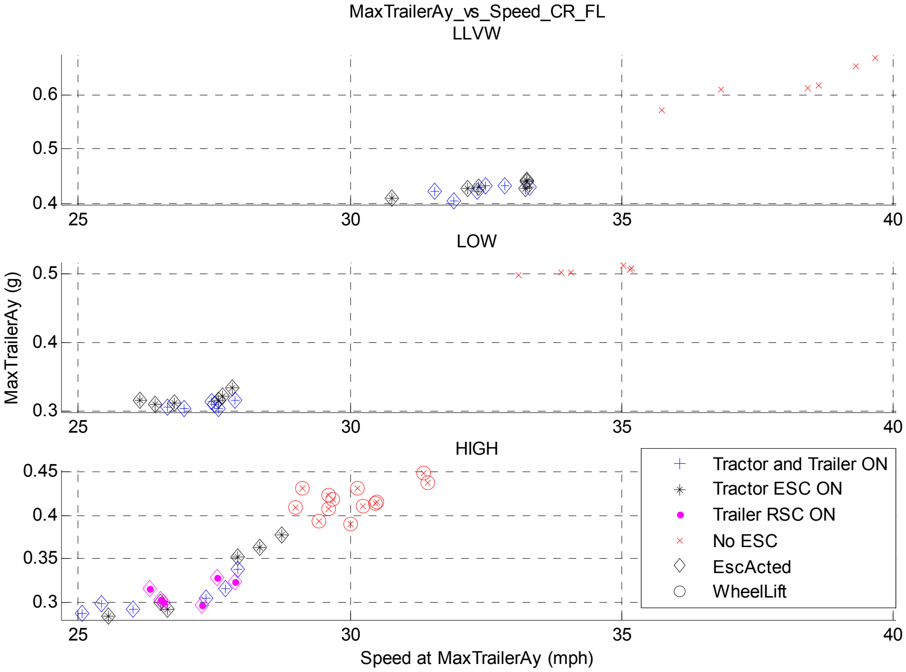

Figure 4.3. Maximum trailer Ay vs. speed for the Freightliner for the different stability control conditions during constant radius increasing velocity test. Tests that resulted in wheel lift being observed are shown as a circle.

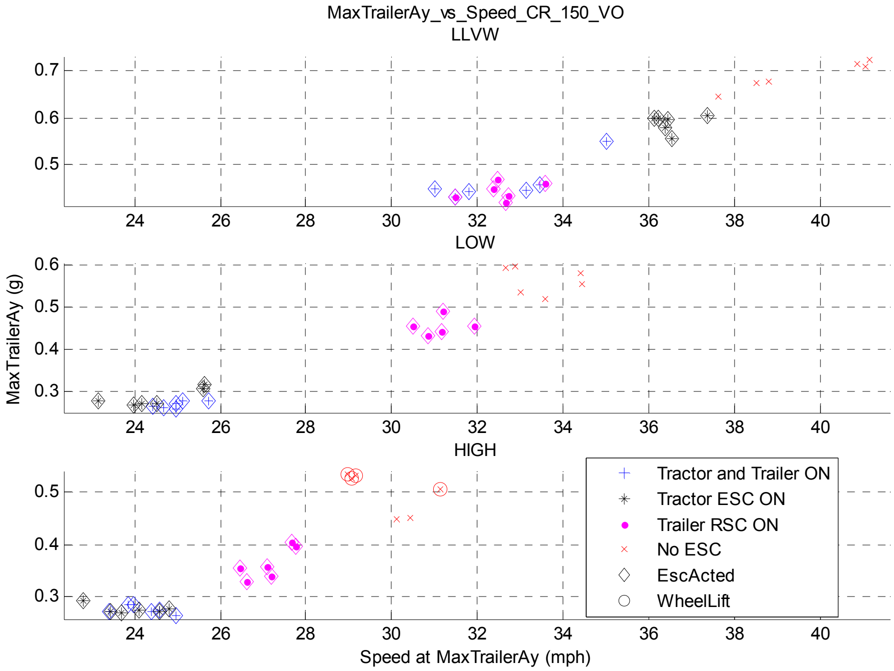

Figure 4.4. Maximum trailer Ay vs. speed for the Volvo for the different stability control conditions during constant radius increasing velocity test. Tests that resulted in wheel lift being observed are shown as a circle.

4.3 J-Turn Results

4.3.1 Speed at Trailer Wheel Lift

Table 4.3 summarizes the test results for the 150-foot radius J-turn maneuver in terms of MES and the time at which wheel lift greater than 2.0 inches was observed. Both left and right maneuvers were performed. Although results were observed to be similar for both directions, only results from tests performed to the left are shown. With tractor SC enabled, tests were not conducted out to speeds where the SC could be overdriven.

The test trailer RSC condition was tested with only the Volvo tractor since it was independent of the power unit. With the trailer-based SC enabled, trailer wheel lift was observed at a MES of 36 mph with the tractor SC system disabled.

With tractor and trailer SC disabled, all conditions but one generated a wheel lift event using the J-turn. The Freightliner in the LLVW condition was severely understeering in this maneuver.

Table 4.3. MES for wheel lift during a 150-foot J-turn maneuver

	Speed (MPH) at Wheel Lift					
	LLVW		Load Condition			
			Low CG		High CG	
	Trailer RSC		Trailer RSC		Trailer RSC	
	OFF	ON	OFF	ON	OFF	ON
Freightliner						
ESC OFF	50^	X	38*	X	31*	X
ESC ON	TC	TC	TC	TC	TC	TC
Volvo						
ESC OFF	48*	TC	40*	TC	33*	36*
ESC ON	TC	TC	TC	TC	TC	TC

* - Denotes wheel lift.
^ - Denotes no wheel lift, but severe understeer
X – Denotes not tested.
TC – Test Complete

Trailer-based RSC was observed to improve the base combination vehicle's roll resistance. As can be seen in Table 4.4, the trailer system was observed to activate at similar speeds as the tractor-based system for the LLVW load condition. When the Low CG and High CG load conditions were tested, the tractor-based system was observed to activate at approximately a 1-3 mph lower speed. For this maneuver, when both systems were enabled, the tractor-based system was observed to dominate the trailer system.

For both truck tractors in the Low CG and High CG loading conditions, tractor-based ESC intervened with braking at a speed well below the speed observed to produce trailer wheel lift. In the LLVW condition, the Freightliner's ESC system activated braking at approximately a 5 mph lower speed than the Volvo's.

Table 4.4. MES when SC activated during a 150-foot J-turn maneuver.

	Speed at First SC Activation (MPH)					
	LLVW		Load Condition			
			Low CG		High CG	
	Trailer RSC		Trailer RSC		Trailer RSC	
	OFF	ON	OFF	ON	OFF	ON
Freightliner						
ESC OFF	~~50^~~	X	~~38*~~	X	~~31*~~	X
ESC ON	33	33	27	27	27	28
Volvo						
ESC OFF	~~48*~~	38	~~40*~~	28	~~33*~~	29
ESC ON	38	38	26	26	26	25

* - Denotes wheel lift.
^ - Denotes no wheel lift, but severe understeer

Table 4.5 shows the difference between the MES speed when wheel lift occurred vs. the MES speed when SC first activated. This delta is representative of how early the SC system can detect that the combination vehicle is approaching its potential roll threshold. It should be noted that SC was tested and able to mitigate roll events up to at least the speed that wheel lift occurred with the technology. The intent of this testing was not to overdrive the SC.

Table 4.5. Change in MES when wheel lift occurred vs. SC activation.

	Delta Speed: Speed @ SC OFF – Speed @ SC Activation (MPH)					
	LLVW		**Load Condition**			
			Low CG		**High CG**	
	Trailer RSC		**Trailer RSC**		**Trailer RSC**	
	OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**
Freightliner						
ESC OFF	~~50^~~	X	~~38*~~	X	~~31*~~	X
ESC ON	Δ17	Δ17	Δ11	Δ11	Δ4	Δ3
Volvo						
ESC OFF	~~48*~~	Δ10	~~40*~~	Δ12	~~33*~~	Δ4
ESC ON	Δ10	Δ10	Δ14	Δ14	Δ7	Δ8

* - Denotes wheel lift.

^ - Denotes no wheel lift, but severe understeer

4.3.2 Maximum Truck Tractor Lateral Acceleration

The effects of stability control can be observed by comparing maximum Ay vs. maneuver entrance speed for each load and stability condition. These data for the J-turn maneuver are displayed in Figure 4.5 and Figure 4.6 for the Freightliner and Volvo. As previously mentioned each subplot represents one of the three loading conditions and are labeled LLVW, Low CG and High CG.

For both truck tractors, in the base configuration with stability control disabled, wheel lift occurred in all load combinations except for the Freightliner in the LLVW condition. For the Volvo and LLVW load condition, wheel lift of the trailer was observed when the tractors' maximum lateral acceleration exceeded 0.75 g.

With stability control disabled and Low CG load condition, wheel lift was observed for tractor maximum lateral accelerations greater than 0.67 g for the Freightliner and 0.6 g for the Volvo. For the High CG condition wheel lift was observed for tractor maximum lateral accelerations that achieved approximately 0.45 g with the Freightliner and 0.42 g for the Volvo.

Enabling tractor ESC limited the maximum lateral acceleration for both the truck tractor and the trailer. As a result, wheel lift was no longer observed for the range of speeds evaluated. When tested in the LLVW load condition, the Freightliner maximum lateral accelerations were limited to just below 0.6 g and the Volvo's were limited to approximately 0.6 g. When loaded in the Low CG or High CG condition, tractor lateral accelerations were limited to 0.5 and 0.4 g for the Freightliner and Volvo respectively.

Trailer RSC was able to mitigate trailer wheel lift in both the LLVW and Low CG conditions. In the High CG condition, several instances of trailer wheel lift were observed with the trailer stability system enabled. The trailer system was overdriven when maximum lateral acceleration exceeded 0.5 g with entry speeds above 35 mph. Although wheel lift was observed at speeds above 35 mph, the trailer system improved roll stability from the base condition. Without any type of stability control enabled, trailer wheel lift was observed at speeds of 30 - 33 mph.

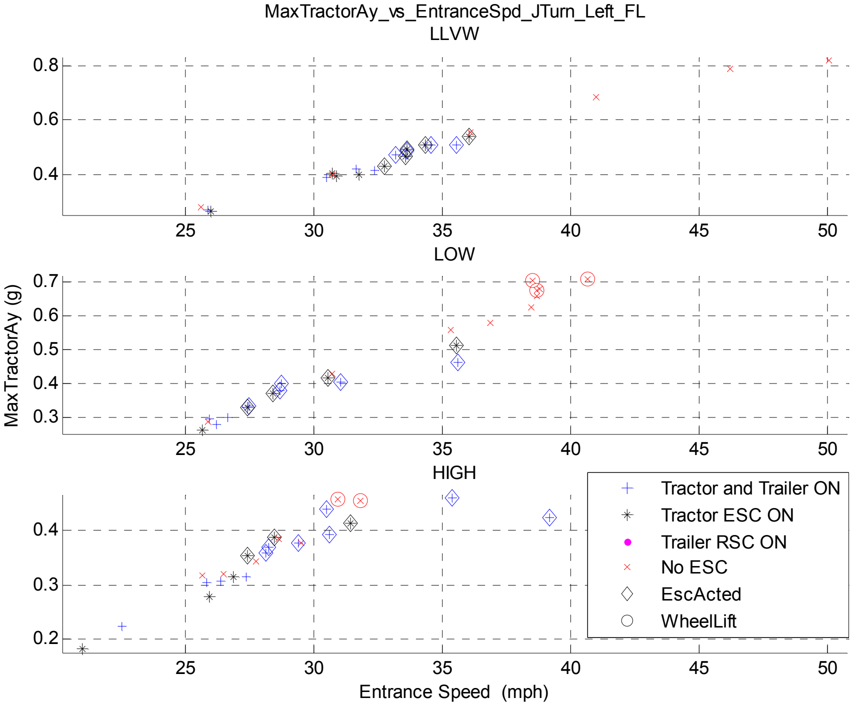

Figure 4.5. Maximum tractor Ay vs. MES during a 150-foot J-turn for the Freightliner tests.

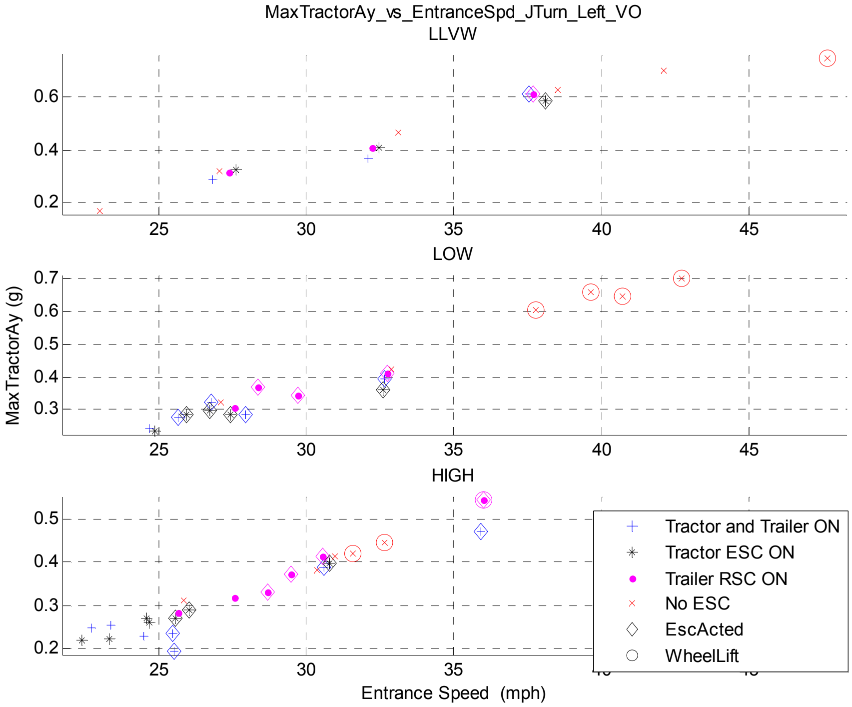

Figure 4.6. Maximum tractor Ay vs. MES during a 150-foot J-turn for the Volvo tests.

4.3.3 Maximum Trailer Lateral Acceleration

Maximum lateral acceleration (Ay) of the trailer vs. tractor speed data for the J-turn maneuver is displayed in Figure 4.7 and Figure 4.8 for the Freightliner and Volvo. In each figure there are three subplots. Each subplot represents results from each of the loading conditions; they are labeled LLVW, Low (Low CG) and High (High CG).

The results show that the maximum trailer Ay is typically 0.05 g lower than the maximum tractor Ay.

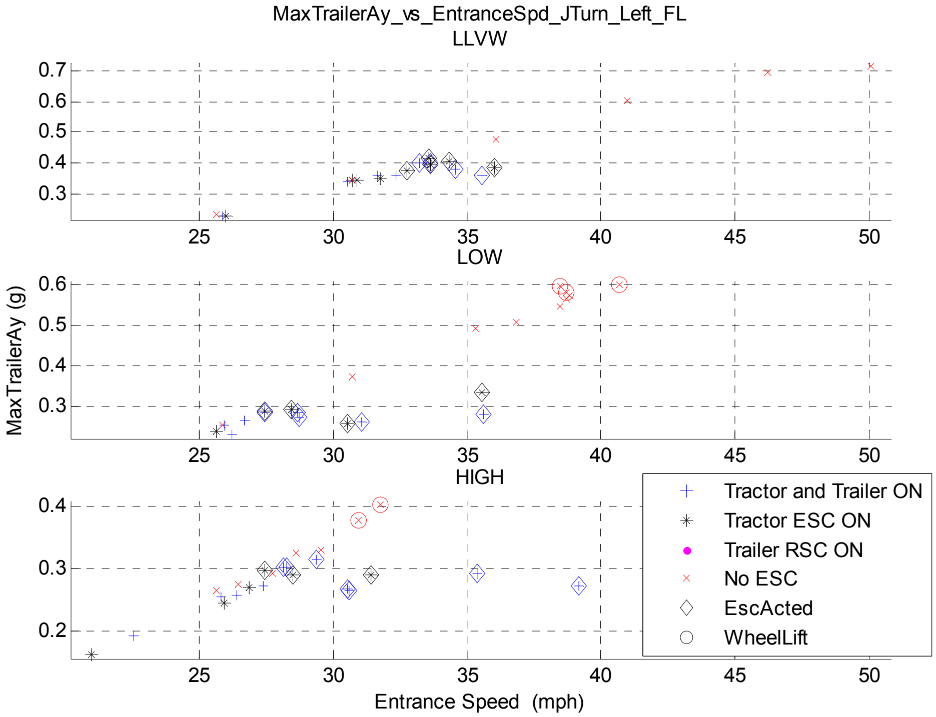

Figure 4.7. Maximum trailer Ay vs. MES with SC activation in a 150-foot J-Turn for the Freightliner.

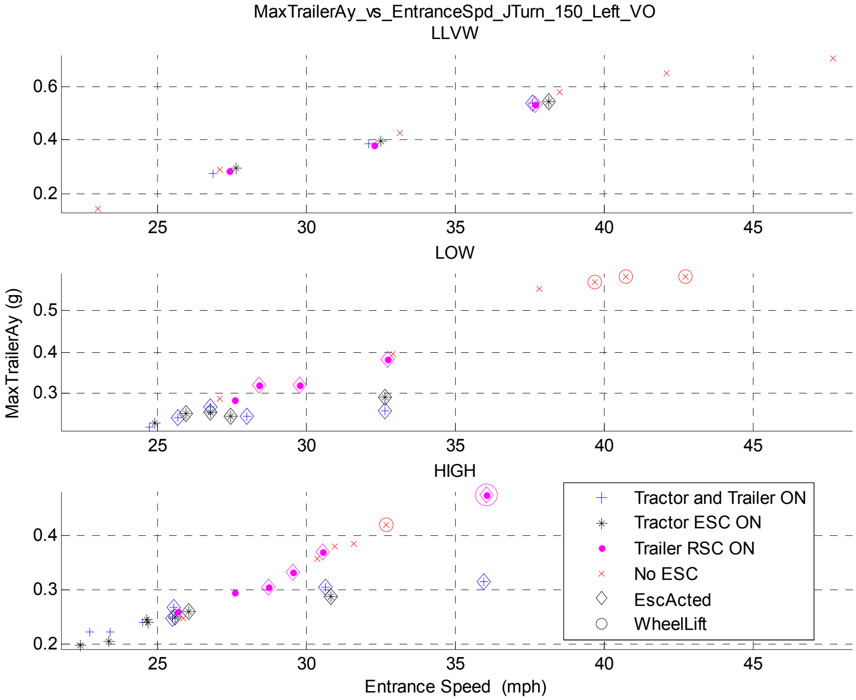

Figure 4.8. Maximum trailer Ay vs. MES with SC activation in a 150-foot J-Turn for the Volvo.

4.4 Double Lane Change Maneuver Results

4.4.1 Speed at Trailer Wheel Lift

Table 4.6 summarizes the results in terms of MES when wheel lift of greater than 2.0 inches was observed during the DLC maneuver. Results for both the LLVW and Low CG conditions are not reported since all tests, including ESC disabled on both the tractor and trailer, were completed without wheel lift up to the termination speed of 50 mph. Results for only the High CG condition are reported.

As shown in Table 4.6, instances of wheel lift were observed for the test conditions conducted with tractor stability control systems disabled and also when the systems were enabled. With both the tractor and trailer SC systems disabled, instances of wheel lift were observed at 39 mph with the Freightliner and 45 mph with the Volvo.

When only the trailer system was enabled (tractor system disabled), two critical events were observed. First, the trailer system was observed to activate at maneuver entrance speeds of 30 and 33 mph for the Freightliner and Volvo, respectively (Table 4.7). Second, wheel lift was then observed at maneuver entrance speeds of 41 and 44 MPH when the trailer was connected with the Freightliner and Volvo, respectively.

With only the tractor-based stability control systems enabled, two critical events were observed with the Freightliner and one event was observed with the Volvo. As shown in Table 4.7, the Freightliner's stability control system activated at 28 mph and then was overdriven at 51 mph (Table 4.6). The Volvo's stability control system activated at 28 mph with no instances of trailer wheel lift occurring up to the highest test speed of 50 mph.

When both truck tractor and trailer stability control systems were enabled, the tractor-based stability control systems were observed to dominate the trailer systems. Two critical events were observed with the Freightliner combination. Stability control activation was first observed at 32 mph and then was overdriven at 51 mph (trailer wheel lift observed.) Stability control activation was observed at 29 mph with the Volvo, and no trailer wheel lift was observed up to the highest test speed of 50 mph.

Differences in MES from Table 4.6 and Table 4.7 can be observed in Table 4.8 for the conditions when SC was enabled. These delta values show that SC was activating at MES much lower than the MES where wheel lift was observed.

Table 4.6. MES when wheel lift occurred during a DLC maneuver.

	MES (mph) at Wheel Lift	
	High CG	
	Trailer RSC	
	OFF	ON
Freightliner		
ESC OFF	39*	41*
ESC ON	51*	51*
Volvo		
ESC OFF	45*	44*
ESC ON	TC	TC

* - Denotes wheel lift.
TC – Test Complete

Table 4.7. MES when SC activation occurred during a DLC Maneuver.

	MES (mph) at First SC Activation	
	~High CG	
	Trailer RSC	
	OFF	ON
Freightliner		
ESC OFF	~~39*~~	30
ESC ON	28	32
Volvo		
ESC OFF	~~45*~~	33
ESC ON	28	29

* - Denotes wheel lift.

Table 4.8. Delta MES when wheel lift occurred vs. SC activation.

	Delta Speed: Speed @ SC OFF – Speed @ SC Activation (mph)	
	~High CG	
	Trailer RSC	
	OFF	ON
Freightliner		
ESC OFF	~~39*~~	Δ11
ESC ON	Δ23	Δ19
Volvo		
ESC OFF	~~45*~~	Δ11
ESC ON	Δ22	Δ21

* - Denotes wheel lift.

4.4.2 Maximum Tractor Lateral Acceleration

Double lane change (DLC) maneuvers were conducted to understand how ESC worked in a dynamic crash avoidance maneuver. Figure 4.9 and Figure 4.10 display the maximum lateral acceleration experienced by the tractor for all DLC maneuvers performed. It should be noted that no instances of wheel lift or lateral instability were observed in the LLVW and Low CG test conditions with the Volvo. Since roll instability was not observed with ESC disabled, it was decided not to test the Freightliner in these conditions.

4.4.3 Maximum Trailer Lateral Acceleration

Figure 4.11 and Figure 4.12 display the maximum lateral accelerations experienced by the trailer for all DLC maneuvers performed. It should be noted that no instances of wheel lift or lateral instability were observed in the LLVW and Low CG test conditions with the Volvo. Since roll instability was not observed with ESC disabled, it was decided not to test the Freightliner in these conditions.

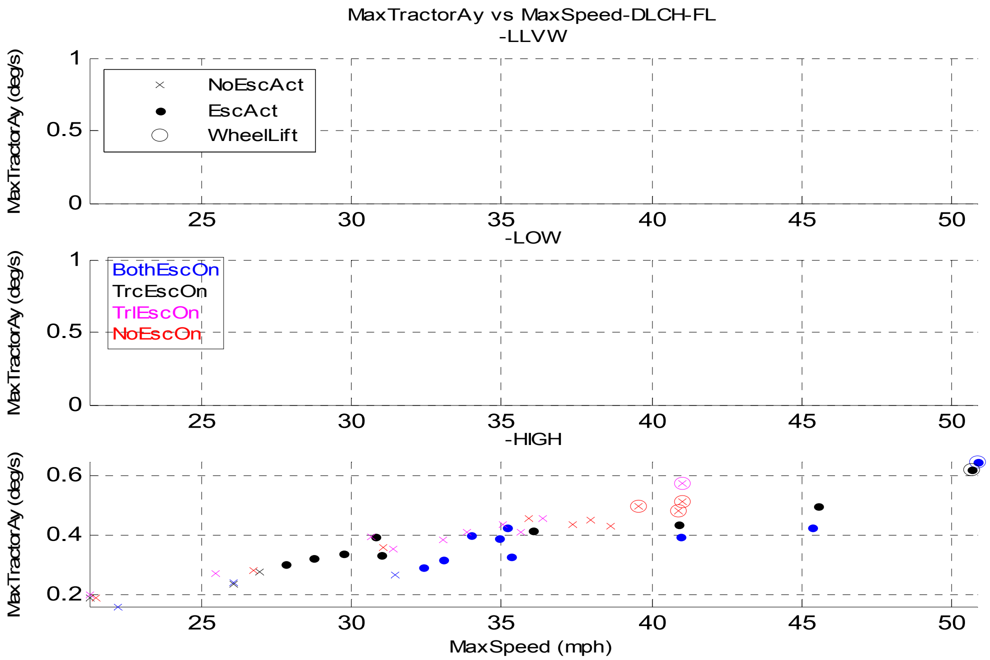

Figure 4.9. Maximum tractor lateral acceleration for the Freightliner during the double lane change maneuver.

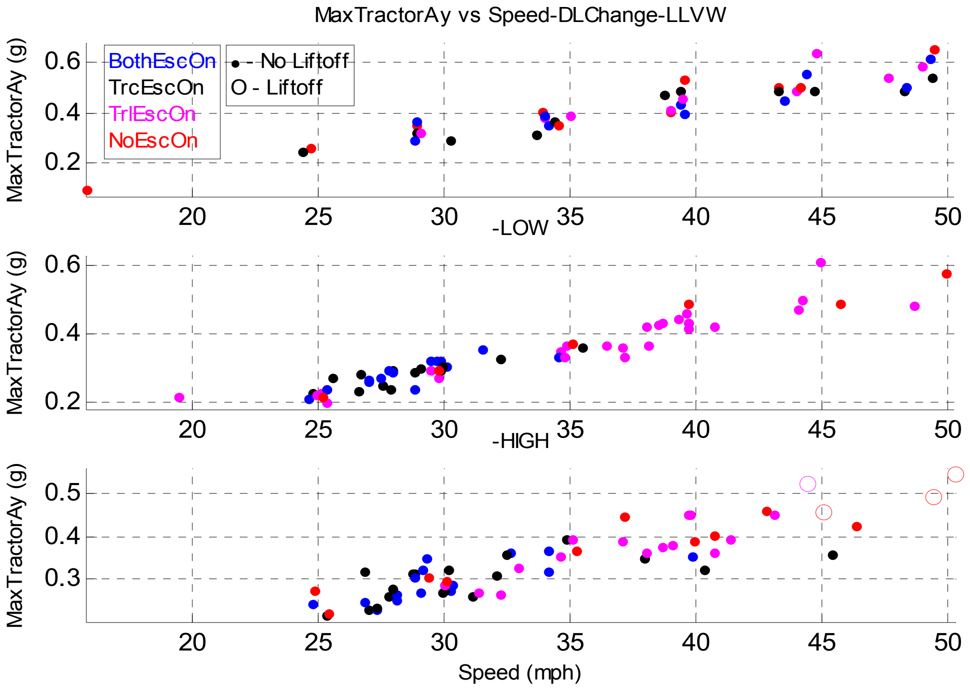

Figure 4.10. Maximum tractor lateral acceleration for the Volvo during the double lane change.

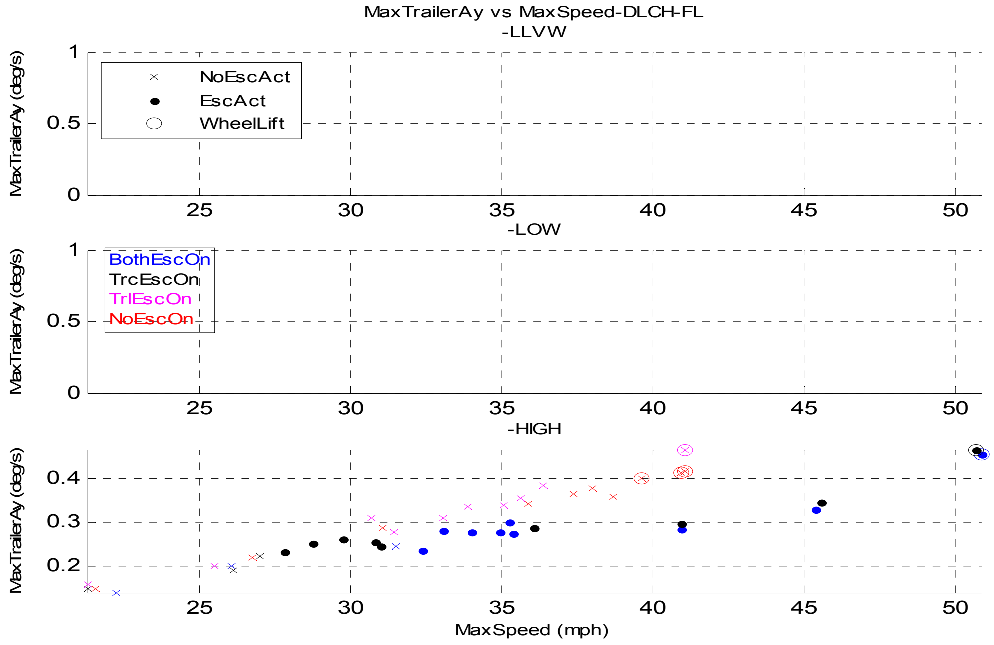

Figure 4.11. Maximum trailer lateral acceleration for the Freightliner tests during the double lane change maneuver.

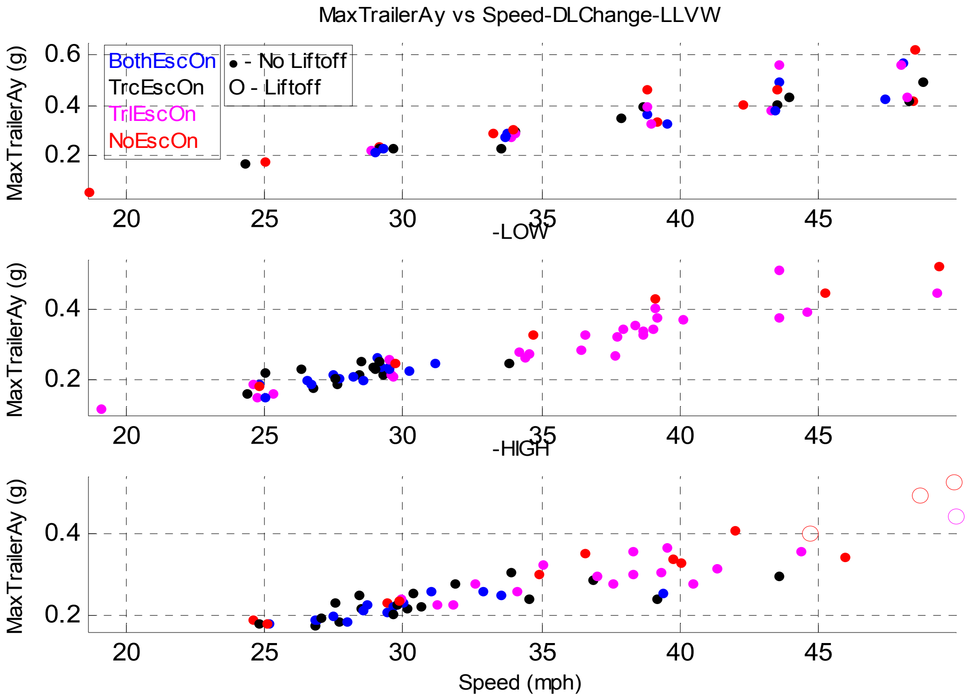

Figure 4.12. Maximum trailer lateral acceleration for the Volvo tests during the double lane change maneuver.

4.5 Phase I Discussion

For both tractor-based stability systems, changes in the tractor lateral acceleration when the stability systems activated were observed between the LLVW, Low CG, and High CG loads. Maximum lateral accelerations were very similar between the Low and High CG conditions. The trailer-based system exhibited similar changes in tractor lateral acceleration when the stability system intervened but with less range. This suggests that the heavy vehicle stability systems tested were capable of sensing or estimating load but are not estimating the CG height of the load.

For the constant radius circle, increasing velocity tests of tractor and trailer systems showed that both were capable of mitigating trailer wheel lift and limiting maximum tractor lateral acceleration. This maneuver increased lateral acceleration at a rate proportionate to the square of velocity. The maneuver did not produce a large amount of dynamic overshoot in lateral acceleration. The maneuver demonstrated differences between tests with and without stability control enabled, but was not very effective in demonstrating the differences between a tractor and trailer-based system.

For the J-turn tests, tractor-based systems were able to mitigate trailer wheel lift in all test series conducted. The trailer-based RSC system provided some improvement in stability but was overdriven before 50 mph was reached. For the J-turn, lateral acceleration increased at a faster rate than for the constant radius maneuver. At higher speeds, the maneuver generated dynamic overshoot in lateral acceleration making this a challenging maneuver. The maneuver was able to distinguish between tests with and without stability systems enabled, and demonstrated performance differences between tractor and trailer-based systems.

Unfortunately, not all J-turn tests with the tractor-based system enabled were conducted to the point of test termination speed or to the point where trailer wheel lift was observed. When these tests were conducted, the initial protocol terminated a test series when SC activation was observed. This was changed because at higher speeds there was the potential to overdrive the tractor systems as well.

During DLC testing, tractor-based systems were able to mitigate trailer wheel lift in most test series. In all completed tests, two instances of wheel lift were observed with the tractor-based ESC system enabled on the Freightliner. In both of these cases, maneuver speed was just over 50 mph and tests were conducted with the same driver. In further review of the data, it was determined that the system was not functioning properly for those test series. Regardless, the system performance was better than the base vehicle's.

The trailer-based system provided some improvement in stability but was able to be overdriven at a lower speed than the tractor-based systems. Again, its performance was still better than the base vehicle's performance.

The DLC maneuver was able to demonstrate differences between tests with and without a stability system enabled and between tractor and trailer-based systems, however, these results were not as clear when compared to the other maneuvers. The DLC is a very dynamic maneuver and can generate rapid rates of change of lateral acceleration, however, results varied by driver. Since the goal of the maneuver is to navigate the lane change gates, drivers can steer the tractor semi-trailer unit in a variety of ways to success complete the maneuver.

One strategy observed entailed the driver smoothly steering the vehicle over time to follow the path marked out for the maneuver. In some cases the driver was observed steering before the gate to anticipate tractor response time. The second observed strategy entailed the driver waiting until the last possible second to abruptly steer, then hold the steering wheel angle and wait for the truck to respond. This type of input was then repeated to make truck navigate the lane change success.

Because of these distinct strategies, the outputs from this maneuver can result in very different lateral accelerations for any test entrance speed. This potentially suggests why the data are not as clean in determining the differences between system performances. The repeatability of the test may suffer from driver influences.

4.6 Phase I Summary

Overall, both tractor and trailer stability control systems improved the roll stability of the base tractor semi-trailer. For a given maneuver, tractor-based stability systems were able to mitigate trailer wheel lift at the same or higher entrance speeds than trailer only based systems. Trailer-based stability systems were able to mitigate trailer wheel lift at the same or higher maneuver entrance speeds than the base tractor semi-trailer vehicle. For all test maneuvers and conditions performed on the test track, enabling stability control was not observed to degrade the stability of the tractor.

Based on the results of this study, a performance test based on the J-turn appears to be suitable to evaluate tractor and trailer stability control systems. Further study of this type of maneuver (Phase II) was necessary to understand how stability control technology and other factors influence the dynamic response of heavy vehicles.

Based on the test track data, tractor-based SC systems increase roll stability by a larger margin than trailer-based SC systems. Based on these results, NHTSA researchers decided that Phase II should focus on truck tractor-based SC systems.

5.0 PHASE II

Test results from Phase I research showed that dynamic tests conducted with a High CG load often resulted in roll instability of the base vehicle during the initial steering input to the maneuvers. Additionally the transient steering maneuvers, like the double lane change, required higher speeds to observe instabilities than the simpler J-turn, Constant Radius and SIS maneuvers. The results also showed that quasi-steady state SIS and Constant Radius maneuvers could result in roll instability at low speeds (30 mph), however, such roll instability was easily mitigated by SC systems with engine torque reduction alone without the support from the foundation brakes. While engine/power unit control was considered an important function of the SC systems, it was observed to be the only an initial response in more dynamic maneuvers like the J-turn.

The J-turn was found to produce roll instabilities at low speeds (30 mph) with the base vehicles and challenged (required foundation braking to remain stable) the SC systems when enabled. Ultimately, a revised version of the J-turn, which we will refer to as the Ramp Steer Maneuver (RSM), was selected over the manual controlled J-Turn as shown in Appendix E. Figure 5.1 offers a steering profile comparison between the 150-foot J-turn and the automated RSM. The J-turn maneuvers were all conducted with test drivers controlling the speed and steering inputs. This resulted in variability in the desired maneuver entrance speed, steering wheel angles and rates as the drivers followed the marked path. In comparison, using the steering controller to conduct the RSM allowed researchers to attain a ± 1 mph tolerance on desired entrance speed and provided consistent steering wheel angles and rates in every test run.

The RSM was chosen for its ability to challenge a truck tractor's roll stability thresholds and for its potential to be developed into an objective, repeatable maneuver from which a set of roll stability performance criteria could be developed. This section discusses the specifics of the RSM and SIS maneuvers and testing methodology used to conduct the research detailed in this report.

In addition to the maneuver changes, three stability control states-of-operation were to be evaluated versus just two in Phase I. Besides "SC disabled" and "SC enabled" a third state was added in which the SC system was enabled, however, the air brake service line to the trailer brakes was disconnected. For this report, the third condition was labeled "SC enabled unbraked". This condition was added to observe the changes to vehicle performance that result from the addition of trailer braking and to potentially develop a test maneuver in which an unbraked control trailer [16] would be used.

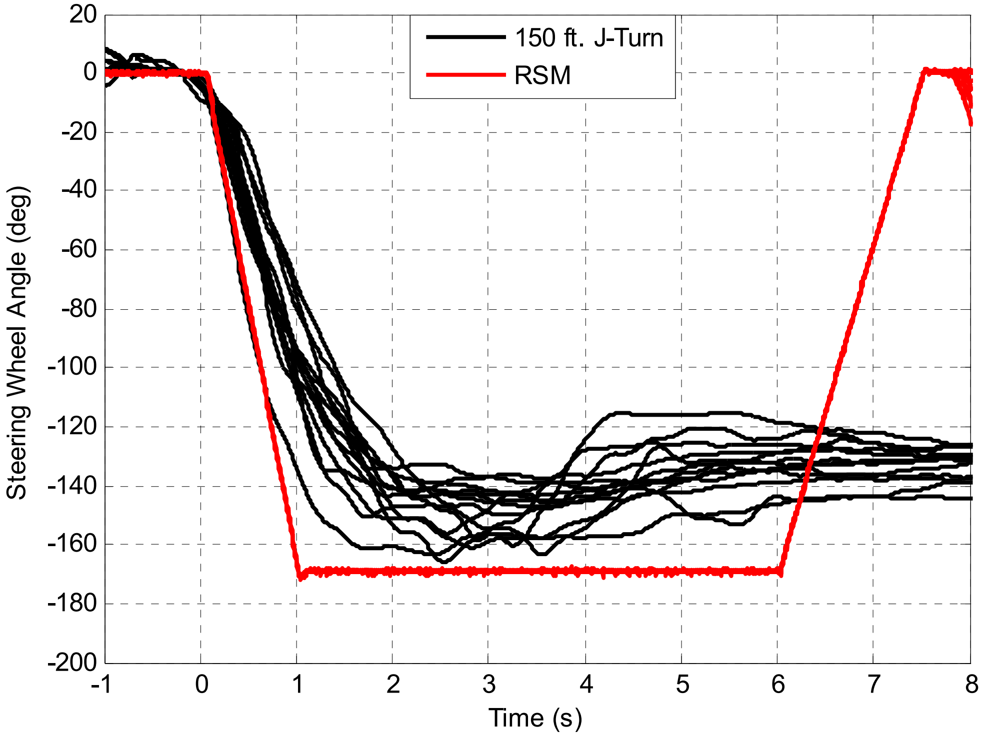

Figure 5.1. Steering wheel angle data from multiple 150 ft. J-Turn (test driver, 13 tests) and RSM (steering controller, 11 tests) tests. Data show the ability to repeat maneuver inputs with an automated steering controller.

5.1 Phase II Test Matrix

After selecting candidate performance tests, the following test matrix and previously mentioned test procedures for the SIS and RSM were used to generate a well defined set of test data that can be used to investigate effective measures of performance. The selected maneuvers exercised the tractor trailer systems through a variety of lateral acceleration levels that allowed different metrics to be evaluated. The test matrix followed for each truck tractor is shown below in Table 5.1. The table shows a comprehensive test matrix including six trailer combinations, two loading conditions, three SC states-of-operation, and two maneuvers. Within each of the SIS matrix cells were six individual tests (three left and three right steering maneuvers). Within each of the RSM matrix of cells there was a potential for 28 individual tests (14 left and 14 right steering wheel inputs). All told, if each cell of the matrix was filled in, there would have been over 5000 tests performed.

To reduce the time required to complete this research not all cells in the test matrix were completed. To streamline the process, SIS maneuvers were only performed in the bobtail condition to characterize the base truck tractor and to determine the normalized δ^{Test}. That δ^{Test} was then used for all RSM test series to be performed with the 6 different trailers and 2 loading conditions. To further reduce the test burden

LLVW condition RSM tests were performed for the SC enabled with an unbraked trailer[4] test condition only. Additionally, only left steering inputs were used in the RSM test series. Prior testing for the truck tractors used in this research was conducted with both left and right steering wheel inputs. From those tests, researchers found each truck tractor combination, when loaded symmetrically, responded symmetrically.

Table 5.1. Table shows test matrix that was performed for each truck-tractor. Test series that were completed are denoted with an "X".

			Maneuvers				
			SIS		RSM		
Vehicle Configuration		Load	SC Disabled	SC Enabled	SC Disabled	SC Enable - No Trailer Brakes	SC Enabled
Bobtail			x	x			
Box Vans	Fruehauf 53 ft.	LLVW				x	
		High CG			x	x	x
	Strick 53 ft.	LLVW				x	
		High CG			x	x	x
Flatbeds	Fontaine 48 ft. Spread Axle	LLVW				x	
		High CG			x	x	x
	Fruehauf 48 ft. Tandem Axle	LLVW				x	
		High CG			x	x	x
	Great Dane 28 ft. Control Trailer	LLVW				x	
		High CG			x	x	x
Tanker	Heil 42.5 ft. 9200 Gal. Tanker	LLVW				x	
		High CG			x	x	x

Besides the tests completed in the test matrix shown in Table 5.1, additional supplemental test series were performed to better understand how SC systems adapt to changes in mass. Data analysis of Phase I test results revealed that SC activated at different lateral acceleration levels. Differences were observed between loaded (Low CG and High CG) and LLVW test conditions. In discussion with industry, it was learned that SC systems estimate mass and modify the performance of the system. In general, it was observed that as the weight of the vehicle increased, SC interventions occurred at a lower lateral acceleration levels.

To better understand how SC systems adapt to different loads, a mass estimation test series was conducted. Using the 28 ft. Great Dane flatbed trailer, each power unit was tested under a variety of loads. For each load, SIS and RSM maneuvers were completed until SC braking interventions occurred or a 50 MPH test entrance speed was achieved.

Multiple SIS maneuvers and RSMs were conducted for each of the following cells in Table 5.2. Maneuver test conditions are shown in Table 5.3 and Table 5.4.

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[4] Research with the LLVW load condition RSM tests series were to observe how the SC systems performed and adapted to a light mass using the 6 different trailers.

Table 5.2. Load estimation test matrix.

Tractor	Number of ~4000 lbs Blocks									
	0	1	2	3	4	5	6	7	8	9
Freightliner ESC	x	x	x	x	x	x	x	x	x	x
Freightliner RSC	x	x	x	x	x	x	x	x	x	x
Volvo ESC	x	x	x	x	x	x	x	x	x	x
Sterling RSC	x	x	x	x	x	x	x	x		

Table 5.3. Test conditions for mass estimation SIS testing.

Property	Value
Speed	30 mph
Max Steer Angle	270 deg
Steering Rate	13.5 deg/s
Trailer Brakes	Disabled
Direction	Left and Right

Table 5.4. Test conditions for mass estimation RSM testing.

Property	Value
Speed	20 - 50 mph
Steer Angle	δ^{Test}
Steering Rate	175 deg/s
Trailer Brakes	Disabled
Direction	Left

Depending on the gross vehicle weight rating (GVWR) for the tractor being tested, loading was accomplished by placing up to nine 4,000-pound ballast blocks on the control trailer. At the completion of each test series, a block was removed from the rear of the trailer. The test vehicle was driven from the test area back to the VRTC garage where the block was unloaded. This allowed convenience in unloading, but also allowed the vehicle some time to be driven and adjust to the load. Several starts and stops occurred in the 1 mile drive from the garage to the test surface. Additionally, before each test series, a mass estimation drive cycle was completed as described in Appendix A. Testing was repeated until all of the ballast blocks were removed. The following table and figure documents the weights of each combination tested.

Table 5.5. Mass Estimation Loading for Each Platform

	Freightliner	Volvo	Sterling
Num Blocks	**Total Mass (Lbs)**	**Total Mass (Lbs)**	**Total Mass (Lbs)**
0	30360	29830	25710
1	34470	34100	29620
2	38810	38820	33850
3	43260	43150	38150
4	47540	47400	42380
5	51680	51520	46530
6	56130	55950	50800
7	60530	60270	55050
8	64880	64750	
9	69200	69070	

5.2 Slowly Increasing Steer Results

This section presents the SIS test results conducted with each of the truck tractors. These test series were conducted with the bobtail configuration with SC enabled and disabled. The following subsections present results for each truck tractor with SC enabled and disabled that show changes to vehicle behavior from SC intervention. The remaining sections are devoted to characterization analysis and linear regression analysis performed with SIS test results.

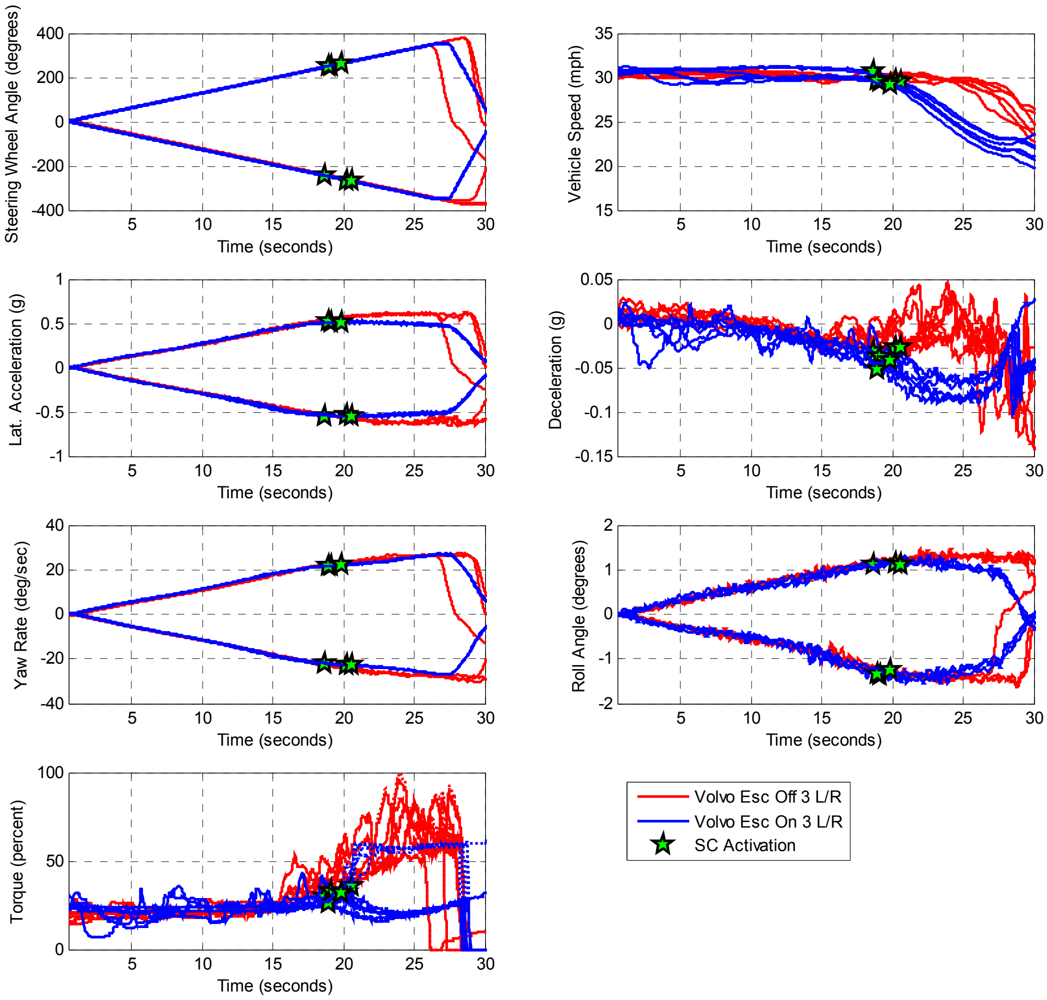
5.2.1 Vehicle Dynamics Changes from SC Intervention

Though the SIS test, as conducted in Phase I, was used for dynamic characterization of each vehicle's sublimit behavior, the additional tests were performed in a manner that would capture their limit responses. This provided sufficient data for a linear regression analysis to determine the RSM steering wheel magnitude, and the ability to observe/compare SC system responses to the given speed and steering inputs. As a result of the SWA input and maneuver speed of 30 mph, enough lateral acceleration and yaw rate were generated to observe SC intervention in every single SIS test completed when the system was enabled. Since the limits of the vehicles were approached in such a gradual manner, the ranges of activation levels of lateral acceleration were observed. Not only were the activation levels observed, but the system responses to the inputs were all very similar for each vehicle in the bobtail configuration.

The SC systems all responded similarly in the SIS test maneuver, regardless of vehicle or type of SC system installed. As the steering input was increased in a slow linear manner, the system eventually activated and reduced engine torque output which in turn reduced the vehicle speed so that lateral acceleration was limited even as the radius of the vehicle was observed to continue to decrease. With SC enabled, none of the SIS tests resulted in understeer, oversteer or roll instability, while the SIS tests with SC disabled resulted in each tractor going into an understeer condition. To show what was observed over time in the SIS maneuver, time history data from the SIS test series with the four SC systems enabled and disabled are shown in Figure 5.2 through Figure 5.5.

Each figure presents, from top to bottom, and left to right, the steering wheel angle, speed, lateral acceleration, deceleration, yaw rate, roll angle, and engine torque. Green pentagrams denote SC activation. Complimenting each figure are tables (Table 5.6-Table 5.11) of the series mean for speed, lateral acceleration, deceleration, yaw rate, roll angle, and engine torque for each vehicle. These tables quantify the changes observed between the two series conditions for each vehicle tested. For a comparison between enabled and disabled tests a common event point was needed for each vehicle and SC system configuration.

For this section, that common event point was determined by monitoring the "driver demanded torque" and the "engine torque" output that was available on each vehicle's communication bus. During normal operation the "driver requested torque" and "engine torque" measures were observed to be equal to each other. During the SIS maneuvers, once the SC activated and invoked engine control, the two measures were observed to separate as the driver demanded an increase in engine torque in attempting to maintain the 30-mph speed while the SC commanded engine torque output reductions. This point of separation was considered the event point (point in time, was set equal to zero for calculations in the tables). Since this event did not occur when SC was disabled, an equivalent event point (time) was determined from the enabled series to allow the comparisons for each vehicle. In the tables, each measure's average value and average change was reported in 0.5 s increments up to four seconds after the event point. "Change" was expressed as a percentage of the value at the separation point. Negative percentages indicate a reduction in the measure and a positive percentage indicates an increase. Each vehicle's typical SIS results are shown below.



Dotted line = driver torque
Solid line = engine torque

Figure 5.2. SIS time history data for the Volvo with and without SC. Activation observations are marked with a pentagram marker. The data represents three SIS maneuvers to the left and three to the right with speed held constant at 30 mph.

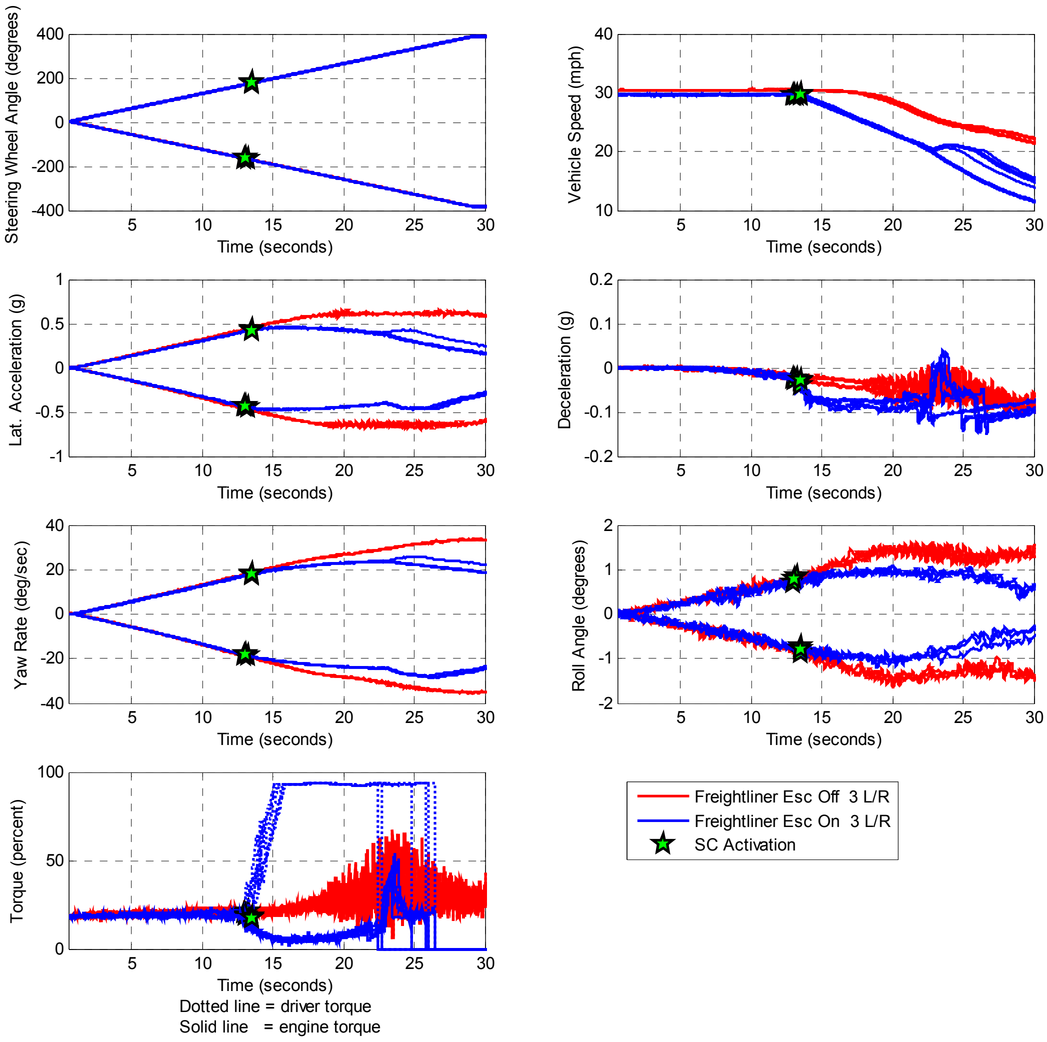
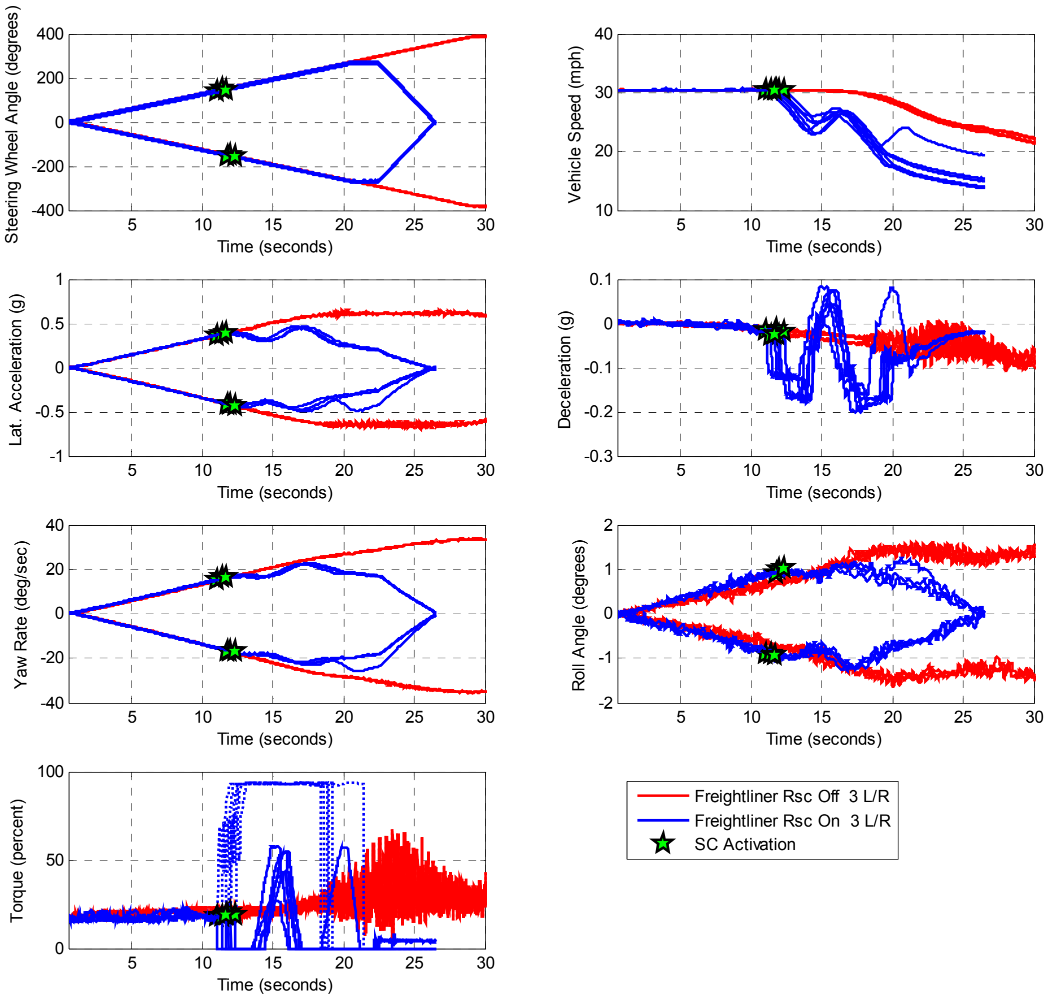


Figure 5.3. SIS time history data from Freightliner (ESC) with and without SC. Activation observations are marked with a pentagram marker. The data represents three SIS maneuvers to the left and three to the right with speed held constant at 30 mph.



Dotted line = driver torque
Solid line = engine torque

Figure 5.4. SIS time history data from Freightliner (RSC) with and without SC. Activation observations are marked with a pentagram marker. The data represents three SIS maneuvers to the left and three to the right with speed held constant at 30 mph.

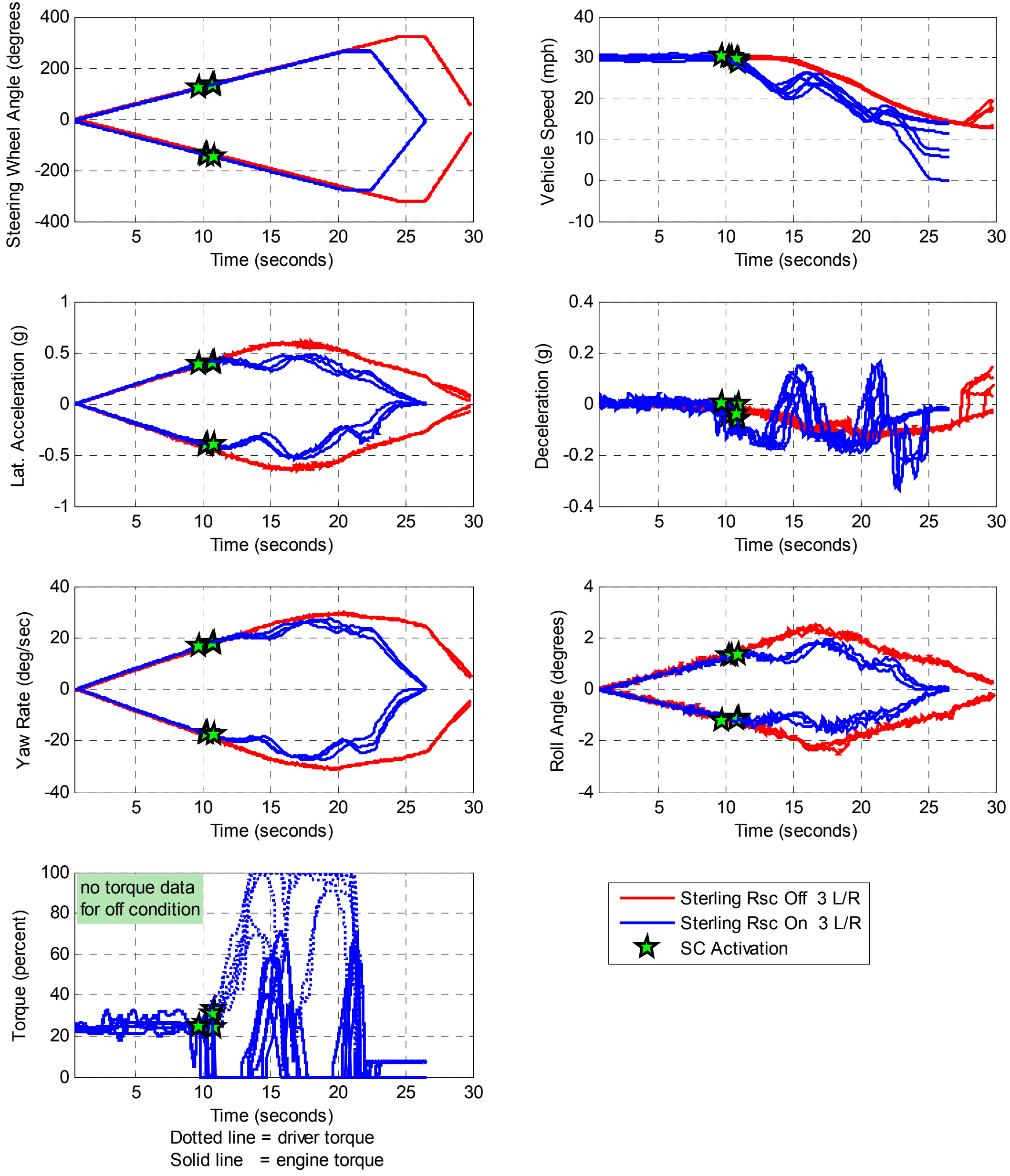


Figure 5.5. SIS time history data from Sterling (RSC) with and without SC. Activation observations are marked with a pentagram marker. The data represents three SIS maneuvers to the left and three to the right with speed held constant at 30 mph.

The figures above for each of the vehicles show that once the SC systems activated, the forward velocity for the SIS test series began to decrease and remained below the disabled series tests for the duration of the maneuver. This observation is quantified in Table 5.6 (shows mean speed and change in speed after activation for each of the vehicles and series conditions). The table shows that four seconds after the SC systems activated, the mean speed ranged from 21.6 mph to 26.0 mph while the disabled series tests ranged from 29.6 mph to 30.3 mph. The change associated with this time increment shows that the mean speed reduction ranged from 12.4% to 27.2%

while the disabled series tests had limited reductions that ranged from 0.6% to 1.9% (i.e., the drivers were able to maintain the constant speed within 0.5 mph)

Like speed, once the SC systems activated the mean lateral acceleration for the SIS test series began to decrease and remained below the disabled series tests for the duration of the maneuver. This observation is quantified in Table 5.7. At time zero the range of mean lateral acceleration at SC activation for the SIS enabled test series were observed to be between 0.398 g and 0.528 g. The table shows that four seconds after the SC systems activated, the mean lateral acceleration ranged from 0.339 g to 0.518 g while the disabled test series ranged from 0.544 g to 0.612 g. The change associated with the four-second time increment shows that the SC enabled series mean lateral acceleration ranged between -14.9% to 6.2%, while disabled series tests were observed to increase by 9.9% to 37.6%.

Table 5.6. Table shows the average vehicle speed and the change in speed at specific time increments referenced from the engine torque reduction event for the 4 vehicles with SC enabled and disabled.

Vehicle	Condition Tested	Series Mean 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	29.7	29.4	29.1	28.7	28.3	27.7	27.2	26.6	26.0
	ESC Disabled	30.0	30.1	30.1	30.1	30.0	29.9	29.9	29.9	29.8
Freightliner	ESC Enabled	29.6	29.4	28.9	28.4	27.9	27.4	26.8	26.3	25.8
	ESC Disabled	30.4	30.5	30.4	30.4	30.4	30.3	30.3	30.2	30.1
Freightliner	RSC Enabled	30.4	29.6	28.4	27.1	25.7	24.7	24.4	24.9	25.7
	RSC Disabled	30.5	30.5	30.5	30.4	30.5	30.4	30.4	30.4	30.3
Sterling	RSC Enabled	29.7	28.9	27.8	26.6	25.2	23.9	22.5	21.6	21.6
	RSC Disabled	30.1	30.2	30.1	30.1	30.1	30.0	29.9	29.8	29.6
Vehicle	**Condition Tested**	**Change In Speed From Time 0**								
Volvo	ESC Enabled	0.0%	-0.8%	-1.9%	-3.2%	-4.7%	-6.7%	-8.4%	-10.3%	-12.4%
	ESC Disabled	0.0%	0.1%	0.2%	0.2%	-0.1%	-0.4%	-0.6%	-0.6%	-0.7%
Freightliner	ESC Enabled	0.0%	-0.7%	-2.3%	-4.0%	-5.6%	-7.4%	-9.3%	-11.0%	-12.8%
	ESC Disabled	0.0%	0.0%	0.0%	-0.1%	-0.3%	-0.4%	-0.6%	-0.9%	-1.3%
Freightliner	RSC Enabled	0.0%	-2.7%	-6.7%	-11.0%	-15.6%	-18.9%	-19.8%	-18.1%	-15.4%
	RSC Disabled	0.0%	-0.1%	0.0%	-0.2%	-0.1%	-0.2%	-0.3%	-0.4%	-0.6%
Sterling	RSC Enabled	0.0%	-2.8%	-6.5%	-10.3%	-14.9%	-19.6%	-24.2%	-27.4%	-27.2%
	RSC Disabled	0.0%	0.1%	0.0%	0.0%	-0.2%	-0.4%	-0.8%	-1.2%	-1.9%

Table 5.7. Table shows the average lateral acceleration and the change in lateral acceleration at specific time increments referenced from the engine torque reduction event for the 4 vehicles with ESC enabled and disabled.

Vehicle	Condition Tested	Series Mean Lateral Accel. (g) 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	0.528	0.537	0.531	0.530	0.531	0.531	0.523	0.524	0.518
	ESC Disabled	0.557	0.567	0.577	0.590	0.598	0.603	0.607	0.608	0.612
Freightliner	ESC Enabled	0.431	0.448	0.458	0.461	0.463	0.466	0.463	0.459	0.458
	ESC Disabled	0.454	0.477	0.494	0.513	0.528	0.545	0.566	0.581	0.592
Freightliner	RSC Enabled	0.398	0.411	0.409	0.394	0.375	0.353	0.348	0.368	0.400
	RSC Disabled	0.396	0.419	0.434	0.456	0.472	0.492	0.514	0.532	0.544
Sterling	RSC Enabled	0.399	0.428	0.427	0.418	0.406	0.392	0.364	0.342	0.339
	RSC Disabled	0.418	0.442	0.460	0.485	0.503	0.528	0.544	0.558	0.575
Vehicle	**Condition Tested**	**Change In Lateral Acceleration From Time 0**								
Volvo	ESC Enabled	0.0%	1.6%	0.6%	0.3%	0.5%	0.5%	-0.9%	-0.8%	-1.9%
	ESC Disabled	0.0%	1.8%	3.6%	5.8%	7.3%	8.3%	8.9%	9.2%	9.9%
Freightliner	ESC Enabled	0.0%	3.8%	6.1%	6.8%	7.4%	8.0%	7.2%	6.4%	6.2%
	ESC Disabled	0.0%	5.2%	9.0%	13.1%	16.3%	20.1%	24.8%	28.1%	30.6%
Freightliner	RSC Enabled	0.0%	3.2%	2.7%	-1.0%	-5.7%	-11.4%	-12.6%	-7.7%	0.5%
	RSC Disabled	0.0%	5.9%	9.6%	15.1%	19.2%	24.3%	29.8%	34.3%	37.4%
Sterling	RSC Enabled	0.0%	7.4%	7.2%	4.8%	1.8%	-1.5%	-8.6%	-14.2%	-14.9%
	RSC Disabled	0.0%	5.8%	10.1%	16.1%	20.4%	26.5%	30.2%	33.6%	37.6%

The longitudinal accelerations for the SC enabled SIS test series were observed to decrease upon activation of the SC systems as compared to the SC disabled test series (see the figures). After activation, the longitudinal acceleration was observed to be similar based on the type of control system installed on the vehicle. Table 5.8 shows that at approximately four seconds after SC activation, the RSC systems allowed the Freightliner and Sterling tractors to accelerate indicated by the positive numbers 0.031 g and 0.017 g. The longitudinal acceleration of the ESC equipped Volvo and Freightliner tractors remained negative at -0.081 g to -0.073 g. The longitudinal acceleration at the event point is relatively small and the change calculated from that value was not considered to be meaningful. This resulted from conducting the SIS tests at a constant 30 mph speed. In this case, the acceleration at the event point (0.0s) will be approximately zero and therefore the change calculated from a number close to zero can show large percentage changes even though the actual numbers for all increments and conditions are relatively small. Therefore, the table does not include the calculation of change from the event point.

Table 5.8. Table shows the average longitudinal acceleration and the change in longitudinal acceleration at specific time increments referenced from the engine torque reduction event for the 4 vehicles with ESC enabled and disabled.

Vehicle	Condition Tested	Series Mean Long. Accel. (g) 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	-0.037	-0.048	-0.051	-0.058	-0.063	-0.066	-0.071	-0.074	-0.073
	ESC Disabled	-0.011	-0.011	-0.010	-0.013	-0.016	-0.011	-0.004	0.006	0.005
Freightliner	ESC Enabled	-0.030	-0.059	-0.070	-0.073	-0.077	-0.083	-0.083	-0.082	-0.081
	ESC Disabled	-0.020	-0.025	-0.026	-0.029	-0.030	-0.031	-0.034	-0.036	-0.039
Freightliner	RSC Enabled	-0.022	-0.125	-0.126	-0.155	-0.134	-0.106	-0.018	0.028	0.031
	RSC Disabled	-0.015	-0.017	-0.020	-0.023	-0.024	-0.025	-0.029	-0.031	-0.032
Sterling	RSC Enabled	-0.034	-0.104	-0.104	-0.141	-0.143	-0.141	-0.147	-0.060	0.017
	RSC Disabled	-0.020	-0.021	-0.027	-0.029	-0.034	-0.037	-0.046	-0.048	-0.060

Table 5.9. Table shows the average yaw rate and the change in yaw rate at specific time increments referenced from the engine torque reduction event for the 4 vehicles with ESC enabled and disabled.

Vehicle	Condition Tested	Series Mean Yaw Rate (deg/sec) 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	22.1	22.5	22.6	22.8	23.1	23.3	23.5	24.0	24.2
	ESC Disabled	23.3	23.8	24.3	24.7	25.0	25.2	25.5	25.8	26.3
Freightliner	ESC Enabled	18.3	18.9	19.5	20.0	20.5	20.9	21.2	21.6	21.9
	ESC Disabled	18.6	19.5	20.4	21.2	21.9	22.6	23.4	24.1	24.9
Freightliner	RSC Enabled	16.4	17.2	17.5	17.7	17.6	17.5	17.6	18.4	19.4
	RSC Disabled	16.2	17.0	17.7	18.5	19.4	20.1	20.9	21.8	22.6
Sterling	RSC Enabled	17.5	18.6	19.3	19.8	20.3	20.1	19.8	19.5	19.6
	RSC Disabled	17.6	18.4	19.4	20.4	21.2	22.3	23.2	24.1	25.0
Vehicle	**Condition Tested**	**Change In Yaw Rate From Time 0**								
Volvo	ESC Enabled	0.0%	2.1%	2.4%	3.2%	4.4%	5.6%	6.2%	8.5%	9.5%
	ESC Disabled	0.0%	2.1%	4.1%	6.0%	7.2%	8.1%	9.2%	10.5%	12.6%
Freightliner	ESC Enabled	0.0%	3.4%	7.0%	9.9%	12.2%	14.5%	16.4%	18.4%	20.0%
	ESC Disabled	0.0%	4.9%	9.7%	14.0%	17.8%	21.6%	26.0%	29.8%	33.8%
Freightliner	RSC Enabled	0.0%	5.0%	7.1%	8.2%	7.5%	6.9%	7.6%	12.4%	18.8%
	RSC Disabled	0.0%	5.0%	9.7%	14.6%	20.0%	24.7%	29.6%	34.8%	40.1%
Sterling	RSC Enabled	0.0%	6.5%	10.1%	13.4%	15.8%	14.8%	13.1%	11.4%	12.3%
	RSC Disabled	0.0%	5.0%	10.2%	15.9%	20.7%	27.0%	32.3%	37.4%	42.4%

For yaw rate, the figures of SIS test data show that once the SC systems activated, the vehicle's yaw rate for the SIS test series began to decrease and/or remained below the disabled series tests for the duration of the maneuver. This observation is quantified in Table 5.9. At time zero, the range of mean yaw rate at SC activation for the SIS enabled test series was observed to be between 16.4 and 22.1 deg/sec. The table shows that four seconds after the SC systems activated, the mean yaw rate ranged from 19.4 to 24.2 deg/sec while the disabled test series yaw rates ranged from 22.6 to 26.3 deg/sec. The change associated with the 4.0 second time increment shows that the SC enabled series mean yaw rates increased by 9.5% to 20.0% while the disabled series yaw rates were observed to increase by 12.3% to 42.2%.

Table 5.10. Table shows the average roll angle and the change in roll angle at specific time increments referenced from the engine torque reduction event for the Freightliner with ESC enabled and disabled.

Vehicle	Condition Tested	Series Mean Roll Angle (deg) 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	1.22	1.27	1.26	1.28	1.29	1.27	1.24	1.24	1.25
	ESC Disabled	1.22	1.27	1.26	1.30	1.33	1.32	1.34	1.30	1.35
Freightliner	ESC Enabled	0.79	0.75	0.82	0.82	0.85	0.93	0.90	0.91	0.94
	ESC Disabled	0.81	0.83	0.92	0.95	1.00	1.02	1.15	1.19	1.27
Freightliner	RSC Enabled	0.937	0.969	0.952	0.943	0.915	0.876	0.815	0.815	0.944
	RSC Disabled	0.730	0.742	0.754	0.815	0.862	0.915	0.937	0.977	1.106
Sterling	RSC Enabled	1.24	1.31	1.31	1.31	1.28	1.25	1.14	1.10	1.10
	RSC Disabled	1.29	1.35	1.44	1.55	1.63	1.71	1.80	1.85	1.93
Vehicle	**Condition Tested**	**Change In Roll Angle From Time 0**								
Volvo	ESC Enabled	0.0%	4.0%	2.7%	4.9%	5.8%	3.3%	1.6%	1.7%	1.9%
	ESC Disabled	0.0%	4.7%	3.8%	6.9%	9.0%	8.6%	10.3%	6.5%	11.0%
Freightliner	ESC Enabled	0.0%	-5.3%	4.5%	4.2%	7.5%	18.1%	14.7%	16.0%	19.7%
	ESC Disabled	0.0%	3.1%	14.1%	17.6%	24.4%	26.5%	42.2%	46.7%	57.1%
Freightliner	RSC Enabled	0.0%	3.4%	1.6%	0.6%	-2.4%	-6.5%	-13.0%	-13.1%	0.7%
	RSC Disabled	0.0%	1.6%	3.2%	11.6%	18.1%	25.3%	28.3%	33.8%	51.5%
Sterling	RSC Enabled	0.0%	6.3%	5.8%	5.7%	3.8%	1.0%	-8.0%	-11.1%	-10.9%
	RSC Disabled	0.0%	4.9%	11.9%	20.3%	26.4%	33.0%	39.6%	43.6%	49.9%

The figures of SIS test data show that once the SC systems activated, the vehicle roll angles for the SIS test series began to change from that observed for the disabled series tests for the duration of the maneuver. These observations are quantified in Table 5.10. At time zero, the range of mean roll angle at SC activation for the SIS enabled test series was observed to be between 0.79 and 1.24 degrees. The table shows that four seconds after the SC systems activated, the mean roll angle ranged from 0.94 to 1.25 degrees while the disabled test series roll angles ranged from 1.106 to 1.93 degrees. The change associated with the 4.0 second time increment shows that the SC enabled series mean roll angles changed by -10.9% to 19.7% while the disabled series roll angles were observed to increase by 11% to 57.1%.

Table 5.11. Table shows the average engine torque and the change in engine torque at specific time increments referenced from the engine torque reduction event for the 4 vehicles with ESC enabled and disabled.

Vehicle	Condition Tested	Series Mean Engine Torque (percent) 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	31.5	26.0	24.7	23.0	21.7	20.7	19.7	19.5	19.5
	ESC Disabled	45.5	45.7	48.5	46.7	47.5	51.5	57.5	63.0	66.3
Freightliner	ESC Enabled	18.8	10.3	8.2	6.5	5.7	5.0	4.7	5.5	5.8
	ESC Disabled	21.0	21.0	21.3	21.2	21.0	22.2	23.3	24.0	25.0
Freightliner	RSC Enabled	18.8	0.0	0.0	0.0	1.0	7.3	20.2	35.8	39.5
	RSC Disabled	21.3	20.8	20.7	20.7	20.8	21.3	21.2	21.5	21.5
Sterling	RSC Enabled	27.2	0.0	0.2	0.0	0.0	0.0	0.7	8.7	27.0
	RSC Disabled	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Vehicle	**Condition Tested**	**Change In Engine Torque From Time 0**								
Volvo	ESC Enabled	0.0%	-17.5%	-21.7%	-27.0%	-31.2%	-34.4%	-37.6%	-38.1%	-38.1%
	ESC Disabled	0.0%	0.4%	6.6%	2.6%	4.4%	13.2%	26.4%	38.5%	45.8%
Freightliner	ESC Enabled	0.0%	-45.1%	-56.6%	-65.5%	-69.9%	-73.5%	-75.2%	-70.8%	-69.0%
	ESC Disabled	0.0%	0.0%	1.6%	0.8%	0.0%	5.6%	11.1%	14.3%	19.0%
Freightliner	RSC Enabled	0.0%	-100.0%	-100.0%	-100.0%	-94.7%	-61.1%	7.1%	90.3%	109.7%
	RSC Disabled	0.0%	-2.3%	-3.1%	-3.1%	-2.3%	0.0%	-0.8%	0.8%	0.8%
Sterling*	RSC Enabled	0.0%	-100.0%	-99.4%	-100.0%	-100.0%	-100.0%	-97.5%	-68.1%	-0.6%
	RSC Disabled	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* A data collection error rendered vehicle communication bus data unusable for the Sterling with RSC disabled SIS test series.

The engine torque data from the SIS test series, shown in bottom left of Figure 5.2 through Figure 5.5, show some of the largest differences when comparing the SC enabled to disabled conditions. These changes are quantified in Table 5.11. The table shows the average engine torque output and the change in engine torque output at specific time increments referenced from the SC activation event for the four vehicles with SC enabled and disabled. At time zero, the range of mean engine torque at SC activation for the SIS test series was observed to be between 18.8 and 31.5 percent of rated output. For vehicles equipped with ESC, the table shows that four seconds after SC activated, the engine output had been reduced to 5.8 to 19.5 percent of rated output, versus the disabled tests that increased to 25.0 to 66.3 percent of rated output. In terms of relative change, at the 4.0 second increment, the ESC equipped vehicles were observed to have engine torque output reductions between 38.1 to 69.0 percent versus increases in engine torque output of 19.0 to 45.8 percent when the ESC was disabled.

The RSC equipped vehicles were observed to have engine torque reduced for shorter durations. After the vehicle's lateral dynamics were reduced to preprogrammed levels, the RSC system was observed to allow engine torque to build until the lateral dynamic thresholds were again reached, at which point the RSC system again intervened. This produced the seesaw pattern observed in the SIS test data for the two RSC equipped vehicles. So, for these two vehicles, the 4.0 second time increment after activation was not appropriate to show differences between the enabled and disabled test data since the RSC was not active and engine torque was allowed to resume driver demanded levels. For these vehicles, the 2.0 second increment was used to compare the enabled to disabled SIS tests. At 2.0 seconds, RSC had reduced engine torque to equal or less than 1.0 percent of rated output for both vehicles, while the disabled test (Freightliner only) showed that engine torque output was at 20.8 percent. In terms of relative change, the RSC enabled vehicles were observed to have engine torque reduced 94.7 to 100 percent at 2.0 seconds after activation, and the disabled test (Freightliner only) was -2.3 percent.

5.2.2 Determining RSM Amplitude From SIS Test Results

The SIS test results were used to estimate the steering wheel angle (SWA) needed to achieve a given level of lateral acceleration at 30 mph for each truck-tractor. This methodology was adapted for truck-tractor testing and was initially developed for NHTSA NCAP Fishhook testing [3], [11]. It was found to be an objective way of determining the steering inputs for other transient maneuvers; it adjusts or normalizes test severity for physical and dynamic differences that exist between vehicles and test surfaces. This section discusses how the SIS test results were used to determine the RSM Amplitude for each truck-tractor.

Researchers looked at several levels of lateral acceleration at which to extrapolate the SWA. Initial analyses investigated the SWA at 0.3 and 0.5 g of lateral acceleration. Ultimately, the SWA at 0.5 g of lateral acceleration was chosen because it was very similar to magnitudes used by drivers in previous maneuver development and it meant a larger input would be used so that less velocity\energy would be needed to challenge the stability of a truck-tractor. Additionally, the 0.5 g limit was selected because a truck tractor combination with a High CG is highly likely to experience roll instability at that level of lateral acceleration. From the SIS maneuver test results the SWA at 0.5 g was found to be different from tractor to tractor depending on the vehicle’s performance at quasi steady-state conditions. The following sub-sections present the results from the linear regression of lateral acceleration test data from SIS test maneuvers.

RSM magnitude calculation example: An example of the SIS data used to calculate the SWA at 0.5 g is shown in Figure 5.6. It shows each truck tractor’s lateral acceleration versus steering wheel angle from three separate SIS tests. Comparing one test from each of the three tractors shows that each has a different steering wheel angle to lateral acceleration relationship. The steepest data trace shown in black was produced with the Sterling 4x2 and the blue and red data traces that are close together were from the Volvo and Freightliner 6x4s. The stars in the figure represent the SC activation point as registered by the data acquisition system. For the Sterling, activation was observed at approximately 0.41 g with a steering input of ~140 degrees. The acceleration activation level for the Freightliner is nearly identical to that observed for the Sterling but required a larger steering input at ~170 degrees. The activation level for the Volvo shown in this example was approximately 0.55 g at ~220 degrees of steering input. For all three examples, lateral acceleration begins to level out or drop back after SC activation was registered.

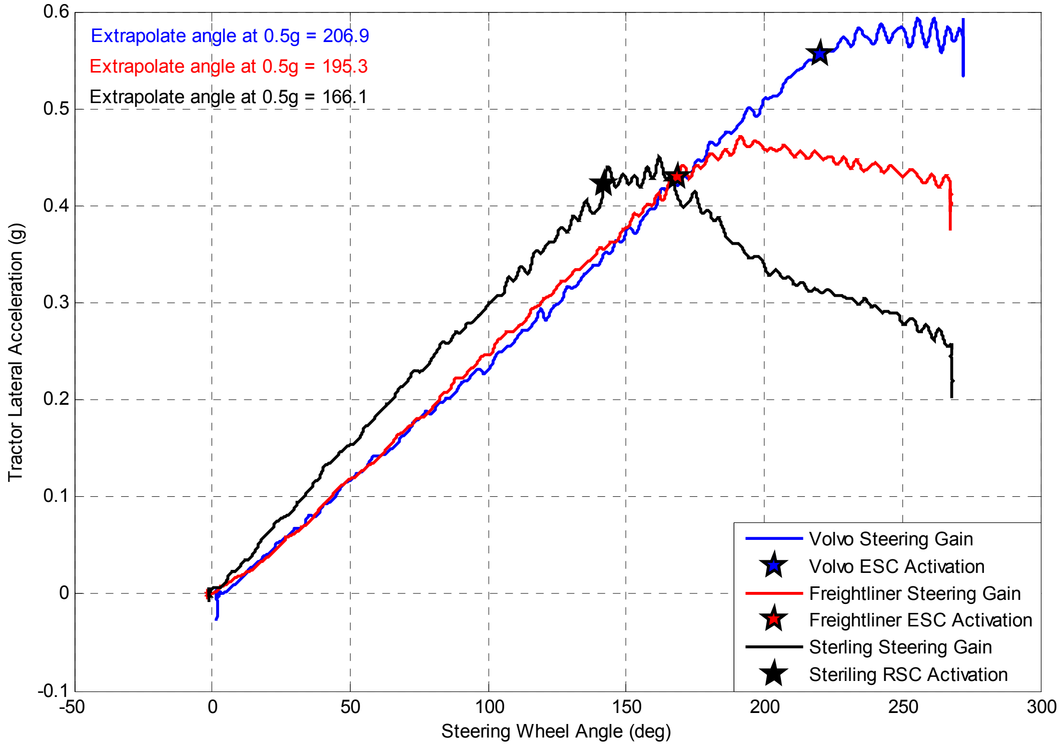


Figure 5.6. Graph shows tractor lateral acceleration versus steering wheel angle data from SIS tests conducted with three different tractors.

Because SC activation was observed before 0.5 g for two of the tractors, and because the vehicles' steering gains were linear for the region of 0.05 to 0.3 g, the steering wheel angle was extrapolated from these data to estimate what steering wheel angle would be required to achieve 0.5 g. The angles that were extrapolated from the data in Figure 5.6 are shown in the upper left hand side of the figure. They were 206.9, 195.3, and 166.1 degrees for the Volvo, Freightliner, and Sterling. Each value represents one of the six tests that were eventually averaged to determine the projected SWA at 0.5 g for each vehicle.

This methodology was applied to each SIS maneuver in a test series and the overall average magnitude to be used in the RSM was calculated using the following equation for each vehicle:

$$\delta^{Test} \cong \frac{\sum_{6}^{1} abs(\delta^{SIS}_{0.5G})}{6}$$

In the above equation, δ^{Test} is the average steering angle that was projected to generate 0.5 g of lateral acceleration, determined from the linear extrapolation of lateral acceleration to steering wheel angle data from six SIS maneuvers. Flow charts for the test procedures that were used to perform the SIS maneuver are provided in Appendix F.

Table 5.12 presents the resulting averaged steering angle magnitude used for all RSM tests for each vehicle, the range of extrapolated angles observed from SIS tests series and the range of observed R^2 statistic that were observed from the linear regression analyses. The average extrapolated SWA at 0.5 g for each vehicle were 199, 193, and 162 degrees.

Table 5.12. Table present the RSM Magnitudes extrapolated from SIS test results.

Vehicle	Average SWA at 0.5 g (Magnitude For RSM)	Range of Extrapolated Angles at 0.5 g	R^2 Range (From Linear Regression)
Volvo 6x4	199	187 – 208	0.996 – 0.999
Freightliner 6x4	193	185 – 202	0.998 – 0.999
Sterling 4x2	162	156 – 167	0.998 – 0.999

5.2.3 Results from Additional SIS Testing

Additional SIS test series were performed for each vehicle (SC enabled) periodically throughout the time required to complete the RSM test matrix. These additional tests were performed since the researchers and the agency had little experience with the performance of Class 8 truck tractors in the SIS maneuver. The researchers wanted to observe how the test results from SIS maneuvers changed and the implications to using the characterization maneuver to normalize steering wheel inputs.

Table 5.13 through 5.15 present the SIS test results from 10 test series with the Volvo, 11 series with the Freightliner and eight series with the Sterling. Each table presents the range of input speeds observed, the average extrapolated SWA at 0.5 g for each series, the range of extrapolated SWA, and the R^2 statistics that were obtained from the linear regression analyses. Additional subsections discuss the observed range of input speeds, the average SWA at 0.5 g, and the range observed for the R^2 statistic.

Table 5.13. Bobtail SIS tests results from the Volvo 6x4. Table shows the test series range of input speeds, average steering angle extrapolated at 0.5 g, the range of angles extrapolated at 0.5g and the R^2 statistic.

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 (6 tests)[1]	30.0 – 30.1	200	0.996 – 0.999
2 (15 tests)[2]	29.9 – 31.4	199	0.991 – 0.999
3 (6 tests)	30.1 – 30.8	200	0.997 – 0.999
4 (6 tests)	30.3 – 30.4	207	0.998 – 0.999
5 (6 tests)	30.5	201	0.999
6 (6 tests)[3]	30.5 – 30.6	229	0.998 – 0.999
7 (6 tests)	31.1 – 31.2	213	0.997 – 0.999
8 (6 tests)	30.4 – 30.6	219	0.975 – 0.989
9 (6 tests)	30.5 – 30.6	218	0.974 – 0.989
10 (6 tests)	30.4 – 30.5	209	0.997 – 0.999

[1] Driver controlled the throttle input. All other tests were performed using cruise control.
[2] Seven tests were conducted with driver controlled steering inputs and all others with a steering controller
[3] A new set of tires were installed prior to running this series of tests with the Volvo.

Table 5.14. Bobtail SIS tests results from the Freightliner 6x4. Table shows the test series range of input speeds, average steering angle extrapolated at 0.5 g, the range of angles extrapolated at 0.5 g and the R^2 statistic.

Vehicle: Freightliner 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)[1]	30.2 – 32.2	212	0.990 – 0.999
2 (16 tests)[2]	30.3 – 30.6	190	0.996 – 0.999
3 (6 tests)	30.1	199	0.998 – 0.999
4 (6 tests)	30.8	191	0.999
5 (6 tests)	30.4 – 30.5	199	0.999 – 1.000
6 (6 tests)	30.0 – 30.1	198	0.993 – 0.996
7 (6 tests)	29.6 – 29.7	199	0.999 – 1.000
8 (6 tests)[3]	29.9 – 30.0	206	0.999 – 1.000
9 (6 tests)	30.5	199	0.999 – 1.000
10 (6 tests)	30.4 – 30.5	189	0.999
11 (6 tests)	30.3 – 30.4	188	0.999

[1] Driver controlled the throttle input. All other tests were performed using cruise control.
[2] Six tests were conducted with driver controlled steering inputs and all others with a steering controller.
[3] Tests series 8 – 11 were conducted with an RSC controller.

Table 5.15. Bobtail SIS tests results from the Sterling 4x2. Table shows the test series range of input speeds, average steering angle extrapolated at 0.5 g, the range of angles extrapolated at 0.5g and the R^2 statistic.

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 – 30.9	161	0.998 – 0.999
2 (6 tests)	30.5 – 30.9	158	0.999
3 (6 tests)	30.2 – 30.6	162	0.998 – 0.999
4 (6 tests)	29.7 – 30.8	165	0.998 – 0.999
5 (6 tests)	30.3 – 30.7	161	0.998 – 1.000
6 (6 tests)	30.2 – 30.9	162	0.991 – 0.996
7 (6 tests)	30.3 – 30.8	161	0.998 – 0.999
8 (12 tests)	30.5 – 31.2	156	0.998 – 0.999

Range of input speeds: The target maneuver entrance speed used for all tests presented was 30 mph, and from test results the actual maneuver input speed reported was calculated from 0.5 seconds of vehicle speed data just prior to the initiation of the maneuver. From the above tables, the ranges of input speeds were very consistent from vehicle to vehicle. The highest SIS entrance speed was observed with the Freightliner at 32.2 mph versus the target speed of 30 mph. These series of tests were performed with a driver rather than cruise control. The initial test series with the Volvo and Freightliner were conducted with the driver manipulating the throttle input to maintain a constant speed of 30 mph for SIS tests. Subsequent testing with the cruise control set to approximately 30 mph improved the maneuver input speed repeatability and was more consistent at maintaining the input speed throughout the maneuver. The lowest entrance speed observed was 29.6 mph, which was also with the Freightliner.

Average of SWA at 0.5 g: The consistency of the average extrapolated SWA at 0.5 g was of particular interest due to its use as the SWA magnitude for the RSM. The SWA at 0.5 g extrapolated from the Volvo SIS data had the largest variation, as shown in Table 5.13. The average angle for that vehicle was the lowest for the second test series at 199 degrees and the largest for the sixth test series at 229 degrees. The sixth series of SIS tests was completed after a new set of OEM tires was installed. As the table shows, the sixth through tenth test series average SWAs at 0.5 g were larger than the first through the fifth series. However, the standard deviation when considering all series was only 10.23 degrees. Comparatively, the Freightliner average SWAs at 0.5 g were between 188 – 212 degrees and had a standard deviation of 7.4 degrees. The Sterling was observed to have the least amount of spread with the average SWA at 0.5 g between 156 – 165 degrees and a standard deviation of approximately 2.5 degrees.

Observed ranges of R^2 statistic: Since the SWA at 0.5 g was extrapolated from a first order line that approximates the lateral acceleration gain versus steering angle input through the range of 0.05 g – 0.3 g of lateral acceleration, how well that line fits the data was also of interest. To give a general idea of how well the linear fit approximates the data through the 0.05 – 0.3 g range, the R^2 statistic was calculated for each SIS test. The last column in the three tables presents the range of R^2 observed for each given SIS test series conducted. The Volvo had an overall range of R^2 between 0.974 and 0.999. The overall R^2 for the Freightliner ranged between 0.990 – 1.000 and the overall R^2 for the Sterling ranged between 0.991 – 1.000. Given how close the observed R^2 values were to 1.0, the use of a first order linear fit through the 0.05 g – 0.3 g range was found to be a repeatable methodology for determining the SWA at 0.5g and validated the methodology's continued use for determining the magnitudes for objective test maneuvers.

5.2.4 Summary

The truck tractors and SC systems all responded similarly in the bobtail SIS test maneuver regardless of vehicle or type of SC system installed. As the steering input was increased in a slow linear manner, the system eventually activated and reduced engine torque output which in turn reduced the vehicle speed so that lateral acceleration was limited even as the radius of the vehicle was observed to continue to decrease. With SC enabled, none of the SIS tests resulted in understeer, oversteer or roll instability, while the SIS tests with SC disabled resulted in each tractor going into an understeer condition. Four seconds after SC activation, the input speed was observed to be reduced from the target MES of 30 mph by 12.4-27.2 percent. On average, lateral acceleration increased by no more than 6.2 percent and yaw rate no more than 20.0 percent. In comparison, tests with SC disabled showed that lateral acceleration was observed to increase by a minimum of 9.9% and yaw rate by 12.3%. These vehicle dynamics changes were a direct result of SC activation and were correlated in time to the SC systems' command to reduce engine output even though the driver was demanding more engine power to attempt to maintain 30 mph. At a minimum, the engine output torque was observed to be decreased by 38% versus a minimum 19 percent increase in engine output torque when the SC systems were disabled.

SIS test results were used to determine the steering wheel angle that would generate 0.5 g of lateral acceleration for each vehicle at traveling at 30 mph. The angles were calculated on a per vehicle basis. The linear range of lateral acceleration between 0.05 and 0.3 g was used to extrapolate the steering wheel angle at 0.5 g. The average steering wheel angle at 0.5 g for the Volvo 6x4 was 199 degrees. For the Freightliner 6x4 it was 193 degrees, and for the Sterling 4x2 it was 162 degrees. These steering wheel angles were used as the amplitudes for the RSM.

Additional SIS test series had MESs that ranged from 29.6-32.2 mph. For the Volvo 6x4 the steering wheel angles extrapolated for 0.5g ranged from 199-229 degrees and had a standard deviation of 10.2 degrees. The Freightliner 6x4 SWAs ranged from 188-212 degrees and had a standard deviation of 7.4 degrees. The Sterling 4x2 SWAs ranged from 156-165 degrees and had a standard deviation of 2.5 degrees. The R^2 statistic ranged from 0.974-1.000, which indicated the range of data used for the extrapolations was linear.

Results from the SIS test series confirmed the ability of the maneuver to characterize the linear dynamics of Class 8 tractors. The test results confirmed the maneuver's ability to normalize the steering inputs for the RSM, and the linearity of the range of data selected for extrapolation. From the range of speeds observed in SIS testing, a target entrance speed of 30 mph with a ±1.0 mph tolerance can be used for future SIS tests conducted to determine the RSM steering wheel angle magnitude.

5.3 Ramp Steer Maneuver Test Results

As previously mentioned, one of the main objectives of this research was to develop performance measures for assessing the roll stability of truck tractor combinations. From previous test data and maneuver development work, the SIS and RSM test maneuvers were determined to be objective maneuvers that could be refined to meet the agency's desire to have a test procedure and roll stability performance measures for SC equipped truck tractors. Specifically, roll stability performance measures could be developed from RSM test results since previous experience with the maneuver had shown a potential for a high degree of objectivity and discriminatory capability between SC and non-SC equipped vehicles. A test matrix was developed in which three truck tractors, four SC systems, six trailer combinations, and two loading conditions were tested with the RSM (test matrix presented in Table 5.1).

The test matrix also shows that each SC system was tested in three states. Those states were SC enabled, SC enabled without trailer brakes, and SC disabled. SC enabled is the condition in which the systems were designed to be operated from the manufacturer. The SC enabled with the trailer brakes disabled state entailed disconnecting the air brake service line between the tractor and trailer combination so that the SC system and vehicle combination could be tested without influence from differences in trailer brake performance. The SC disabled state required disconnecting the SC control module so that comparisons could be made back to the base vehicle without SC.

After completing this test matrix with the RSM, researchers then began to assess SC effectiveness using the RSM test data. The changes in MES at which instabilities were observed with and without SC were used to assess the effectiveness of the SC system installed on the vehicle. Test data were also used to help quantify how much SC was able to be effective. For instance, tests for a given MES were compared to observe how peak lateral acceleration was changed. This type of data analysis was then extended to observe the changes to peak yaw rate, deceleration, roll angle, and the reduction in speed at the end of the maneuver.

This section presents the results from the RSM testing. The RSM test series were conducted after completing the SIS test series and the SWAs at 0.5 g were determined. That methodology was presented in Section 5.2.2. The resulting RSM steering magnitude used for each of the vehicles was 193 degrees for the Freightliner 6x4, 199 degrees for the Volvo 6x4, and 162 degrees for the Sterling 4x2. This section was split by loading condition, with the High CG load condition results followed by the LLVW condition test results. All RSM tests were conducted by entering the maneuver one to two mph over the desired maneuver entrance speed, at which point the driver was instructed to release the throttle and disengage the clutch pedal. The vehicle would then coast down to the desired maneuver entrance speed at which point the RSM was initiated. Also note that all RSM tests were conducted with a left steering input. Prior testing for the vehicles in which both left and right maneuvers were conducted showed that the vehicles responded symmetrically. So, in the interest of saving time and keeping the test matrix size manageable, only left steering inputs were used for the RSM.

5.3.1 High CG Condition RSM Test Results

Using the steering wheel angle magnitudes presented in the previous section, the High CG load condition RSM test series were begun at 20 mph. Using the same steering magnitude, each subsequent test was increased by two mph until a MES of 50 mph was attained or instability was observed. If instability was observed, the previous test at which instability was not observed was re-tested. If instability was still not observed, subsequent test MESs were increased by one mph increments until instability was once again observed. This methodology was applied to all test series conducted with the High CG load condition, unless denoted otherwise[5]. A test series with all tractor/trailer combinations was conducted with SC enabled, SC without trailer brakes, and SC disabled. The test termination speeds are presented in Table 5.16 for all tractor/trailer combinations and SC conditions for the High CG load condition.

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[5] The Volvo 6x4 tractor in combination with the Fruehauf 53 foot box van and the 48 foot tandem axle Fruehauf flatbed trailer disabled test series were conducted in a prior year before development of RSM testing methodology used for the research presented in this report. However, researchers believe those test termination speeds reported are comparable for the SC disabled test condition.

Table 5.16. Test termination speed that resulted in 2.0 inches or more of wheel lift for the RSM. All tests were conducted with a High CG load condition (CG height> 75 inches).

Vehicle	Dry Box Van (mph)						Flatbed (mph)									Tanker (mph)		
	Fruehauf 53 ft.			Strick 53 ft.			Fontaine 48 ft. Spread Axle			Fruehauf 48 ft. Tandem Axle			Great Dane 28 ft. Control Trailer			Heil 42.5 ft. 9200 Gal.		
	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked
2006 Freightliner 6x4 ESC	27 T	32 T	32 T	28 T	40 T	36 T	26 D	32 D	29 D	27 D	32 D	29 D	28 D/T	32 D/T	31 D/T	28 T	35 T	32 T
2006 Freightliner 6x4 RSC	27 T	35 T	33 T	28 T	35 T	34 T	26 D	31 D	30 D	27 D	33 D	32 D	28 D/T	34 D/T	33 T	28 T	35 T	34 T
2006 Volvo 6X4 ESC	30[2] T	38 T	37 T	31 T	42 T	41 T	28 D	38 D	37 D	30[1] D	35 D	33 D	30 T	41 T	39 T	30 T	40 T	38 T
2008 Sterling 4x2 RSC	28 T	32 T	31 T	28 T	28 T	28 T	25 D	25 D	25 D	26 D	28 D	26 D	28 T	30[3] T	30[3] T	28 T	28 T	28 T

[1] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 183 degrees.
[2] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 170 degrees.
[3] Test series were conducted with the vehicle in neutral rather then depressing the clutch pedal for the duration of the maneuver.
D = Wheel lift observed at tractor drive wheels
T = Wheel lift observed at trailer wheels

Table 5.16 presents the lowest target MES that resulted in 2.0 inches or more of wheel lift during the RSM test series with a High CG load. The first column shows the truck tractor and from left to right, the combinations are grouped by type of trailer. Dry box vans are first, then flatbeds and finally the tanker. Within each group, the individual trailers are broken out by manufacturer and under each trailer the individual results in combination with each tractor and stability control condition are shown. For the stability control condition under each trailer, the test termination speeds are shown for the SC disabled condition first, followed by SC enabled and then SC enabled with an unbraked trailer. Under each speed value reported are the letters “T,” “D,” or “D/T” indicating the axle(s) at which wheel lift was observed. “T” indicates wheel lift was observed at the trailer axle(s), “D” indicates wheel lift was observed at the tractor drive axle(s) and “D/T” indicates that wheel lift was observed at both the tractor drive axles and the trailer axles.

Wheel Lift Results Overview

The results in Table 5.16 indicate that there were no instances showing a dis-benefit to the test termination speeds from the SC systems, whether enabled or enabled without the trailer brakes. For the 6x4 truck tractor/trailer combinations, the MES at which wheel lift was observed was improved for all High CG test series conducted when SC was both enabled and enabled without the trailer brakes. For the 4x2 tractor/trailer combinations, no improvement in MES was observed with SC enabled in three of the trailer combinations, and only a modest improvement in MES with the other three trailer combinations was observed. The most improvement in test termination MES was always observed with the SC systems enabled for each combination. This makes sense since testing with an unbraked trailer reduces the number of brakes the SC systems could use to reduce the vehicle speed and hence the tipping forces acting on the test units.

Without stability control, the truck tractors were observed to produce wheel lift with MESs that ranged between 25-31 mph. With SC enabled and the unbraked trailers, the test termination MESs ranged between 25-41 mph. For this test condition the net increase in test termination speed over the disabled test condition was observed to be between 0-10 mph. With SC enabled the test termination speeds ranged between 25 – 42 mph. For this test condition the net increase in test termination speed over the disabled test condition was observed to be between 0-12 mph.

Comparing the results for ESC and RSC shows that ESC had the largest improvements in test termination MESs observed. The range of test termination MESs for truck-tractors equipped with ESC enabled were between 29 – 42 mph. This nets a 4 – 12 mph increase over the SC disabled test condition results. The range of test termination MESs for truck tractors equipped with RSC enabled were between 25 – 35 mph. This nets a 0 – 8 mph increase over the SC disabled test condition results.

Wheel Lift Results by Truck Tractors

Freightliner 6x4 with ESC: From Table 5.16, the Freightliner with SC disabled produced wheel lift with MESs that were between 26 – 28 mph. When the tractor was tested with the ESC system enabled with the unbraked trailer, wheel lift was observed at MES(s) between 29 – 36 mph. The net increase in test termination speed was observed to be between 2 – 8 mph. When tested with the ESC system enabled, the MESs observed to produce wheel lift ranged between 32 – 40 mph. This resulted in a 5 – 12 mph net increase in test termination speed over the SC disabled test condition. The net benefits to test termination speed from allowing the trailer to be braked were observed to be between 0 – 4 mph.

Freightliner 6x4 with RSC: The Freightliner with SC disabled produced wheel lift with MESs that were between 26 – 28 mph. When the RSC system was installed and tested with the system enabled with the unbraked trailer, wheel lift was observed at MESs between 30 – 34 mph. The net increase in test termination speed was observed to be between 4 – 6 mph. When tested with the RSC system enabled, the MESs observed to produce wheel lift ranged between 31 – 35 mph. This resulted in a 5 – 8 mph net increase in test termination speed over the SC disabled test condition. The net test track performance gains in test termination speed from allowing the trailer to be braked were observed to be between 1 – 2 mph.

Volvo 6x4: The Volvo 6x4 with ESC disabled produced wheel lift with MESs that were between 28 – 31 mph. With its SC system enabled with the unbraked trailer test condition, wheel lift was observed for MESs between 33 – 41 mph. This equates to a net increase in test termination speed between 3 – 10 mph. With the system enabled, wheel lift was observed with MESs between 35 – 42 mph. This nets a 5 – 11 mph increase in test termination speeds over the disabled SC test condition. The net test track performance gains in terms of test termination speed from allowing the trailer to be braked were observed to be between 1 – 2 mph.

Sterling 4x2: The Sterling 4x2 with RSC disabled produced wheel lift with MES(s) that were between 25 – 28 mph. When the RSC system was enabled and tested with the unbraked trailers, the MESs observed to produce wheel lift ranged from 25 – 31 mph. For this condition the net increase to MES at which wheel lift was observed was between 0 – 3 mph. When the Sterling was tested with the RSC system enabled, the MESs observed to produce wheel lift ranged between 25 – 32 mph. For this test condition the net increase was observed to be 0 – 4 mph over the disabled test condition. The net increases in test termination speed from allowing the trailer to be braked were observed to be between 0 – 1 mph.

Wheel Lift Results by Trailer Type

While the main focus of this testing was centered on SC effectiveness and the development of a roll stability performance test for truck tractors, the agency was also interested to observe the differences between trailer types. At the time this research was conducted, little information was available to show if SC systems are beneficial on a wide range of trailer applications available to the industry. The test track results from this research indicated that there are clear roll stability improvements from the addition of SC systems to tractors in combination with any of the trailers tested. However, there were a few observed differences between the trailer types that were tested. Those differences are discussed. Additionally, only the results from the 6x4 configured vehicles were used to compare the different trailer types in the section below; the Sterling 4x2 is excluded.

Box Van Trailers: The test results presented in Table 5.16 show that the highest RSM MESs were attained with the Strick box van when considering data from all the truck tractor combinations with the High CG load condition. Combining results for both box van trailers, the margin of improvement to MES observed to produce wheel lift from the SC disabled to SC enabled with an unbraked trailer ranged between 5 – 10 mph. With the SC systems enabled, the margin increased slightly to 5 – 12 mph. Wheel lift was observed at the trailer wheels with the vehicles in combination with either of the box vans.

Long Flatbed Trailers: The test results from combinations with the 48-foot flatbeds were different from the longer, torsionally stiffer box vans. Wheel lift was now observed at the truck tractor drive wheels rather than at the trailer wheels. Also, the lowest RSM MESs to produce instability were observed with the long flatbeds. However, the margin of improvement to the MESs observed to produce wheel lift from SC disabled to SC enabled with an unbraked trailer ranged from 2 – 9 mph, which was very similar to the margins observed with the box vans. With the SC systems enabled, the observed range of improvement was increased to 5 – 10 mph.

Tanker Trailer: Like the box vans, wheel lift was observed at the trailer wheels for all combinations and conditions tested. The performance of the tanker was most similar to the box vans and can be observed by the margins of improvement in MESs that produced wheel lift. The margin of improvement to the MESs observed to produce wheel lift from SC disabled to SC enabled with an unbraked trailer ranged from 4 – 8 mph. With the SC systems enabled, the observed range of improvement was increased to 7 – 10 mph.

Short Flatbed Trailer: Interestingly, wheel lift was observed at multiple axle locations for combinations tested with the short Great Dane 28-foot flatbed. When in combination with the Freightliner, wheel lift was observed at both the tractor drive wheels and the trailer wheels. However, when in combination with the Volvo tractor, the wheel lift events were observed at the trailer wheels only. The margin of improvement to the MESs observed to produce wheel lift from SC disabled to SC enabled with an unbraked trailer ranged from 3 – 9 mph. With the SC systems enabled, the observed range of improvement was increased to 4 – 11 mph. The ranges of improvements to the MESs observed to produce wheel lift were within the ranges observed with the box vans, long flatbeds and tanker trailers.

Vehicle Dynamics Changes from SC Intervention

Test data were used to determine how the SC systems were improving the MESs at which wheel lift was observed and to get a general idea of what vehicle dynamics measures were the most affected by intervention from SC systems. For the RSM maneuver, the only available control strategy for the SC systems tested to improve stability was the application of one or more of the foundation brakes[6]. If SC applies the brakes, the combination vehicle's forward velocity is reduced. Then the lateral acceleration of the vehicle is reduced. The vehicle's lateral acceleration is related to the forward velocity and radius of the path ($Ay=V^2/R$). The production of lateral acceleration in the curve generates the tipping forces acting on the vehicle, and excessive lateral acceleration can lead to roll instability. By reducing the forward velocity, the SC systems were observed to change lateral accelerations, longitudinal accelerations, yaw rates, and roll angles to name a few measures.

The observed changes that resulted from SC activations were quantified by looking at the changes that occurred to the previously mentioned measures between the SC test conditions (disabled, enabled, enabled with unbraked trailer). Test data examples and tabular data are shown in the following sections for each of the truck tractors tested. This section focuses on the dynamic changes observed with each tractor in combination

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[6] The SC systems tested have the option to improve stability though engine torque reduction, engine braking, and/or application of one or more of the foundation brakes. Since the RSM is conducted in the clutch-in position, the ability of the SC system to use either engine torque reduction or engine braking are removed as options for stability improvement. The RSM methodology is intended to remove these intermediate steps to improve stability and aimed at evaluating the system's use of the foundation brakes.

with the 28-foot flatbed trailer. This decision was made because the SC systems were observed to increase the dynamic roll stability for all combinations of tractors/trailers tested and this section was intended to provide a general idea of the dynamic changes made by the SC systems to the test vehicles. From Table 5.16, the test results for RSM test termination speeds show that the test series conducted with the 28-foot control trailer were representative of the average increase in test termination speed from enabling SC systems.

As discussed above, this section focuses only on series conducted with the 28-foot flatbed trailer. To show the differences to dynamic measures from enabling SC systems these sections will compare three tests, one test each from the three SC test conditions tested. Although each series started with a test at 20 mph and was incrementally increased to the point that wheel lift was observed, a comparison between the three test conditions at 20 mph would not show significant differences, since at this speed the resulting dynamics are below the threshold that would activate SC. Therefore, in the interest of illustrating the differences between the three test conditions, the speed at which the series was terminated with the SC disabled were used. For example, the Volvo, in combination with the 28-foot flatbed trailer, with a High CG load, and with the SC system disabled, had a test termination speed of 30 mph. So, the three SC test conditions (disabled, enabled and enabled with an unbraked trailer) would be compared at the same MES of 30 mph for the Volvo 6x4/28-foot flatbed combination. Evaluations of all four SC systems were performed as described below.

<u>Volvo 6x4</u>: Figure 5.7 shows the RSM test data for the Volvo 6x4 in combination with the 28-foot flatbed trailer and a High CG load. The tests shown were all performed with a target MES of 30 mph. From left to right, and top to bottom, are the steering and speed input traces followed by truck tractor's lateral acceleration, longitudinal acceleration, yaw rate, roll angle and wheel lift (trailer wheels). All three SC test conditions are represented: red traces indicate SC was disabled, green traces indicate SC was enabled, and blue traces indicate that SC was enabled with an unbraked trailer. This figure format is used for all figures shown for each tractor and SC in this section.

In the figure, the SC disabled data trace for trailer wheel height shows that over two inches of wheel lift was observed for this MES. However, when the SC was enabled, wheel lift was no longer observed at this MES. The figure shows that the SC system intervention has changed the dynamics of the vehicle and improved the test outcome. Test data were compared at key times to quantify some of the dynamic changes observed from SC system activation and intervention. For comparison, the key time used to compare all three test conditions was the time at maximum wheel lift when SC was disabled (red trace). So, for these three tests, the time used for comparison was ~3.58 seconds. The values at 3.58 seconds for tractor speed, lateral acceleration, yaw rate, and roll angle for the three SC test conditions are compared in Table 5.17. The last column in the table shows the overall minimum longitudinal acceleration observed for each test condition. Below the values shown for the SC enabled with unbraked trailer and SC enabled test conditions are the changes observed from enabling the SC system. These values are expressed as the percentage change from the value observed with the system disabled.

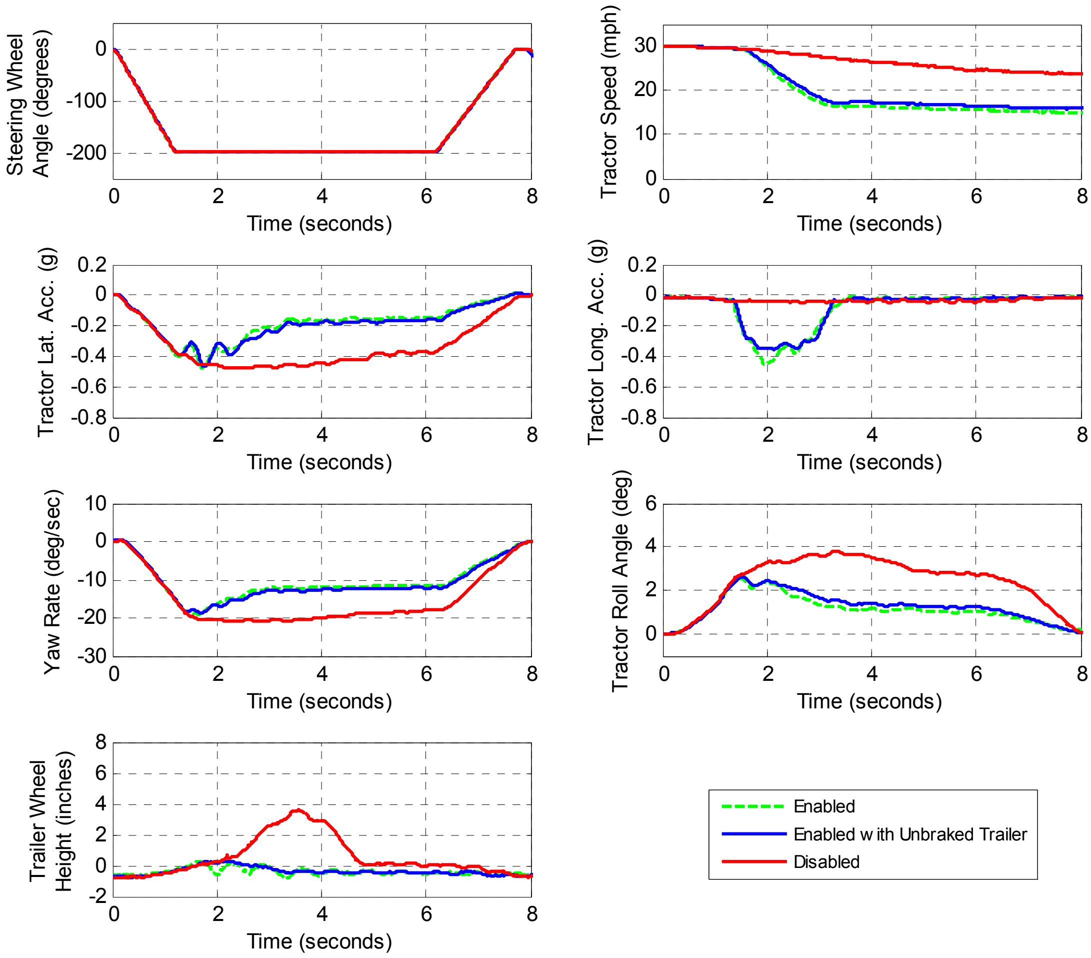

Figure 5.7. Graph shows test data from the Volvo 6x4 with 28 foot single axle flatbed trailer combination with the High CG load. Tests were performed at an approximate MES of 30 mph. The disabled test is shown in red, the SC enabled is shown in green, and the SC enabled with unbraked trailer is shown in blue.

From the table, the Volvo's SC system when enabled with an unbraked trailer was able to increase roll stability by reducing the vehicle's speed by 35.5%, which in turn reduced the lateral acceleration by 58.8%, the yaw rate by 36.5%, and the tractor roll angle by 61.6%. When the system was enabled, the reductions observed were even larger. The tractor's speed was reduced by 39.2%, the lateral acceleration by 62.9%, the yaw rate by 39.0%, and the roll angle by 69.5%. These changes are not surprising given the amount of braking commanded by the SC system. This amount of braking can be shown by the change in minimum longitudinal acceleration. The SC system increased the longitudinal deceleration from the base disabled condition by 422% when SC was enabled with an unbraked trailer and by 508% when SC was enabled. Thus, from the coasting deceleration of 0.07 g, the SC-commanded braking on the tractor increased the deceleration to 0.38 g and the addition of trailer braking increased the deceleration further to 0.44 g.

Table 5.17. Table presents the Volvo's lateral acceleration, yaw rate, and roll angle values and changes observed at the instant in the time history data (shown in Figure 5.7) that maximum wheel lift was observed with SC disabled. The minimum longitudinal acceleration observed is shown in the last column.

SC Condition	Speed (mph) [Change (%)]	Lateral Acceleration (g) [Change (%)]	Yaw Rate (deg/sec) [Change (%)]	Roll Angle (deg) [Change (%)]	Minimum Longitudinal Acceleration (g) [Change (%)]
ESC Disabled	26.9	-0.456	-20.4	3.62	-0.073
ESC Enabled with unbraked trailer	17.3 [-35.5%]	-0.188 [-58.8%]	-13.0 [-36.5%]	1.39 [-61.6%]	-0.381 [422%]
ESC Enabled	16.4 [-39.2%]	-0.169 [-62.9%]	-12.5 [-39.0%]	1.10 [-69.5%]	-0.444 [508%]

Freightliner 6x4 with ESC: Figure 5.8 shows RSM test data for the Freightliner 6x4 in combination with the 28-foot flatbed trailer and a High CG load. These data traces are from tests conducted with the ESC controller, and tests conducted with the Freightliner and the RSC controller are compared in the following section.

In the figure, the SC disabled data trace for trailer wheel height shows that wheel lift was observed for this MES of ~28 mph. However, when the SC system was enabled wheel lift was no longer observed at this MES. The SC system intervention has changed the dynamics of the vehicle and improved the test outcome. For comparison, the key time used to compare all three test conditions was the time at maximum wheel lift when SC was disabled (red trace), which was ~3.71 seconds.

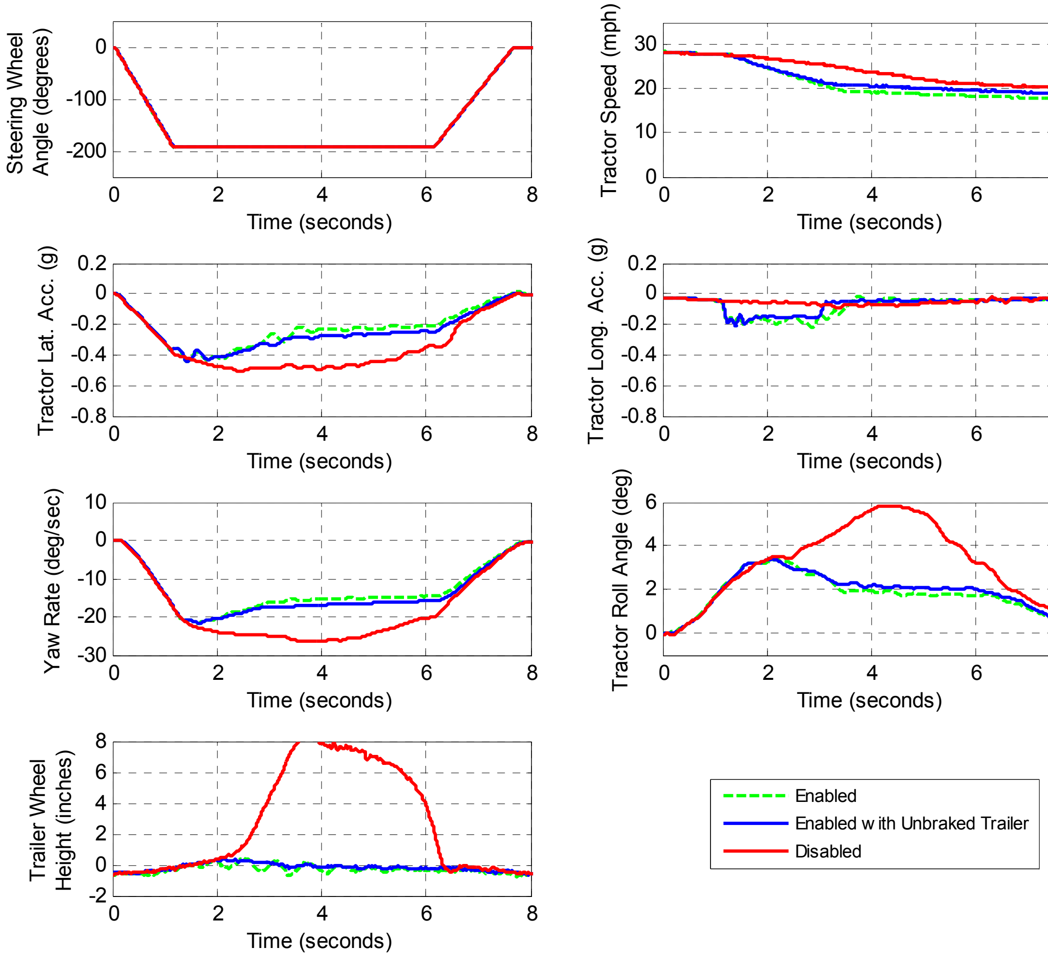

Figure 5.8. Graph shows test data from the Freightliner 6x4 (ESC Controller) with 28 foot single axle flatbed trailer combination with the High CG load. Tests were performed at an approximate MES of 28 mph. The disabled test is shown in red, the SC enabled is shown in green, and the SC enabled with unbraked trailer is shown in blue.

As shown in Table 5.18, the Freightliner's ESC system when enabled with an unbraked trailer was able to increase roll stability by reducing the vehicle's speed by 14.2%, which in turn reduced lateral acceleration by 40.5%, the yaw rate by 34.8%, and the tractor roll angle by 56.7%. When the system was enabled, the reductions observed were even larger. The tractor's speed was reduced by 20.4%, the lateral acceleration by 51.2%, the yaw rate by 39.9%, and the roll angle by 63.4%. These changes are not surprising given the amount braking commanded by the SC system. This amount of braking can be shown by the change in minimum longitudinal deceleration. The ESC system increased the longitudinal acceleration from the base disabled condition by 111% when ESC was enabled with an unbraked trailer and by 130% when ESC was enabled. Thus, from the coasting deceleration of 0.09 g, the SC-commanded braking on the tractor increased the deceleration to 0.19 g and the addition of trailer braking increased the deceleration further to 0.21 g. This is about one-half of the deceleration of the Volvo ESC tractor tested at a slightly higher speed of 30 mph, but was still sufficient to keep the vehicle roll stable.

Table 5.18. Table presents the Freightliner's (with ESC controller) lateral acceleration, yaw rate, and roll angle values and changes observed at the instant in the time history data (shown in Figure 5.8 that maximum wheel lift was observed with SC disabled. The minimum longitudinal acceleration observed is shown in the last column.

SC Condition	Speed (mph) [Change (%)]	Lateral Acceleration (g) [Change (%)]	Yaw Rate (deg/sec) [Change (%)]	Roll Angle (deg) [Change (%)]	Minimum Longitudinal Acceleration (g) [Change (%)]
ESC Disabled	24.3	-0.469	-26.2	5.30	-0.089
ESC Enabled with unbraked trailer	20.9 [-14.2%]	-0.279 [-40.5%]	-17.1 [-34.8%]	2.29 [-56.7%]	-0.188 [111%]
ESC Enabled	19.4 [-20.4]	-0.229 [-51.2%]	-15.8 [-39.9%]	1.94 [-63.4%]	-0.205 [130%]

Freightliner 6x4 with RSC: Figure 5.9 shows RSM test data for the Freightliner 6x4 in combination with the 28-foot flatbed trailer and the High CG load. These data traces are from tests conducted with the RSC controller.

In the figure, the RSC disabled data trace for trailer wheel height shows that wheel lift was observed for this MES of ~28 mph. However, when the RSC system was enabled wheel lift was no longer observed at this MES. Like the observations made with the ESC system, the RSC system's intervention improved roll stability by changing the vehicle's dynamic response for the given inputs. For comparison, the key time used to compare all three test conditions was the time at maximum wheel lift when RSC was disabled (red trace), which was ~3.71 seconds.

As shown in Table 5.19, the Freightliner's RSC system when enabled with an unbraked trailer was able to increase roll stability by reducing the vehicle's speed by 18.2%, which in turn reduced the lateral acceleration by 48.2%, the yaw rate by 39.7%, and the tractor roll angle by 61.6%. When the system was enabled, the reductions observed were even larger. The tractor's speed was reduced by 25.5%, the lateral acceleration by 57.4%, the yaw rate by 46.2%, and the roll angle by 69.4%. These changes are not surprising given the amount braking commanded by the SC system. This amount of braking can be shown by the change in minimum longitudinal acceleration. The RSC system increased the longitudinal deceleration from the base disabled condition by 191% when RSC was enabled with an unbraked trailer and by 284% when RSC was enabled. The resulting deceleration for this SC system fell in between the more aggressive Vovlo ESC system and the less aggressive ESC system installed on the Freightliner.

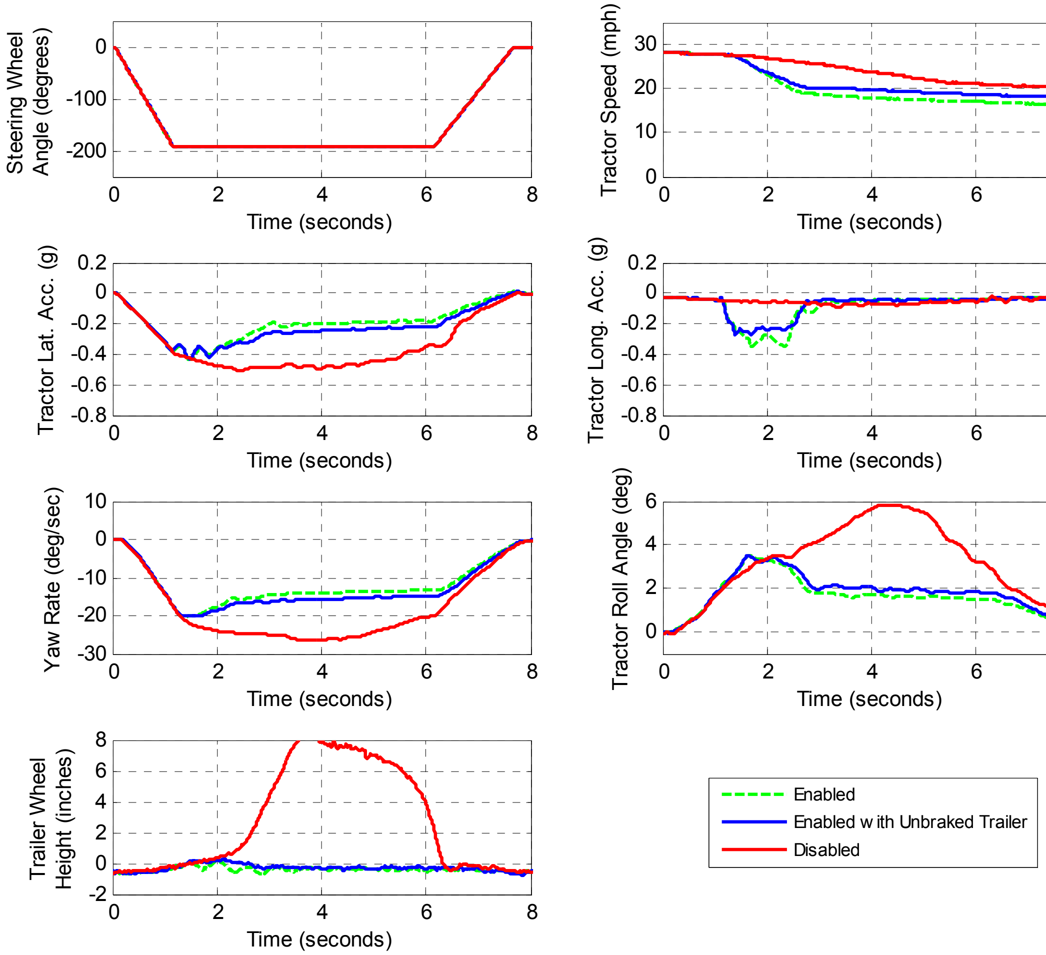

Figure 5.9. Graph shows test data from the Freightliner 6x4 (RSC Controller) with 28-foot single axle flatbed trailer combination with the High CG load. Tests were performed at an approximate MES of 28 mph. The disabled test is shown in red, the SC enabled is shown in green, and the SC enabled with unbraked trailer is shown in blue.

Table 5.19 Table presents the Freightliner's (with RSC controller) lateral acceleration, yaw rate, and roll angle values and changes observed at the instant in the time history data (shown in Figure 5.9) that maximum wheel lift was observed with SC disabled. The minimum longitudinal acceleration observed is shown in the last column.

SC Condition	**Speed (mph) [Change (%)]**	**Lateral Acceleration (g) [Change (%)]**	**Yaw Rate (deg/sec) [Change (%)]**	**Roll Angle (deg) [Change (%)]**	**Minimum Longitudinal Acceleration (g) [Change (%)]**
RSC Disabled	24.3	-0.469	-26.2	5.30	-0.089
RSC Enabled with unbraked trailer	19.9 [-18.2%]	-0.243 [-48.2%]	-15.8 [-39.7%]	2.04 [-61.6%]	-0.259 [191%]
RSC Enabled	18.1 [-25.5%]	-0.200 [-57.4%]	-14.1 [-46.2%]	1.62 [-69.4%]	-0.342 [284%]

<u>Sterling 4x2</u>: Figure 5.10 shows RSM test data for the Sterling 4x2 in combination with the 28-foot flatbed trailer and the High CG load. In the figure, the RSC disabled data trace for trailer wheel height shows that wheel lift was observed for this MES of ~28 mph. However, when the RSC system was enabled wheel lift was no longer observed at this MES. Like the observations made with the previous tractors and SC systems, the Sterling's RSC system intervention improved roll stability by changing the vehicle's dynamic response to the RSM. For comparison, the key time used to compare all three test conditions was the time at maximum wheel lift when RSC was disabled (red trace), which was ~3.50 seconds.

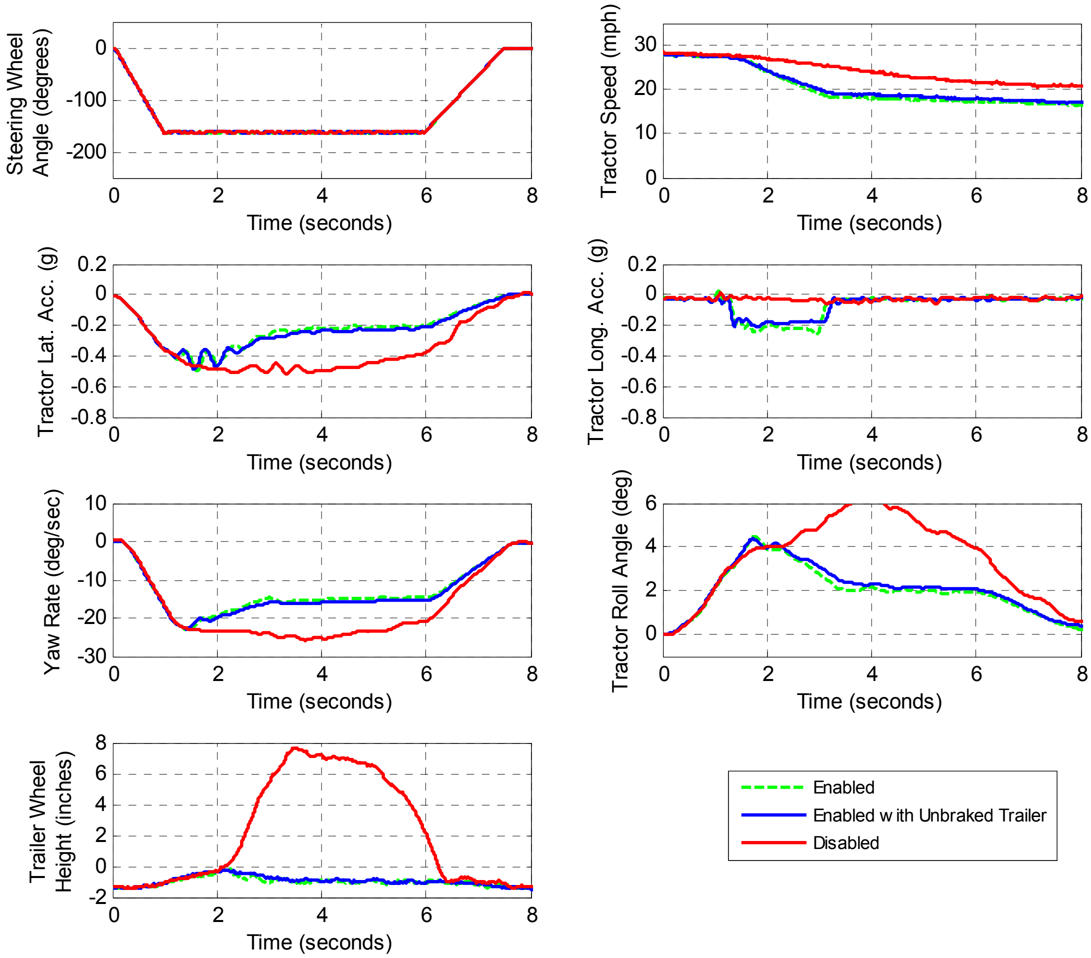

Figure 5.10. Graph shows test data from the Sterling 4x2 (RSC Controller) with 28-foot single axle flatbed trailer combination with the High CG load. Tests were performed at an approximate MES of 28 mph. The disabled test is shown in red, the SC enabled is shown in green, and the SC enabled with unbraked trailer is shown in blue.

As shown in Table 5.20, the Sterling's RSC system when enabled with an unbraked trailer was able to increase roll stability by reducing the vehicle's speed by 24.5%, which in turn reduced the lateral acceleration by 46.6%, the yaw rate by 34.3%, and the tractor roll angle by 59.2%. When the system was enabled, the reductions observed were even larger. The tractor's speed was reduced by 27.2%, the lateral acceleration by 47.5%, the yaw rate by 38.1%, and the roll angle by 65.1%. These changes are not unexpected given the amount braking commanded by the SC system. This amount of braking can be shown by the change in minimum longitudinal acceleration. The ESC system increased the longitudinal deceleration from the base disabled condition by 186% when ESC was enabled with an unbraked trailer and by 230% when ESC was enabled. Thus, this system produced decelerations that were slightly higher than for the Freightliner equipped with the ESC system.

Table 5.20. Table presents the Sterling's lateral acceleration, yaw rate, and roll angle values and changes observed at the instant in the time history data (shown in Figure 5.10) that maximum wheel lift was observed with SC disabled. The minimum longitudinal acceleration observed is shown in the last column.

SC Condition	Speed (mph) [Change (%)]	Lateral Acceleration (g) [Change (%)]	Yaw Rate (deg/sec) [Change (%)]	Roll Angle (deg) [Change (%)]	Minimum Longitudinal Acceleration (g) [Change (%)]
RSC Disabled	25.0	-0.455	-24.9	5.85	-0.079
RSC Enabled with unbraked trailer	18.9 [-24.5%]	-0.243 [-46.6%]	-16.3 [-34.3%]	2.39 [-59.2%]	-0.226 [186%]
RSC Enabled	18.2 [-27.2%]	-0.239 [-47.5%]	-15.4 [-38.1%]	2.04 [-65.1%]	-0.261 [230%]

5.3.2 LLVW Condition RSM Test Results

The LLVW load conditions were tested to observe the performance changes made by the SC systems at lighter loading conditions as compared to the High CG load for multiple trailers. SC systems estimate the mass being pulled by the truck tractor and then use that estimate to adjust the SC systems' strategy to improve stability and reduce nuisance system activations for unloaded or lightly-loaded tractors. This is an important part of the control system, since truck tractors are meant to transport a wide range of payloads. As its mass is either increased or decreased, the vehicle's behavioral thresholds can be significantly changed. Performing the RSM with the truck tractor/trailer combinations loaded to the LLVW condition provided the researchers with insight into these changes to the control strategy and vehicle thresholds. It should be noted that additional research was performed detailing each truck tractor's response to incremental increases in loading with a single trailer and two maneuvers. This work was performed to define SC activation thresholds across a wide range of loads. Results from those test series are presented in Section 5.4.

This section presents RSM test results from the four truck tractors and the six trailer combinations with the LLVW load conditions. The overall results for the LLVW load are shown in Table 5.21. The table presents the end result of each test series. That section is then followed by more detailed comparisons for each vehicle. For this load condition the RSM tests were performed for the SC enabled with an unbraked trailer[7] test condition only.

Results Discussion Overview

Similarly to the High CG load RSM test series, the LLVW load condition RSM test series were begun at 20 mph with each subsequent test increased by 2 mph until a MES of 50 mph was attained or instability was observed. If instability was observed, the previous test at which instability was not observed was re-tested, and if instability was still not observed, subsequent test MES(s) were increased by one mph increments until instability was once again observed. This methodology was applied to all test series conducted with the LLVW load. The test termination speeds and conditions are presented in Table 5.21 for all tractor/trailer combinations and the LLVW load.

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[7] LLVW load configuration RSM tests were conducted with SC enabled and with unbraked trailer only. LLVW configurations RSM's for the SC disabled and SC enabled test conditions were not performed. This was due to the large size of the test matrix, and the desire to keep needed to test manageable. Also, the main objectives of this research were to observe SC effectiveness with high C.G. load configurations and develop objective RSC test methodology and performance criteria. Therefore, the researchers reduced the test matrix by evaluating the LLVW configuration in the SC enabled with unbraked trailer condition only.

Table 5.21. Table presents the test termination conditions.

Vehicle	LLVW Load Condition (SC enabled only, unbraked trailer)					
	Dry Box Van		Flatbed			Tanker
	Fruehauf 53 ft.	Strick 53 ft.	Fontaine 48 ft. Spread Axle	Fruehauf 48 ft. Tandem Axle	Great Dane 28 ft. Control Trailer	Heil 42.5 ft. 9200 Gal.
2006 Freightliner 6x4 ESC	TC	TC	TC	TC	TC	TC
2006 Freightliner 6x4 RSC	35.4 mph Articulation Angle 39.4°	37.3 mph Articulation Angle 43.4°	35.4 mph Articulation Angle 44.8°	39.4 mph Articulation Angle 76.1°	TC	TC
2006 Volvo 6X4 ESC	TC	TC	TC	TC	TC	47.4 mph T/D ~ 2.0 inches
2008 Sterling 4x2 RSC	35.4 mph Articulation Angle 30.4°	41.5 mph Articulation Angle 27.6°	34.3 mph Articulation Angle 46.9°	38.3 mph Articulation Angle 29.9°	TC	40.4 mph Articulation Angle 37.6°

D = Wheel lift observed at tractor drive wheels
T = Wheel lift observed at trailer wheels
TC = Test Complete up to a MES of 50 mph

Table 5.21 presents the lowest MES that resulted in 2.0 inches or more of wheel lift, or the MES that resulted in oversteering and engagement of the safety cables limiting the tractor-trailer articulation angle, for the RSM test series conducted with a LLVW load. The first column shows the tractor and from left to right the combinations were grouped by type of trailer. Dry box vans are first, then flatbeds and finally the tanker. Within each group the individual trailers are broken out by manufacturer and under each trailer the individual results in combination with each tractor are shown. The letters “T” or “D” or “D/T” indicate which axle(s) the wheel lift were observed. “T” indicates wheel lift was observed at the trailer axle(s), “D” indicates wheel lift was observed at the tractor drive axle(s) and “D/T” indicates that wheel lift were observed at both the tractor drive axles and the trailer axles. Tests that resulted in safety mitigated articulation angles are denoted with the maximum angle displayed below the MES. Test complete (TC) indicates the maneuver was performed to 50 mph without an observed instability.

The following sections discuss individually, the two different types of instabilities observed and briefly discusses results by truck-tractor, then by trailer type and lastly followed up by a summary.

Observation of Wheel lift

A lone test series, conducted with the Volvo 6x4 in combination with the Heil Tanker and the LLVW load resulted in wheel lift. When tested with a target maneuver entrance speed of 47 mph more than 2.0 inches of wheel lift was observed at the trailer axles. Test data are shown for this test in the following sections. Other instances of wheel lift were observed, however, after data reduction and filtering, it was determined that the measured wheel heights did not exceed 2.0 inches. These instances were observed with the maximum RSM MES of 50 mph. Therefore, the series were considered completed and denoted as “TC” or Test Complete in Table 5.21.

Comparatively, the observation of wheel lift greater than 2.0 inches dropped to one instance out of 24 test series conducted with the LLVW conditions from 24 out of 24 test series when conducting test series with the High CG load (comparing only the SC with an unbraked trailer RSM test series). Interestingly, none of the test series conducted with RSC equipped truck tractors were observed to result in wheel lift. However, some of those series did result in tractor oversteer and engagement of the safety cables.

Observation of Tractor Oversteer and Safety Limited Articulation Angles

Nine of the LLVW RSM test series conducted were ended because the tractor went into an oversteer condition and the safety cables[8] limiting articulation angle were engaged, as shown in Table 5.21. This compares to the wheel lift results presented in the previous section where only one instance of wheel lift was observed for the series conducted with the LLVW load condition. That lone observation was limited to the Volvo/Tanker combination. For the test series that engaged the safety cables, the range of maximum articulation angles observed is quite large and was between 27.6 to 76.1 degrees. Typically, when preparing to test the target allowable articulation angle was set near 45 degrees. However, there were certain combinations that had to be limited to less than 45 degrees to assure that enough clearance was provided between the safety roll bar mounted behind the cab of the truck and the trailer. Other combinations exceeded 45 degrees because the safety cables were not adjustable and were fixed in length. The 76.1 degree articulation angle was measured after incorrect length cables were installed for the test series conducted with the Freightliner 6x4 with the Fruehauf 48-foot tandem axle flatbed trailer.

Though a wide range of allowable articulation angles were utilized, the RSM entrance speed at which the vehicle combinations engaged the safety cables were observed to be similar. From Table 5.21, the minimum MES to result in engagement of safety cables ranged between 34.3 – 41.5 mph. Interestingly, none of the tests series conducted with ESC equipped tractors resulted in engagement of the safety cables.

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[8] The safety cables are driver safety devices that are also intended to prevent damage to the tractor or trailer from a jackknife event. These safety devices work by limiting articulation angle between the tractor and trailer.

Results by Truck Tractor

Freightliner 6x4 with ESC: The Freightliner 6x4 truck tractor when equipped with the ESC controller in combination with all of the trailers reached the maximum RSM MES of 50 mph and was denoted as "TC" or test complete in Table 5.21. Test data from all six test series with a MES of 50 mph are presented Figure 5.11 through Figure 5.14. Figure 5.11, from left to right, and top to bottom, shows the time history data of steering wheel angle, tractor speed, tractor lateral acceleration, tractor longitudinal acceleration, tractor yaw rate, drive axle slip angle, articulation angle, and trailer axle wheel height. Figure 5.12 presents for those same tests, the time history data of the steering wheel angle, tractor speed, left steer axle brake pressure, right steer axle brake pressure, left drive axle brake pressure, and right drive axle brake pressure. Figure 5.13 shows the time history data of the gladhand pressure that applies brake pressure at the trailer axles. This figure is mainly shown to illustrate that even though the trailer air brake service line was disconnected for all these test series, the SC system was commanding the trailer brakes to be applied in response to the RSM maneuver.

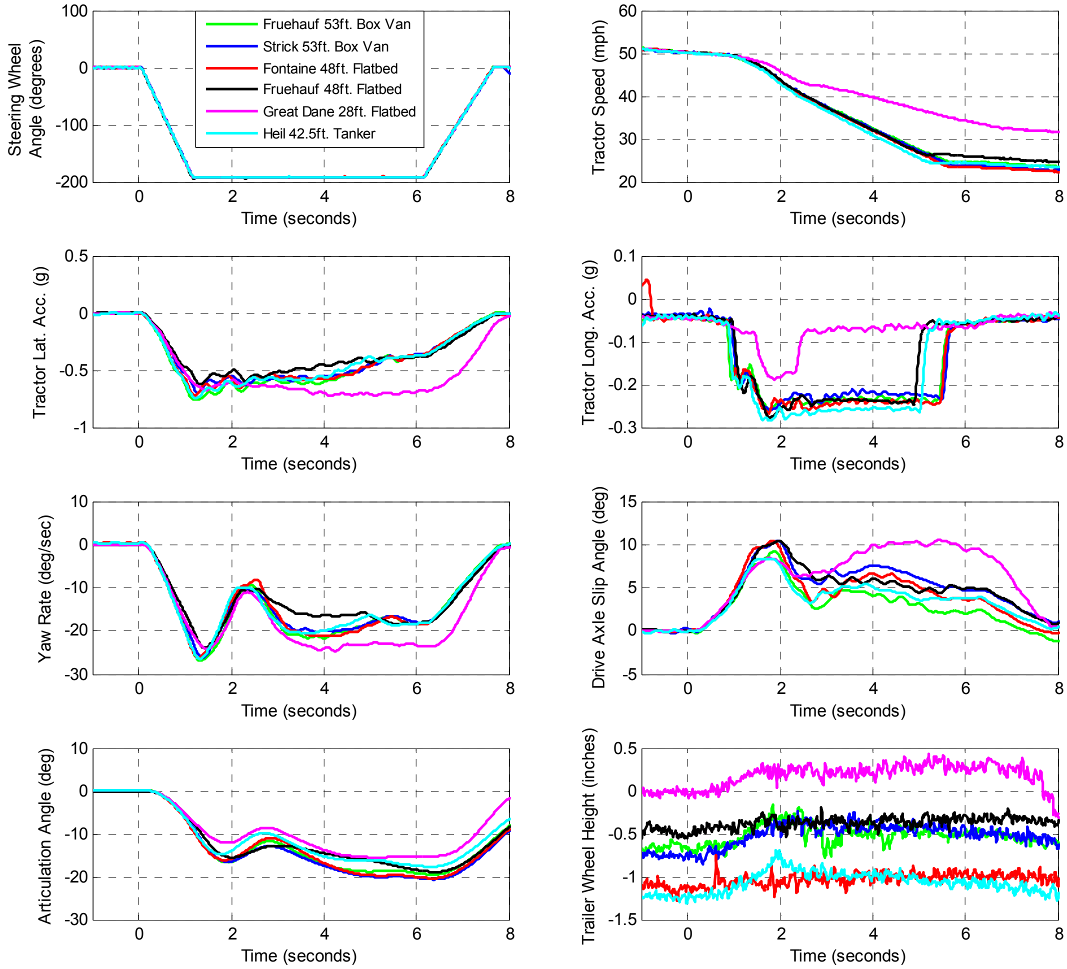

Figure 5.11. Graph shows RSM test data from the Freightliner 6x4 (ESC controller) when combined with the six different trailers and the LLVW load condition. All tests presented were conducted at maximum target MES of 50 mph.

Figure 5.12 shows that the Freightliner's ESC system used different side-to-side brake pressures to apply moments at the wheels of the truck tractor. For all tests shown, those moments and forces can be observed by looking at the large change to the tractor's longitudinal acceleration at approximately 1.0 seconds after the beginning of the ramp steer input (1.5 seconds with the Great Dane 28-foot flatbed). While the tractor's lateral acceleration was still building at that time, it does peak and then gradually degrades over time until approximately 3.0 seconds. During this time period yaw rate also peaks and then is reduced by more than one-half and then begins to recover. This is also similar to what was observed with the calculated drive axle slip angles. These changes to yaw rate and side slip (reductions between 1.5 – 3.0 seconds) were caused by the ESC system's control and application of the foundation brakes on the tractor. These effects are also evident in the calculated tractor-trailer articulation angle. The articulation angle peaks at 2.0 seconds and then is degraded back to 9 – 15 degrees at 3.0 seconds. The test data show that articulation angles were clearly less than the allowable limits set with the articulation-limiting safety cables. The trailer wheel height test data shows that the wheels remained well below 2.0 inches.

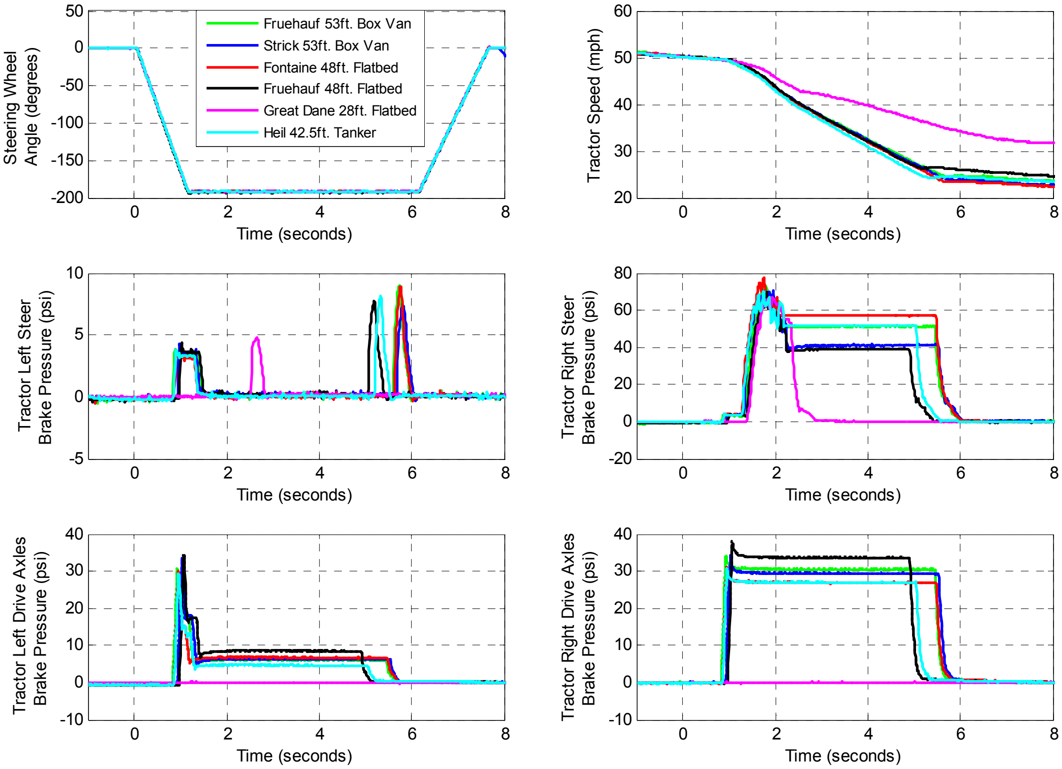

Figure 5.12. Graph shows more RSM test data from the Freightliner 6x4 (ESC controller) when combined with the six different trailers and the LLVW load condition. All tests presented were conducted at maximum target MES of 50 mph.

For the Freightliner, ESC RSM test data shown in Figure 5.11 through Figure 5.14, the ESC applied the foundation brakes and then reductions in lateral acceleration, yaw rate, side slip, and articulation angles were observed. These changes improved the overall stability of the tractor-trailer combinations. Given the magnitude of the changes to yaw rate, it is interesting to note that upon investigating flag data collected from the ESC controller that both the RSC and YSC algorithms were commanding brake pressure during that time (approximately 1.5 – 2.25 seconds).

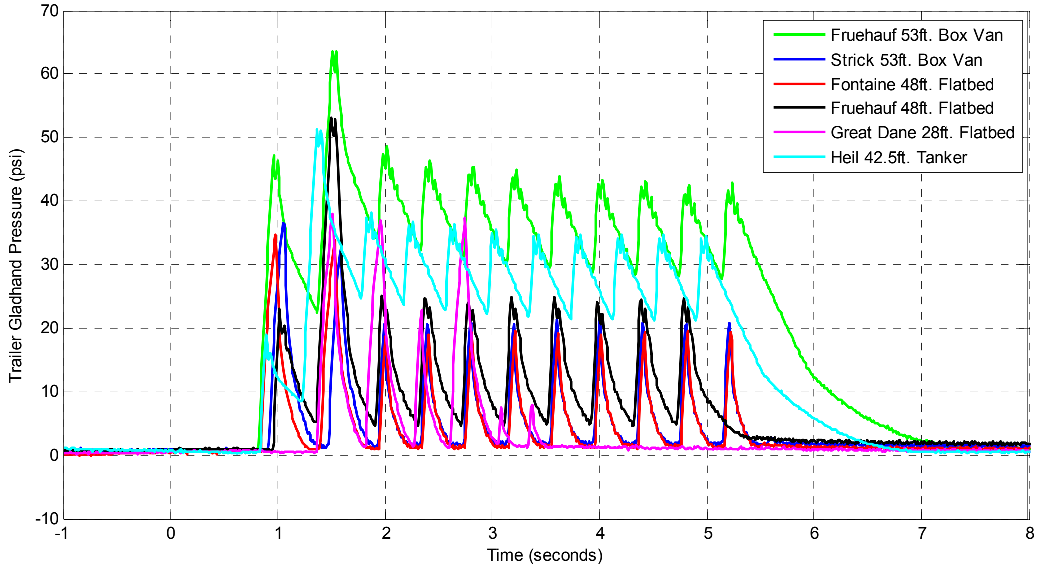

Figure 5.13. Graph shows more RSM test data from the Freightliner 6x4 (ESC controller) when combined with the six different trailers and the LLVW load condition. All tests presented were conducted at maximum target MES of 50 mph. Although the trailer service line was disconnected, the ESC system was commanding application of the trailer brakes as shown by the trailer gladhand pressure signal.

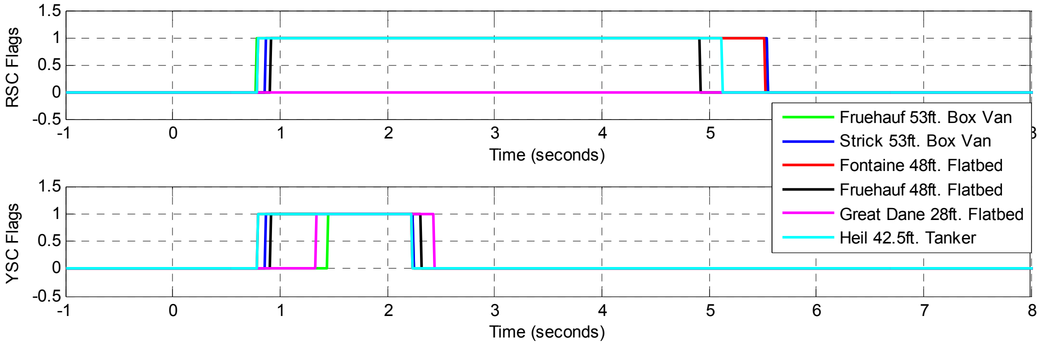

Figure 5.14. Graph shows more RSM test data from the Freightliner 6x4 (ESC controller) when combined with the six different trailers and the LLVW load condition. Graph shows that both roll and yaw stability algorithms were commanding and/or applying foundation brake pressure.

<ins>Freightliner 6x4 with RSC</ins>: After installing the RSC controller in the Freightliner and completing the LLVW RSMs, differences in performance were observed that contrasted with data collected with ESC. Test results in Table 5.21 show that the Freightliner with the ESC system was able to complete all test series to a MES of 50 mph. With the RSC controller installed, the Freightliner completed two RSM test series to 50 mph. The four series that did not reach an MES of 50 mph all were observed to go into a tractor

oversteer condition and engage the articulation-limiting safety cables at speeds that ranged between 35.4 – 39.4 mph. Figure 5.15 shows the RSM test data from the Freightliner equipped with the RSC controller and the six trailers tested in the LLVW load condition. Figure 5.15, from left to right, and top to bottom, shows the time history data of steering wheel angle, tractor speed, tractor lateral acceleration, tractor longitudinal acceleration, tractor yaw rate, drive axle slip angle, articulation angle, and trailer axle wheel height. Figure 5.16 presents for those same tests, the time history data of the steering wheel angle, tractor speed, left steer axle brake pressure, right steer axle brake pressure, left drive axle brake pressure, and right drive axle brake pressure.

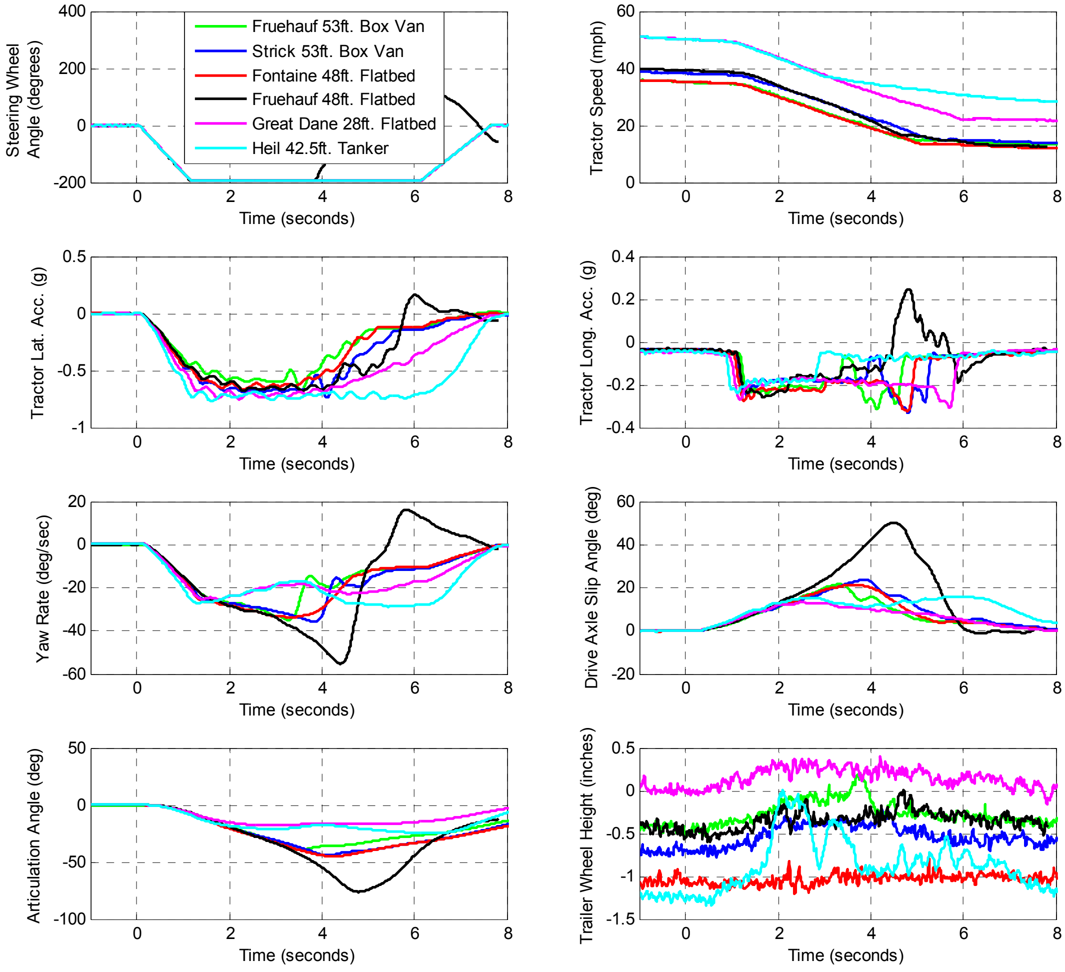

Figure 5.15. Graph shows test data from the Freightliner 6x4 (RSC controller) with the six different trailer combinations with LLVW load condition.

In the figures, the tests shown were conducted with a target MES between 35 – 50 mph. When the Freightliner (RSC) was combined with the 28-foot flatbed and the tanker, the RSM test series was completed up to a speed of 50 mph. Tests shown with a MES less than 50 mph represent the lowest MES at which the combinations were observed to engage the safety cables.

The test data shows that the truck tractor when combined with the tanker and the short 28-foot flatbed generated more lateral acceleration in comparison to the other combinations. Although those two combinations had larger peak lateral accelerations, the yaw rate and side slip data show that they had smaller peak values compared to the other four combinations. From Figure 5.16, the applications of pressure at the drive axle brakes were similar for all the combinations. Though the RSC system was applying differential (side-to-side) braking at the tractor's drive axles for those four combinations, the test speed and RSM inputs overwhelmed the stabilizing forces and moments applied by the RSC system. The differential braking can be observed in Figure 5.16, which also shows that the brakes on the steer axle are not applied (the RSC system does not have the ability to apply the steer axle brakes). However, the RSC system is commanding pressure to be applied to the trailer brakes as shown in Figure 5.17. The unbraked trailer had the added affect of pushing the tractor around. Had the trailer been allowed to contribute brake forces as commanded by the RSC system the tractor's yaw rates, it is possible that the rear axle slip angles and tractor-trailer articulation angles would have been reduced and higher MESs would have been observed.

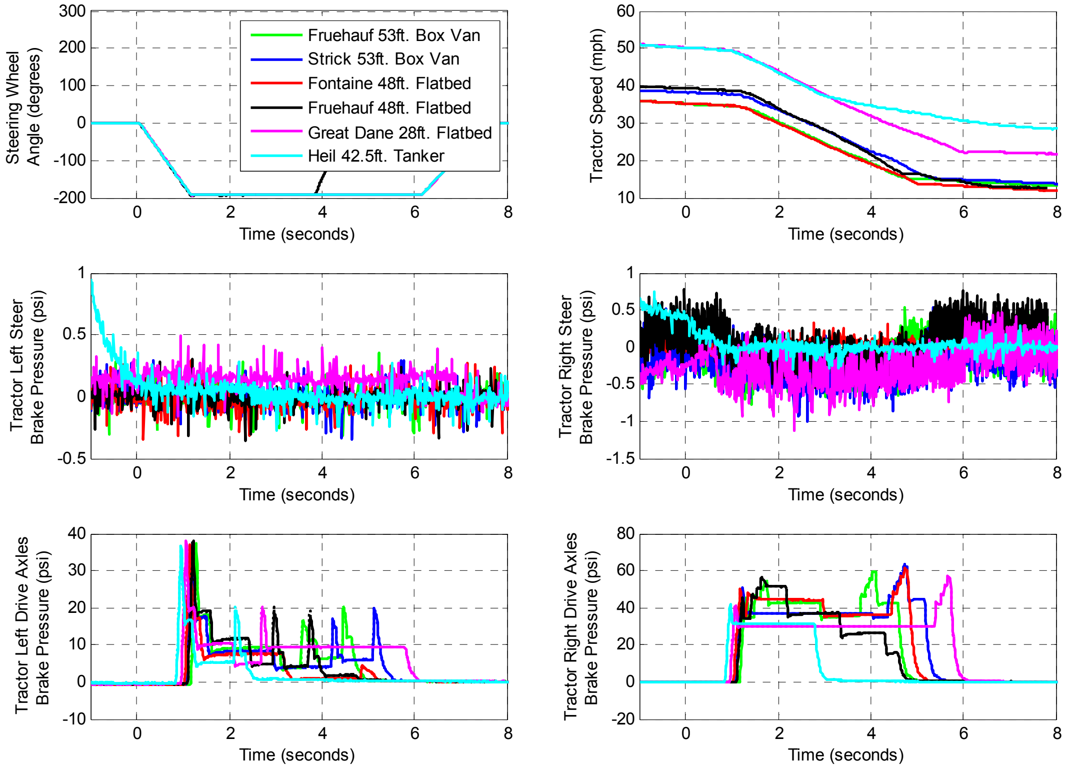

Figure 5.16. Graph shows more test data from the Freightliner 6x4 (RSC controller) with the six different trailer combinations with LLVW load condition.

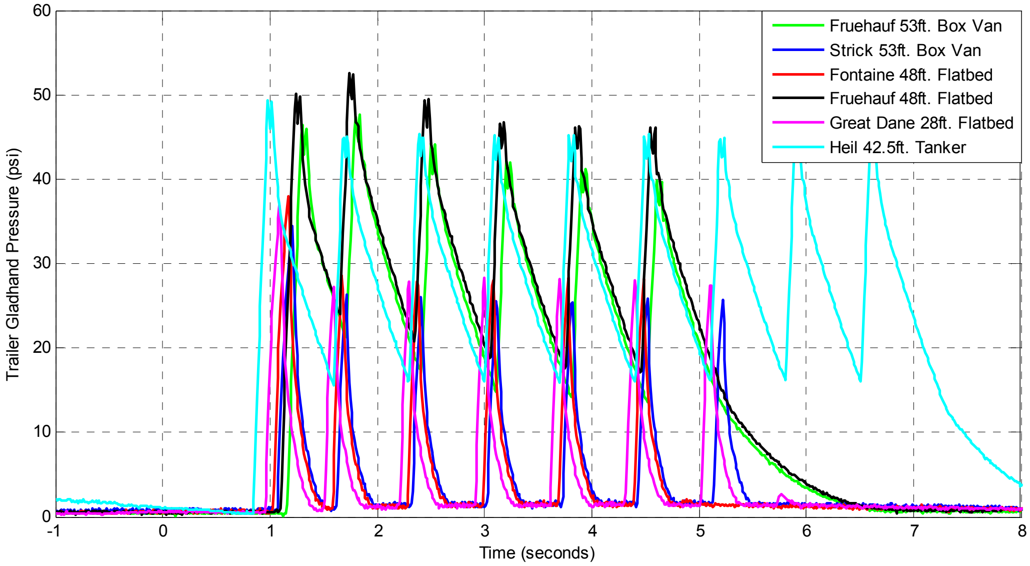

Figure 5.17. Graph shows more test data from the Freightliner 6x4 (RSC controller) with the six different trailer combinations with LLVW load condition.

Volvo 6x4: Five of the six trailer combinations with the Volvo 6x4 attained the MES of 50 mph. Test data from each combination are shown in Figure 5.18. Although test data exist in two-mph increments up to 50 mph, the figure shows only the results for tests completed at the maximum attained maneuver entrance speed.

In the figure, from left to right, top to bottom, are the time history data of steering wheel angle, tractor speed, tractor lateral acceleration, longitudinal acceleration, yaw rate, drive axle slip angle, hitch articulation angle, and the left side trailer wheel height. For the Volvo/tanker combination, as the MES was increased the amount of wheel lift observed at the trailer axles also increased and that test series was terminated at a MES of 47 mph due to ~2.00 inches of wheel lift. The Volvo 6x4's measured lateral acceleration was very similar for all of the trailer combinations shown. With the similarities in lateral acceleration, it is interesting to note the observable differences in yaw rate, articulation angle, and drive axle side slip angle among the different trailers.

Figure 5.19 presents for those same Volvo 6x4 tests, the time history data of the steering wheel angle, tractor speed, left steer axle brake pressure, right steer axle brake pressure, left drive axle brake pressure, and right drive axle brake pressure. Figure 5.20, shows the time history data of the gladhand pressure that applies brake pressure at the trailer axles. This figure is mainly shown to illustrate that even though the brake trailer service brake air line was disconnected for all these test series, the ESC system was commanding the trailer brakes to be applied in response to the RSM maneuver.

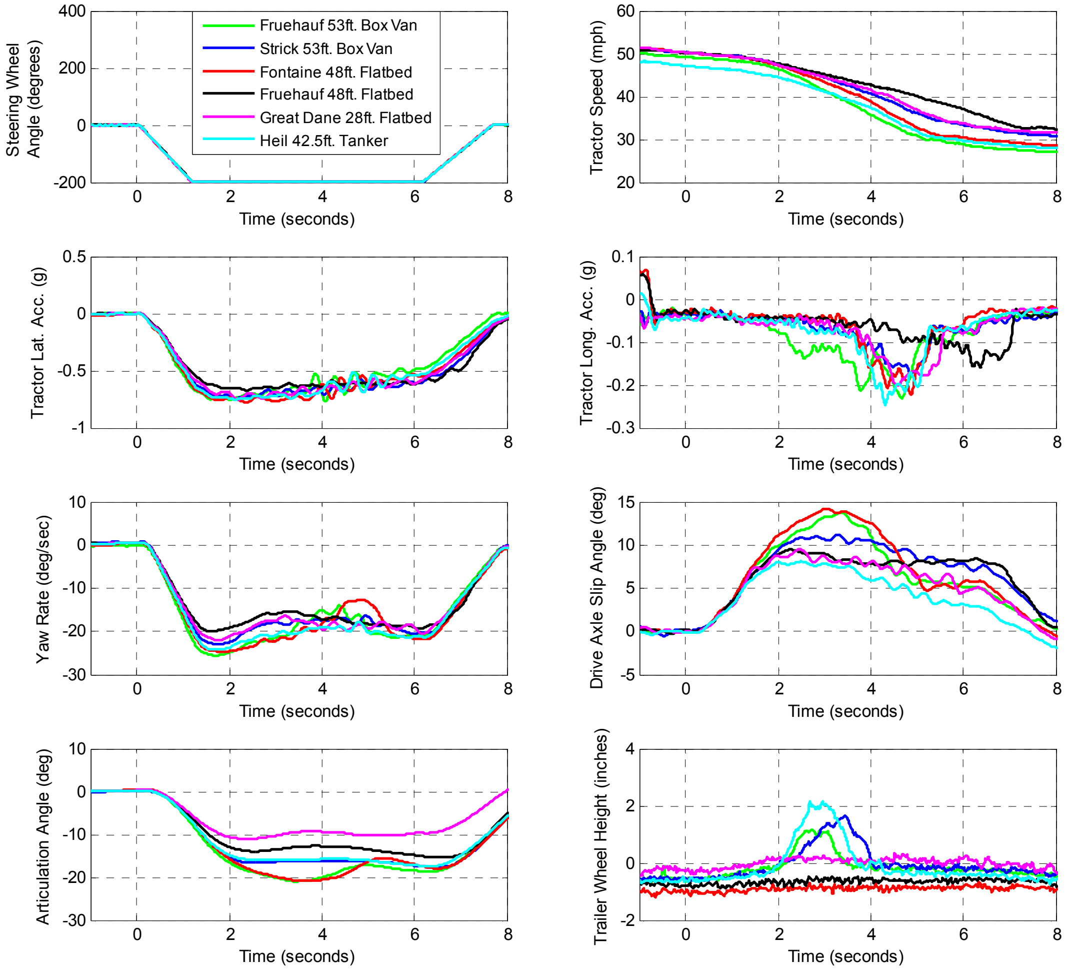

Figure 5.18. Graph shows more RSM test data from the Volvo 6x4 when combined with the six different trailers and the LLVW condition. All tests presented were the performed at the maximum attained maneuver speed from each test series.

Figure 5.19 shows that the Volvo's ESC system used different side-to-side brake pressures to apply moments at the wheels of the tractor. For all tests shown, those moments and forces can be observed by looking at the large change to the truck tractor's longitudinal acceleration between 2.0 – 4.0 seconds after the beginning of the steer input. The tractor's lateral acceleration was peaking in that window of time and upon SC activation lateral acceleration gradually degraded over time. Yaw rate peaked just prior to the window and after being reduced upon SC activation, it begins to recover at about 5.0 seconds. Even though yaw rate peaked early, the calculated drive axle slip angles shows that the tractor's lateral sliding velocity peaked in the 2.0 – 4.0 second window. The reductions to yaw rate and side slip (between 2.0 – 4.0 seconds) were caused by the ESC system's control and application of the foundation brakes on the tractor. These effects also show up in the calculated articulation angle and are especially pronounced for the Volvo/Fruehauf 53-foot box van and the Volvo/Fontaine 48-foot flatbed combinations. The articulation angle peaks at 3.0 seconds and then is degraded back to ~15 degrees at 5.0 seconds. The test data show that the articulation angles were clearly less than the allowable limits set with the articulation-limiting safety cables. With the exception of the Volvo/tanker combination, the trailer wheel heights remained below 2.0 inches.

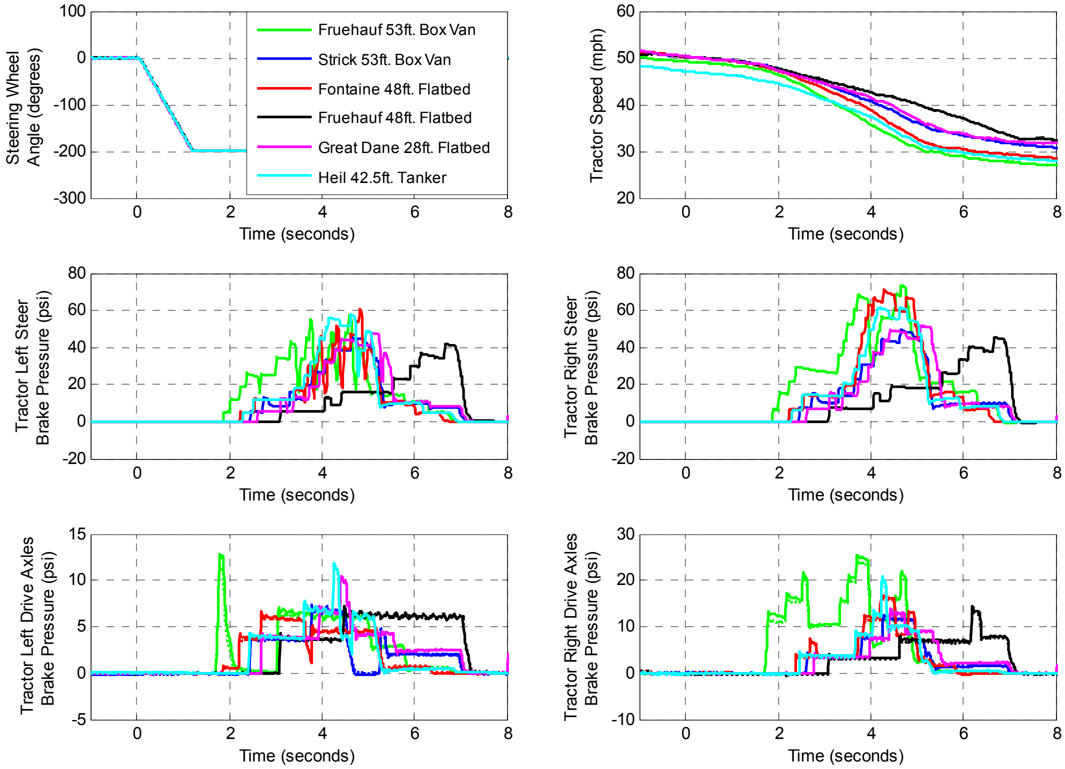

Figure 5.19. Graph shows test inputs and brake pressures for the steer and drive axles from the Volvo 6x4 combined with the six different trailer and the LLVW load condition. These data traces are from the same tests shown in Figure 5.18.

Figure 5.21 shows that the Volvo's activations of the ESC system were coming from the roll stability portion of the algorithm. The figure shows that the ESC system recognized the dynamic event inside the 1.5 to 2.5 second window. The brake pressure data in Figure 5.19 and Figure 5.20 show that brake applications soon followed the recognition of the dynamic event. The data show that the magnitude of the applications to the trailer glad-hand pressure were larger than those applied at any of the wheel ends of tractor. Had the trailer brakes been connected, it is likely that this would have further improved the yaw stability of the vehicle by acting as an anchor or tensor to stretch the combinations out.

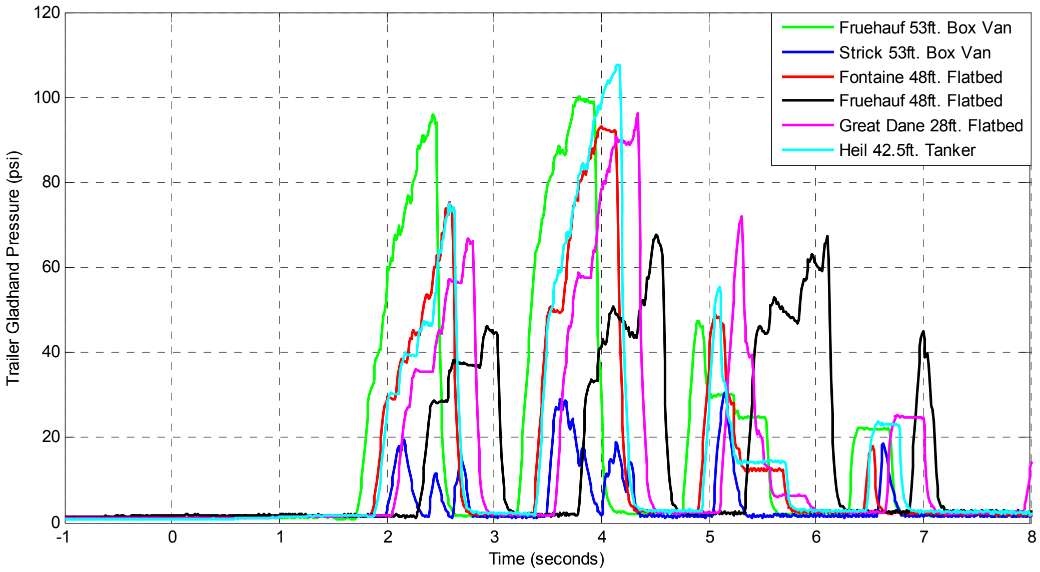

Figure 5.20. Graph shows more RSM test data from the Volvo 6x4 when combined with the six different trailers and the LLVW loading condition. These data traces are from the same tests shown in Figure 5.18. Although the trailer service line was disconnected, the ESC system was commanding application of the trailer brakes as shown by the trailer glad-hand pressure signal.

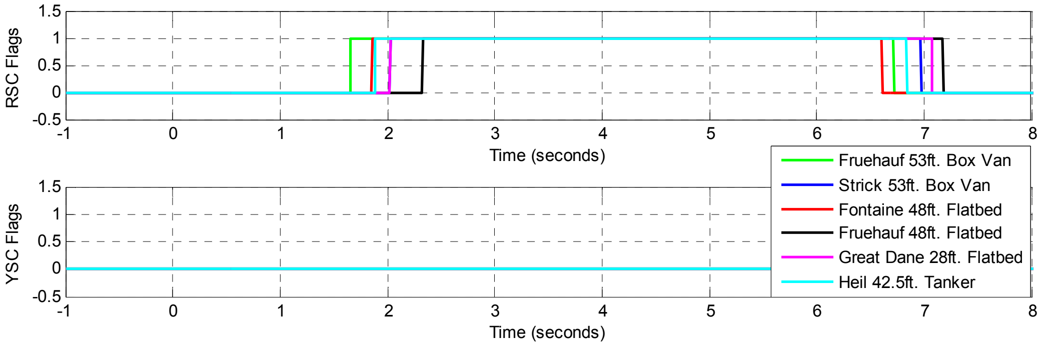

Figure 5.21. Graph shows more RSM test data from the Volvo 6x4 when combined with the six different trailers and the LLVW loading condition. These data traces are from the same tests shown in Figure 5.18. Graph shows that the roll stability portion of the algorithm was commanding and/or applying foundation brake pressure.

Sterling 4x2: One of the six trailer combinations with the Sterling 4x2 attained an MES of 50 mph. As shown in Table 5.21, the Sterling 4x2 in combination with the 28-foot Great Dane flatbed trailer attained the maximum MES of 50 mph. All other combinations were observed to experience a tractor oversteer condition and engage the articulation-limiting safety cables at lower speeds. The time history data from those tests are shown in Figure 5.22.

The time history data are from the tests completed at the maximum attained maneuver entrance speed for each combination. In the figure, from left to right, and top to bottom, are steering wheel angle, tractor speed, tractor lateral acceleration, tractor longitudinal acceleration, tractor yaw rate, tractor drive axle slip angle, articulation angle, and the wheel height observed at the trailer axles.

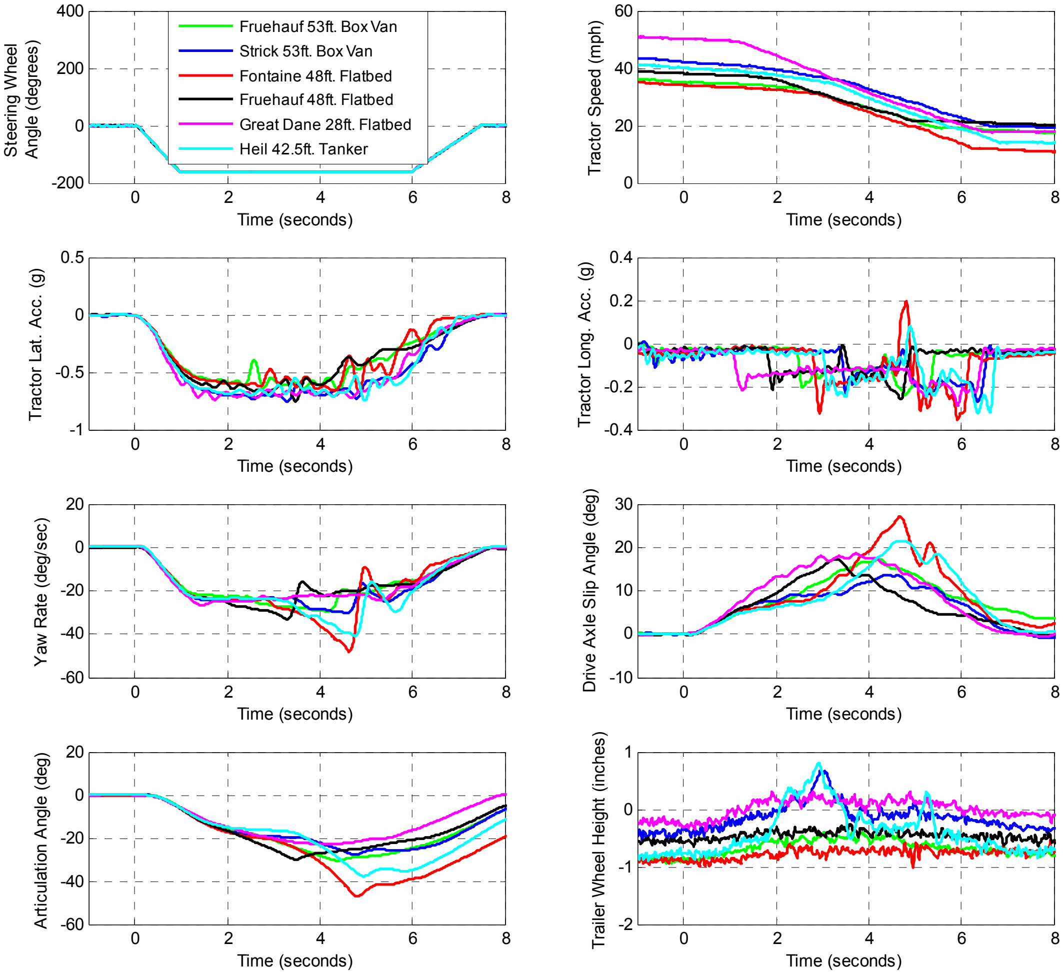

Figure 5.22. Time history data from the Sterling 4x2 in combination with the six different trailers and LLVW load condition. Data are from the tests completed at the maximum attained maneuver entrance speed for each combination.

As shown in Figure 5.22, the lateral acceleration for each combination builds initially from approximately time 0s and plateaus at approximately 2.0s. Longitudinal acceleration is relatively constant up to the point in time that the RSC system applies the foundation brakes. Then it steps to approximately -0.15 g at different times between 1.0s and 3.5s for each of the combinations.

The yaw rate responses for the combinations shown are quite similar up to approximately 2.0s. After that time the yaw rate data begins to show differences among the different combinations. With the exception of the combination with the Great Dane 28-foot flatbed, all of the combinations built more yaw rate as the tractor went into an understeer condition until they hit the safety cables limiting the articulation angle. After the cables were engaged, the yaw rate of the truck tractor was observed be sharply reduced (in the figure, at times between 3.5 and 4.5s) and rebounded to a lower level.

The drive axle side slip angle data show that the rear axle of the truck tractor was sliding laterally at different rates and magnitudes for each of the combinations. Each combination’s magnitude was greater than 12 degrees and interestingly the combination with the Great Dane 28-foot flatbed built at a quicker pace and achieved the third highest magnitude for the tests shown, but was not observed to engage the safety cables.

The articulation angle time history data from the combinations show that each trailer initially articulated similarly up to approximately 2.0 seconds, at which point differences were observable between the combinations. With the exception of the Great Dane 28-foot flatbed combination, each combination builds and peaks at the time the combinations engaged the safety cables limiting the articulation angle.

The last subplot in the figure shows that a few combinations had a small amount of wheel lift between zero and one inch. This is well below the threshold of two inches used for this research. For this LLVW condition, all Sterling 4x2 combinations remained roll stable.

For all of the test series represented in Figure 5.22, the RSC system was observed to apply the foundation brakes. This can be observed in Figure 5.23 and Figure 5.24. Figure 5.23 shows the time history data of the same six tests. In the figure from left to right, and top to bottom, are the steering wheel angle, tractor speed, tractor left steer brake pressure, tractor right steer brake pressure, tractor left drive axle brake pressure, and tractor right drive axle brake pressure. The RSC system did not have control over the steer axle brakes and these series were conducted with the trailer brakes (not displayed) disabled. Although the trailer brakes were disabled, the system was commanding pressure to the trailer axles as shown in Figure 5.24. The unbraked trailer had the added affect of pushing the tractor around. Had the trailer been allowed to contribute brake forces as commanded by the RSC system, the tractor's yaw rates, it is possible that the rear axle slip angles and articulation angles would have been reduced and higher MESs would have been attained.

Figure 5.26 shows the RSC brake commands at the tractor gladhand for RSM tests conducted with the 53-foot Strick box van trailer at three increasing MESs. In each of the tests, an initial trailer brake pulse of approximately 65 psi was followed by subsequent pulses of approximately 45 psi. The tests show that as the MES increased, the RSC commanded trailer braking pulses for a longer amount of time.

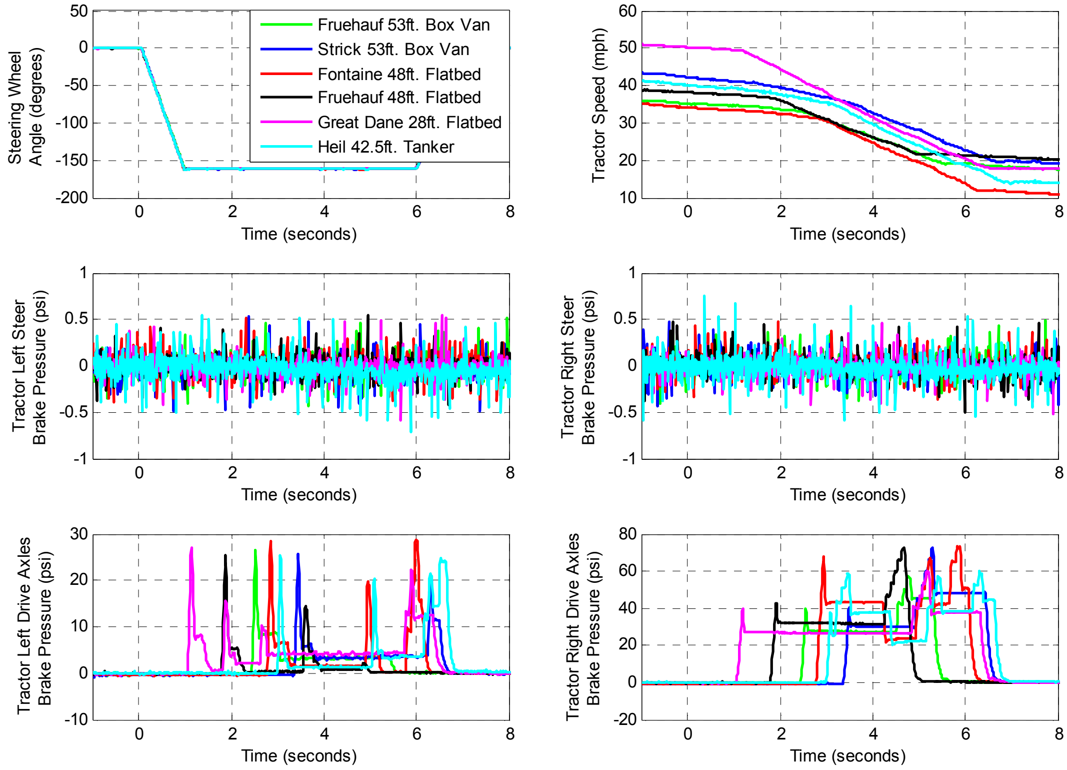

Figure 5.23. Brake pressure test data from the tests shown in Figure 5.22.

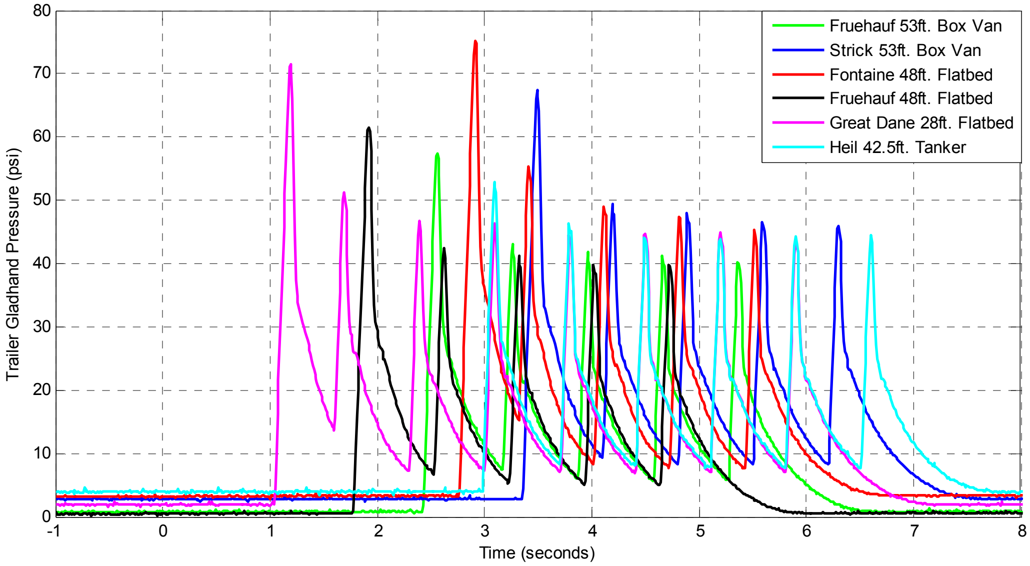

Figure 5.24. Time history data of the trailer glad-hand pressure from the tests shown in Figure 5.22.

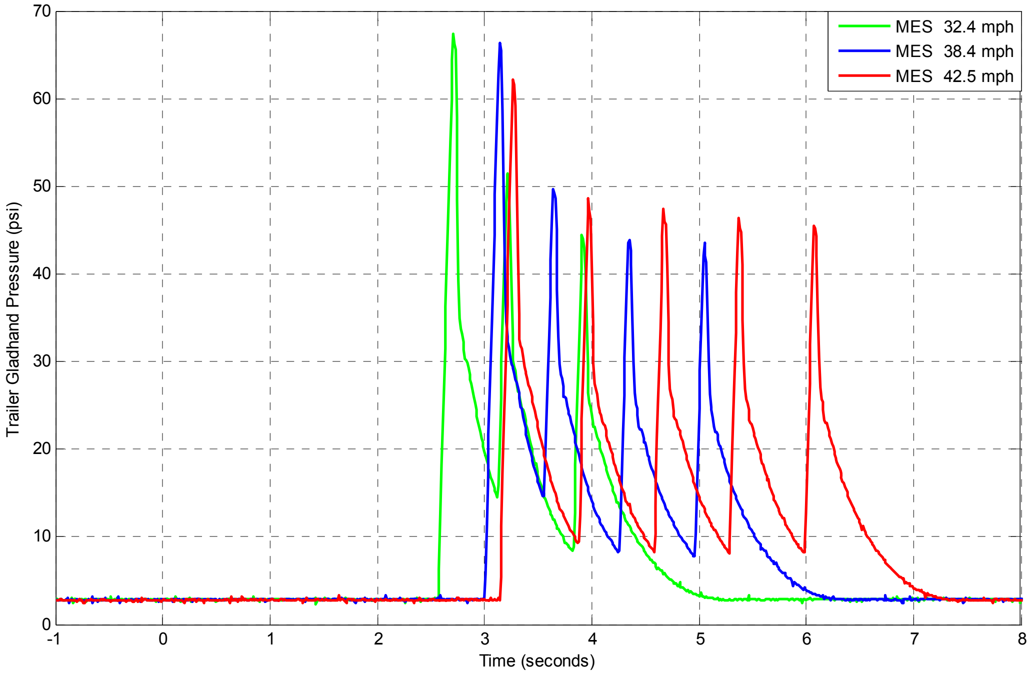

Figure 5.25. Graph shows test data from the Sterling 4x2 with the 53 ft. Strick dry box van trailer with LLVW load condition. Examples show that even though the trailer brakes had been disconnected the system was applying pressure at the gladhand service line.

Results by Trailer Type

For Box Vans and Long Flatbed Trailers: From Table 5.21, another observation to note are the performance differences from combining the different truck tractors and SC systems to different types of trailers. RSM test series conducted with truck tractors equipped ESC controllers and either box vans or long flatbeds achieved a maximum MES of 50 mph without observation of significant wheel lift or exceeding allowable articulation angles. In contrast, RSM test series conducted with truck tractors with RSC controllers and either box vans or long flatbeds were terminated for exceeding maximum allowable articulation angles as a result of excessive tractor oversteer. The ranges of MES at which these test series were terminated were also similar for both RSC-equipped tractors, with the terminating MESs ranging between 35.4 – 41.5 mph.

Short Flatbed Trailer: All RSM test series conducted with the short flatbed trailer were observed to achieve the maximum MES of 50 mph without the observance of wheel lift or excessive articulation angles.

Tanker Trailer: Two of the four RSM test series conducted with the tanker trailer achieved the maximum MES of 50 mph. The other two test series were terminated for either wheel lift at the trailer axles or excessive articulation angle. The lone instance of wheel lift with the test condition was observed with the Volvo/tanker trailer combination at a MES of 47.4 mph. The lone instance that articulation angle exceeded the allowable amount was with the Sterling/tanker combination at a MES of 40.4 mph.

All of these LLVW condition RSM test series were performed with the trailer brakes disabled. It should be noted that the additional benefit of allowing the trailer brakes to be utilized by the SC system may increase the yaw stability of the tractor/trailer system. Presumably, the additional braking forces provided by the trailer would act like an anchor and reduce the articulation angles from what was observed and extend the MES at which instabilities were observed upward. With that said, both ESC and RSC equipped tractors were tested with the same methodology and the end result was that the ESC-equipped tractors had one observed instability event versus nine for the tractors equipped with RSC. The ESC systems showed more capability when directional control was necessary to reduce tractor oversteering and side slip angles observed at the tractor drive axles.

5.3.3 LLVW versus High CG Activation Comparison

This section briefly compares the RSM test series conducted with the LLVW conditions to those performed in the High CG conditions. Table 5.22 through Table 5.25 provide some insight into the differences observed between load conditions, and show several dynamic parameters from the lowest MES at which brake activity was commanded by each vehicle's SC system. The tables from left to right show the specific test trailer, the MES at which the brake command occurred, the maximum truck tractor lateral acceleration observed for the test, maximum tractor yaw rate for the test, maximum tractor roll angle for the test, maximum tractor drive axle side slip angle for the test, and maximum longitudinal deceleration observed for the test. Results from the LLVW load condition are shown first followed by the High CG results.

Maximum values are shown in the tables rather than the observed values at SC brake activation. A later section of this report will show more detailed SC comparisons on activation thresholds that resulted from changing a combination's mass. These sections are intended to show overall minimum dynamic performance of the vehicles in a RSM maneuver at which the SC systems begin to augment dynamic behavior. The activations of the SC systems were monitored by tapping the vehicles' communication ports. Information was decoded to indicate when the system commanded engine torque reduction or brake pressure applications. For this analysis, only system commands to activate the foundation brakes were considered since the RSM maneuver was conducted without engine torque applied.

Freightliner ESC: The Freightliner equipped with the ESC system changed its activation thresholds when the mass of the combination was changed. Table 5.22 shows some of the changes observed from the LLVW and High CG loads. In the LLVW load, the MES at which ESC first commanded foundation braking ranged from 30.4 to 32.5 mph. When mass was added to raise the combinations to the High CG load, the MES observed to initiate SC foundation brake activity ranged from 24.5 to 26.5 mph. The maximum lateral accelerations observed ranged from 0.48 to 0.52 g with the LLVW loads and fell to 0.36 to 0.41 g with the High CG loads. The maximum yaw rate observed with the tractor for these tests ranged from 21.5 to 24.0 deg/sec with the LLVW load and from 19.0 to 20.4 deg/sec with the High CG load. Maximum roll angle, side slip at the drive axle, and longitudinal accelerations are provided to show the dynamic state of the vehicle. The test weights for the truck tractors in combination with the six trailers were measured and are provided in Appendix D.

Table 5.22. Table presents Freightliner 6x4 (ESC controller installed) test data from the first test observed to activate SC when configured with the High and LLVW loads and the 6 different trailers.

Trailer	MES (mph)	Maximum Lateral Acceleration (g)	Maximum Yaw Rate (deg/sec)	Maximum Roll Angle (deg)	Maximum Drive Axle Side Slip Angle (deg)	Maximum Longitudinal Deceleration (g)
LLVW Load Condition						
Frue. Box Van	30.4	0.50	22.5	1.3	3.3	0.19
Strick Box Van	30.5	0.49	23.7	1.8	5.0	0.18
48ft. Font. Flatbed	30.5	0.50	24.0	1.6	6.1	0.21
48ft. Frue. Flatbed	30.4	0.48	21.5	1.3	4.4	0.20
28 ft Flatbed	32.5	0.52	23.1	1.5	5.5	0.24
Heil Tanker	30.4	0.50	23.4	1.4	3.9	0.22
High CG Load Condition						
Frue. Box Van	26.4	0.38	19.5	2.3	2.7	0.15
Strick Box Van	26.5	0.40	19.7	2.7	3.8	0.19
48ft. Font. Flatbed	24.5	0.36	20.3	4.0	7.1	0.12
48ft. Frue. Flatbed	26.3	0.38	19.3	3.2	4.8	0.16
28 ft Flatbed	26.5	0.41	20.4	3.1	5.1	0.18
Heil Tanker	26.4	0.37	19.0	2.7	2.9	0.20

Freightliner RSC: The Freightliner equipped with the RSC system also adjusted its activation thresholds when the mass of the combination was changed. Table 5.23 shows some of the changes observed from the LLVW and High CG loading conditions. In the LLVW load, the MES at which RSC first commanded foundation braking ranged from 26.4 to 28.6 mph. When mass was added to raise the combinations to the High CG load, the MES observed to initiate RSC foundation brake activity ranged from 24.4 to 26.4 mph. The maximum lateral accelerations observed ranged from 0.38 to 0.42 g with the LLVW loads and fell to 0.33 to 0.41 g with the High CG loads. The maximum yaw rate observed with the tractor for these tests ranged from 18.8 to 19.5 deg/sec with the LLVW loads and from 18.0 to 19.5 deg/sec with the High CG loads

Table 5.23. Table presents Freightliner 6x4 (RSC controller installed) test data from the first test observed to activate SC when configured with the High and LLVW loads and the 6 different trailers.

Trailer	MES (mph)	Maximum Lateral Acceleration (g)	Maximum Yaw Rate (deg/sec)	Maximum Roll Angle (deg)	Maximum Drive Axle Side Slip Angle (deg)	Maximum Longitudinal Deceleration (g)
LLVW Load Condition						
Frue. Box Van	28.4	0.42	19.5	1.1	5.21	0.06
Strick Box Van*	N/A	N/A	N/A	N/A	N/A	N/A
48ft. Font. Flatbed	26.6	0.38	19.4	1.1	4.16	0.06
48ft. Frue. Flatbed	28.4	0.40	18.8	1.1	3.46	0.05
28 ft Flatbed	28.5	0.41	19.4	1.1	3.07	0.05
Heil Tanker	26.4	0.38	18.9	1.0	3.90	0.06
High CG Load Condition						
Frue. Box Van	26.4	0.37	18.9	2.2	5.3	0.22
Strick Box Van	24.5	0.34	18.1	2.0	2.9	0.05
48ft. Font. Flatbed	24.5	0.36	19.5	3.6	6.9	0.19
48ft. Frue. Flatbed	26.4	0.41	19.0	3.6	6.9	0.19
28 ft Flatbed	24.5	0.34	18.8	2.6	4.1	0.05
Heil Tanker	24.4	0.33	18.0	2.5	2.7	0.23

* Vehicle CAN bus data used to identify SC activation was lost during LLVW test series conducted with the Strick box van.

Volvo ESC: Like the Freightliner, the Volvo equipped with the ESC system changed its activation thresholds when the mass of the combination was changed. Table 5.24 shows some of the changes observed from the LLVW and High CG loads. In the LLVW load condition, the MES at which ESC first commanded foundation braking ranged from 36.7 to 42.7 mph. When mass was added to raise the combinations to the High CG load, the MES observed to initiate SC foundation brake activity ranged from 24.4 to 26.5 mph. The maximum lateral accelerations observed ranged from 0.59 to 0.69 g with the LLVW loads and fell to 0.28 to 0.34 g with the High CG loads. The maximum yaw rate observed with the tractor for these tests ranged from 20.0 to 24.6 deg/sec with the LLVW loads and from 16.0 to 17.1 deg/sec with the High CG loads.

Table 5.24. Table presents Volvo 6x4 test data from the first test observed to activate SC when configured with the High and LLVW conditions and the 6 different trailers.

Trailer	MES (mph)	Maximum Lateral Acceleration (g)	Maximum Yaw Rate (deg/sec)	Maximum Roll Angle (deg)	Maximum Drive Axle Side Slip Angle (deg)	Maximum Longitudinal Deceleration (g)
LLVW Load Condition						
Frue. Box Van	36.7	0.67	24.6	1.8	6.5	0.06
Strick Box Van	38.5	0.64	22.5	2.0	5.9	0.07
48ft. Font. Flatbed	38.7	0.69	24.6	2.1	8.1	0.08
48ft. Frue. Flatbed	42.7	0.59	20.0	1.9	7.1	0.06
28 ft Flatbed	40.8	0.64	21.7	1.9	7.4	0.09
Heil Tanker	38.5	0.67	23.7	1.8	6.5	0.07
High CG Load Condition						
Frue. Box Van	24.4	0.32	16.5	1.7	2.6	0.07
Strick Box Van	26.5	0.34	16.6	2.3	2.4	0.10
48ft. Font. Flatbed	24.4	0.32	16.9	2.8	5.6	0.08
48ft. Frue. Flatbed	22.5	0.28	16.0	2.4	3.3	0.07
28 ft Flatbed	24.4	0.31	16.7	2.3	4.5	0.07
Heil Tanker	24.5	0.32	17.1	2.1	2.7	0.08

<u>Sterling 4x2</u>*:* The Sterling 4x2 equipped with the RSC system changed its activation thresholds when the mass of the combination was changed. Table 5.25 shows some of the changes observed from the LLVW and High CG loads. In the LLVW loads, the MES at which RSC first commanded foundation braking ranged from 28.1 to 30.7 mph. When mass was added to raise the combinations to the High CG loads, the MES observed to initiate SC foundation brake activity ranged from 22.3 to 24.4 mph. The maximum lateral accelerations observed ranged from 0.42 to 0.51 with the LLVW loads and fell to 0.32 to 0.38 g with the High CG loads. The maximum yaw rate observed with the tractor for these tests ranged from 20.1 to 24.3 deg/sec with the LLVW loads and from 18.4 to 19.8 deg/sec with the High CG loads.

Table 5.25. Table presents Sterling 4x2 test data from the first test observed to activate SC when configured with the High CG and LLVW conditions and the 6 different trailers.

Trailer	MES (mph)	Maximum Lateral Acceleration (g)	Maximum Yaw Rate (deg/sec)	Maximum Roll Angle (deg)	Maximum Drive Axle Side Slip Angle (deg)	Maximum Longitudinal Deceleration (g)
LLVW Load Condition						
Frue. Box Van	30.7	0.51	24.3	2.1	6.1	0.28
Strick Box Van	28.5	0.42	20.0	1.8	2.1	0.08
48ft. Font. Flatbed	28.7	0.43	20.6	1.7	3.1	0.09
48ft. Frue. Flatbed	30.5	0.48	21.8	2.4	4.0	0.24
28 ft Flatbed	28.1	0.44	20.6	1.7	2.1	0.06
Heil Tanker	28.4	0.43	20.1	1.5	2.1	0.09
High CG Load Condition						
Frue. Box Van	24.4	0.35	18.6	2.2	3.1	0.05
Strick Box Van	24.4	0.34	18.5	2.6	2.5	0.05
48ft. Font. Flatbed	22.3	0.34	19.6	3.5	6.5	0.06
48ft. Frue. Flatbed	22.5	0.32	18.6	3.3	4.5	0.05
28 ft Flatbed	24.2	0.38	19.8	3.4	4.6	0.21
Heil Tanker	24.3	0.34	18.4	3.2	3.2	0.21

5.3.4 RSM Test Results Summary

The RSM maneuver was conducted with two load conditions (High CG and LLVW) with each combination of truck tractor and test trailer (24 total combinations).

High CG load condition results summary: The RSM results from testing with the High CG loads show that all 24 combinations and SC conditions (enabled, enabled without trailer brakes, and disabled) had instances of observed wheel lift. Overall, with SC (ESC and RSC equipped vehicles) enabled without trailer brakes, the net increase in MES at which wheel lift was observed increased by 0-10 mph (over disabled test conditions). With SC enabled, the net increase in MES at which wheel lift was observed increased 0-12 mph (over disabled test conditions).

Differences were observed when comparing ESC and RSC equipped truck tractors. The net increase in MES at which wheel lift was observed increased by 2-10 mph (over disabled test conditions) for the ESC enabled without trailer brakes test condition. This range improved to 4-12 mph for ESC enabled test series. MESs for the RSC enabled without trailer brakes series were observed to increase by 0-6 mph and for the RSC enabled series increased by 0-8 mph.

The improvements in MES wheel lift speed over the SC disabled test condition for each tractor were as follows. The Freightliner 6x4 with ESC, without trailer brakes, resulted in a 2-8 mph increase, and with ESC enabled it ranged from 5-12 mph. The Freightliner 6x4 with RSC, without trailer brakes, resulted in a 4-6 mph increase, and with RSC enabled it ranged from 5-8 mph. The Volvo 6x4 with ESC, without trailer brakes, resulted in a 3-8 mph increase, and with ESC enabled it ranged from 5-11 mph. The Sterling 4x2 with RSC, without trailer brakes, resulted in a 0-3 mph increase, and with RSC enabled it ranged from 0-4 mph.

Overall, the test trailers in combination with the different truck tractors were observed to perform similarly considering that when the SC systems were disabled the range in MESs observed to produce wheel lift had a spread of 6 mph (25 – 31 mph). The resulting CG heights for the High CG loads ranged from 74.1 inches to 89.5 inches for the fleet of trailers tested. When wheel lift was observe it was typically at the trailer axles first for box vans and the tanker. For the long flatbeds wheel lift was typically observed at the tractor's drive axles first and the short flatbed exhibited both wheel lift at the tractor's drive axles and trailer axle.

Vehicle dynamics changes observed from SC Intervention were quantified to illustrate SC effectiveness (only test series conducted with the 28-foot Great Dane flatbed trailer were used for this portion of the results analysis). SC disabled tests were compared to the SC enabled test conditions at the same lowest speed that wheel lift was observed when the system was disabled. The SC systems all applied the foundation brakes in response to the RSM to slow the tractor/trailer combination which also resulted in the observed improvement to roll stability. The times at maximum wheel lift for each of the four combinations were used as a way to quantify changes to dynamic measures for the same given RSM test inputs. Overall, ESC (with and without unbraked trailer) systems reduced vehicle speed by 14.2% to 39.2%, while RSC (with and without unbraked trailer) systems reduced vehicle speed by a comparable 18.2% to 27.2%. Both systems reduced lateral acceleration, with ESC systems reducing lateral acceleration by 40.5% to 62.9% and RSC systems reducing the tractor's lateral acceleration by 46.6% to 57.4%. ESC reduced yaw rate by 34.8% to 39.9%, while RSC reduced yaw rate by a comparable range of 34.3% to 46.2%. ESC was observed to reduce tractor roll angle by 56.7% to 69.5%, while RSC reduced roll angle by 59.2% to 69.4%. Since these reductions were the direct result of each respective SC systems' use of the foundation brakes to slow the vehicle, the deceleration was observed to increase by 111% to 508% with ESC and 186% to 284% with tractors equipped with RSC.

<u>LLVW load condition results summary:</u> Testing with this load condition was performed at only one SC test condition, SC enabled without trailer brakes. The RSM test results from the LLVW loads show that only one of the 24 combinations tested, resulted in two inches or more of wheel lift. The Volvo 6x4 (ESC) combined with the tanker was observed to produce just over two inches of wheel lift in the RSM when tested with a MES of 47.4 mph.

Nine of the 24 combinations were terminated after the tractor went into an oversteer condition and engaged the safety cables that limited the articulation angle between the truck tractor and trailer combinations. These nine combinations were observed to engage the safety cables at MESs that ranged from 34.3-41.5 mph. All nine combinations were with RSC equipped vehicles (see Table 5.21). An additional benefit of allowing the trailer brakes to be utilized by the SC system may be increased yaw and roll stability of the tractor/trailer system. The additional braking provided by the trailer could act like an anchor to slow the combination down which in turn would reduce the articulation angles and extend the MES at which instabilities were observed upward.

Results for each tractor show that the Freightliner 6x4 with ESC completed each RSM test series with the six different trailers to an MES of 50 mph without an observed instance of instability. The Freightliner 6x4 with RSC was observed to engage the safety cables in four of the six combinations at MESs that ranged from 35.4-39.4 mph. The remaining two combinations completed the RSM test series to an MES of 50 mph without an observed instance of instability. Five of the six combinations tested with the Volvo 6x4 ESC completed the RSM test series to an MES of 50 mph without an observed instance of instability. Approximately two inches of wheel lift were observed in the RSM at an MES of 47.4 mph with the remaining combination. The Sterling 4x2 RSC was observed to go into oversteer and engage the safety cables in five of the six combinations at MESs that ranged from 34.3-41.5 mph. The remaining combination completed the RSM test series to an MES of 50 mph without an observed instance of instability.

Comparing trailers, the RSM test results from combinations with box vans and long flatbeds were similar depending on whether the tractor had RSC or ESC. All LLVW RSMs series either achieved an MES of 50 mph without an observed instance of instability (ESC equipped tractors) or experienced tractor oversteer and engaged the safety cables (RSC equipped tractors). All combinations with the short 28-foot flatbed trailer completed the RSM test series to 50 mph without an observed instance of instability. Two tanker combinations were observed to complete the RSM test series up to 50 mph without an observed instance of instability. The other two resulted in one instance of roll instability at 47.4 mph and the other engaged the safety cables at 40.4 mph.

5.4 Mass Estimation Tests

To better understand how SC systems adapt to different loads, additional SIS and RSM test series were conducted. Using the Great Dane 121 style control trailer, each power unit was tested under a variety of loads. For each load, SIS and RSM maneuvers were completed until SC engine output torque or braking interventions occurred, or a 50 MPH test entrance speed was achieved. SIS maneuvers and RSM test series were conducted for each of the following cells in Table 5.2 with resulting combination weights shown in Table 5.26.

Table 5.26. Mass Estimation Loading for Each Platform

	Freightliner	Volvo	Sterling
Num Blocks	Total Mass (Lbs)	Total Mass (Lbs)	Total Mass (Lbs)
0	30360	29830	25710
1	34470	34100	29620
2	38810	38820	33850
3	43260	43150	38150
4	47540	47400	42380
5	51680	51520	46530
6	56130	55950	50800
7	60530	60270	55050
8	64880	64750	
9	69200	69070	

Figure 5.27, Figure 5.28, Figure 5.29, and Figure 5.30 document the observed data from each of the three tractors (four SC conditions) in terms of lateral acceleration at the time SC intervention was observed during the SIS test. Since directional asymmetries were minimal, data were combined for both left and right tests. SC activation was considered to be the instance in time when either engine torque reduction or braking was triggered by the system.

Differences between engine torque (ROP_engine) and braking (ROP_brake) interventions are indicated by the dots and circles on the figures respectively. Data in red indicate tests conducted with RSC, whereas data in blue indicate tests conducted with ESC. In cases where both engine torque reduction and braking was observed, tests are connected by lines. Not all tests resulted in the brakes being activated.

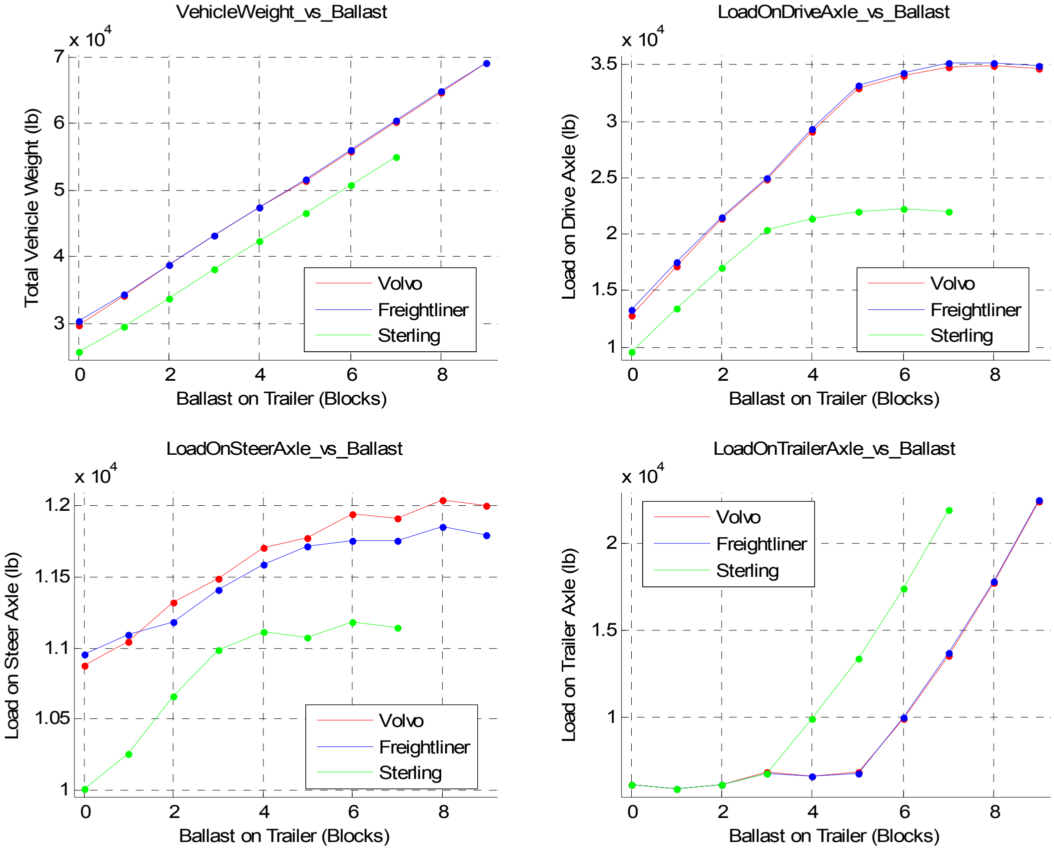

Figure 5.26. Vehicle loading conditions for mass estimation testing.

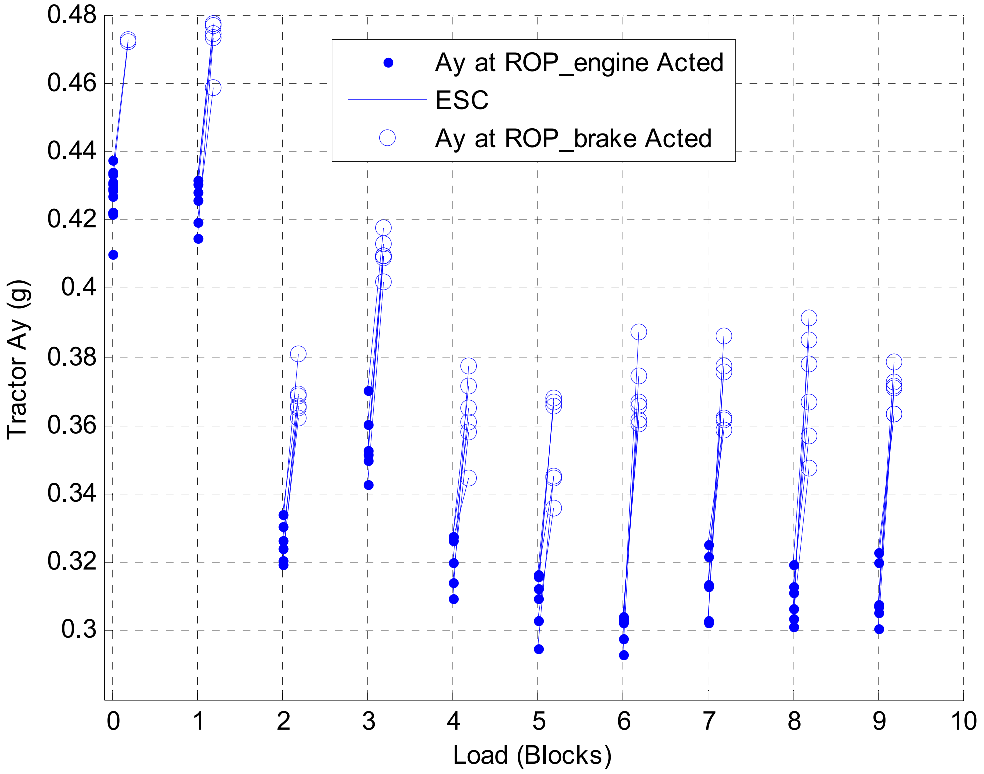

Figure 5.27. Freightliner Ay vs. load condition at different SC interventions for the ESC condition.

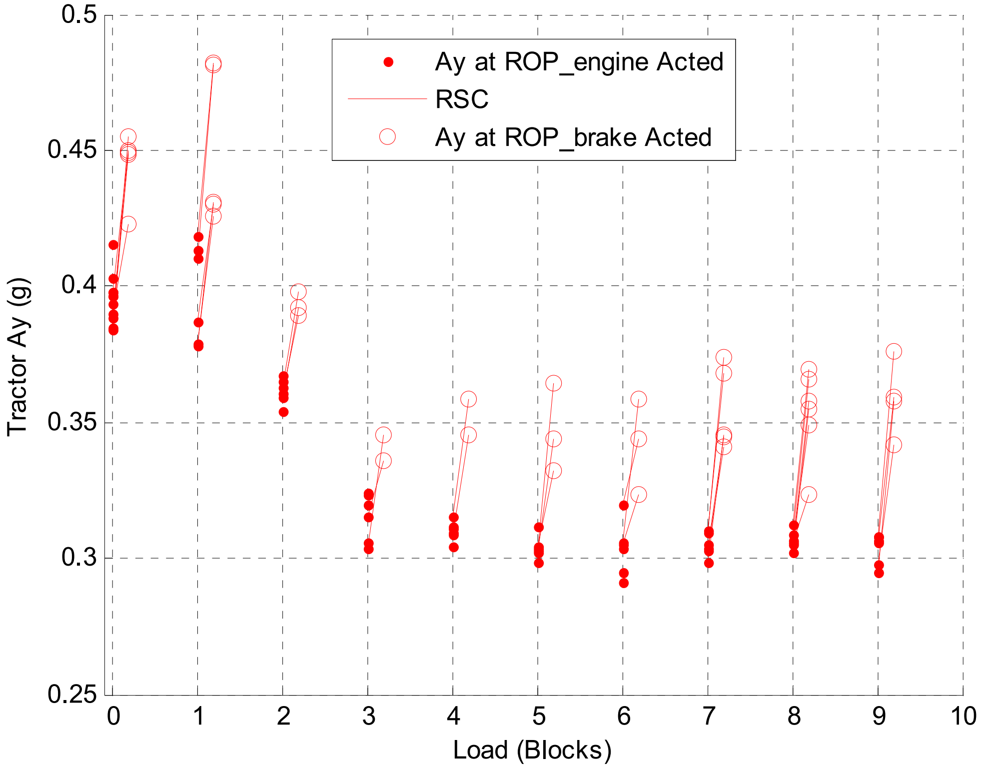

Figure 5.28. Freightliner Ay vs. load condition at different SC interventions for the RSC condition.

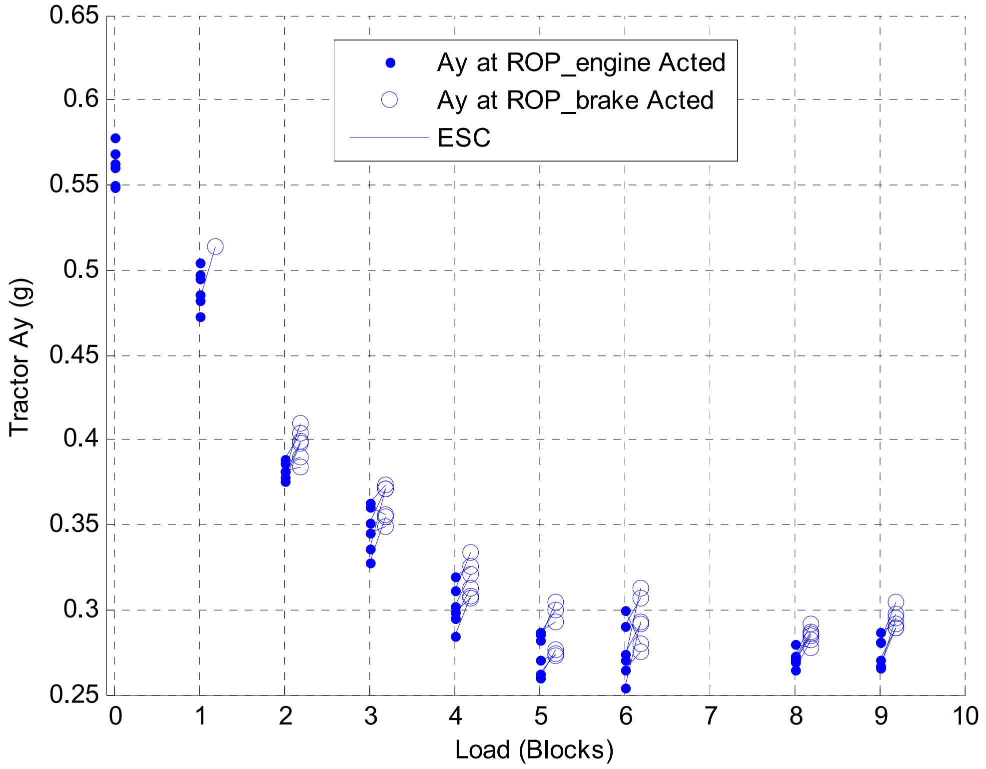

Figure 5.29. Volvo Ay vs. ballast at different SC interventions.

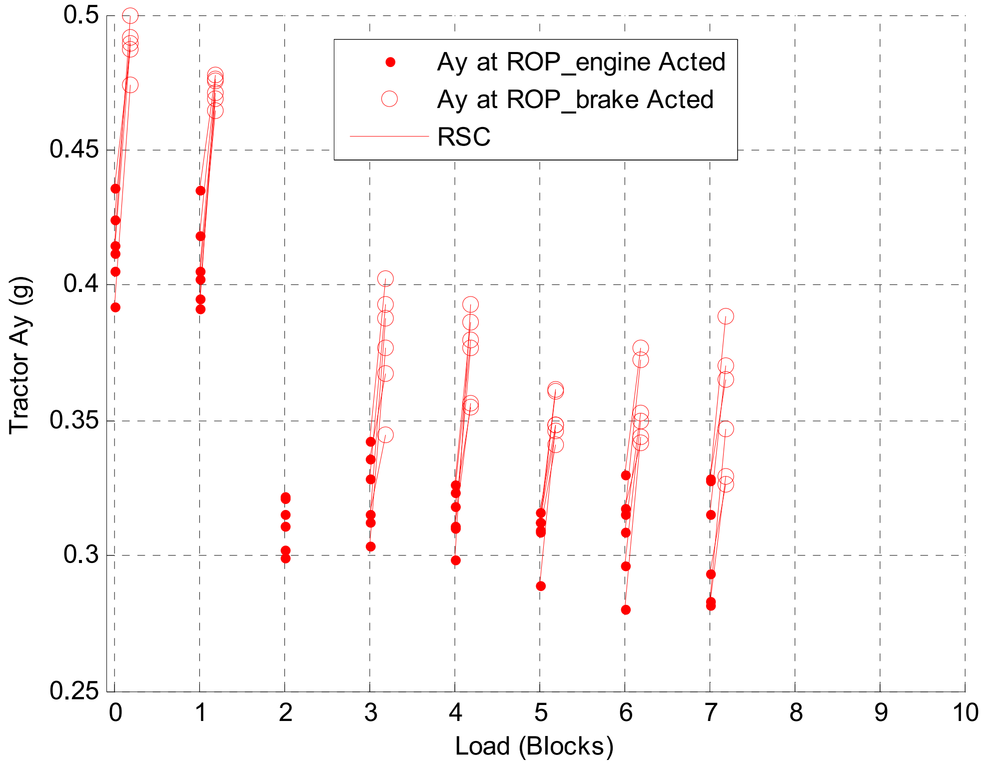

Figure 5.30. Sterling Ay vs. ballast at different SC interventions.

5.4.1 RSM Mass Estimation Tests

The following figures document the observed data from each of the three truck tractors in terms of lateral acceleration at the instance SC intervention was observed during the RSM. Since directional asymmetries were minimal, tests were conducted turning to the left. SC activation is considered to be the instance when braking occurs. Engine torque reduction was observed in every case of RSM testing. However, since the RSM is more dynamic and demanding, braking interventions were determined to be more significant to the scenario. Braking interventions are indicated by the dots on the figures.

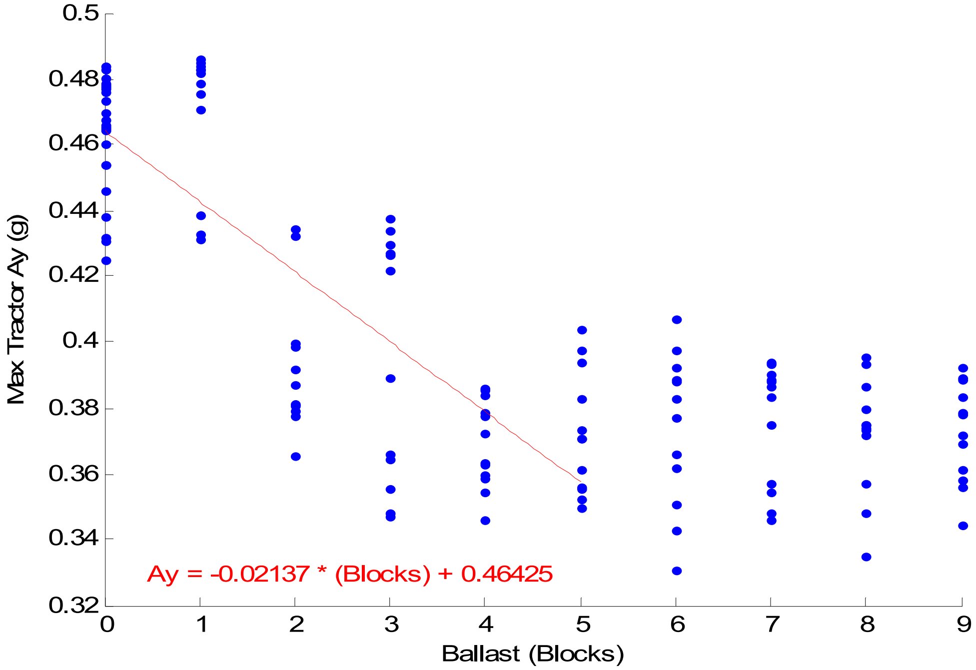

Figure 5.31. Freightliner- maximum tractor Ay vs. ballast condition for the ESC condition.

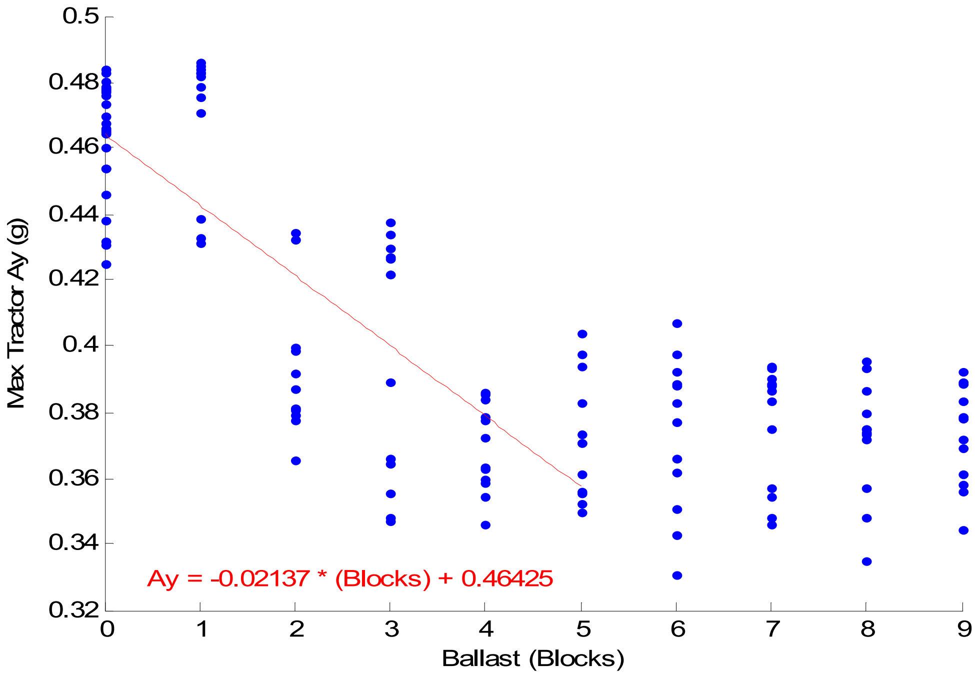

Figure 5.32. Freightliner- maximum tractor Ay vs. ballast condition for the RSC condition.

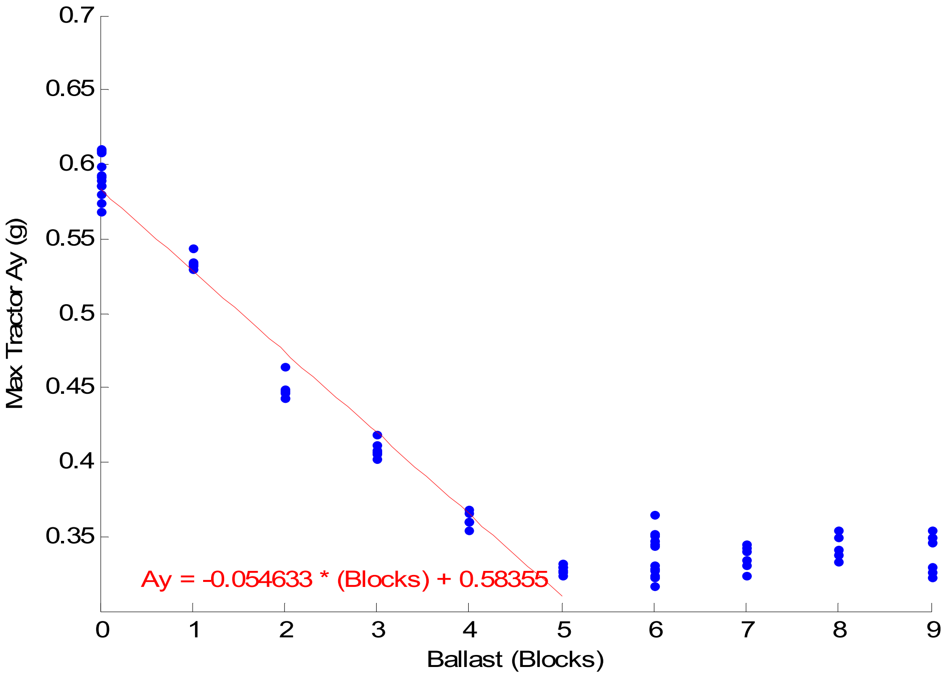

Figure 5.33. Volvo- maximum tractor Ay vs. ballast condition for the ESC condition.

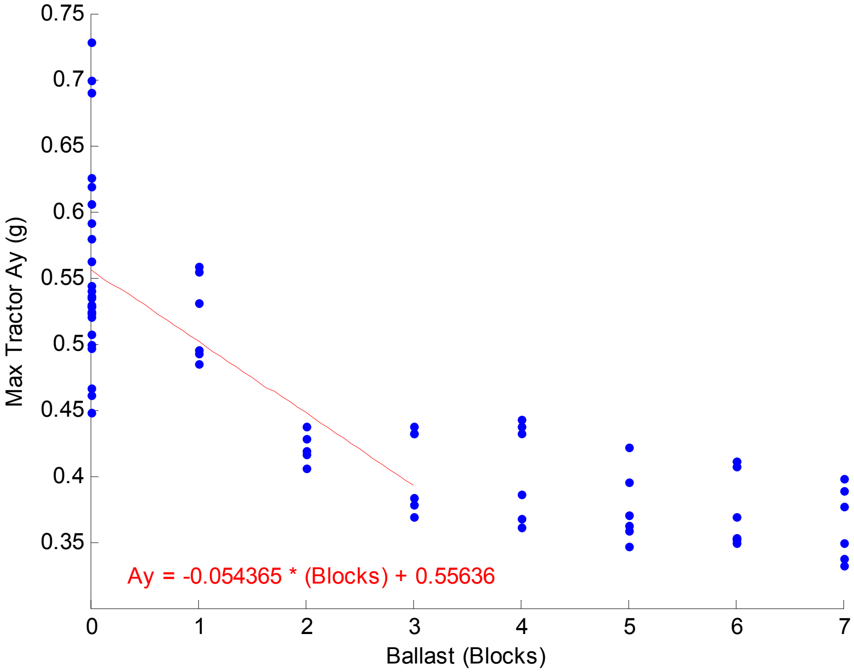

Figure 5.34. Sterling- maximum tractor Ay vs. ballast condition for the RSC condition.

The data suggest that all of the systems adjust the activation threshold based on a mass estimation process. Lateral acceleration thresholds were the highest in the unloaded condition for each platform tested. As the load increased, each system reached a mass where the lateral acceleration intervention level stabilized (approximately 3 to 5 blocks).

Given that higher mass often equates to a higher CG, lowering the activation threshold as the mass increases seems appropriate. All systems tested from different tractor manufacturers and SC type (RSC or ESC) were observed to operate in a similar manner under loaded conditions.

Differences were observed under the SIS when the platforms were lightly loaded. With 0 and 1 block, the Volvo did not exhibit any SC brake interventions except in a single test, whereas the Freightliner and Sterling activated SC braking in several tests at lateral accelerations just under 0.5 g. Since tests unloaded generally result in the vehicle combination understeering, it is unclear if this was occurring as a result of understeer mitigation. There were no observed cases of wheel lift in any of the lightly loaded tests. This result may warrant further investigation into understeer mitigation.

5.4.2 Electronic Stability Control vs. Roll Stability Control

Another interesting comparison in this test series was the ability to observe the performance between an ESC and a RSC system on the same platform. SIS and RSM maneuvers were performed with both RSC and ESC enabled under each load condition.

Figure 5.35 documents the observed performance of ESC vs. RSC during an RSM maneuver for the mass estimation series. Each colored trace represents a test series under a given load condition. It can be observed that both systems are operating in a similar mode up to about a MES of 35 mph. The slope formed by comparing maneuver entry speed vs. peak lateral acceleration observed during the maneuver is approximately the same. Although there are cases where the ESC system performs yaw interventions ("+" symbol), performance is very similar in peak lateral acceleration experienced by the truck tractor.

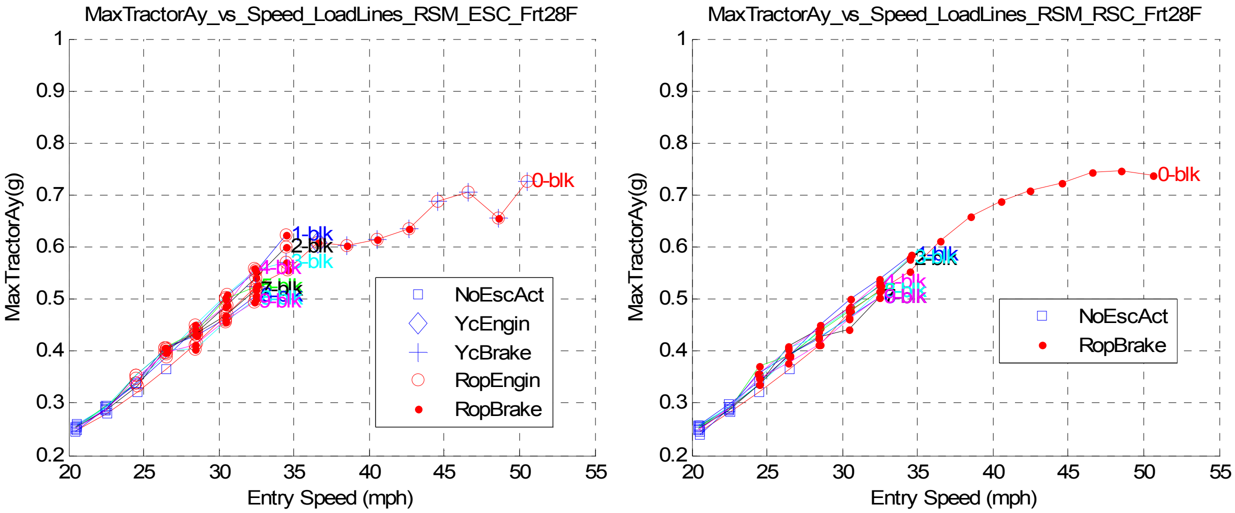

Figure 5.35. Maximum tractor Ay vs. MES for each test series conducted on the Freightliner with ESC and RSC during load estimation testing.

6.0 ROLL STABILITY MEASURES OF PERFORMANCE

The development of a set of performance measures would not only ensure that a Class 8 truck tractor is equipped with a stability control (SC) system but would also ensure that the SC provides a minimum level of effectiveness. Observations of test results from Phases I and II have shown that SC is able to improve the stability of the vehicles by exerting control over the power unit (engine) or applying the foundation brakes on the truck tractor and trailer or both. 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 are needed to improve stability.

Engine/power unit control by itself can improve stability in situations in which the vehicle's lateral limits are approached in a gradual manner. Therefore, the first subsection 6.1 focuses on development of a Measure of Performance (MOP) that indicates SC has the ability to reduce engine/power unit output. In addition, when the stability limits of the vehicle are approached rapidly, the SC system must use the foundation brakes to improve the roll stability. For that reason, subsection 6.2 focuses on a complimentary MOP for evaluating an SC system's ability to improve roll stability by applying the foundation brakes.

6.1 MOP for Engine/Power Unit Control in SIS tests

Engine torque reductions by SC systems were observed to mitigate roll instability in two test track maneuvers. Those maneuvers were the constant radius maneuver from Phase I and the SIS maneuver performed in Phase II research. These two maneuvers were similar in that the lateral forces acting on the vehicle were built slowly. In the constant radius maneuver the vehicle was driven around a circle with a constant radius. Starting from rest, the vehicle speed was gradually increased by the driver. In the SIS maneuver the input speed was maintained by the driver or cruise control and an automated steering controller slowly (~13.5 deg/sec) increased the steering wheel input. In both maneuvers, all SC systems were observed to activate and exert control over the engine/power unit. The systems either decreased the speed and lateral acceleration, or decreased the speed and allowed a set level of lateral acceleration.

From Phase II SIS test data, several measures were investigated for development as MOPs for engine/power unit control. They were as follows:

- truck tractor speed
- truck tractor lateral acceleration
- truck tractor longitudinal acceleration
- engine torque/driver requested engine torque

These measures represent are those most directly affected by the SC systems. Only SIS data collected with the SC enabled were considered for further development. While the disabled data offered insight into the operation and the ability to compare test series with and without SC, the measure of performance should be able to identify the attempt to improve stability with engine control from test data in which the system was active. This increases test driver safety and does not require the equivalent of a failed system test in which a comparison would be made to determine the SC activation. The following subsections discuss each measure and presents data as to whether the measure merits further development as a MOP.

6.1.1 Truck Tractor Speed

The forward speed of the truck tractor has good face validity and is directly related to the production of the lateral forces that are applied during untripped rollovers. Figure 6.1 shows examples of the forward speed, lateral acceleration and longitudinal acceleration from SIS steering inputs conducted with 4 different vehicles with SC enabled. Additionally, color coded pentagram markers indicate the approximate time of SC activation for each of the vehicles. Once activation was observed, each vehicle's forward velocity was reduced from the target maneuver entrance speed of 30 mph. From the data in this figure, forward speed also appears to be a possible candidate for further development. However, due to the nature of the maneuver it is possible for the vehicle to produce enough lateral load transfer to lose traction on the inside wheels, which would cause the vehicle to slow down. Therefore, any measure developed from forward speed would need to be perceptive between the loss of drive wheel traction and SC activation.

6.1.2 Truck Tractor Lateral Acceleration

Lateral acceleration is attractive as a potential MOP due to its high face validity and direct relationship in producing the forces associated with untripped rollover. Figure 6.1 shows test data of lateral acceleration from four different tractors performing SIS test maneuvers. The figure shows that each combination of tractor and SC system has a different lateral limit that the system has allowed. It also shows that the control strategy is different depending on the vehicle and employed SC system. One strategy allows the vehicle to build lateral acceleration to a given level and then allows that level to be maintained throughout the maneuver. The other strategy allows lateral acceleration to build and then the SC system reduces the lateral acceleration from that which activated the system and then at a later time in the maneuver may allow it to build once more. Each employed strategy was observed to increase lateral stability. Since the limits were quite different and the SC strategies after activation were also quite different, lateral acceleration alone does not merit continued development as the MOP to determine if SC was capable of improving stability through the use of engine control.

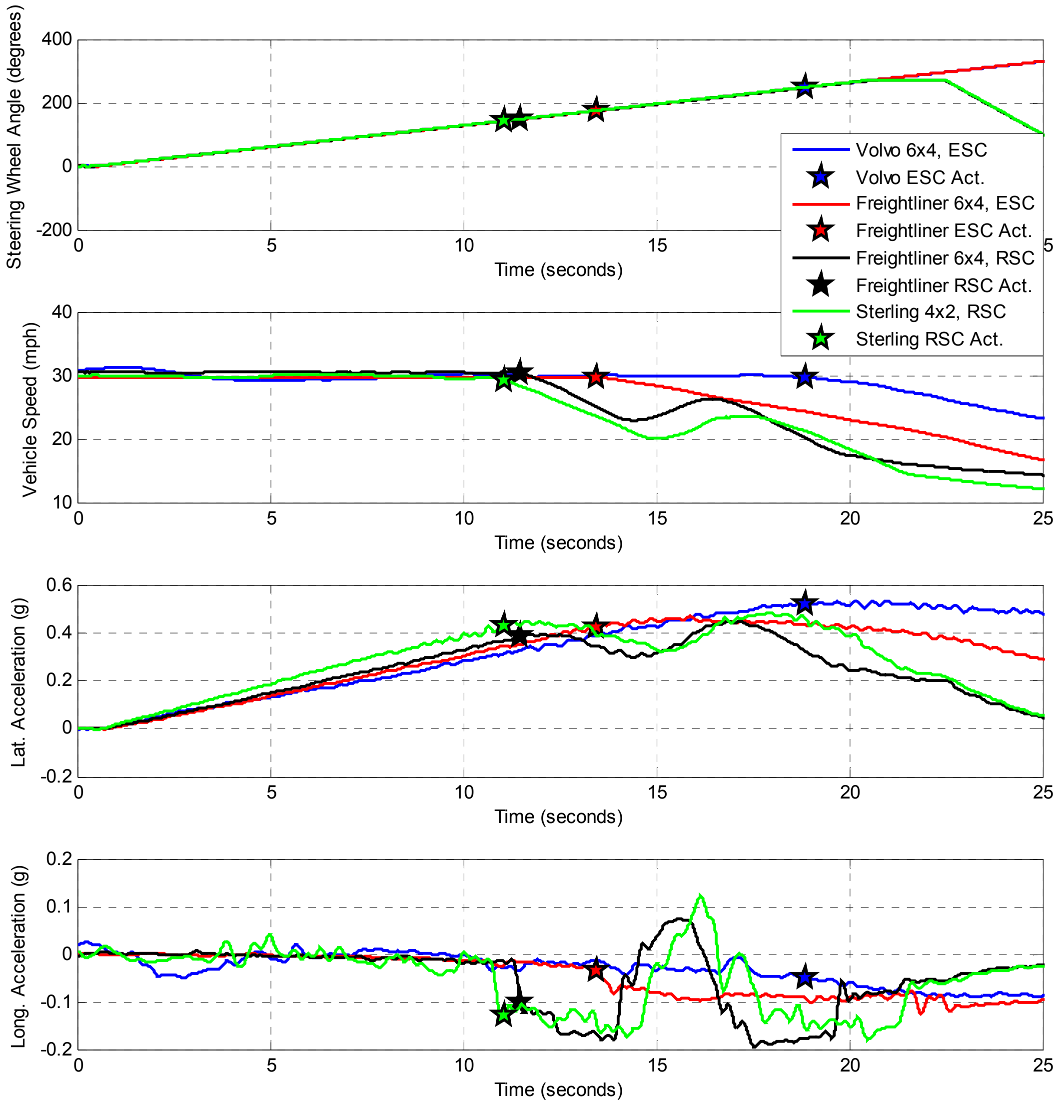

Figure 6.1. SIS test data of SC activation points in speeds, lateral accelerations, and longitudinal accelerations (bobtail tractor condition).

6.1.3 Truck Tractor Longitudinal Acceleration

Since the SC systems responded to the SIS tests by reducing engine torque, which in turn reduced forward speed, a corresponding increase in deceleration was observable. Figure 6.1 also shows examples of deceleration of during SIS test maneuvers for the four different vehicles with SC. For these tests the effect on deceleration from SC activation was observed and appears to have measureable differences. This measure, like speed, would need to be perceptive between the loss of drive wheel traction and SC activation. Additionally, the magnitudes of deceleration are relatively small (less than 0.2 g) and more advanced systems could reduce speed at such a gradual deceleration that a MOP developed from deceleration may not appropriately identify SC.

6.1.4 Truck Tractor Engine Torque

Truck tractor engine torque measures were a direct way to observe SC activation during the SIS test series. In this section, engine torque refers to two different measures. The first was related to the torque output from the engine and is expressed as a percentage of maximum engine output. The second torque measurement was related to the throttle peddle used by the driver to control engine torque output. This value was also expressed as a percentage of maximum engine output and for this report is referred to as the “driver requested torque”. 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 torque” was much less than the “driver requested torque”. These reductions to engine torque caused the changes to lateral acceleration, forward speed and deceleration discussed in the previous subsections.

Figure 6.2 provides a detailed example of test data from a SIS test. The “driver requested torque” is shown with a solid thin blue line and the engine torque output is shown with the heavy solid green line. The thin red line indicates SC activity with 0 being inactive and 50 active. The figure shows that the “driver requested torque” and the engine torque output measures were equal up to approximately 12.74 seconds. SC activation was registered just prior to this time, and from 12.74 seconds and on, the two signals for torque were not equal, as the driver was requesting more engine torque in an attempt to continue to maintain the 30-mph speed through the maneuver. However, the SC was mitigating the actual engine torque output. By 13.5 seconds, the “driver requested torque” was ~46 percent and the actual engine torque output was at zero. Figure 6.3 shows examples of engine torque mitigation during SIS test maneuvers for four different vehicles with SC.

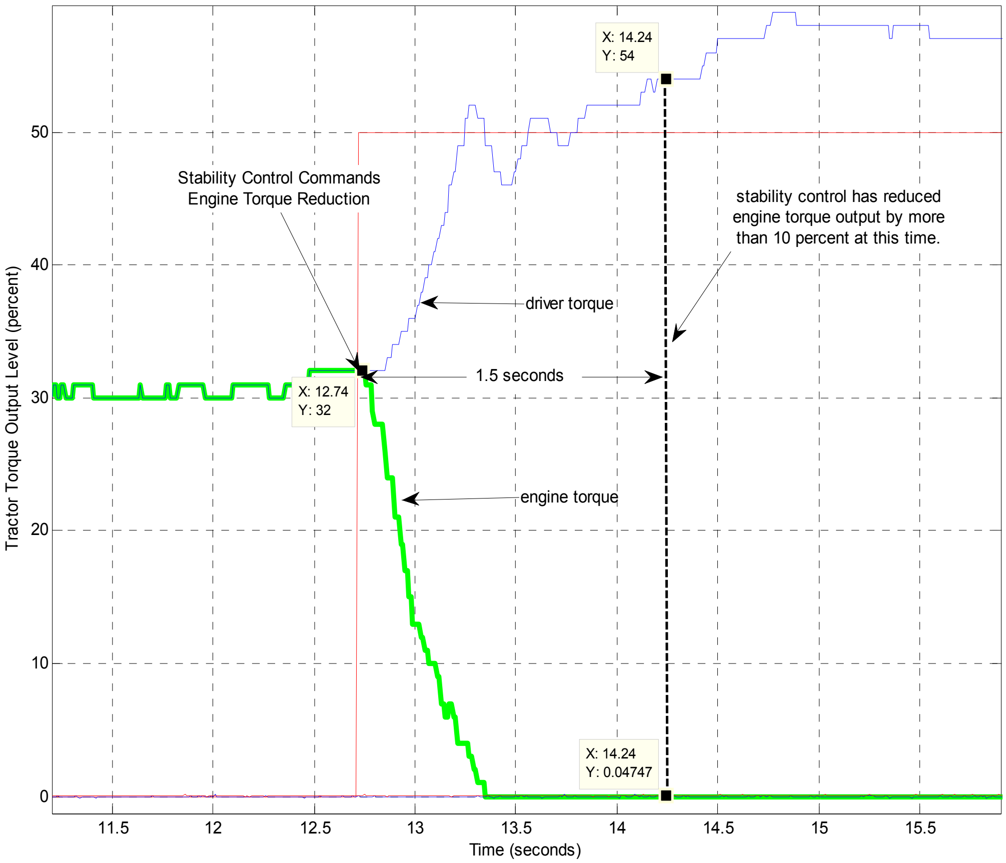

Figure 6.2 Example of observed tractor torque output level during an SC intervention.

Figure 6.3 shows, from top to bottom, time history data of typical SIS steering inputs, speed inputs and torque measures for the four different tractors. These examples are representative of each vehicle's SIS test series. The figure shows that each SC system reduced engine torque at some point in the SIS maneuver. At the beginning of the maneuver both "driver requested torque" and "engine torque" measures were equal and overlay one another. This is shown by laying down a heavy line representing "engine torque" and then overlaying the "driver requested torque" with a thinner line of a different color. SC intervention can be observed by following the lines for each individual vehicle to the right and looking for the point that the two measures separate. The figure also shows that the SC systems did not always reduce engine torque completely to zero. From the data in these figures "driver requested torque" and "engine torque" output measures do appear to be possible MOP candidates for further development.

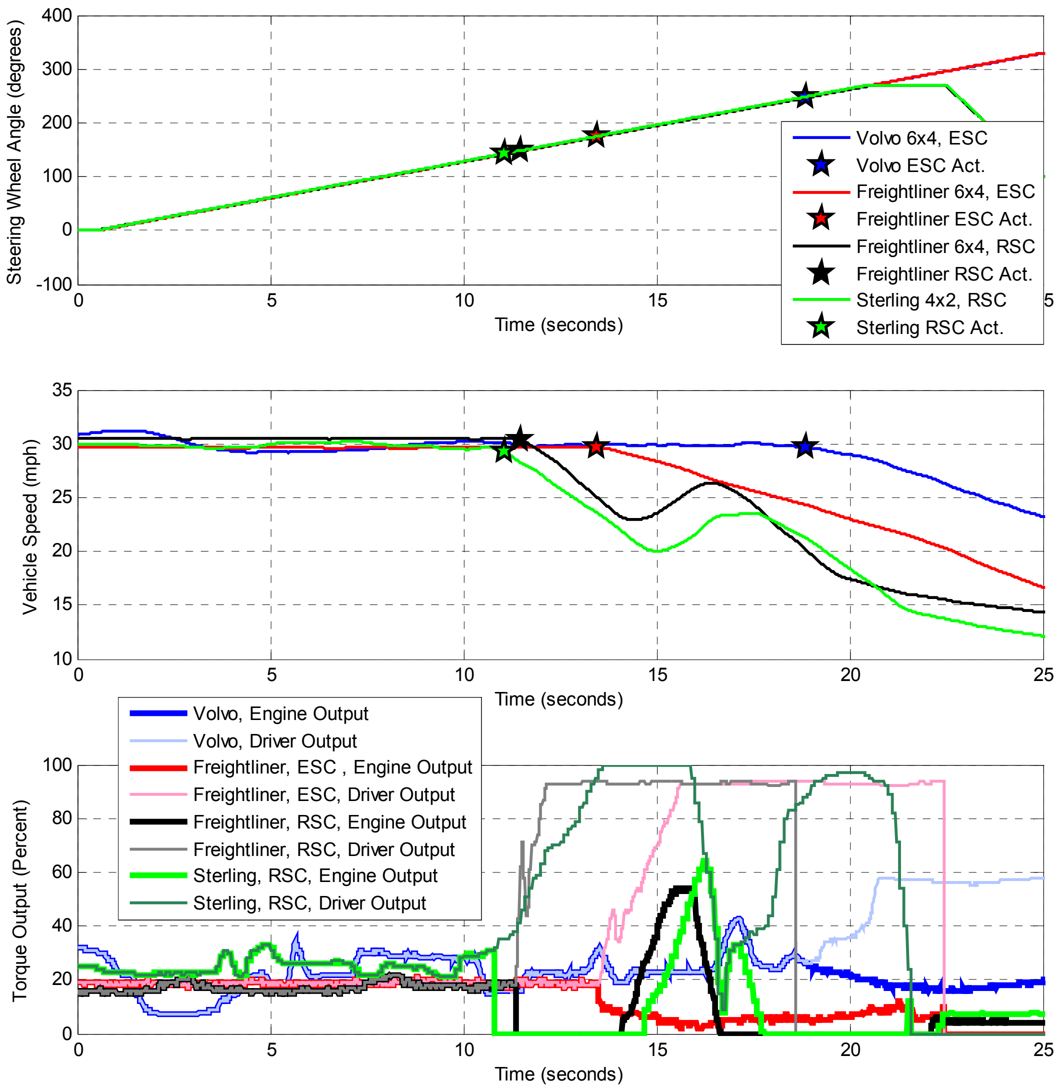

Figure 6.3. Example of observed tractor torque output level during an SC intervention for 4 SC systems.

Truck Tractor Engine Torque Data Analysis

After initial review, the torque separation activity observed between "driver requested torque" and actual engine torque output was confirmed for all of the SIS test series in which the SC systems were enabled for each vehicle. This fact led researchers to conclude that this measure was a good candidate for further analysis and development towards a MOP to indicate that a truck tractor is equipped with a SC system that exhibits engine/power unit control. This section discusses the basic data analysis that was performed.

The analysis is predicated on the test driver attempting to maintain a constant vehicle speed at the point of SC engine torque intervention by making a substantial increase in driver-requested engine torque. For the four examples shown in Figure 6.3, the driver requested engine torque after SC intervention was between 60 and 100 percent of engine output, while the engine torque output after SC intervention ranged from zero to 60 percent. Note that the Sterling RSC and Freightliner RSC engine torque interventions reduced engine output torque to zero but then approximately four seconds later, both systems allowed engine torque to be momentarily reapplied to over 50 percent of engine output. The analysis on engine torque differentials was therefore limited to the first four seconds after SC engine torque intervention, since none of the SC systems were observed to make substantial reapplications of engine torque output during this initial time frame. The Volvo ESC had the highest engine torque output during the first four seconds after intervention, ranging from approximately 23 percent to 18 percent.

To quantify the change in the torque signals, the difference was calculated and expressed as a percentage change over time for each test in a SIS test series. To depict these changes the data were all aligned from the observed point of separation between the two torque signals and the mean values were calculated for the SIS test series. This is shown in Figure 6.4.

In Figure 6.4, the black trace represents the mean difference between the torque measures after separation occurred. The black bars represent ±2 standard deviations of driver and engine torques for all of the vehicles at one-half second intervals from the torque separation point. The other traces represent the mean difference in the torque measures for each of the vehicles tested over one-half second intervals. The blue trace represents the Volvo 6x4 with ESC. The red trace represents the Freightliner 6x4 with ESC. The green trace represents the Freightliner 6x4 with RSC, and the cyan trace represents the Sterling 4x2 with RSC.

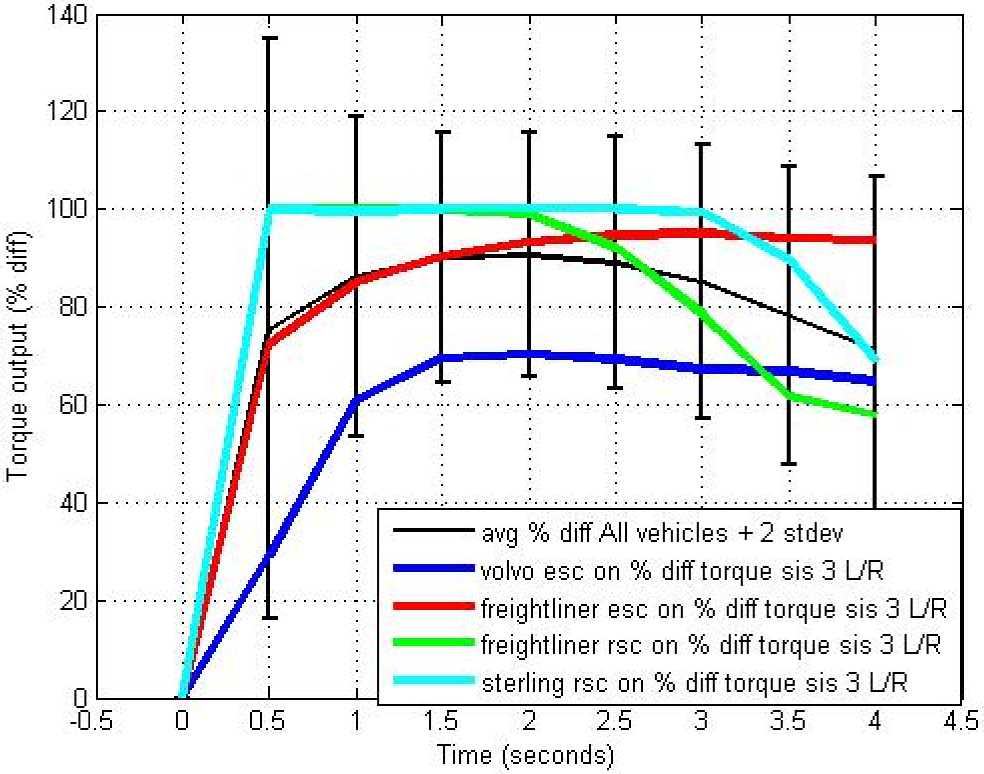

Figure 6.4. Average of the percent difference found from driver and engine torque starting at SC activation out 4 seconds for a SIS test series.

6.2 MOP for Foundation Braking in RSM Tests

Earlier sections presented RSM test results that showed the maneuver entrance speed required to produce roll instability for each test load condition. SC was observed to improve the combination's roll stability by applying the foundation brakes. For the purposes of this report, effectiveness has been defined as the additional speed required to produce roll instability in vehicles equipped with SC systems enabled compared to the baseline, SC system disabled condition. Roll instability has been defined by the measurement and observation of wheel lift of either the tractor drive wheels and\or trailer wheels. Table 6.1 (identical to Table 5.16; presented here for convenience) shows the test results from the RSMs with High CG loading conditions. Measures were assessed according to how well they discriminated between SC and non-SC equipped vehicles and their correlation to the results in Table 6.1. Additional consideration was then given to validity, ease of computation and\or measurement. For example, large differences in longitudinal acceleration were observed between a tractor with SC enabled and disabled. However, these differences did not necessarily indicate that lateral stability was improved. Therefore, longitudinal acceleration was ruled out for use as a performance measure. After an initial review of the data, researchers found six dynamic measurements that merited further analysis and development. These are:

- truck tractor wheel height
- trailer wheel height

- truck tractor lateral acceleration
- trailer lateral acceleration
- truck tractor roll angle
- trailer roll angle

Some of these measures were used directly while others were developed further through equations and data reduction. The following sections document the analysis of the six listed measurements to be developed.

6.2.1 Wheel Lift Metric

Wheel lift is a direct MOP with minimal calculations needed to determine its value provided that wheel heights relative to the test surface can reliably be measured. Grossly, it can be visually observed by the experimenter during the test maneuver. Historically, wheel lift has been used to characterize a vehicle's roll propensity in many research programs. The measure is simple and directly represents the pre-crash condition that immediately precedes a rollover. If wheel lift can be prevented from occurring, a rollover cannot take place.

NHTSA currently uses "2 wheel lift" as the pass / fail criteria for the New Car Assessment Program (NCAP) Vehicle Rollover Confirmation Test [11]. NCAP considers 2 wheel lift to be two wheels simultaneously lifting 2.0 inches or greater from the test surface during the Fishhook test maneuver.

For the research presented in this report, wheel lift[9] of either the truck tractor's or test trailer's inside wheels were used as one of the test termination criteria for the SIS and RSM maneuvers. Termination was initiated upon either the driver's or experimenter's observation of wheel lift and\or verification of the event via displacement sensors mounted on the axles. To researchers this was a clear indication of impending roll instability and therefore all metric analyses have been based on this event. Figure 6.5 presents an example of wheel height test data for a RSM test with wheel lift. The top plot shows the wheel height for the truck tractor versus time and the bottom shows wheel height for the test trailer versus time. In this example, the left side wheels of the trailer were observed to leave the test surface for approximately 3.5 seconds and peaked at approximately 4.00 inches. The left side tractor wheels were observed to just lift off the ground for approximately 1.5 seconds during that time and reached a peak lift of 0.75 inches. Negative values for wheel lift indicate that the tires are loaded and compressed to the test surface. In this example, the maximum wheel lift observed at the tractor axles did not exceed the 2.0 inch threshold and therefore would not be cause for terminating the test series. However, the trailer axles exceeded the wheel lift threshold and this event was the cause for test series termination.

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[9] Wheel lift was considered for wheel height data that measured more than 2.00 inches for the trailer wheels or wheel height greater than 2.00 inches at the tractor drive wheels.

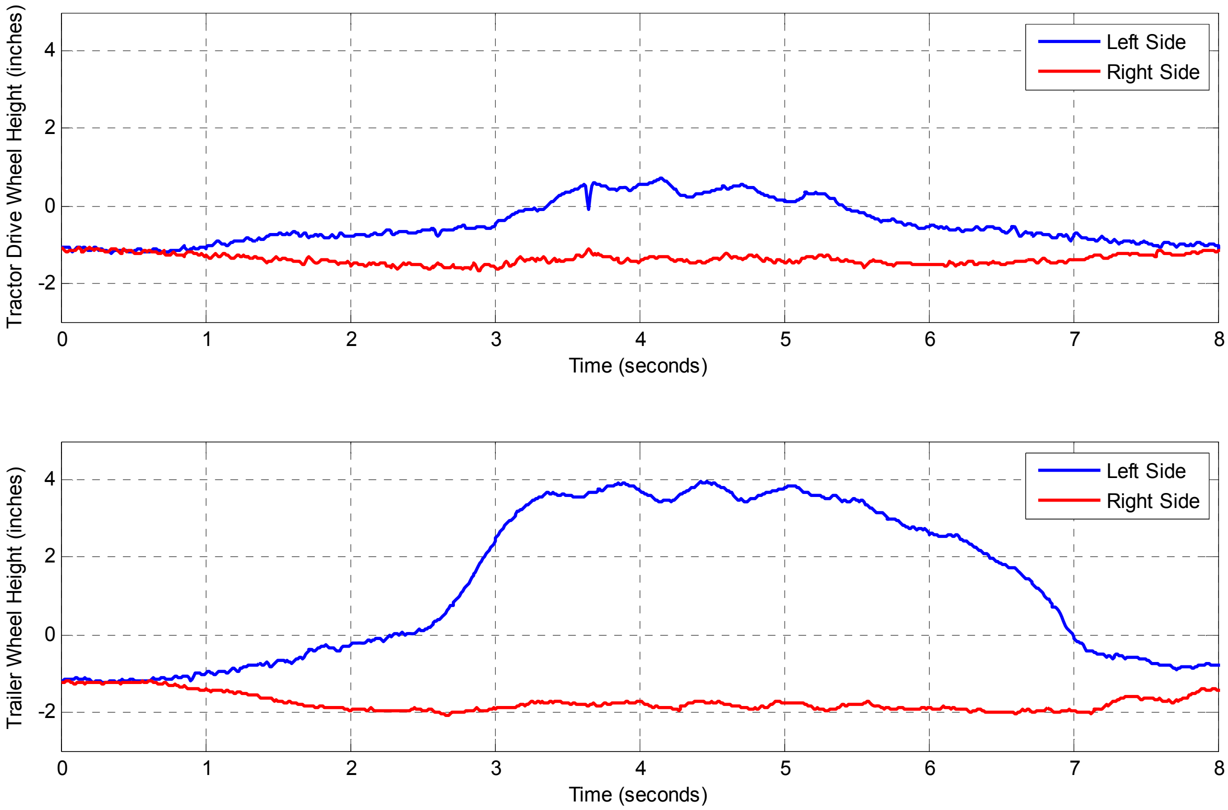

Figure 6.5. Wheel height data from a RSM test. Negative heights indicate tires are loaded and compressed to the test surface. Positive height values indicate the lowest point on the wheels that are above the ground plane.

Wheel lift does not always indicate that rollover is imminent. For example, certain suspension designs will lift a wheel during hard cornering, or non-uniform test surfaces can cause brief instances of wheel lift. However, the wheel lift observed during RSM testing was conclusively due to roll instability and in most cases would have resulted in a rollover if safety outriggers were not installed. Given this observation, using wheel lift as a performance metric is attractive since it is discriminatory between stability and instability. It is easy to observe and measure. It easy to understand and has high face validity since rollover cannot occur without the wheels leaving the pavement.

Even with these positive attributes, a number of concerns would need to be addressed before adopting it as a performance metric. Researchers performed a statistical analysis that investigated the relationship of MES to wheel lift for the test conditions shown in Table 6.1.

Table 6.1. Test termination speed that resulted in 2.0 inches or more of wheel lift for the RSM. All tests were conducted with the High CG load conditions (CG heights> 75 inches).

Vehicle	Dry Box Van (mph)						Flatbed (mph)									Tanker (mph)		
	Fruehauf 53 ft.			Strick 53 ft.			Fontaine 48 ft. Spread Axle			Fruehauf 48 ft. Tandem Axle			Great Dane 28 ft. Control Trailer			Heil 42.5 ft. 9200 Gal.		
	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked
2006 Freight-liner 6x4 ESC	27 T	32 T	32 T	28 T	40 T	36 T	26 D	32 D	29 D	27 D	32 D	29 D	28 D/T	32 D/T	31 D/T	28 T	35 T	32 T
2006 Freight-liner 6x4 RSC	27 T	35 T	33 T	28 T	35 T	34 T	26 D	31 D	30 D	27 D	33 D	32 D	28 D/T	34 D/T	33 T	28 T	35 T	34 T
2006 Volvo 6X4 ESC	30[2] T	38 T	37 T	31 T	42 T	41 T	28 D	38 D	37 D	30[1] D	35 D	33 D	30 T	41 T	39 T	30 T	40 T	38 T
2008 Sterling 4x2 RSC	28 T	32 T	31 T	28 T	28 T	28 T	25 D	25 D	25 D	26 D	28 D	26 D	28 T	30[3] T	30[3] T	28 T	28 T	28 T

[1] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 183 degrees.
[2] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 170 degrees.
[3] Test series were conducted with the vehicle in neutral rather then depressing the clutch pedal for the duration of the maneuver.
D = Wheel lift observed at tractor drive wheels
T = Wheel lift observed at trailer wheels

Maneuver Entrance Speeds That Produce Wheel Lift

To statistically understand the performance of stability control a logistical regression model was developed. The model used maneuver entrance speed (MES) to predict if a test condition would result in wheel lift. All test conditions were conducted with a heavy load and a CG height greater than 75”. Factors included in the model were SC (0 = No, 1 = ESC, and 2 = RSC), trailer brakes (1 = Enabled, 2 = Disabled), and trailer type (1 – 6). MES was chosen as the factor being manipulated in the RSM to control the magnitude of lateral acceleration. Results from this model are shown in Table 6.2.

Lateral acceleration was modeled using a similar technique but was found not to be as robust due to the inherent noise in the measurement data. Since kinematics describe that lateral acceleration is equal to the square of the velocity divided by the vehicle path radius, velocity can be considered equivalent to lateral acceleration for the RSM (i.e. for a given speed for the same tractor, fixed since the steering controller makes R the same for all maneuvers.)

Table 6.2. Probability of wheel lift (P<hat>) observed in RSM testing at various MES and under different SC conditions.

MES	Probability Confidence Limits								
	SC Disabled			SC, Unbraked Trailer			SC Enabled		
	N=121	pCL		N=189	pCL		N=208	pCL	
MPH	P<hat>	Low	High	P<hat>	Low	High	P<hat>	Low	High
29	.79	.61	.90	.11	.06	.20	.04	.01	.10
30	.91	.75	.97	.17	.10	.26	.07	.03	.15
31	.97	.85	.99	.24	.16	.34	.06	.12	.21
32	.99	.91	1.0	.33	.24	.44	.19	.11	.30

As shown in this table, with SC disabled the probability of wheel lift greatly increases with speed. At 32 mph, the model predicts a very high probability with tight probability confidence levels.

When SC is enabled without trailer brakes, the probability of wheel lift is greatly reduced for the same speeds. The model shows even lower probabilities of wheel lift when trailer brakes are enabled.

This is encouraging given the fact that the model is considering the effects of SC from four different truck tractors[10] and six different test trailers with slight variations in rollover propensity. Focusing this analysis onto specific configurations may be possible; however, there may not be enough data from this test program to produce a robust model. It is thought that analyzing the data as a whole population is valid (as in the above case) because in real world service, tractors with stability control systems are expected to function with different trailers and loads.

Wheel Lift Timing in the RSM

During RSM testing wheel lift was observed for a wide range of speeds due to differences in the roll stability of truck tractors, test trailers, and load condition combinations. Test results were analyzed to identify the time at which wheel lift occurred during the RSM test. This was of interest to determine if there were specific maneuver time(s) that should be used to evaluate SC effectiveness. Figure 6.6 presents the vehicle maneuver entrance speed versus the time elapsed from the beginning of steer input at which wheel height first reached 2.00 inches. Red squares represent SC disabled tests in which wheel lift was observed, diamonds represent SC enabled with unbraked trailer tests, and pentagrams represent SC enabled tests in which wheel lift was first observed. From the figure, a large majority (46 out of 51) of instances of wheel lift were initiated between 2.00 and 4.00 seconds after the beginning of steer input. Also note that the tests observed outside of this range were at test speeds below 29 mph. Therefore, the critical time in the maneuver at which to asses

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[10] Some Sterling 4x2 RSC data was not included in the data groups. Several Sterling RSM test series with different trailers were observed to have a delayed SC system response. The delay in system response influenced the speed at which wheel lift was observed and therefore those data sets were omitted from this analysis.

roll stability ranges between 2.0 – 4.0 seconds after the initiation of a RSM test, for RSM tests with MESs between 29 and 32 mph.

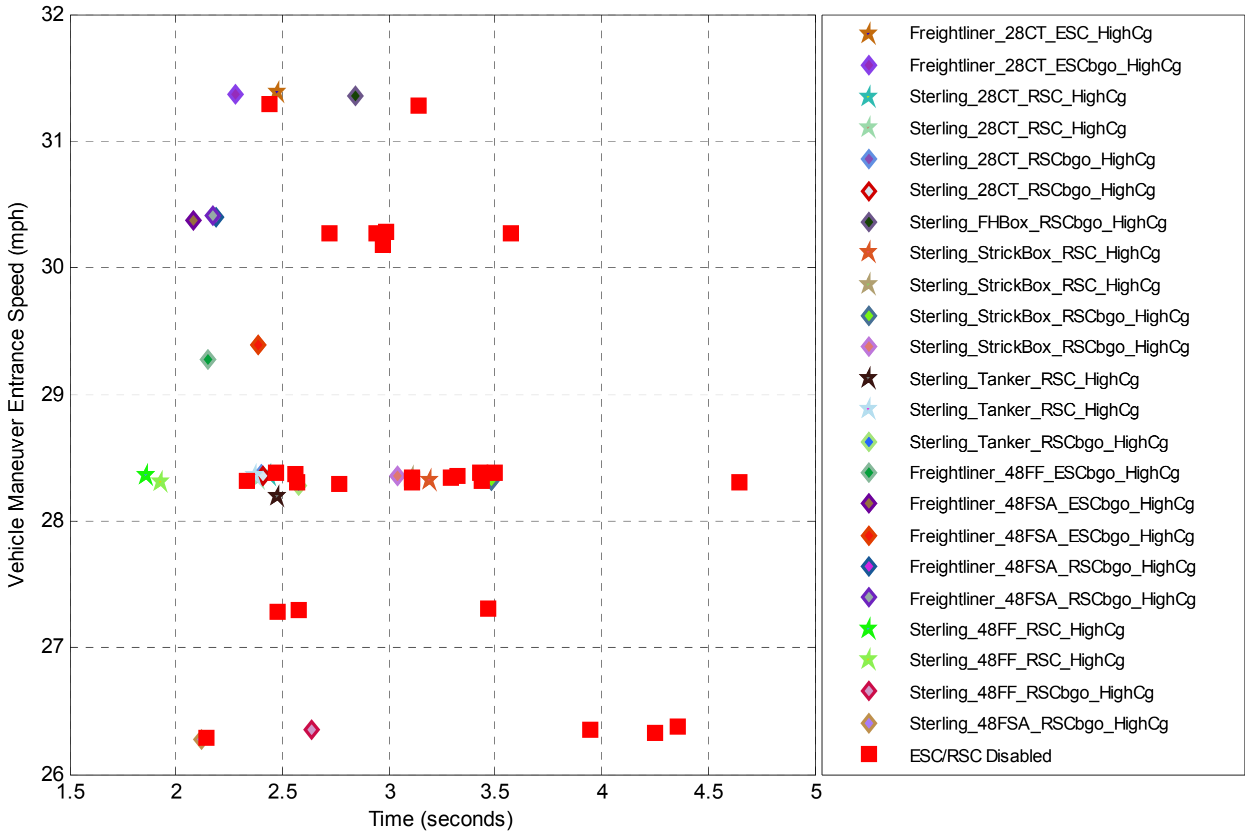

Figure 6.6. Figure shows all tests that had wheel lift between MESs of 26 – 32 mph and when wheel lift first reached 2.00 inches. Time is referenced from the initiation of the RSM test.

6.2.2 Truck Tractor Lateral Acceleration Maxima and Degradation

Initially truck tractor lateral acceleration maxima and degradation (differential) data from RSM tests were explored for possible use as roll stability performance criteria. Using maximum lateral acceleration as the criteria is conceptually founded upon the principle that a Class 8 tractor/trailer combination with a high center of gravity will rollover in the linear region of vehicle dynamics and thus should be very predictable. This has been found to be repeatable and could possibly be used in conjunction with maneuvers that approach or cross the tipping lateral acceleration in a slow gradual manner (i.e. the SIS maneuver or the constant radius maneuver). However, the steering inputs required to perform the RSM are intended to be quicker (crash avoidance like) and excite the roll dynamics of the test vehicle(s). As a result, the maximum lateral accelerations observed for each tractor that experienced wheel lift in the RSM are quite different.

Figure 6.7 shows the maximum lateral accelerations versus time from end of ramp input observed for each of the truck tractors with all combinations of test trailers configured with a High CG load. Tests performed with the 28-foot flatbed trailer are highlighted to show that differences were not necessarily caused by the different trailers. All tests were performed with approximately the same MES of 28 mph. Also, the lines shown represent the average maximum lateral acceleration plus two and three standard deviations of the tests that did not produce wheel lift. This shows that using tractor maximum lateral acceleration as a performance criteria would not discriminate between vehicles equipped with stability control and those without it. Although the maximum lateral acceleration does not merit further development, the tractor's lateral acceleration data traces show that there are clear and observable differences that result from stability control intervention. This is observable in Figure 6.8.

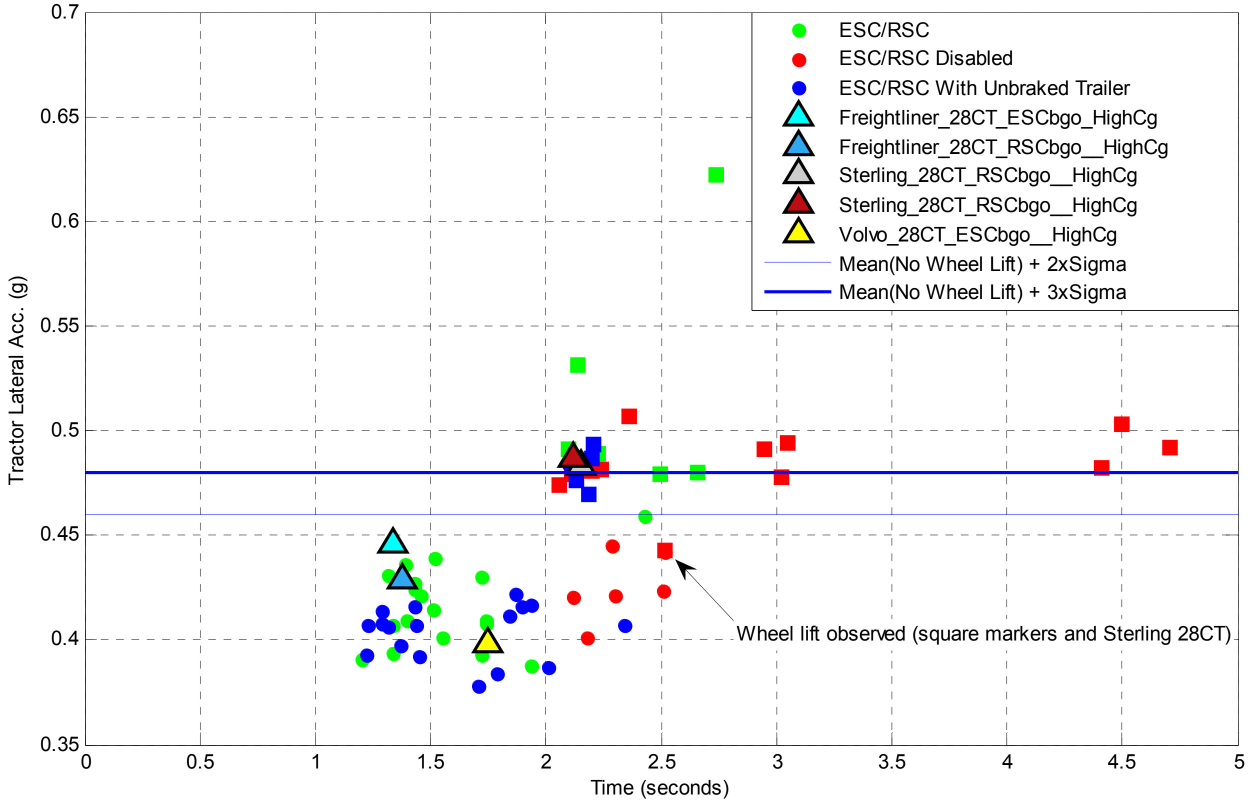

Figure 6.7. Example shows maximum tractor lateral acceleration versus time from end of ramp input for all four tractors. Each data point represents an RSM test conducted at approximately 28 mph. Square markers indicate wheel lift and the Sterling 4x2 in combination with the 28-foot control trailer tests that are highlighted were observed to have wheel lift.

Figure 6.8 shows the lateral acceleration versus time in the top plot and the degradation (differential) of lateral acceleration versus time in the bottom plot. These RSM tests were conducted with the Freightliner 6x4 in combination with all the trailers configured with a High CG load. From the top plot it is clear that stability control (with or without trailer brakes enabled) degrades lateral acceleration. However, after calculating the degradation by differentiation it became obvious that using it as a metric would also be difficult given the oscillatory nature of the calculation (through the region of interest, 2 – 4 seconds). Though this methodology does not initially seem to warrant further development, it is clear from the top plot that differences in the enabled and disabled data could be exploited for metric development and led NHTSA researchers towards exploring a ratio based metric rather than continuing research into maxima or degradation.

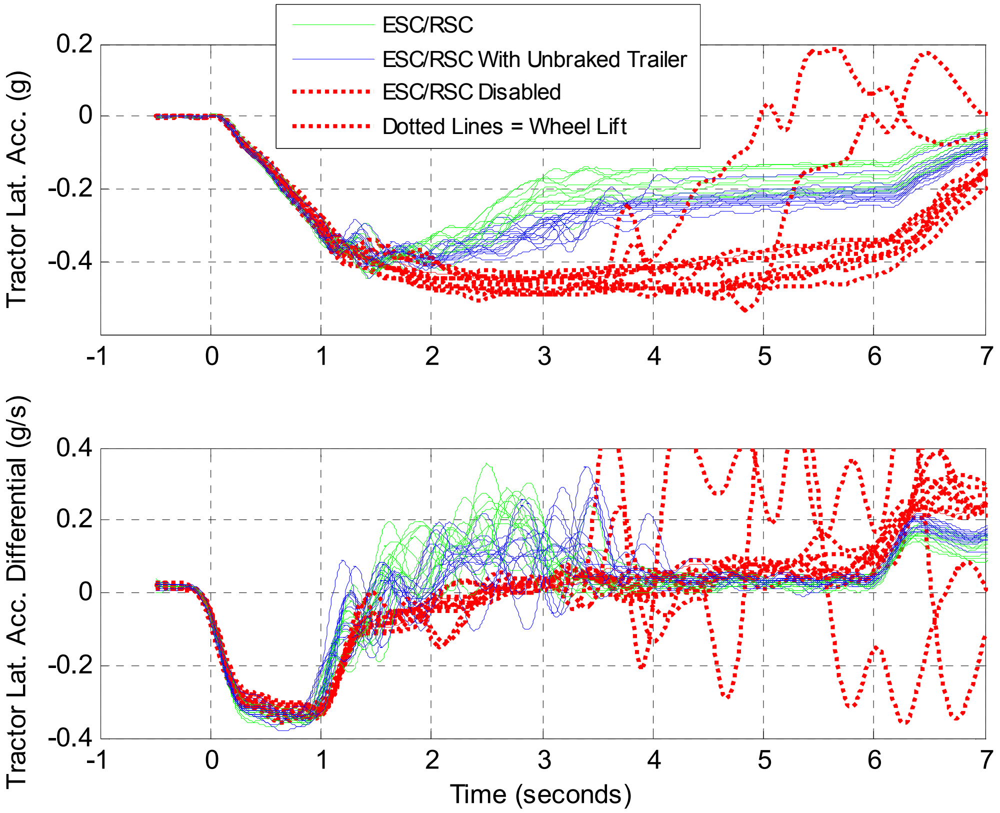

Figure 6.8. Top shows tractor lateral acceleration versus time for the Freightliner 6x4. Bottom shows the lateral acceleration degradation (differential) versus time.

6.2.3 Lateral Acceleration Ratio (LAR)

Based on data that has been presented in previous sections of this report, it can be observed that lateral acceleration was significantly reduced for tests conducted with SC enabled as compared to tests with the system disabled. Conceptually, ESC reduces lateral acceleration of the vehicle(s) during a crash avoidance type maneuver such as the RSM. This is apparent in test data for a given entrance speed and loading condition that produces a severe enough response from the vehicle requiring an SC system to selectively apply the foundation brakes to improve roll stability. This intervention increases the roll stability of the vehicle(s) by reducing the tipping forces produced from lateral acceleration (F=ma) acting on the mass of the vehicle(s). Truck tractor lateral acceleration ratio was investigated as a possible roll stability performance metric for Class 8 vehicles. Figure 6.9 shows an example of the ESC system's ability to reduce tractor lateral acceleration.

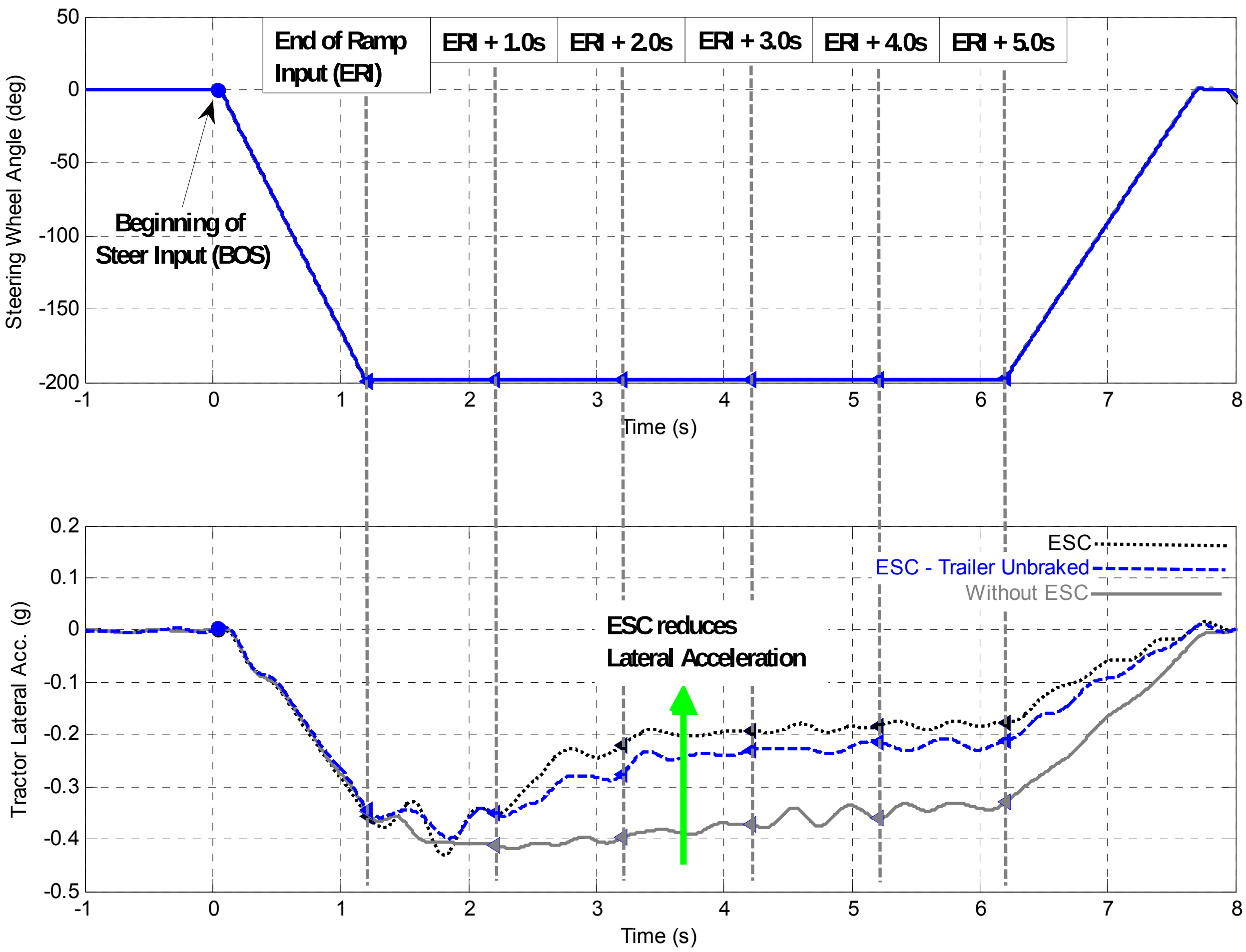

Figure 6.9. Time history data of steering wheel angle and lateral acceleration for three 28 mph RSM(s). Tests shown were conducted with the same tractor\trailer and load condition: the three tests represent SC enabled, SC (tractor only) with the trailer brakes disabled, and the vehicle without SC.

Figure 6.9 shows typical test data from a RSM conducted at a target maneuver entrance speed of 28 mph. The top plot shows steering wheel angle versus time and the bottom plot shows truck tractor lateral acceleration measured at the tractor CG versus time. The test data in the figure are from the same tractor and trailer with a High CG load condition conducted with three different SC states. Those states were SC enabled, SC enabled with the trailer brakes disabled, and without SC (system disabled). The effect of SC intervention on the vehicle is clearly represented in the tractor lateral acceleration traces when comparing the data from the different system conditions. In this example, SC reduces the tractor's lateral acceleration from approximately 2.0 seconds to the end of the maneuver. Several timing events are indicated during the steering input such as the beginning of steer (BOS) input, the end of initial ramp input (ERI), and then five one-second intervals as measured from the ERI event. These timing events were used to further investigate the possibility of a performance metric based on measured tractor lateral acceleration.

Lateral acceleration ratio (LAR) is calculated by dividing the tractor's lateral acceleration at a given time interval by the measured lateral acceleration at the ERI. The LAR at five equal 1.0 second intervals from ERI (as shown in Figure 6.9) was plotted to observe the increase\reduction in tractor lateral acceleration from the lateral acceleration at ERI.

$$\text{Tractor LAR} = \frac{Ay_{Tractor}\left(ERI + 1.0, +2.0 \ldots + 5.0\,\text{sec}\right)}{Ay_{Tractor}\left(ERI\right)}$$

Five LAR values for the tests in Figure 6.9 are shown in Table 6.3 and depicted graphically in Figure 6.10.

Expanding the type of comparison shown in Figure 6.10 to multiple truck tractors and test trailers indicated similar reductions to LAR due to stability control's application of the foundation brakes. Graphically, those separations in the data between the ESC enabled and disabled states merited further investigation of the methodology to all tests in the matrix completed in the High CG load condition.

Table 6.3 Example of tractor lateral acceleration ratio at specific intervals from ERI.

ESC	0.985	0.620	0.542	0.515	0.497
ESC –Trailer Unbraked	1.04	0.803	0.671	0.625	0.617
Without ESC	1.178	1.139	1.071	1.035	0.943

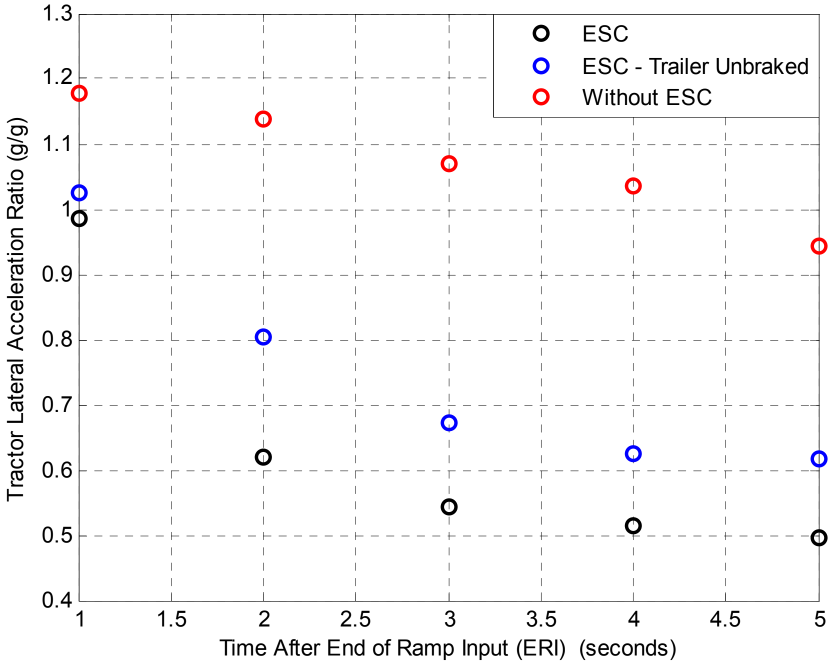

Figure 6.10. Tractor lateral acceleration ratio at time specific intervals form the test data shown in

LAR Applied to the High CG Test Condition

The LAR was calculated for 0.5-second intervals after ERI for all RSMs performed with the High CG load condition. Data were then plotted for the 10 initial time increments after ERI for a range of speeds. Figure 6.11 shows all RSM tests conducted with a MES speed range between 20 – 25 mph, with all vehicle combinations represented. Much of the data are overlapping for this speed range. This would be expected since very few observations of stability control intervention were observed with entrance speeds less than 25 mph. As the figure shows (dotted lines) there were three cases of wheel lift and those were observed with the Sterling in combination with the 48-foot spread axle flatbed trailer with SC disabled. Those tests all produced a LAR of greater than 1.2 at 0.5 seconds. These tests were aborted due to the wheel lift that was observed; time history data was considered valid up until the time the test was aborted. Even though only a few instances of stability control intervention were observed, the data clearly show that the largest LAR values were produced when stability control was disabled. The lowest values of LAR were observed with stability control enabled. As speed was increased over 25 mph, the separation between the different stability control test states became more evident.

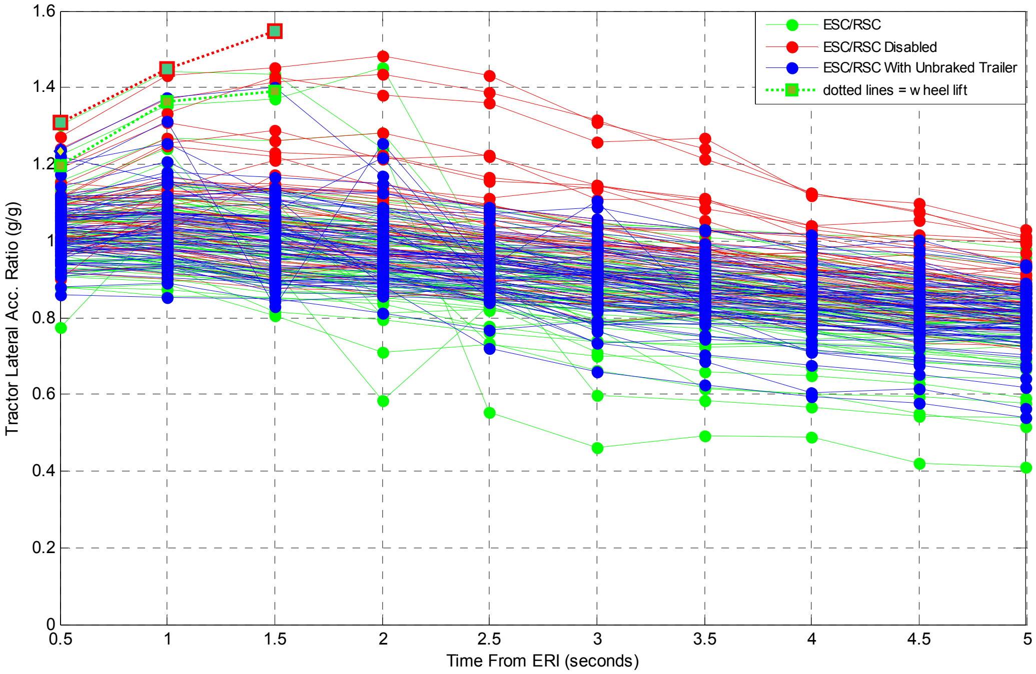

Figure 6.11. LAR versus time after ERI for 195 RSM tests conducted with a MES between 20 – 25 mph.

Figure 6.12 through Figure 6.15 show LAR versus time after ERI for the Freightliner 6x4 and all combinations, the Volvo 6x4 and all combinations, and finally the Sterling and all combinations for MES's that ranged between 26 – 32 mph. The tests in which wheel lift were observed are shown with the dotted lines. To limit the size of the legend, only SC enabled and SC enabled with unbraked trailer tests in which wheel lift were observed are defined in the legends. This speed range was selected because it encompassed the majority of speeds at which instances of wheel lift were first observed when SC was disabled.

The LAR data for the Freightliner 6x4, (Figure 6.12, with ESC and Figure 6.13, with RSC) shows that SC reduces the lateral acceleration over time. The disabled data remain much higher than the data collected with the enabled SCs. The population of tests observed to have a LAR of less than 0.5 clearly show the added performance the braked trailer can provide. Although SC intervention is clearly reducing the lateral forces on the vehicle, there were several tests with different Freightliner combinations that produced wheel lift in this speed range. Those tests that produced wheel lift with stability control enabled generally had larger LAR's than enabled tests that did not produce wheel lift. This is especially true for earlier time increments. Three of the six tests were aborted due to the wheel lift that was observed; time history data were considered valid up until the time the tests were aborted.

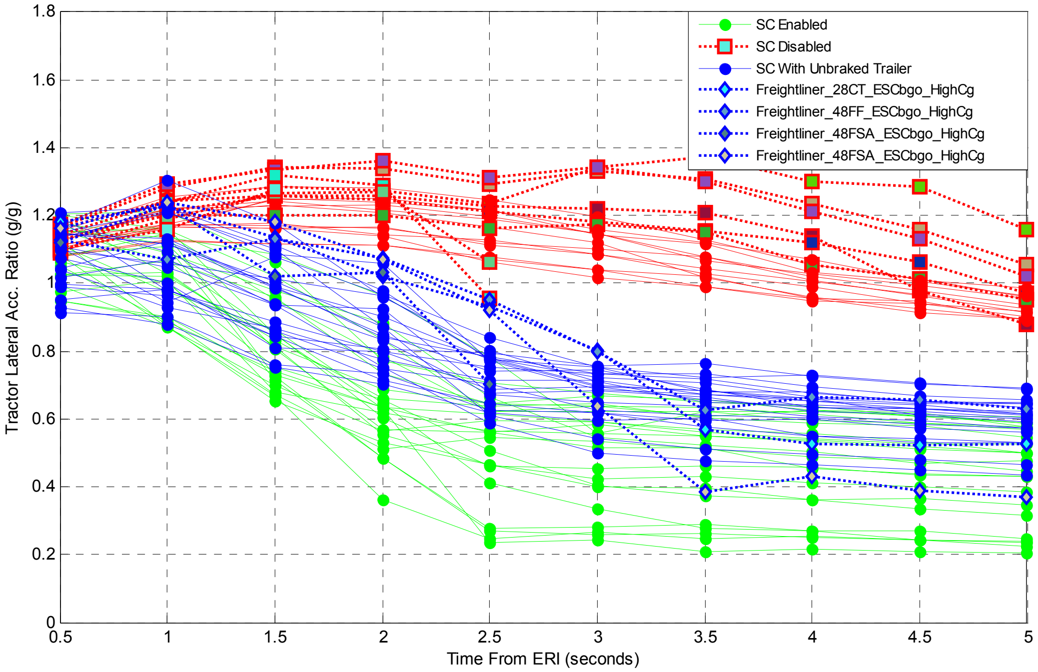

Figure 6.12. LAR versus time after ERI for Freightliner 6x4 with ESC RSM tests conducted with a MES between 26 – 32 mph. Dotted lines indicate wheel lift was observed during the test.

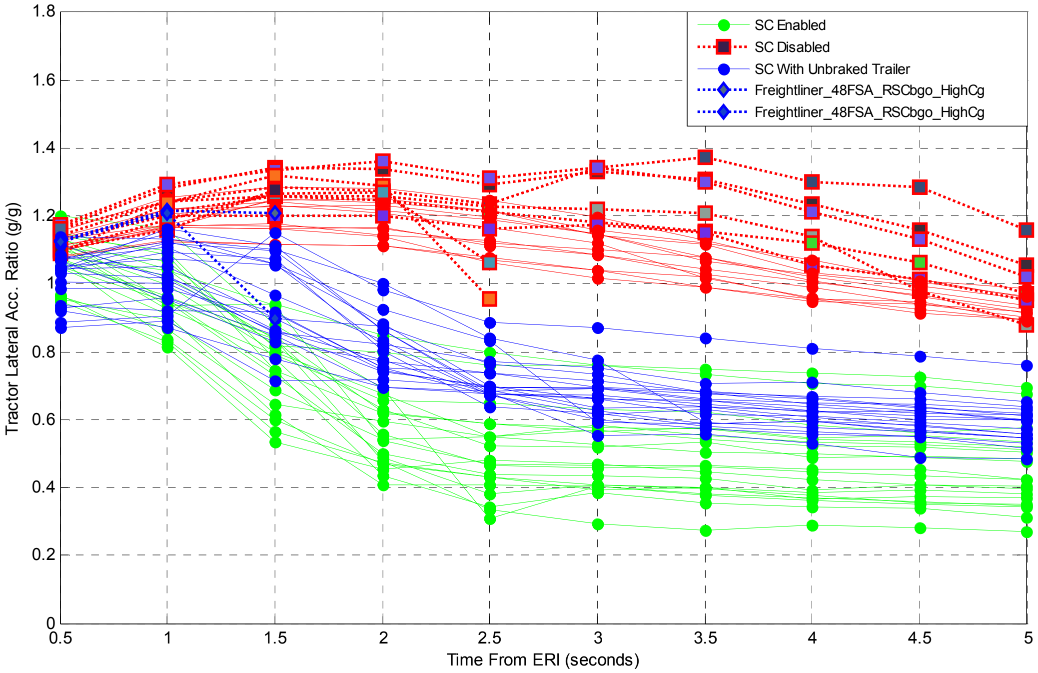

Figure 6.13. LAR versus time after ERI for the Freightliner 6x4 with RSC. Dotted lines indicate wheel lift was observed during the test.

Figure 6.14 presents LAR data versus time after ERI for the Volvo 6x4. Like the Freightliner, the Volvo shows a much larger separation in reduction of lateral acceleration from tests conducted above 26 mph. In general, as speed was increased the level of intervention of stability control increased, resulting in larger changes to LAR at an MES of 32 mph versus 26 mph. With stability control enabled the Volvo did not have any instances of wheel lift for this speed range. The added benefit of allowing the trailer brakes to intervene is observable but less so than with the Freightliner LAR data.

Figure 6.15 presents LAR data versus time after ERI for the Sterling 4x2. Like the Freightliner and the Volvo, the LAR data shows more reduction to lateral acceleration from tests conducted with a MES greater than 26 mph. However, the Sterling LAR reduction from stability control occurs later in time. Also, the traces show that the Sterling produced the maximum observed LAR's for both enabled and disabled tests. Like the two 6x4s, there is a larger observable reduction to lateral acceleration from allowing stability control to apply the trailer brakes.

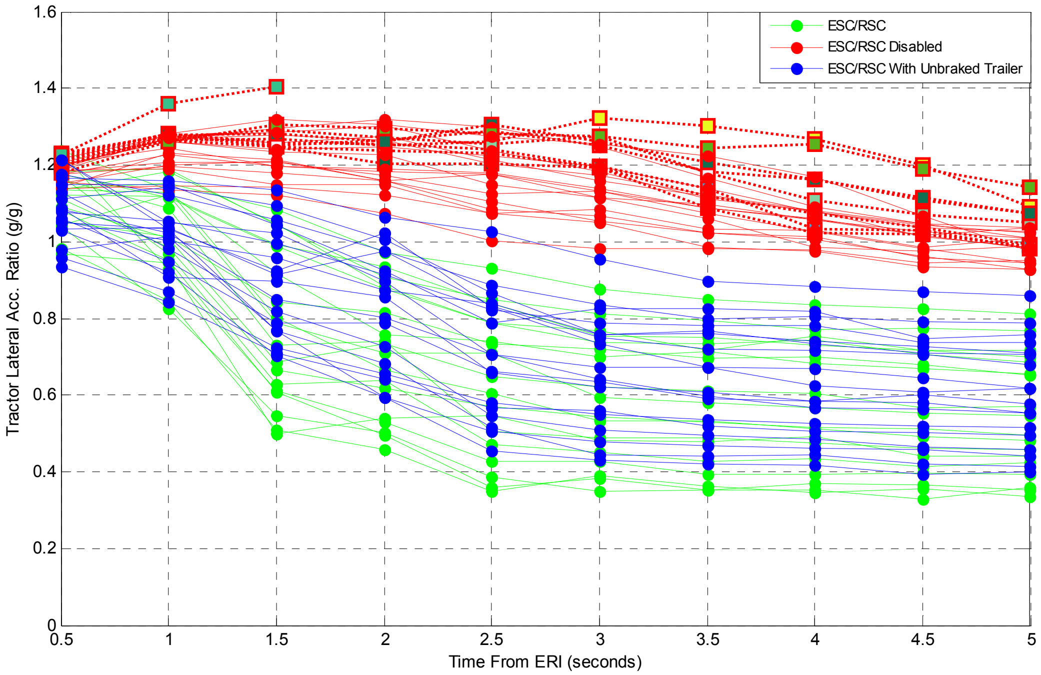

Figure 6.14. LAR versus time after ERI for Volvo 6x4 RSM tests conducted with a MES between 26 – 32 mph. Dotted lines indicate wheel lift was observed during the test.

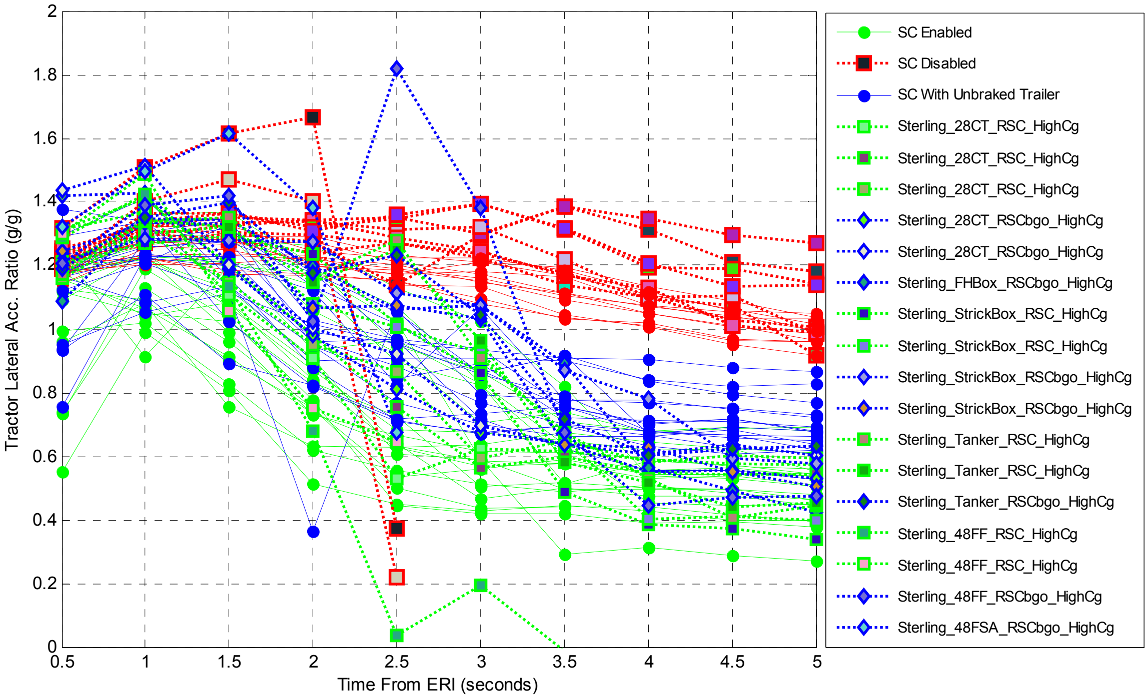

Figure 6.15. LAR versus time after ERI for Sterling 4x2 RSM tests conducted with a MES between 26 – 32 mph. Dotted lines indicate wheel lift was observed during the test.

The LAR data for RSM tests with a MES greater than 32 mph are shown in Figure 6.16. No disabled test conditions are represented for this speed range since all of these test series were terminated due to wheel lift at speeds less than 32 mph. None of the Sterling test series are represented since all of these test series were terminated due to wheel lift at speeds less than 32 mph. The figure does show that the Freightliner and Volvo were performing similarly for test speeds above 32 mph with respect to reduction in LAR. Regardless of the reduction in the tractor's lateral acceleration shown by reduction in LAR, the systems were eventually overwhelmed and the combinations produced wheel lift even if the LAR was low. This is the nature of calculation of LAR and the testing methodology, meaning that as MES increases the lateral acceleration at the ERI will grow larger ($a = V^2/R$) requiring earlier and larger reductions in lateral acceleration/LAR to maintain stability for elevated speeds combined with RSM like steering inputs.

As previously presented, the additional reduction in LAR from allowing the trailer to be braked by stability control was clearly observable. There were a few tests with the system functional that resulted in LAR dropping to zero (at 4.0 – 5.0 second time increments) which indicate the stability control system brought the vehicle to a near complete stop.

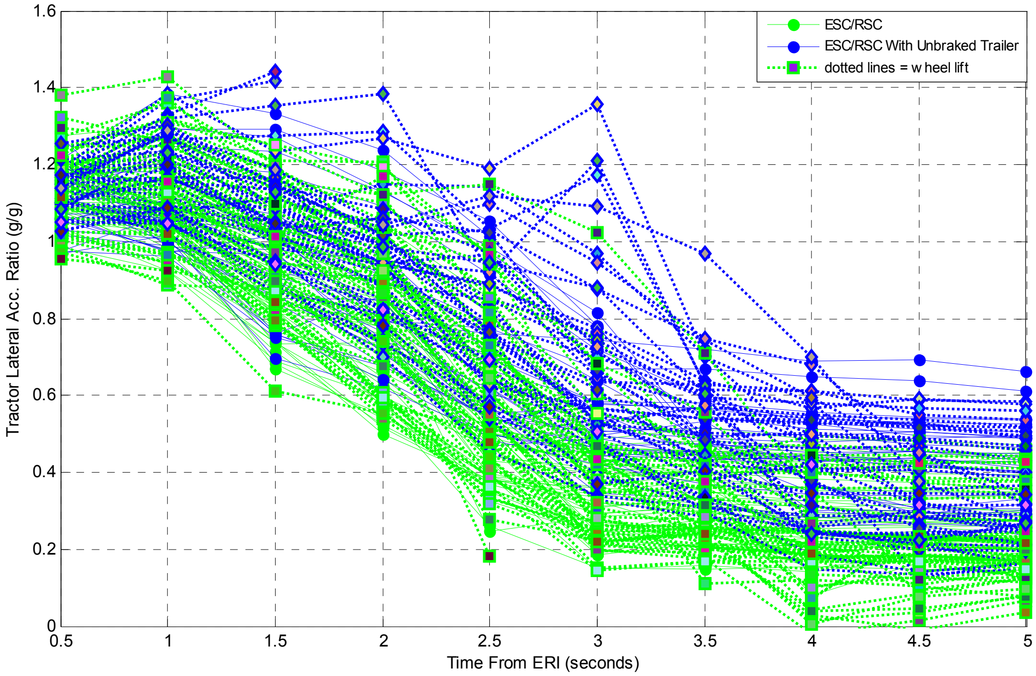

Figure 6.16. LAR versus time after ERI for 167 RSM tests conducted with a MES greater than 32. Dotted lines indicate wheel lift was observed during the test.

Truck Tractor LAR Summary

From the analysis of the RSM LAR data for the three MES ranges 20 – 25, 26 – 32 and greater than 32 mph, several observations were made. First, the low speed range, while ideal from a testing safety stand point, does not merit further use for roll stability testing since it does not produce a severe enough response to consistently activate stability control. Second, the MES greater than 32 mph range clearly activated stability control, however, testing at these speeds was consistently pushing the boundaries of what stability control equipped vehicles could recover from for the given steering inputs and loading conditions. Therefore, it should not be used to define the roll stability test or performance criteria. Third, the RSM LAR results for the speed range 26 – 32 mph show merit for further development of roll stability performance criteria. This is based on the fact that the vehicles had good performance improvements and (from Figure 6.12 through Figure 6.15) there were clear observable differences in LAR data from the addition of stability control. Lastly, a smaller range of speeds within the 26-32 mph range should be used to correlate LAR values and wheel lift and then be used to help define an effective MOP. This would be used to ensure that a minimum level of performance is observed from the addition of stability control to a Class 8 truck tractor. Most of the disabled test series combinations reached roll instability in the High CG load condition by a maneuver entrance speed of 28 mph. To get a more in-depth comparison between enabled and disabled stability control effects, a subset of the data was further analyzed in subsection 6.2.6.

Given LAR's initial potential to be developed into a metric and the observance of similar reductions in other measures, this type of ratio metric was also applied to test trailer lateral acceleration and roll angle measures. Figure 6.17 shows typical test data from a RSM conducted at a target maneuver entrance speed of 28 mph. From top to bottom are time history data of steering wheel angle, truck tractor lateral acceleration, trailer lateral acceleration, truck tractor roll angle, and trailer roll angle. The test data in the figure are from the same tractor trailer combination loaded to a High CG condition and conducted with the three different SC states. The effect of SC intervention on the vehicle is clearly represented in the lateral acceleration and roll angle measures. Several timing events are indicated: beginning of steer (BOS), end of the initial ramp input (ERI), and then five one-second intervals measured from the ERI event. The following two subsections present the additional ratios considered.

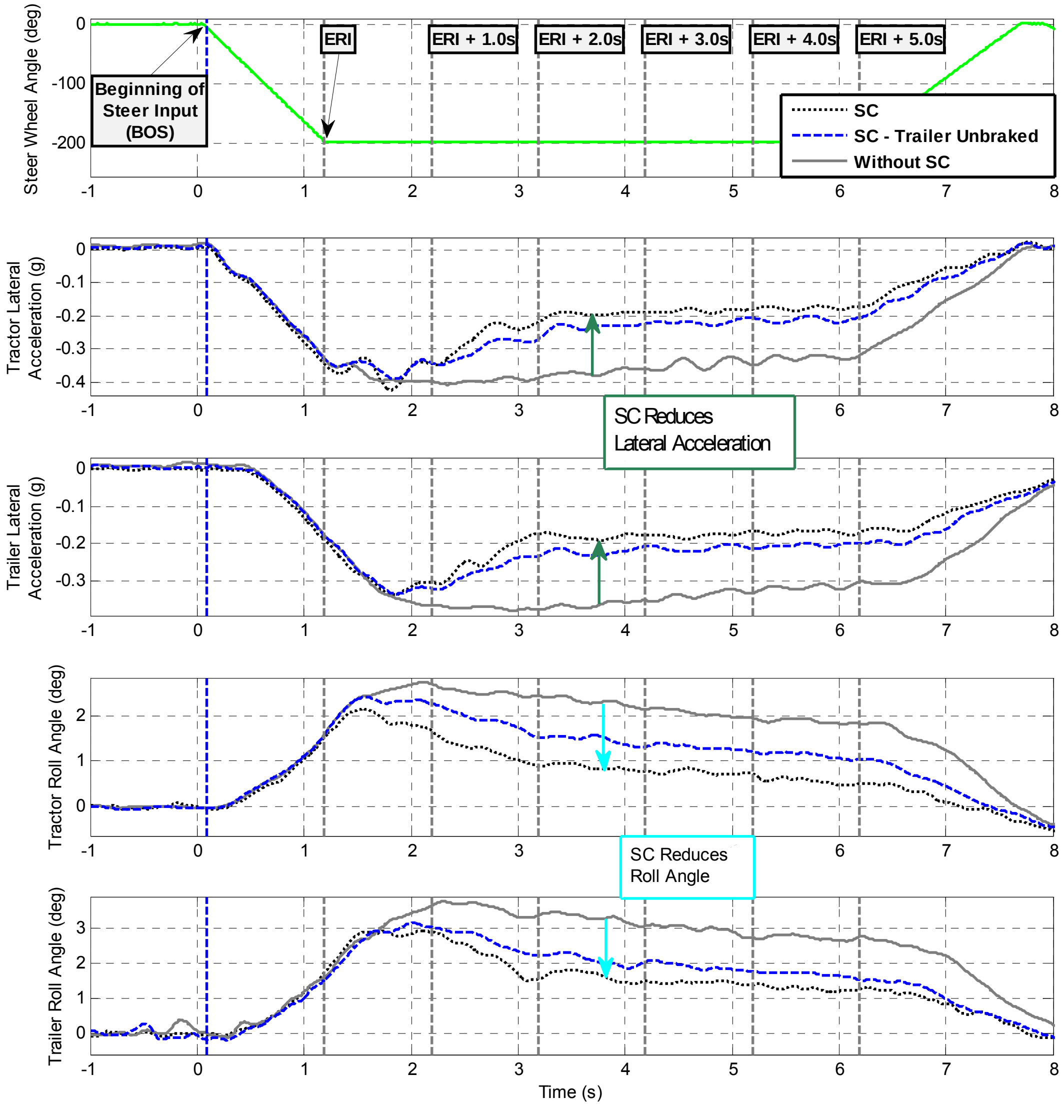

Figure 6.17: Time history data of steering wheel angle, truck tractor and trailer lateral acceleration, and truck tractor and trailer roll angle for three 28 mph RSM(s). Tests shown were conducted with the same tractor\trailer combination. The three tests represent SC enabled, SC (tractor only) with the unbraked trailer, and the tractor without SC.

6.2.4 Trailer Lateral Acceleration Ratio (TrlLAR)

Using the same technique applied to the truck tractor, a test trailer-based ratio MOP was considered. Trailer LAR is similar, however, the lateral acceleration values in the numerator are now trailer-based rather than tractor-based.

$$\text{Trailer LAR} = \frac{Ay_{Trailer}\left(ERI + 1.0, +2.0 ... + 5.0\right)}{Ay_{Tractor}\left(ERI\right)}$$

Figure 6.18 through Figure 6.21 present TrlLAR for the Freightliner 6x4, Volvo 6x4, and Sterling 4x2 tractors. For each tractor, TrlLAR is plotted from RSM test data with each of the trailer combinations for MESs between 26-32 mph. From the previous section's discussion of LAR, the 26-32 mph speed range was determined to be most appropriate for further analysis. Speeds less than 26 mph were not always observed to activate SC and speeds greater than 32 mph were overdriving the SC systems. Each figure shows test conditions of SC enabled, SC enabled without trailer brakes, and SC disabled.

All four figures show that TrlLAR was able to discriminate between the different SC test conditions. With SC disabled, the ratios were observed to increase during the initial 2.0-2.5 seconds after ERI and then remained greater than 0.8 for the remainder of the time shown. With the systems enabled without trailer brakes, the ratios were observed to peak between 1.0-1.5 seconds after ERI and then the ratios were observed to be reduced by SC to less than 0.8. With the system enabled, the ratios were observed to peak between 1.0-1.5 seconds after ERI and then were reduced to less than 0.7 by 5.0 seconds.

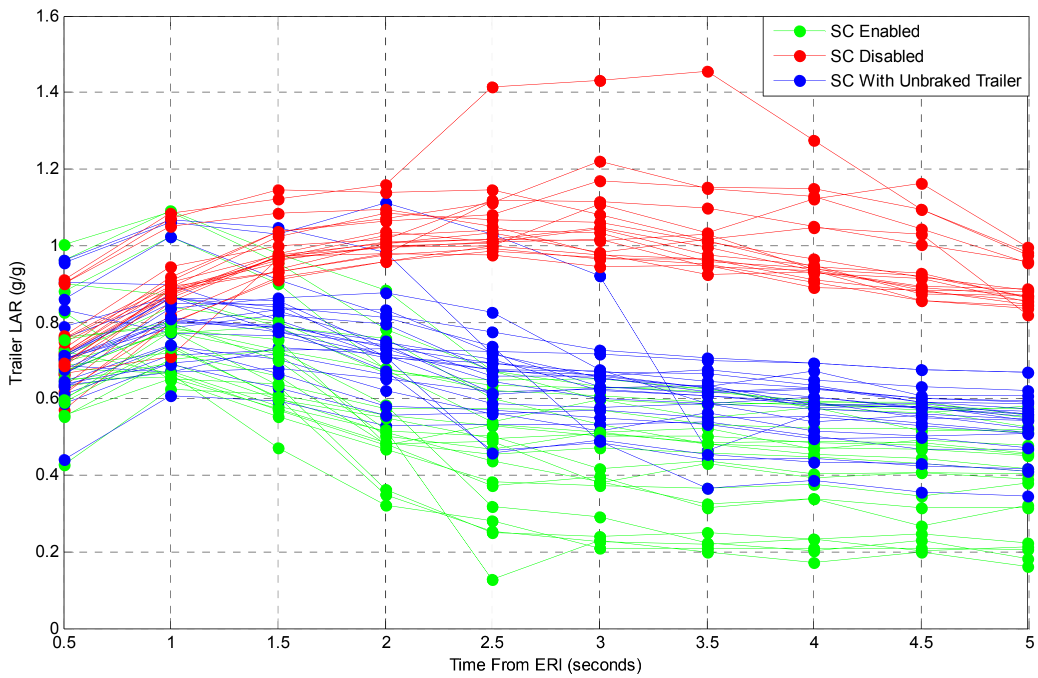

Figure 6.18. Trailer LAR from combinations with the Freightliner 6x4 (ESC) for MEEs 26-32 mph.

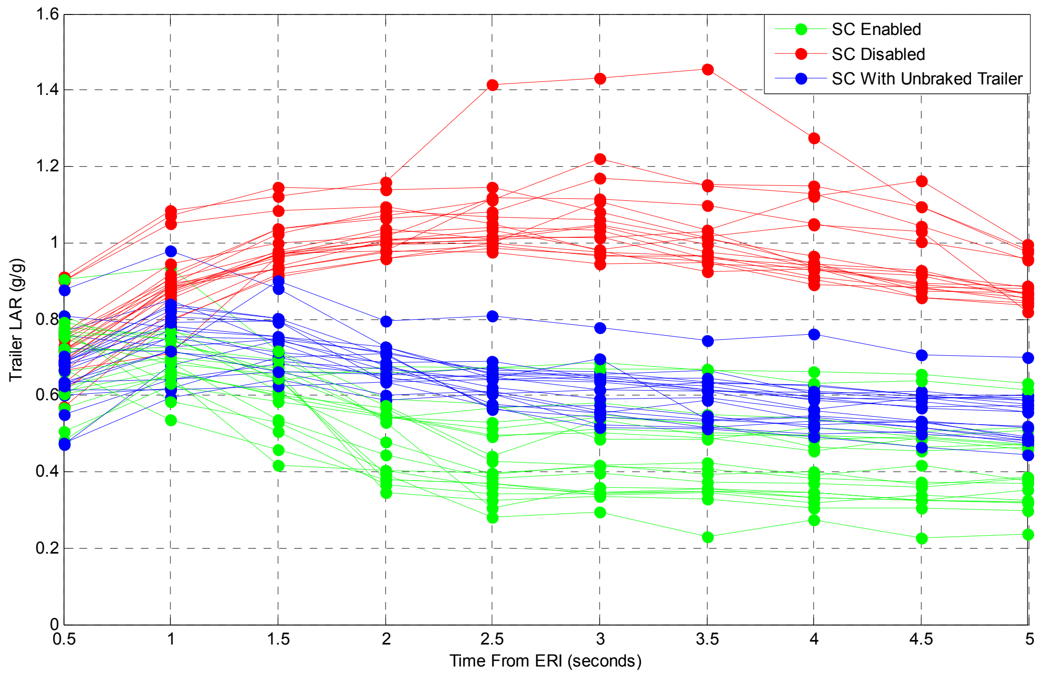

Figure 6.19. Trailer LAR from combinations with the Freightliner 6x4 (RSC) for MEEs 26-32 mph.

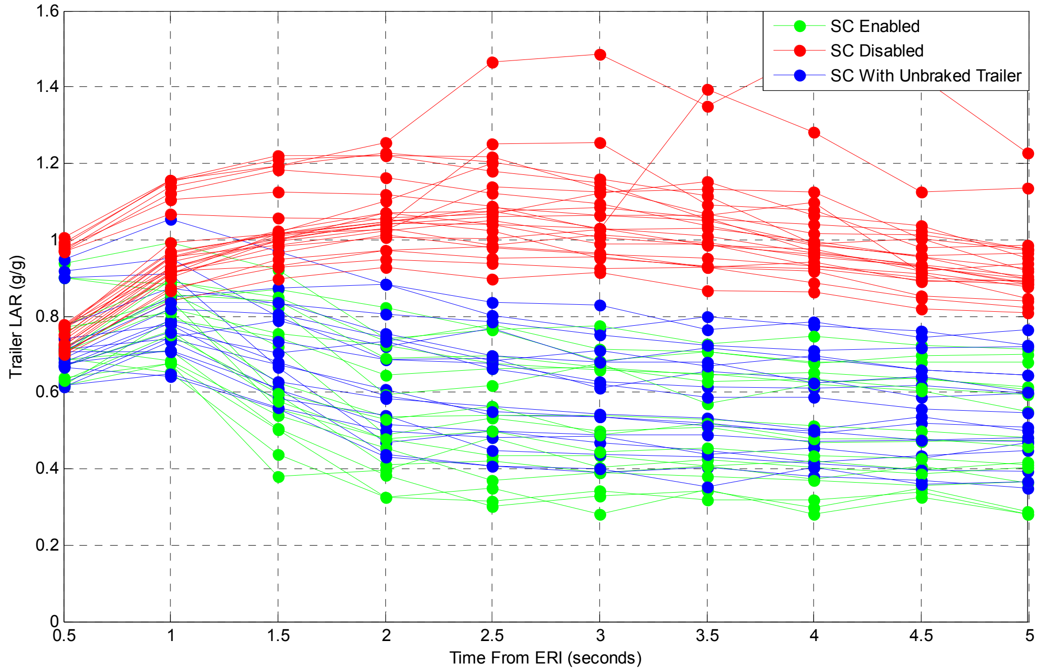

Figure 6.20. Trailer LAR from combinations with the Volvo 6x4 for MESs 26-32 mph.

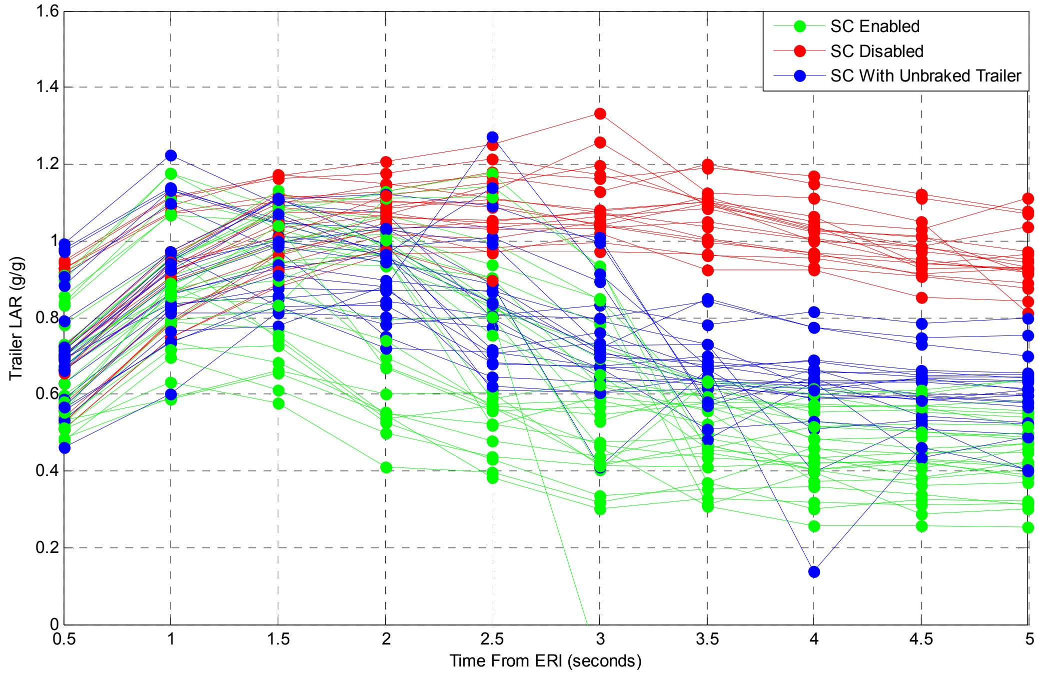

Figure 6.21. Trailer LAR from combinations with the Sterling 4x2 with MESs 26-32 mph.

6.2.5 Test Trailer Roll Angle Ratio (TrlRAR)

Using the same technique as LAR and TrlLAR, a test trailer-based roll angle ratio MOP was considered. Trailer roll angle ratio is calculated in a similar manner, however, the lateral acceleration values in the numerator are now trailer roll angles and the denominator is truck tractor roll angle at ERI.

$$\text{Trailer RAR} = \frac{RollAngle_{Trailer}\left(ERI + 1.0, +2.0 \ldots + 5.0\right)}{RollAngle_{Tractor}\left(ERI\right)}$$

Figure 6.22 through Figure 6.25 present TrlRAR for the Freightliner 6x4, Volvo 6x4, and Sterling 4x2 tractors. For each tractor, TrlRAR is plotted from RSM test data with each of the trailer combinations for MESs between 26-32 mph. Each figure shows the test conditions of SC enabled, SC enabled without trailer brakes, and SC disabled.

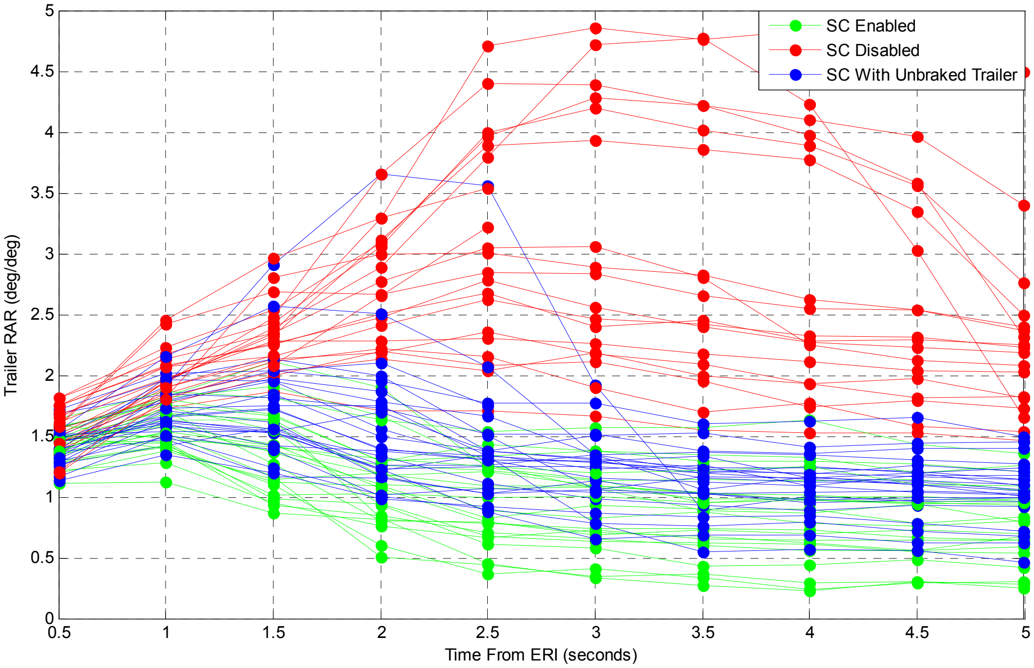

Figure 6.22. Trailer RAR from combinations with the Freightliner 6x4 (ESC) for MES 26-32 mph.

The figures show that a wider range (0.25-5.00) of ratios for TrlRAR was observed versus the ratios based on lateral acceleration (0.0-1.8). With the systems disabled, TrlRAR steadily increased and peaked between 2.0-3.5 seconds after ERI. The largest values for the TrlRAR were observed with the Freightliner 6x4 and they indicated that the trailer roll angles for a few tests were nearly 5 times that measured at the tractor at ERI when the systems were disabled. The blue and green lines show that the SC systems were responsible for the reduction in TrlRAR from the SC disabled test condition. This trend is more prominent in the latter time increments. While TrlRAR does show good discrimination between test conditions, it does have large overlapping areas. The following section further investigates LAR, TrlLAR, and TrlRAR and compares the ratios to wheel lift for a narrower set of speeds and test conditions.

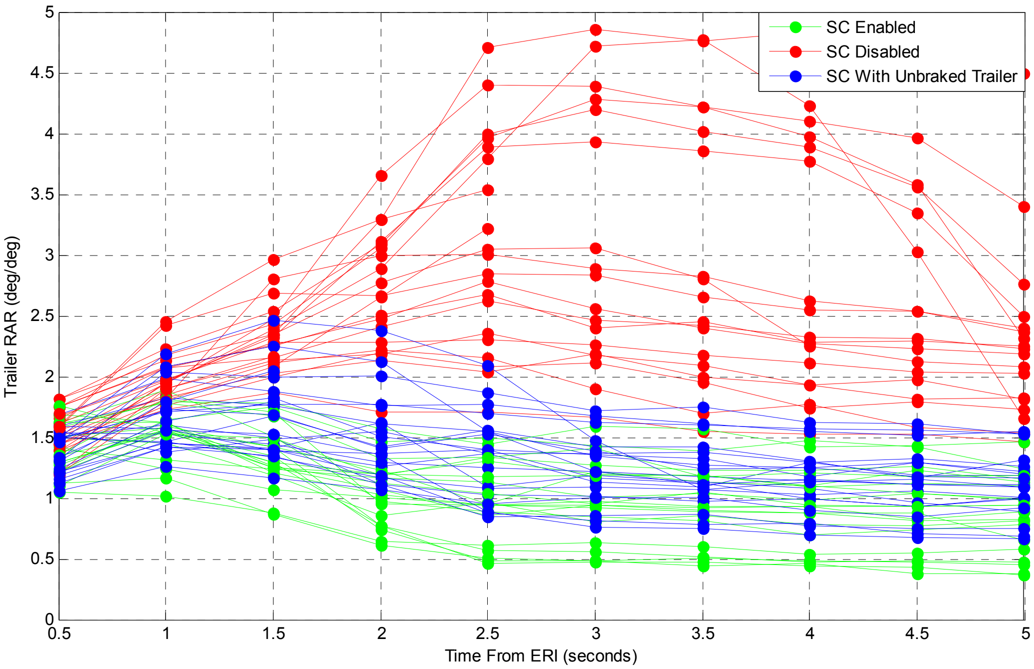

Figure 6.23. Trailer RAR from combinations with the Freightliner 6x4 (RSC) for MES 26-32 mph.

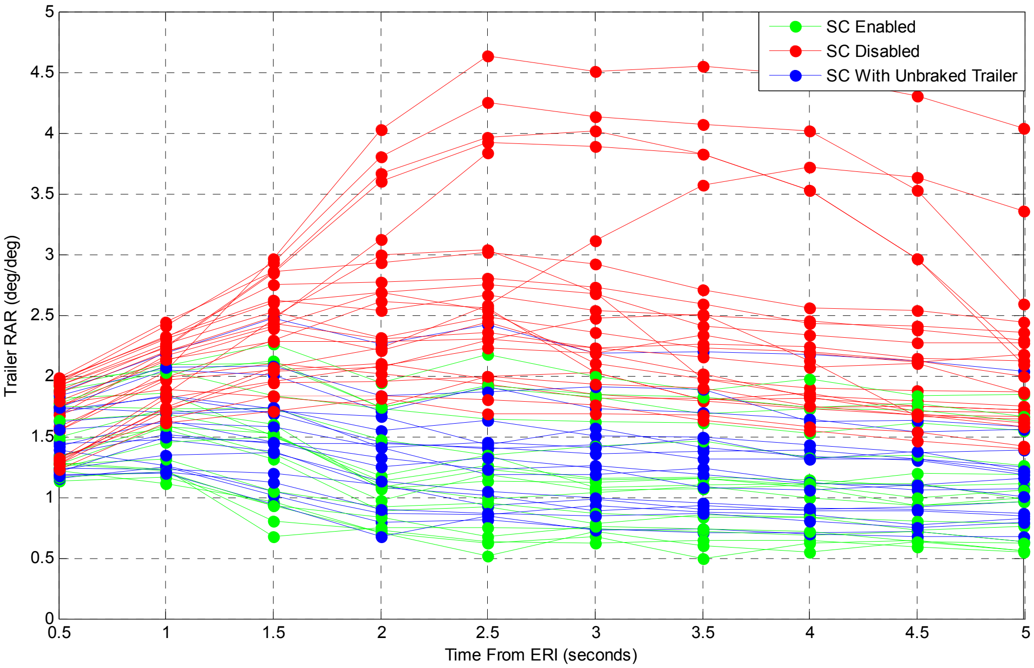

Figure 6.24. Trailer RAR from combinations with the Volvo 6x4 for MES(s) 26-32 mph.

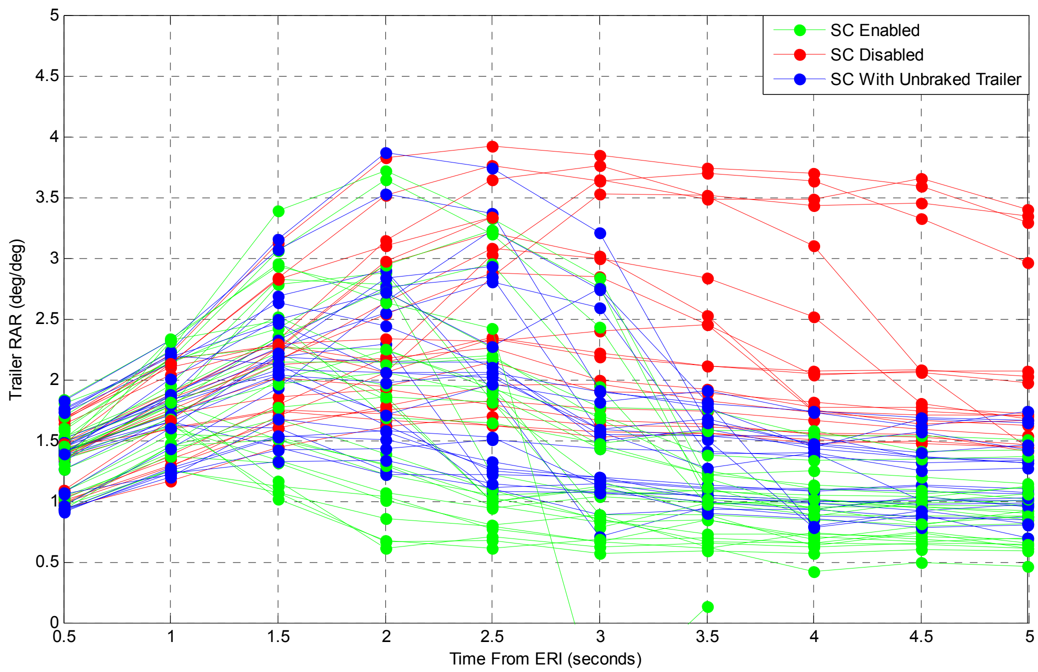

Figure 6.25. Trailer RAR from combinations with the Sterling 4x2 for MESs 26-32 mph.

6.2.6 Ratio Metrics Versus Wheel Lift

The ratios LAR, TrlLAR, and TrlRAR have shown graphically to have potential as performance metrics that would indicate a Class 8 truck tractor is equipped with a roll stabilizing algorithm as part of the vehicle's electronic stability control system. From previous discussion in this section, stability control uses one or more foundation brakes to decelerate the vehicle(s) and reduce the tipping forces produced from lateral acceleration (F=ma) acting on the mass of the vehicle(s) as it negotiates a curve. Lateral acceleration is responsible for producing the forces that eventually generate vehicle roll angle. The reduction of lateral forces can be observed with each of the different ratios and is inferred[11] to improve the roll stability of the vehicle through a reduction after a given time. Test data in the previous section show the observed differences in the ratios between ESC enabled and disabled test conditions without correlation to observed wheel lift events. Adding that information to previously presented data would indicate the ratio's relationship to roll stability. These data are shown in Figure 6.26 for each of the three ratios.

Figure 6.26 shows LAR, TrlLAR, and TrlRAR over time after ERI for several Freightliner and Sterling tests conducted with a MES between 29-31 mph (SC enabled) and using

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[11] In searching for the methodology that would indicate a Class 8 tractor is equipped with SC, researchers looked strictly at differences in test data between SC enabled and disabled test conditions without correlating those differences to wheel lift events observed in field test data. This was done to simplify the analysis and because the RSM combined with the Sterling tractor and certain trailers produced wheel lift at the same maneuver entrance speeds regardless of stability control intervention.

the High CG load condition. The SC enabled without trailer brakes tests are denoted with blue lines and dots. Red lines and dots denote SC disabled tests. If a test was observed to have wheel lift it was denoted with dotted lines. A majority of tests conducted with SC disabled were terminated at lower MESs due to wheel lift. Representative ratios for the SC disabled test condition for tests that had measured wheel lift and were conducted at MESs below 28 mph are also shown. To simplify these plots, the test series are not shown for the enabled SC test condition in which the trailers brakes were connected.

The plots show that each of the ratios was able to discriminate the difference between the SC enabled and disabled test conditions shown. They also show that as the ratio increases, the frequency of observed instances of wheel lift increases. This is especially true for the latter time increments.
2-4

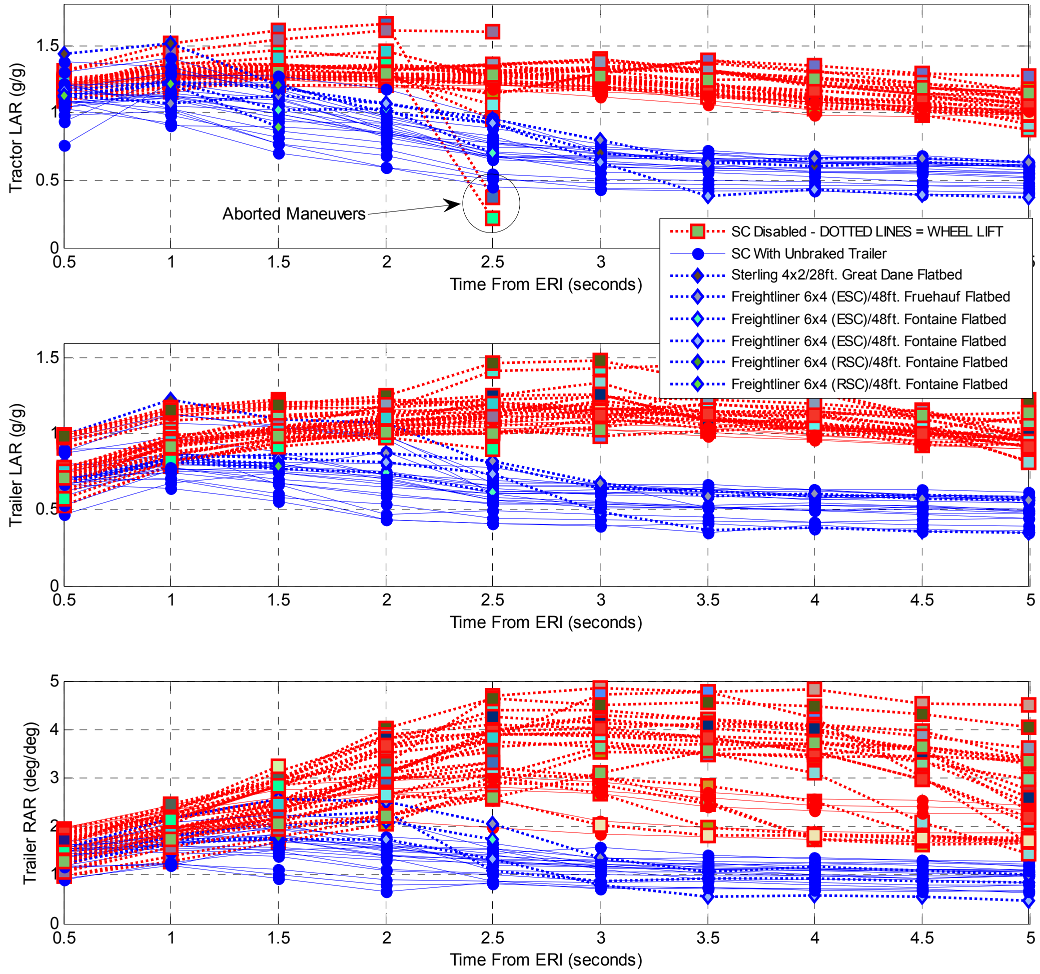

Figure 6.26. Shows the three ratios versus time from end of the ramp steer input. Dotted lines indicate that wheel lift was observed during the test.

A more detailed beak down of the ratios and the frequency of observed wheel lift are shown in Figure 6.27 through Figure 6.29. These figures show the histograms for the 2.0 s and 3.0 s time increments for each of the ratios. These time increments were selected inside the 1.0-3.0 second critical time range shown in Subsection 6.2.1 in which measured wheel lift reached the two inch threshold. The data in the histograms bin test results into four categories. The red bars denote the SC disabled test condition and the observance of wheel lift. The yellow bars denote the same test condition, however, wheel lift was not observed for the MES ranges shown. The blue bars denote the SC enabled test condition in which wheel lift was not observed and the magenta bars indicated the same test condition in which wheel lift was observed. The y-axis indicates the number of observed tests for each category and the x-axis shows the ratio values observed.

The left side graph in Figure 6.27 shows the histogram of LAR for the 2.0 second increment. For this increment, SC disabled tests with wheel lift were observed to have LARs between 1.20 and 1.70. The SC disabled tests in which no wheel lift was measured fell near the bottom of that range between 1.15 and 1.30. SC enabled tests with no measured wheel lift had a LAR range of 0.60 to 1.20. Only two tests with SC enabled were observed to have a LAR greater than 1.00 and not have wheel lift. Four tests with SC enabled produced measurable wheel lift greater than two inches in the 1.00 to 1.10 range. These tests are represented in Figure 6.26 with the blue dotted lines. Out of the six total tests with SC enabled and LAR greater than 1.00, five were conducted with the Freightliner 6x4 in combination with the two long flatbeds and three of those tests were aborted due to wheel lift. The remaining test with SC enabled and LAR greater than 1.00 was for a Sterling 4x2/28-foot Great Dane flatbed combination that had wheel lift over two inches. Therefore, the ranges of LAR for three of these tests were prematurely reduced from being aborted.

The right hand graph in the same figure shows the histogram of LAR for the 3.0 second increment. For this increment, the SC disabled tests with wheel lift were observed to have LARs between 1.20 and 1.40. The SC disabled tests in which no wheel lift was measured fell near the bottom of that range between 1.15 and 1.20. The SC enabled tests without measureable wheel lift had a LAR range of 0.40 to 0.80.

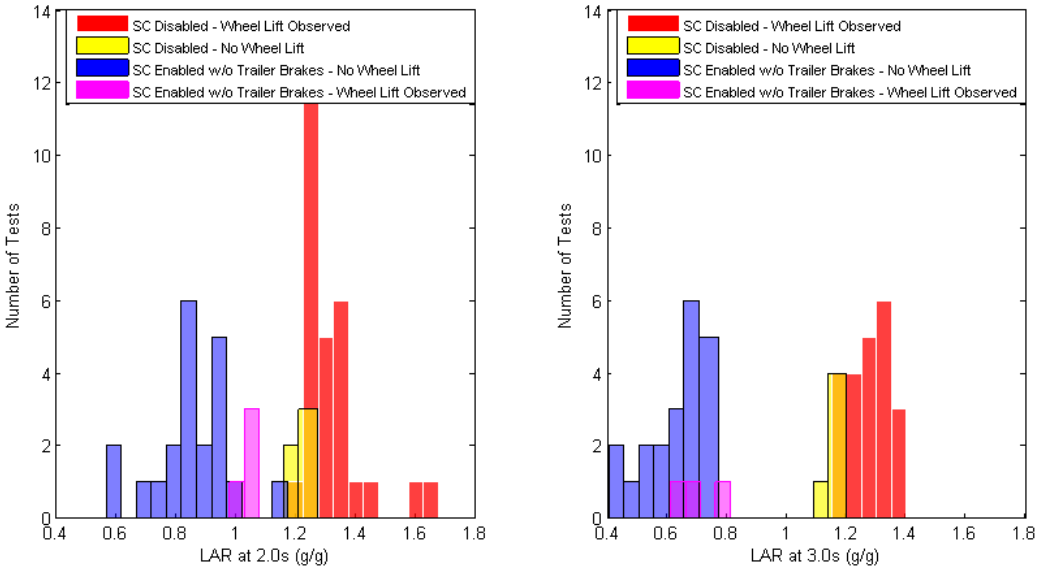

Figure 6.27. Left: Histogram of LAR at 2.0 seconds. Right: Histogram of LAR at 3.0 seconds.

The left side graph in Figure 6.28 shows the histogram of Trailer LAR for the 2.0 second increment. For this increment, SC disabled tests with wheel lift were observed to have TrlLAR(s) between 0.90 and 1.25. SC disabled tests in which no wheel lift was observed ranged from 1.00 to 1.25. SC enabled tests with no measureable wheel lift ranged from 0.40 to 1.00; a majority of these tests were in the 0.4 to 0.8 range.

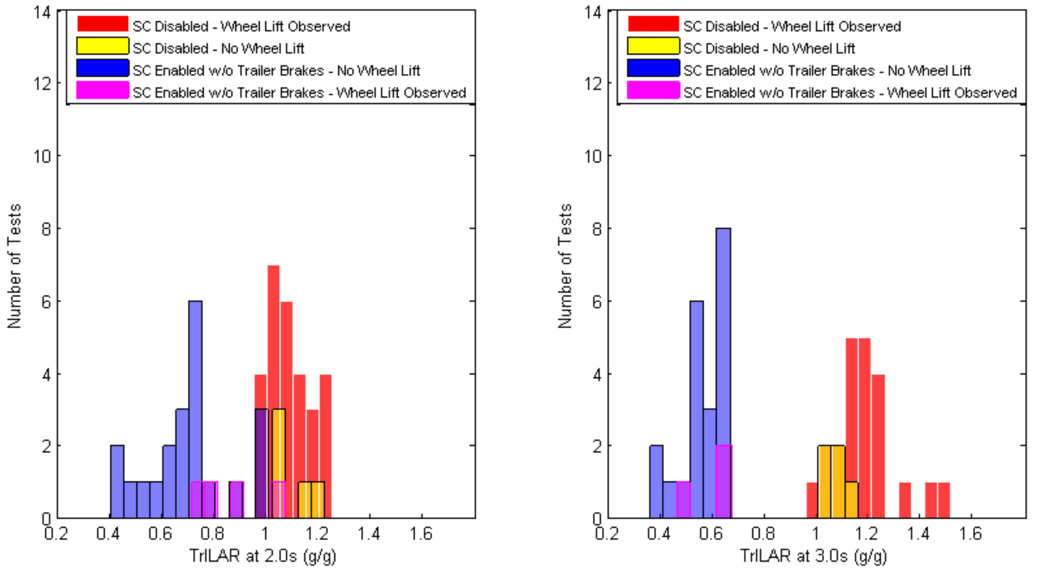

Figure 6.28. Left: figure Histogram of TrlLAR at 2.0 seconds. Right: Histogram of TrlLAR at 3.0 seconds.

The right side graph in Figure 6.28 shows the histogram of Trailer LAR for the 3.0 second increment. For this increment, SC disabled tests with wheel lift were observed to have TrlLARs between 1.00 and 1.50. SC disabled tests in which no wheel lift was observed ranged from 1.00 to 1.20. SC enabled tests with no measureable wheel lift ranged from 0.40 to 0.70.

The left side graph in Figure 6.29 shows the histogram of Trailer RAR for the 2.0 second increment. For this increment, SC disabled tests with wheel lift were observed to have TrlRARs between 3.0 and 4.0. SC disabled tests in which no wheel lift was observed ranged from 2.5 to 3.0. SC enabled tests with no measureable wheel lift ranged from 0.50 to 2.00; a majority of these tests were in the 1.0 to 2.0 range.

The right hand graph in the same figure shows the histogram of Trailer RAR for the 3.0 second increment. For this increment, the SC disabled tests with wheel lift were observed to have LAR(s) between 2.0 and 5.0. The SC disabled tests in which no wheel lift was measured fell near the bottom of that range between 1.5 and 3.0. The SC enabled tests without measurable wheel lift had a LAR range of 0.5 to 1.5.

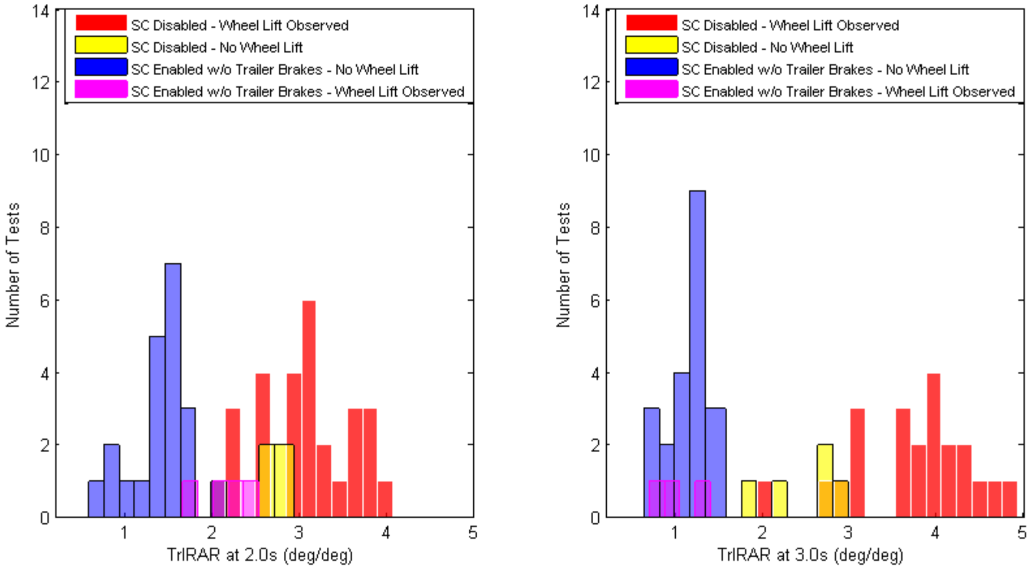

Figure 6.29. Left: figure Histogram of TrlRAR at 2.0 seconds. Right: Histogram of TrlRAR at 3.0 seconds.

The figures all show a discriminatory capability of certain time increments for LAR, TrlLAR, and TrlRAR. There was separation between tests conducted with SC enabled and disabled. With the wheel lift information included, there appears to be a population of data in which stability control was enabled and a reduction in wheel lift events was observed, and then another population of data in which wheel lift events were observed for SC disabled tests. All three ratios appear to have a degree of ability to indicate that a tractor is equipped with SC, and each was able to indicate that by a reduction in the ratio, SC intervention provided some performance improvement. Additional analyses on the variance of the test results were performed as described in the next subsection.

6.2.7 Ratio Metrics Analysis of Variance

In the previous section, the concepts of Truck Tractor LAR, Test Trailer LAR and Test Trailer RAR for four[12] different tractors tested in combination with six different trailers for a range of MESs were presented. Those figures show graphically that each of the ratios was reduced by SC. To verify whether performance criteria may be developed from the ratios, it was necessary to determine statistical differences and the variation of each measure from the populations of SC enabled (unbraked trailer) tests and disabled tests. Though there are clear differences in performance between the different tractor/trailer combinations, the authors decided to separate the data based on the state of the SC system. It was believed that if an overall analysis including many combinations shows that one of the ratios is able to indicate that a truck tractor is equipped with stability control within some statistical limits, then this would establish the ratio as a robust measure. To reduce the influences that may result from different MESs, this analysis focused on tests conducted with an MES of 30 mph. An MES of 30 mph was selected for several reasons. Section 6.2.1 found 30 mph to be a MES at which a truck tractor/trailer combination with a CG height greater than 75 inches was 91 percent likely to produce wheel lift when SC was disabled during the RSM. When the system was enabled, the likelihood was reduced to just seven percent. A MES of 31 mph or greater was observed to be where some of the vehicle combinations transitioned from stability to instability with SC enabled (for the given High CG load and RSM maneuver). A MES of 30 mph is also used for the SIS characterization test for which the RSM steering amplitudes are derived and therefore support its use in this analysis.

Figure 6.26 shows LAR and RAR versus time after ERI for all RSMs conducted with a MES of approximately 30 mph. From the figure, disabled SC and enabled SC tests in which the test trailer was unbraked were used to perform statistical analyses. Six SC enabled (unbraked trailer) tests were observed to have wheel lift and are indicated with dotted lines and colored markers. Those tests were omitted from this statistical analysis for several reasons. The test driver aborted three of those six tests which would influence LAR and RAR over time. They were also excluded because sample size of the remaining three valid tests with the condition of SC enabled and wheel lift was so small that it would provide little statistical power. Figure 6.30 shows the SC disabled and SC enabled RSM test groups used to perform the analysis of the three different ratios. All tests shown were performed at a MES of approximately 30 mph. The dotted lines indicate that wheel lift greater than two inches was measured during the test. There are 10 individual tests representing SC disabled and 27 individual tests representing SC enabled.

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[12] The Freightliner 6x4 was considered as two vehicles since it was tested separately with both a RSC and an ESC system.

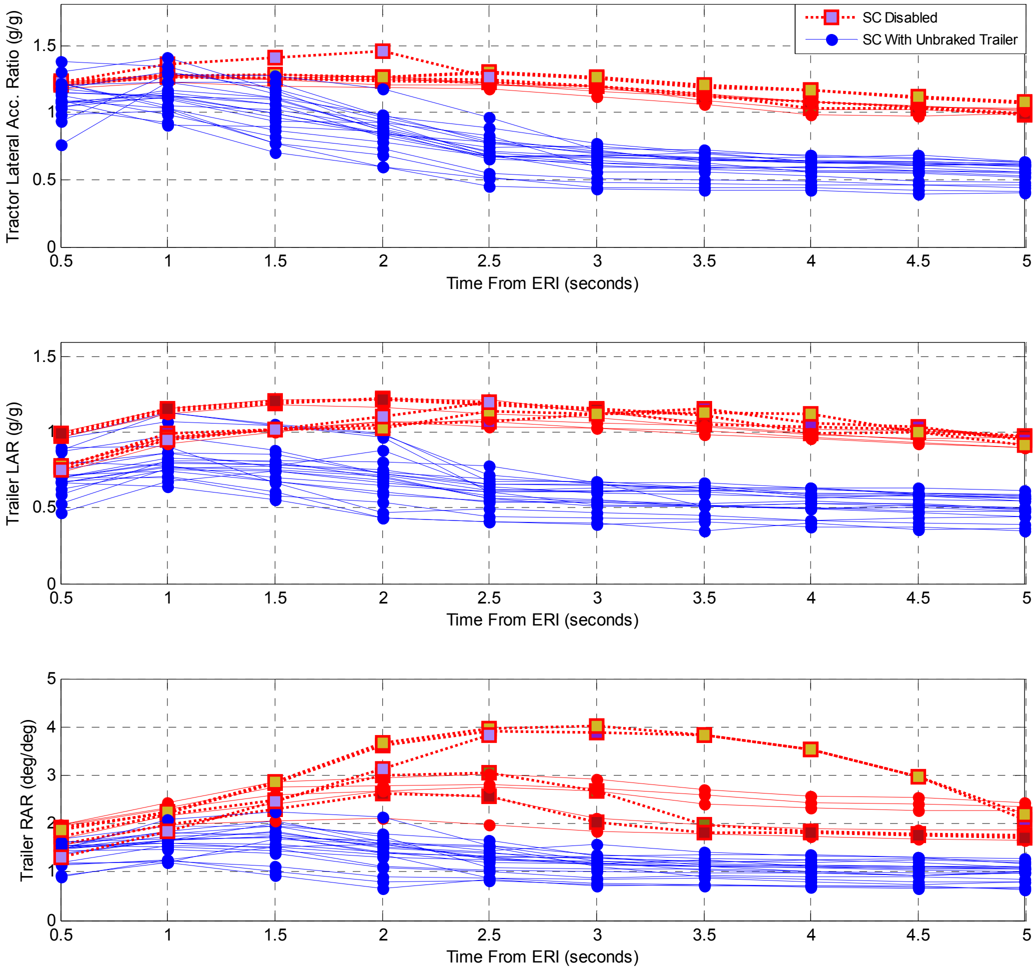

Figure 6.30. LAR and RAR data groups used for the statistical analyses. All RSM tests shown had a MES of approximately 30 mph. Dotted lines indicate that wheel lift was observed during the test.

Since the number of samples representing the test groups is unequal, and relatively small with an unknown distribution, a Kruskal-Wallis test was used to quantify the ratio differences between the SC enabled (unbraked trailer) and SC disabled 30 mph RSM tests. The Kruskal-Wallis test is the nonparametric version of the traditional one-way ANOVA. It compares the medians of the groups, and returns the p-value for the null hypothesis that all samples are drawn from the same population. For this analysis the p-value was considered statistically significant if the result was less than 0.01. This indicates that there was less than a one percent chance that the ratio's values were drawn from the same population. This type of test was performed on each of the time increments being considered.

The statistics from the Kruskal-Wallis test are shown in Table 6.4 through Table 6.6 for each of the ratios. They include the p-values between the SC enabled and SC disabled (OFF) RSM tests. Also shown are the means, medians, delta means and standard deviations (STD) for the two groups at each time increment. Ideally, the p-value results would be used to not only quantify each ratio's ability to discriminate SC equipped vehicles from non-SC equipped vehicles, but would also indicate which combination of ratios and time increments were suitable for performance criteria. Then the candidate ratio's means, medians and STDs at those time increments could be used to locate a region of possible candidate performance criteria.

p-values

The p-values for certain time increments were found to be significant and indicated that the SC enabled group was different from the SC disabled group for each of the ratios. For tractor LAR, the time increments 0.5 and 1.0 seconds after ERI had the highest p-values of 1.93 $E10^{-2}$ and 8.91 $E10^{-3}$. Time increments 1.5 through 5.0 seconds after ERI had p-values of 2.60 $E10^{-5}$ or less. The p-values for Trailer LAR were similar to those observed with the tractor-based metric. Time increments 0.5, 1.0, and 1.5 had higher p-values of 5.99 $E10^{-2}$, 5.90 $E10^{-3}$, and 1.12 $E10^{-3}$. Time increments 2.0 through 5.0 seconds had p-values of 3.64 $E10^{-5}$ or less. Trailer RAR was observed to have one higher p-value; it was 8.10 $E10^{-4}$ at 0.5 seconds after ERI. Time increments 1.0 through 5.0 seconds had p-values of 2.60 $E10^{-5}$ or less.

The latter time increments may be better candidates for MOP criteria since the p-values at the earliest time increments are larger by at least a factor of 10. However, differences between the medians for these latter time increments were so large that the resulting p-value has little weight for narrowing the field of choices for possible performance criteria between 1.5 – 5.0 seconds using tractor LAR, 2.5 – 5.0 seconds using trailer LAR, and 1.0 – 5.0 seconds using trailer RAR.

Table 6.4. Results from statistical analysis of Tractor LAR.

	Time Increments from ERI (seconds)																			
Times	**0.5**		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
SC State	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**
P-value	1.93E-02		8.91E-03		1.98E-05		1.31E-05		1.31E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05	
Mean	1.14	1.21	1.14	1.28	0.99	1.27	0.84	1.27	0.69	1.24	0.64	1.19	0.61	1.13	0.59	1.08	0.58	1.05	0.56	1.02
Delta Mean	0.072		0.137		0.272		0.423		0.542		0.557		0.522		0.488		0.467		0.458	
Median	1.15	1.21	1.12	1.28	0.99	1.25	0.86	1.26	0.69	1.23	0.67	1.19	0.65	1.12	0.62	1.08	0.61	1.04	0.60	1.01
STD	0.15	0.02	0.16	0.03	0.16	0.05	0.12	0.07	0.12	0.04	0.10	0.05	0.09	0.05	0.08	0.06	0.08	0.04	0.08	0.04
Mean On + (STD x 2)	1.44		1.46		1.31		1.08		0.94		0.84		0.79		0.75		0.75		0.72	

Table 6.5. Results from statistical analysis of Trailer LAR.

	Time Increments from ERI (seconds)																			
Times	**0.5**		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
SC State	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**
P-value	5.99E-02		5.90E-03		1.12E-03		3.64E-05		1.31E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05	
Mean	0.76	0.85	0.86	1.03	0.79	1.09	0.72	1.12	0.60	1.13	0.57	1.10	0.56	1.07	0.54	1.02	0.53	0.98	0.52	0.94
Delta Mean	0.092		0.173		0.297		0.403		0.537		0.530		0.510		0.476		0.452		0.426	
Median	0.71	0.78	0.80	0.98	0.77	1.02	0.72	1.09	0.61	1.13	0.61	1.12	0.61	1.05	0.57	0.96	0.58	1.00	0.55	0.95
STD	0.14	0.12	0.17	0.10	0.17	0.10	0.19	0.08	0.10	0.06	0.09	0.05	0.09	0.06	0.08	0.05	0.09	0.04	0.08	0.03
Mean On + (STD x 2)	1.05		1.20		1.12		1.10		0.80		0.76		0.74		0.71		0.70		0.68	

Table 6.6. Results from statistical analysis of Trailer RAR.

	Time Increments from ERI (seconds)																			
Times	**0.5**		**1.0**		**1.5**		**2.0**		**2.5**		**3.0**		**3.5**		**4.0**		**4.5**		**5.0**	
SC State	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**	**On**	**OFF**
P-value	8.10E-04		1.61E-05		1.61E-05		1.61E-05		1.31E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05		2.60E-05	
Mean	1.41	1.76	1.59	2.17	1.65	2.56	1.42	2.92	1.22	3.04	1.13	2.76	1.09	2.54	1.05	2.41	1.02	2.25	1.00	2.04
Delta Mean	0.34		0.58		0.91		1.50		1.83		1.64		1.46		1.36		1.23		1.03	
Median	1.48	1.81	1.66	2.21	1.72	2.54	1.50	2.85	1.25	2.91	1.18	2.68	1.12	2.41	1.09	2.33	1.03	2.27	1.02	2.09
STD	0.19	0.22	0.23	0.18	0.35	0.27	0.38	0.47	0.23	0.67	0.23	0.77	0.19	0.80	0.19	0.70	0.20	0.51	0.18	0.29
Mean On + (STD x 2)	1.80		2.04		2.35		2.18		1.68		1.58		1.47		1.43		1.41		1.36	

Mean and Median

The mean, delta mean, and median of the ratios observed for SC enabled and disabled groups of tests are shown in Table 6.4 - Table 6.6. For tractor LAR, both mean and median values for each column are nearly identical, and all values are within 0.04 of each other. From left to right in the table, comparing the enabled group mean and median values to the disabled group values shows that the Kruskal-Wallis tests indicated that the groups were significantly different from each other. Also evident in the table is that the difference between the means/medians increases from time increment-to-time increment up to 3.0 seconds from ERI and then begins to decrease for the remaining time increments. To illustrate this, the delta mean was calculated between the groups at each time increment and is shown in the row below the mean values. The deltas observed were between 0.423 – 0.557 for the 2.0 – 3.0 second region.

Trailer LAR mean and median values in each column were within 0.07 of each other. Like the observations made with tractor LAR, Trailer LAR SC disabled mean and median values increasingly diverge from the SC enabled test group up to ~2.5 seconds, and then the gap is slightly reduced from increment-to-increment up to the 5.0 second mark. The delta mean illustrates this as it increases from 0.092 at 0.5 seconds to 0.537 at 2.5 seconds and then falls off to 0.426 at 5.0 seconds.

Trailer RAR mean and median values in each column were within 0.13 of each other. Like Tractor LAR and Trailer LAR, Trailer RAR SC disabled mean and median values increasingly diverge from the SC enabled test group up to ~ 2.5 seconds, and then the gap narrows at the latter time increments. The delta mean increased from 0.34 at 0.5 seconds to 1.83 at 2.5 seconds and then decreased to 1.03 at 5.0 seconds.

Standard Deviation

The standard deviations of the three ratios were calculated for the two SC groups at each time increment. The values are displayed in Table 6.4 through Table 6.6. The standard deviation was calculated to show the dispersion of the ratios about each time increment for the two groupings.

For tractor LAR in Table 6.4: The SC disabled group standard deviation values start at 0.02 and peak at 0.07 at the 2.0 second time increment then drop back from that value at the latter time increments. In contrast, the SC enabled group standard deviations start out at nearly an order of magnitude larger at 0.15 at 0.5 seconds, peak out at 0.16 at the 1.0 and 1.5 second time increments, and then consistently get smaller (0.08 at 5.0 seconds) at the latter time increments.

For trailer LAR in Table 6.5: The SC disabled group standard deviation values start at 0.12 and then gradually drop back from that value to 0.03 in the latter time increments. In contrast, the SC enabled group standard deviation values start out at 0.14 at 0.5 seconds, peak out at 0.19 at the 2.0 second time increment, and then get smaller (0.08 at 5.0 seconds) at the latter time increments.

For trailer RAR in Table 6.6: The SC disabled group standard deviation values start at 0.22, increase to 0.80 at 4.0 seconds, and then gradually drop back from that value to 0.29 at the 5.0 increment. The SC enabled group standard deviations start out at 0.19 at 0.5 seconds, peak out at 0.38 at the 2.0 second time increment, and then drop back to 0.18 at the 5.0 second time increment.

The last row in each of the tables is labeled “Mean On + STDx2”[13]. These values were calculated by taking the mean value of the SC enabled group at each increment and adding two standard deviations. For example, tractor LAR for the SC enabled group at the 0.5 second time increment had a mean value of 1.14 and a standard deviation of 0.15. Two x STD was equal to 0.30 and adding that to 1.14 gives a value of 1.44 as shown in the last row. These values indicate the 95th percentile upper boundary of the SC enabled ratios and slightly more than 95 percent of the test data will fall below this upper boundary.

Summary of Ratio Analyses of Variance

The analyses of variance of the three ratios gave more insight into each metric. The higher p-values for the initial time increments indicated that for the two groups of data, SC enabled and SC disabled, the ratios were closer together in the earlier time increments than in the latter time increments. Based on p-values, potential time increments to evaluate performance would be 1.5 – 5.0 seconds for tractor LAR, 2.0 – 5.0 seconds for trailer LAR, and 1.0 – 5.0 seconds for trailer RAR. The mean, median and delta means were also found show large differences between the test groups for the same time increments. Standard deviations within each group for each ratio indicated that the tractor-based LAR ratio had the smallest deviations followed by trailer LAR and then trailer RAR. Using the mean value and adding two standard deviations yielded the upper boundary of the SC enabled group for each time increment and ratio.

Upper and lower bounds to determine the overall 95th percentile range for the test data, for each ratio metric, were also calculated as illustrated below in Figure 6.31.

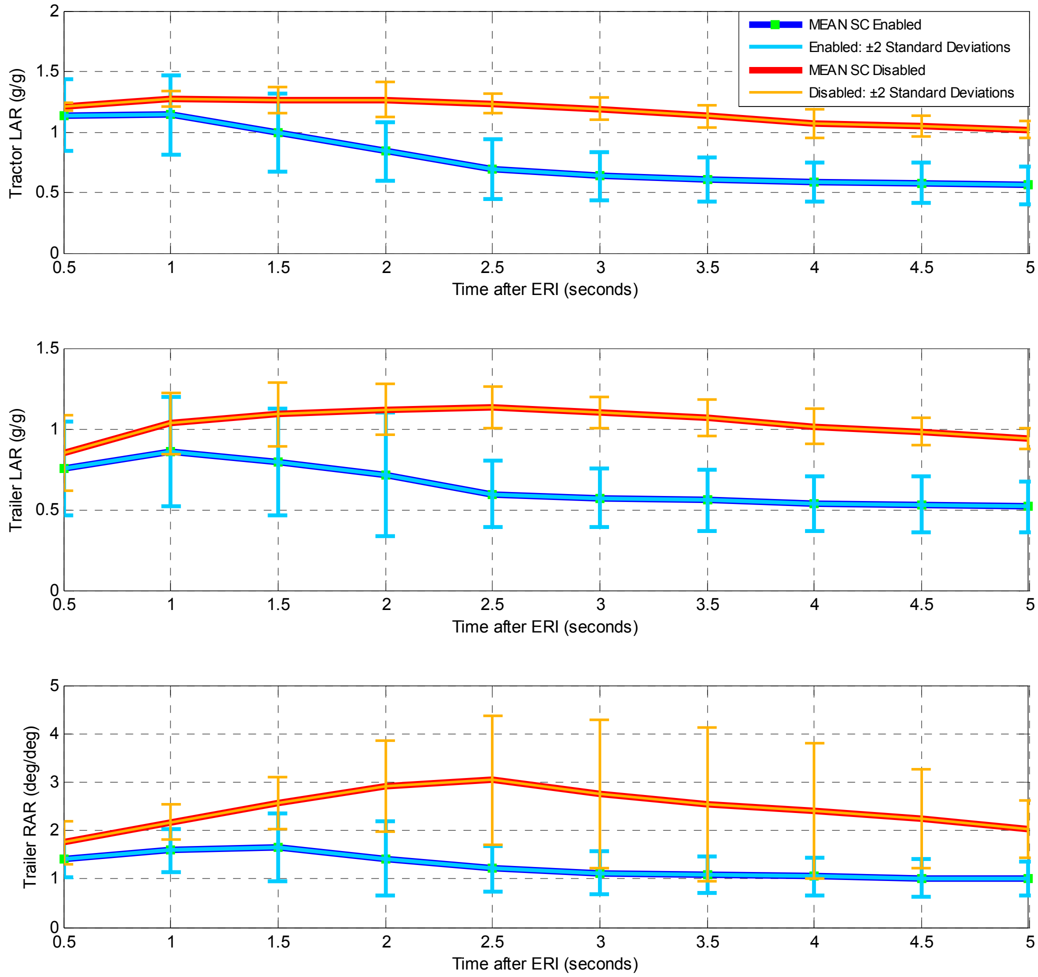

Figure 6.31. Graphical presentation of the statistics shown in Table 6.4 - Table 6.6.

Figure 6.31 presents for the each of the three ratios, the mean values and the mean ± two standard deviations[13] for both the SC enabled and SC disabled test groups. The SC disabled mean values are shown in red, and SC enabled in blue. The mean ± two standard deviations are shown in orange and light blue bars overlaying the mean values for the disabled and enabled groups, respectively. This figure shows graphically that the two groups, SC enabled and SC disabled, diverge up to ~2.5 seconds and then gradually begin to come back towards each other. Overlaying the mean ± two standard deviations for both SC enabled and SC disabled test group's shows the degree of overlap or separation for each ratio and time increment. For Tractor LAR, the increments from 2.0 – 5.0 seconds show no overlap. For Trailer LAR, the range shifts to 2.5 – 5.0 seconds. For Trailer RAR there is only one increment, at 2.5 seconds, that does not show overlapping regions between the groups of data.

Section 6.2.1 presented data on the time elapsed from ERI at which two inches of wheel lift was first observed for RSM tests with a High CG load and the SC disabled. Figure 6.6 shows that the wheel lift time domain started at approximately 2.0 seconds and

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[13] For normally distributed data a little more than 95% of the data fall within ±2 standard deviations.

ended at approximately 3.5 seconds after ERI. Combining the statistical results in Figure 6.31 with the test results for initiation of wheel lift (onset of roll instability), the time increments between 2.0 and 3.0 seconds after ERI are suitable candidates for possible performance criteria for each of the ratios.

6.3 Phase II Conclusions

SIS Maneuver: The truck tractors' SC systems all responded similarly in the bobtail SIS test maneuver regardless of vehicle or type of SC system installed. As the steering input was increased in a slow linear manner, the system eventually activated by commanding engine torque output reductions that reduced the vehicle speed (12.4 – 27.2 percent after 4.0 seconds). Thus, the lateral acceleration was limited (maximum increase of 6.2 percent) even as the radius of the vehicle was observed to continue to decrease. None of the SIS tests resulted in oversteer or roll instability, but in SIS tests with SC disabled, all of the tractors experienced understeer at their limit of performance. These vehicle dynamics changes were a direct result of SC activation and were correlated in time to the SC system's command to reduce engine torque output even though the driver was demanding more engine power to attempt to maintain 30 mph. At a minimum, the engine torque was observed to be decreased by 38% versus a minimum 19 percent increase in engine output when the SC systems were disabled.

Results from the SIS test series confirmed the ability of the maneuver to characterize the linear dynamics of Class 8 truck tractors. The test results confirmed the maneuver's ability to normalize the steering inputs for the RSM. The test results confirmed the linearity of the range of data selected for extrapolation (0.05 – 0.3 g). From the range of speeds observed from SIS testing a target entrance speed of 30 mph with a ±1.0 mph tolerance can be used for future SIS tests conducted to normalize the RSM or other maneuver's steering magnitudes.

RSM Maneuver: High CG load condition test results from the RSM test series confirmed the ability of SC systems to improve roll stability by applying the vehicles' foundation brakes. The results also show that given a High CG load condition, with sufficient speed and steering inputs the SC systems can be over-driven. Thus, all 24 combinations of tractors and trailers, and all three SC conditions (enabled, enabled without trailer brakes, and disabled), had instances of observed wheel lift. Overall, with SC (ESC and RSC equipped vehicles) enabled without trailer brakes, the net increase in MES at which wheel lift was observed ranged from 0 to 10 mph (over disabled test conditions). With SC enabled, the net increase in MES at which wheel lift was observed ranged from 0 to 12 mph (over disabled test conditions).

In terms of overall performance by type of SC system, ESC equipped vehicles saw the most improvement to MES at which wheel lift events were observed. The MES at which wheel lift was observed increased by 2-10 mph (over disabled test conditions) for the ESC enabled without trailer brakes test condition. This range improved to 4-12 mph for the ESC enabled test series. While the RSC systems did not degrade stability in the RSM, they also did not always improve it. The RSC equipped vehicles with RSC enabled without trailer brakes series were observed to increase MES by 0-6 mph and RSC enabled increased MES by 0-8 mph.

The observed improvements to roll stability in the RSM were a direct result of the ability of the SC systems to activate and selectively apply the truck tractors' foundation brakes. Vehicle dynamics changes observed from SC intervention were quantified for a RSM test series performed with the 28-foot Great Dane flatbed trailer with a High CG load condition. In these tests, the SC systems reduced vehicle speed by 14.2 to 39.2 percent, lateral acceleration by 40.5 to 62.9 percent, yaw rate by 34.3 to 46.2 percent, and roll angle by 56.7 to 69.5 percent, compared to the baseline SC disabled condition. Since these reductions were the direct result of each respective SC system's use of the foundation brakes to slow the vehicle, the deceleration was observed to increase by 111% to 508%.

RSM test results for the four tractors and six trailers tested in the LLVW[14] condition indicated that the roll stability threshold was above the yaw stability threshold for several vehicle combinations. This conclusion was drawn from results showing that only one of the 24 combinations tested had two inches or more of wheel lift. However, nine of the 24 combinations were terminated after the tractor went into an oversteer condition and engaged the safety cables that limited the articulation angles between the tractor and trailer combinations. These nine combinations were observed to engage the safety cables at MES(s) that ranged from 34.3-41.5 mph.

Additionally, all nine combinations that experienced oversteer were with RSC equipped tractors (see Table 5.21). The researchers believe that the additional benefit of allowing the test trailer brakes to be utilized by the SC system would increase the yaw and roll stability thresholds of the tractor/trailer system. The additional braking provided by the trailer would act like an anchor and would slow the combination down which in turn would reduce the articulation angles and would extend the MES at which instabilities were observed upward.

Mass Estimation Series: A series of tests (SIS and RSM) were performed to observe the SC responses to changes in vehicle mass. From the test results it was concluded that all of the systems adjust activation thresholds based on a mass estimation process. Lateral acceleration thresholds were the highest in the unloaded condition for each platform tested. As the load was increased, each system reached a mass where the lateral acceleration intervention level stabilized (approximately 42k to 52k lbs).

Given that higher mass often equates to a higher CG, lowering the activation threshold as the mass increases was deemed appropriate. All systems tested by different manufactures and different types (RSC or ESC) were observed to operate in a similar manner under the given load conditions.

Differences were observed under the SIS when the platforms were very lightly loaded. At test weight of 25.7k to 34.5k lbs, the Volvo SC used engine torque reduction intervention to limit lateral acceleration to below 0.58 g and only had one brake system intervention. The Freightliner and Sterling SC systems used brake system interventions in every test and maintained lateral accelerations to just under 0.5 g. Since constant

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[14] With the LLVW condition only one SC test condition, "SC enabled without trailer brakes" was evaluated.

radius testing in the unloaded condition generally resulted in the vehicle combination understeering, it is unclear if this is occurring as a result of understeer mitigation. There were no observed cases of wheel lift in any of the lightly loaded tests. This result may warrant further investigation into understeer mitigation.

Roll Stability Engine Torque Reduction MOP: It was concluded from the analysis of SIS test results that it held the potential to evaluate the SC systems ability to mitigate engine/power unit torque. Several potential measures were identified and investigated for development as a MOP. They were as follows:

- tractor speed
- tractor lateral acceleration
- tractor longitudinal acceleration
- engine torque/driver requested engine torque

The “driver requested torque” and “engine torque” output measures were concluded to be potential MOP candidates that warranted further analysis. Tractor forward speed also exhibited potential to be used in conjunction with a primary measure such as ensuring that there was no drive axle wheel lift that could also reduce vehicle speed. Review of the torque separation activity observed between the “driver requested torque” and the actual engine torque output were confirmed for every SIS test series in which the SC systems were enabled for each vehicle. This fact led researchers to conclude that during the SIS maneuver, the torque reduction measure was a good MOP candidate that has the potential to indicate that a tractor is equipped with an SC system that exhibits engine/power unit control. The changes in the torque signals were quantified and averaged. These data are shown in Figure 6.32. As shown in the figure, the mean change shows that a good region for assessing performance lies between 1.0 and 2.5 seconds after SC initiates engine torque intervention. While these data show that the respective changes in the torque signals were quite large, it was concluded that a small (5-20 percent) change would also be sufficient to establish that engine torque reduction occurred. It is also conceivable that vehicles with low power to weight ratios may not need as much reduction in torque output to limit the dynamic responses of the truck tractor.

The authors recommend that additional data be collected and statistically analyzed to determine/refine the times and limits to assess performance from the ranges discussed in this report.

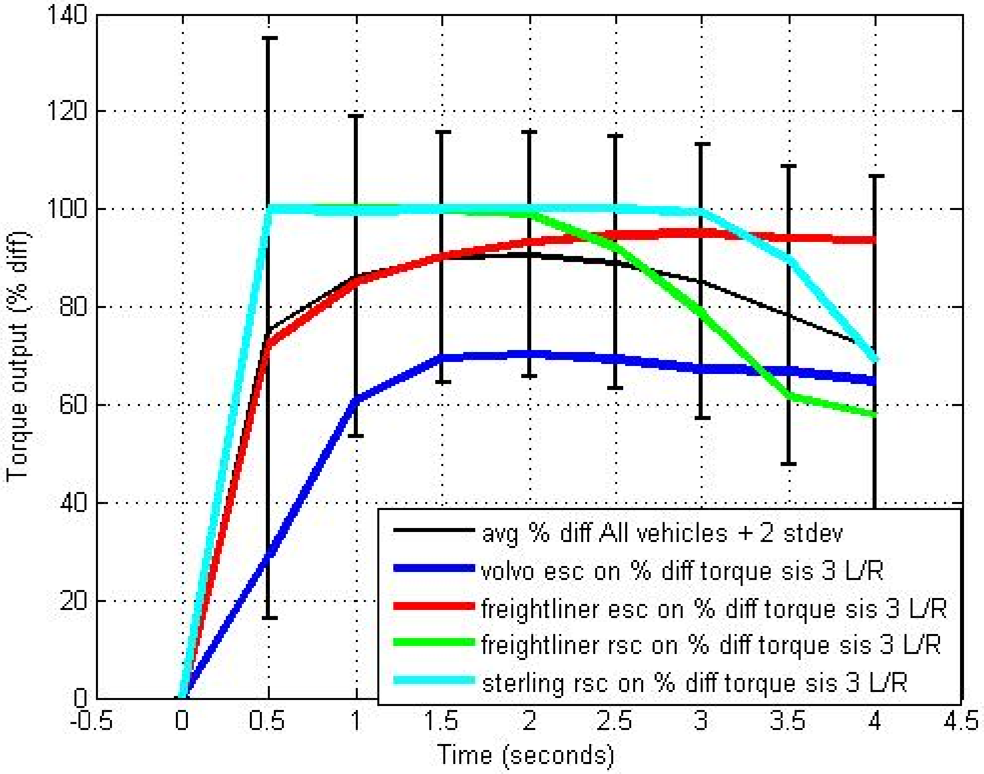

Figure 6.32. Average of the percent difference found from driver and engine torque starting at SC activation out 4 seconds for a SIS test series.

Roll Stability Foundation Braking MOP: It was concluded from the analysis of the High CG RSM test results that the RSM has the potential to evaluate an SC system's ability to selectively apply the tractor's foundation brakes with the intent to improve roll stability. From the RSM test data, wheel height, lateral acceleration, and roll angle measurements were identified as potential MOPs. With the exception of wheel lift, each measure by itself was concluded to be unusable without further reduction and normalization. However, as examples have shown, there were clear differences in the measured responses between the different SC test states. As a result, ratio metrics were developed and analyzed and compared to wheel lift measurements. The following paragraphs provide the conclusions that were drawn from those analyses.

MESs to Assess Performance: For this analysis a roll stability threshold definition was needed to make an assessment of stability. The threshold used was 2.00 inches of wheel lift. If a test resulted in the production of 2.00 or more inches of wheel lift at any of the wheel ends, the series was terminated and the resulting MES reported in Table 6.7 (identical to Table 5.16; presented here for convenience). From these data, a logistical model was developed that produced the probability of wheel lift at different MESs for the tested SC conditions. For the given load and maneuver, with a MES between 29 – 32 mph, the probability of wheel lift occurring without stability control was between 0.79 – 0.99. The probability dropped to 0.11 – 0.33 with the "SC enabled unbraked trailer" test condition, and dropped further to 0.04 – 0.19 with the SC enabled test condition. From the logistical regression of MESs that produced wheel lift, it was concluded that a RSM performed at ~30 mph (tolerance ±1 mph) would be appropriate to assess roll stability performance. At this MES, the probability of generating two or more inches of wheel lift was 0.91 without SC, and with SC enabled the probability dropped to 0.07. Increasing the MES to assess performance would make the test more challenging for the SC system. However, it would only marginally increase the probability of wheel lift without the technology.

Table 6.7. Test termination speed that resulted in 2.0 inches or more of wheel lift for the RSM. All tests were conducted with the High CG load conditions (CG heights> 75 inches).

Vehicle	Dry Box Van (mph)						Flatbed (mph)									Tanker (mph)		
	Fruehauf 53 ft.			Strick 53 ft.			Fontaine 48 ft. Spread Axle			Fruehauf 48 ft. Tandem Axle			Great Dane 28 ft. Control Trailer			Heil 42.5 ft. 9200 Gal.		
	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked	Disabled	Enabled	Enabled Unbraked
2006 Freight-liner 6x4 ESC	27 T	32 T	32 T	28 T	40 T	36 T	26 D	32 D	29 D	27 D	32 D	29 D	28 D/T	32 D/T	31 D/T	28 T	35 T	32 T
2006 Freight-liner 6x4 RSC	27 T	35 T	33 T	28 T	35 T	34 T	26 D	31 D	30 D	27 D	33 D	32 D	28 D/T	34 D/T	33 T	28 T	35 T	34 T
2006 Volvo 6X4 ESC	30[2] T	38 T	37 T	31 T	42 T	41 T	28 D	38 D	37 D	30[1] D	35 D	33 D	30 T	41 T	39 T	30 T	40 T	38 T
2008 Sterling 4x2 RSC	28 T	32 T	31 T	28 T	28 T	28 T	25 D	25 D	25 D	26 D	28 D	26 D	28 T	30[3] T	30[3] T	28 T	28 T	28 T

[1] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 183 degrees.
[2] Results are from a prior year using slightly different methodology to determine RSM magnitude. Magnitude used was 170 degrees.
[3] Test series were conducted with the vehicle in neutral rather then depressing the clutch pedal for the duration of the maneuver.
D = Wheel lift observed at tractor drive wheels
T = Wheel lift observed at trailer wheels

Wheel lift Metric: Wheel lift was considered as a MOP since it has good face validity, it precedes a rollover event, is well understood by researchers and the public, is easily observable on the test track, and has been previously documented and applied in NHTSA NCAP Tests [11]. However, wheel lift results from the High CG RSM tests indicate that this MOP is dependent on trailer type. More specifically, the results changed as a function of geometric, suspension, torsional rigidity differences that existed between the trailers. If wheel height were to be used as a MOP, tight specifications would also be required for the test trailer, location of the load, and corrections to the measured data. In addition, a characterization test could be conducted to determine the precise MES that produces wheel lift for a particular tractor-trailer combination with the SC system disabled.

Ratio Metrics: The ratio metrics LAR, Trailer LAR and Trailer RAR, were found to be less dependent on the test trailer type and location of the load. These measures were found to correlate well with wheel lift and are considered easily measurable. From the analysis of variance for the three ratios, each was found to have a range of potential time increments from the end of ramp input at which performance could be assessed. For LAR that range was 2.0 – 5.0 seconds, for Trailer LAR it was 2.5 – 5.0 seconds, and for Trailer RAR it was a single time increment of 2.5 seconds. Combining the statistical results with wheel lift results for instability, the time increments between 2.0 and 3.0 seconds after ERI were concluded to be the most suitable candidates for possible performance criteria. Although the ratios were found to be less dependent on the trailer type, trailer and load influences were still present in the Trailer LAR and RAR measures given that standard deviations were larger than for Tractor LAR. Therefore, it was concluded that Tractor LAR has the most potential to be developed into a MOP.

The authors recommend that additional data be collected and statistically analyzed to determine/refine the LAR limits and times to assess performance from those presented in this research. Additionally, by assessing performance through a reduction in LAR at a given time, indicates the forces were reduced on the lead unit. Testing of certain load conditions and vehicle combinations have shown that some instances of roll instability (wheel lift) still occurred at the trailer even though substantial reductions to LAR were present. Therefore, the performance metric developed from lead unit lateral acceleration would indicate that it has SC with some given level of intervention, but does not necessarily indicate that the trailer remained roll stable throughout the RSM test.

Regarding Directional (Yaw) Stability: The research presented in this report was performed in support of efforts to develop roll stability tests and potential MOPs. However, several instances of loss of directional control were observed under light load conditions with several types of trailers during the RSM testing. The authors recommend that additional research be performed with the truck-tractors and trailers and light and Low CG load conditions in conjunction with maneuvers and test surfaces focused at assessing yaw stability.

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APPENDIX

A. TESTING PROCEDURES (APPENDIX A)

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.) to bring tractor brake temperatures to a minimum of 150-200 degrees [FMVSS 121]

SIS Characterization Maneuver [13]

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 <u>IF</u>
   a. Steering magnitude = δ^{SIS} deg
   b. Tractor wheel lift is observed
   c. Articulation angle is limited by safety cables
4. Calculate RSM [illegible]

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.

RSC Performance Maneuver

1. Perform Pre-Test Conditioning
2. Perform RSM
   a. steering magnitude = δ^{Test}
   b. steering rate = 175 deg/sec
   c. speed start= 20 mph
   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 speed for each test @ 2 MPH until one of the following conditions occur.
    a. Speed = 50 MPH – Test Complete
    b. Tractor or Trailer wheel lift occurs
    c. Articulation angle is limited by safety cables
    d. If “3.b.” or “3.c.” is visually observed – 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.
    e. Test Driver feels its unsafe to continue
4. If “3.b.” or “3.c.” occurred, test should be decremented by 2 MPH.
    a. Repeat test at major wheel lift speed – 2 MPH.
    b. Repeat test at major wheel lift speed – 1 MPH.
    c. Repeat test at major wheel lift speed
    d. If “3.b.” or “3.c.” has not occurred, continue to increment speed until “3.b.” or “3.c.” or <u>“3.a.”</u> occurs.
    e. Test is complete when “3.b.” or “3.c.” or “3.a.” occurs (jump step 6).
5. Test is complete when wheel lift has occurred 2 times or condition “3a.” has been met.
6. Test Complete

Note: All tests are conducted to the left. Test drivers should be sensitive to this issue and make right 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.

B. TRUCK TRACTOR AND TEST TRAILER PARAMETERS (APPENDIX B)

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

Table B.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.

Table B.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.

Table B.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.

Table B.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.

Table B.5. Truck Tractor CG Positions (LLVW Load Condition)

(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

Table B.6. Test Trailer General Information

	Trailer Model	VIN	Date of Manufacture
Fruehauf Box Van	53-Foot Box Van	1JJV532F51F729840	9/00
Fontaine Spread Axle Flatbed	VFT-1-8048WSAWK	13N-14820-9-81547919	8/07
Fruehauf Flatbed	NW2S-48W	xxxxxxxFCXS529307 (tag unreadable)	11/98
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.

Table B.7. Test Trailer Tire Specifications

	Tire Size	Tire Brand	Tire Model	Tire Pressure (psi)
Fruehauf Box Van	295/75 R22.5	Goodyear	G314	100
Fontaine Spread Axle Flatbed	11 R22.5	Hankook	Radial F80	95
Fruehauf Flatbed	295/75 R22.5	Goodyear	G314	105
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.

Table B.8. Test Trailer GAWRs and GVWRs

(All dimensions in pounds)	GAWR Front Axle	GAWR Rear Axle	GVWR
Fruehauf Box Van	20,000	20,000	68,000
Fontaine Spread Axle Flatbed	20,000	20,000	70,543
Fruehauf Flatbed	20,000	20,000	(tag unreadable)
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.

Table B.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)
Fruehauf Box Van	632.0	36.0	135.0	473.0	49.0	48.0	77.5
Fontaine Spread Axle Flatbed	581.0	33.5	144.0	425.0	123.0	57.0	77.5
Fruehauf Flatbed	578.0	38.0	148.0	474.0	49.0	56.0	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.

Table B.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)
Fruehauf Box Van	350.71	1.16	46.0	81.1	81.0
Fontaine Spread Axle Flatbed	329.10	-1.06	51.0	87.4	89.5
Fruehauf Flatbed	337.59	-0.03	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.

Table B.11. Test Trailer Torsional Stiffness and Roll Stiffness

(All dimensions in ft-pound per degree) (Condition as delivered)	Whole Unit Torsional Stiffness	Roll Stiffness of Trailer Suspension	Torsional Stiffness of Trailer Chassis
Fruehauf Box Van	16,270	26,759	41,505
Fontaine Spread Axle Flatbed	739	7,979	815
Fruehauf Flatbed	537	11,831	563
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

C. INSTRUMENTATION AND SAFETY EQUIPMENT (APPENDIX C)

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 the maneuver 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, you could evaluate whether 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 [5], [6].

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 I and Phase II of this 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 1500 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 [17] .

Figure C.1. Tractor and trailer mounted outriggers.

Anti-Jacknife Safety System: Each tractor semi-trailer combination had an anti jack-knife 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 bulk head 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.

Figure C.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 jack-knife. 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.

Figure C.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 jack-knife support was measured. The final measurement was matched to the closest cable length.

Figure C.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 1500 pounds of weight to the vehicle. The roll bar was constructed from six inch diameter quarter inch thick steel round tubing.

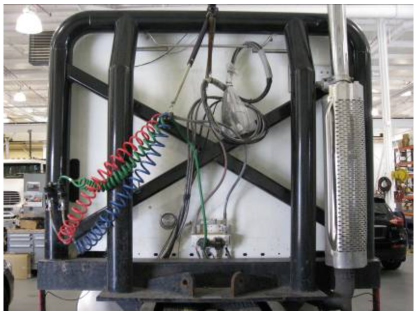

Figure C.5. Example of a tractor rollbar.

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.

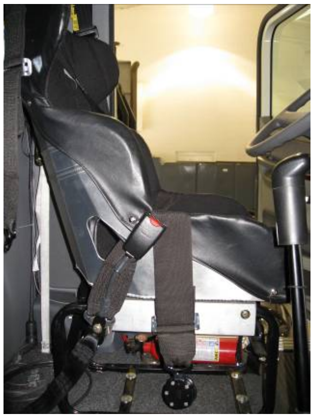

Figure C.6. Driver restraint system.

D. LOAD CONDITIONS (APPENDIX D)

A total of four 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 Slowly Increasing Steer maneuver, the Bobtail load condition was used. The Slowly Increasing Steer 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 at relatively low speeds, it was determined that additional safety equipment (such as outriggers) was not 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). Each vehicle was at least three-quarters full of fuel. The Bobtail load condition was used during Slowly Increasing Steer testing.

Table D.1. Bobtail Load Condition Weights

(All weights in pounds)	Steer Axle Total	Drive Position Total	Total Weight
Freightliner	10,730	9,020	19,750
Volvo	10,830	8,780	19,610
Sterling	9,640	5,490	15,130

LLVW (Lightly Loaded Vehicle Weight):

It is understood that current RSC (and ESC) systems can estimate total combination weight (tractor and trailer) by using required engine torque under acceleration. (It is understood that current RSC and ESC systems are not capable of determining load CG position.) From this load estimation, the RSC (and ESC) systems perform differently according to a look up table. To exploit this fact, two load conditions were used in order to evaluate the test tractors' performance during Ramp Steer Maneuver testing at different points on the RSC systems' look up tables.

To maximize safety during Ramp Steer Maneuver testing, both of the load conditions required the use of outriggers. Therefore, both load conditions required the use of a test trailer. In order to evaluate the "lower end" of the look up table, it was necessary to minimize weight. Thus, the LLVW load condition was chosen as the best compromise between low weight and adequate safety.

In addition to the equipment used for the Bobtail load condition, the LLVW (Lightly Loaded Vehicle Weight) condition included a test trailer with its associated instrumentation, ballast load frames (except Heil Tanker), and safety equipment (anti-jackknife brackets, anti-jackknife cables, and outriggers). The LLVW load condition was used during Ramp Steer Maneuver testing.

Table D.2. LLVW Load Condition Weights

(All weights in pounds)	Steer Axle Total	Drive Position Total	Trailer Position Total	Total Combination Weight
Freightliner with Fruehauf Box Van	10,990	14,520	12,000	37,510
Freightliner with Fontaine Spread Axle Flatbed	10,800	14,360	9,440	34,600
Freightliner with Fruehauf Flatbed	11,050	14,640	9,840	35,530
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 Fruehauf Box Van	11,080	13,910	11,640	36,630
Volvo with Fontaine Spread Axle Flatbed	10,960	13,860	9,520	34,340
Volvo with Fruehauf Flatbed	11,020	14,060	10,210	35,290
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 Fruehauf Box Van	10,190	10,560	11,730	32,480
Sterling with Fontaine Spread Axle Flatbed	10,130	10,380	9,890	30,400
Sterling with Fruehauf Flatbed	10,140	10,710	9,890	30,740
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

<u>High CG:</u>

As discussed in the previous section, in order to evaluate the “higher end” of the RSC (and ESC) systems’ look up table, it was necessary to maximize weight. Therefore, in addition to the equipment used for the LLVW condition, ballast was used. To truly maximize weight, the test tractor and trailer combinations could have been loaded to maximum GAWRs and GVWRs. However, in some cases this would have resulted in a total weight that is not legal according to Federal Motor Carrier Safety Administration (FMCSA) regulations. In order to simulate “real world” conditions that the RSC (and ESC) systems would experience, we chose to follow the FMSCA regulations, specifically, Part 658: Truck Size and Weight, Route Designations — Length, Width and Weight Limitations:

> “§658.17 Weight.
> (a) The provisions of the section are applicable to the National System of Interstate and Defense Highways and reasonable access thereto.

> (b) The maximum gross vehicle weight shall be 80,000 pounds except where lower gross vehicle weight is dictated by the bridge formula.
> (c) The maximum gross weight upon any one axle, including any one axle of a group of axles, or a vehicle is 20,000 pounds.
> (d) The maximum gross weight on tandem axles is 34,000 pounds."

This meant that for a typical 6x4 test tractor and tandem-axle trailer combination, a steer axle, tractor drive position, and trailer position weight specification would be 12,000 pounds, 34,000 pounds, and 34,000 pounds, respectively. (Two tandem axle positions at 34,000 pounds, with 12,000 pounds on the steer axle position to total no more than 80,000 pounds. Typical GAWR rating for test tractor steer axles was 12,000 pounds.)

Testing also included using a test tractor with a single drive axle (Sterling, limited to 20,000 pounds per the FMCSA regulation) and a single-axle test trailer (Great Dane 28-Foot Flatbed, also limited to 20,000 pounds per the FMCSA regulation). However, the single-axle test trailer we used was based upon the specifications used in Federal Motor Vehicle Safety Standard (FMVSS) 121, Air Brake Systems, which states:

> "The control trailer is an un-braked flatbed semi-trailer which has a single axle with a gross axle weight rating (GAWR) of 18,000 lb. and a length of 258 ± 6 inches when measured from the transverse centerline between the axle to the centerline of the kingpin."

In following the guidelines of FMVSS 121, for the convenience of those organizations (such as NHTSA and heavy truck manufacturers) who have previously invested in such a trailer, we made the exception that the Great Dane 28-Foot Flatbed trailer would be loaded to 18,000 pounds.

In summary, the High CG load condition used the following to determine axle loads:

12,000 pounds per steer axle
20,000 pounds per single tractor drive axle
34,000 pounds per tandem tractor drive axles
34,000 pounds per tandem trailer axles
18,000 pounds per single trailer axle

We allowed a +/- 2% tolerance on each axle and total weight, except where the tractor steer axle was under-loaded due to limited fifth-wheel adjustability. In those cases, we allowed the steer axle to exceed the -2% tolerance.

In addition to the equipment used for the LLVW load condition, the High CG condition included ballast, typically 24-inch high steel load tables and concrete blocks, secured to the deck of the trailer with steel chains. Loads were centered (as much as possible) over the test tractor fifth-wheel and the trailer axle(s). The exception was the Heil Tanker, which used water as ballast in the configuration recommended by the manufacturer. For all test tractors, tank 4 was filled to the maximum recommended level. Additionally, for the Freightliner and Volvo tractors, tank 1 was filled to the maximum recommended level. For the Sterling tractor, the water level in tank 1 was reduced to prevent overloading the tractor drive axle. The High CG load condition was used during Ramp Steer Maneuver testing, Pulse Steer Testing, and Understeer Gradient Testing (Slowly Increasing Steer-type maneuver).

The 24-inch high load tables were used to raise ballast CG in order to reduce roll stability of the test tractor and trailer combinations in the High CG load condition. (The exception was the Heil Tanker, which used water ballast in fixed tanks.) All test trailers were tested with the vertical CG of the loaded trailer at approximately 80 inches.

Table D.3. High CG Load Condition Weights

(All weights in pounds)	Steer Axle Total	Drive Position Total	Trailer Position Total	Total Combination Weight
Freightliner with Fruehauf Box Van	11,770	33,990	33,450	79,210
Freightliner with Fontaine Spread Axle Flatbed	11,780	34,660	33,920	80,360
Freightliner with Fruehauf Flatbed	12,050	34,670	33,750	80,470
Freightliner with Great Dane 28-Foot Flatbed	11,740	34,200	18,130	64,070
Freightliner with Strick Box Van	11,510	34,400	34,240	80,150
Freightliner with Heil Tanker	11,820	33,890	30,360	76,070
Volvo with Fruehauf Box Van	12,160	33,460	33,440	79,060
Volvo with Fontaine Spread Axle Flatbed	11,780	34,030	34,150	79,960
Volvo with Fruehauf Flatbed	11,970	33,720	33,910	79,600
Volvo with Great Dane 28-Foot Flatbed	11,950	33,480	18,040	63,470
Volvo with Strick Box Van	11,860	33,880	34,330	80,070
Volvo with Heil Tanker	12,070	33,130	30,410	75,610
Sterling with Fruehauf Box Van	11,220	20,000	34,260	65,480
Sterling with Fontaine Spread Axle Flatbed	10,830	20,060	33,820	64,710
Sterling with Fruehauf Flatbed	10,910	19,960	34,280	65,150
Sterling with Great Dane 28-Foot Flatbed	10,950	19,850	18,030	48,830
Sterling with Strick Box Van	11,060	19,970	33,730	64,760
Sterling with Heil Tanker	10,890	20,330	29,570	60,790

Low CG:

In addition to the High CG load condition method of evaluating the “higher end” of the RSC (and ESC) systems’ look up table, the Low CG condition was tested using the Freightliner and Volvo truck tractors with the Fruehauf Box Van. The same axle loads were used, however, the concrete ballast blocks were secured with steel chains directly to the floor of the test trailer in order to obtain a loaded trailer CG height of approximately 60 inches.

Table D.4. Low CG Load Condition Weights

(All weights in pounds)	Steer Axle Total	Drive Position Total	Trailer Position Total	Total Combination Weight
Freightliner with Fruehauf Box Van	11,720	33,420	33,720	78,860
Volvo with Fruehauf Box Van	11,870	33,380	33,730	78,980

E. WHITE PAPER (APPENDIX E)

WHITE PAPER: NEXT STEPS IN DEVELOPING AN OBJECTIVE TEST FOR ROLL STABILITY CONTROL (RSC)

Objective

The objective of this white paper is to propose a test (maneuver and methodology) that all parties can use to gather a common dataset from which an optimal Measure of Performance (MOP) can be determined for truck tractor RSC.

Background

There are three main components that need to be determined in order to develop a repeatable performance-based objective test for RSC. These are: (1) test maneuver, (2) test methodology that utilizes said maneuver, and (3) the measure of performance (MOP) to use for pass/fail criteria (e.g. lateral acceleration, wheel lift etc). However, prior to selecting a MOP, the immediate next step is to determine a single test maneuver/methodology that can be used by all parties to collect a common data set from which an optimal MOP can be determined. This white paper discusses and analyzes the tests discussed thus far and based on this analysis, describes a way forward that (1) proposes a single test that synthesizes together the best aspects of the various candidate tests and (2) proposes a test matrix that results in a dataset that can be analyzed to determine an appropriate MOP.

Overview of Tests Proposed

All test maneuvers proposed to date are basically the same maneuver but are performed using a slightly different methodology. Each test is fundamentally derived from the basic equation:

$$Ay = \frac{V^2}{R}$$

Where:

A_y = Lateral Acceleration
V^2 = Vehicle forward velocity
R = Radius of travel

Each test maneuver generates lateral acceleration in a controlled manner. Some of the maneuvers manipulate Ay by increasing V while the others manipulate it by decreasing R. As a result, they differ in terms of test severity and measures of performance (MOP) rather than their purpose.

This suggests that a single test maneuver should be used and in order for different MOP's to be evaluated, the accompanying test methodology should exercise the full range of RSC performance. This would allow different MOP's to be evaluated under a range of lateral acceleration levels (low to severe). Similarly, data from test track testing and simulation results, has shown these maneuvers to be similar, suggesting that these candidate maneuvers can be narrowed to 1 characterization test and 1 performance test.

Summary and Analysis of Candidate RSC Tests

Thus far, 3 candidate tests have been identified that show merit for possible use in evaluating stability control performance of Class 8 truck tractors. Of the three tests, two of them require that a characterization maneuver be conducted. The characterization maneuver is used to determine the hand wheel amplitude to be used for the test maneuver. The three test maneuvers discussed in this paper are as follows:

1. Decreasing Radius Test
2. Roll Stability Control Test
3. Ramp Steer Test

It should be noted that a fourth test known as a "Lane Change on a Large Diameter Circle" was considered, however, it was decided not to include it in this discussion. Based on a qualitative engineering assessment, it appears that it would be difficult to have repeatable and consistent test results with this type of maneuver. Additionally, it requires a specific geometry and a large test area to perform the test.

Candidate test No. 1 - Decreasing Radius Test (DRT)

Test Overview

For this maneuver, two versions of the test maneuver have been discussed in previous meetings. The major difference between the different versions of the test is that one is a driver based path following maneuver (V1) while the other is a steering controller based maneuver (V2). The test is to be performed on a dry asphalt test course that begins as a 150 ft. (inner) radius curve that continuously and linearly decreases over an arc of 120 degrees to a 90 ft. (inner) radius curve. The drivers enter the course tangent to the 150 ft. (inner) radius and must steer the tractor within a 12-foot wide lane (trailer is allowed to "cut" the radius as necessary).

Test Summary

Number of Tests	2 (loaded w/ trailer and bobtail)
Control Trailer	Unbraked configured similar to FMVSS-121
Loading	Trailer will be loaded such that the tractor drive axles are loaded to their rated capacity, and minimal load placed on the trailer axle.
Outrigger	Yes
Test Throttle Condition	V1- Used to maintain speed. V2 – Cruise control[15]
Test Speed	V1 - 29 mph start. V2 – 30 mph
HW Angle	Determined by theoretical steering wheel input needed to follow the curved path as prescribed at test speed.
HW Rate	Determined by theoretical steering wheel input needed to follow the curved path as prescribed at test speed.
Steering Controller	V1 – No. V2 –Yes
Surface	Asphalt; High Mu.
Gear Selection	N/A

Candidate Test No. 2 - Roll Stability Control Test (RSCT)

Test Overview

This test utilizes a non-path following maneuver. The RSCT maneuver relies on a steering controller that commands the steering to ramp to a magnitude that is determined by a SIS or a theoretical steering equation over a time of 1 to 2 seconds. It is then held at this maximum amplitude for some amount of time and then returns to zero amplitude. This test is conducted at 30 mph with an unbraked test trailer in a similar configuration that is consistent with FMVSS 121. When the maneuver begins, the test driver is to engage the throttle position to 100%.

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[15] It is unclear if all trucks are equipped with cruise control.

Test Summary

Number of Tests	2 depending on method used for HW amplitude
Control Trailer	unbraked configured similar to FMVSS-121
Loading	Trailer will be loaded such that the tractor drive axles are loaded to their rated capacity, and minimal load placed on the trailer axle.
Outriggers	Yes
Test Throttle condition	Full on at the start of steering maneuver
Test Speed	30 mph
Handwheel Angle	Use methods 1 or 2 for determining amplitude
Handwheel Rate	85 to 220 deg/sec[16]
Steering Robot	Yes
Gear Selection	Not defined
Surface	High friction dry asphalt surface consistent with the specifications in FMVSS-126

Characterization Maneuver for Determining Steering Amplitude

Method 1

The steering amplitude is based on assumed vehicle characteristics, using a simple equation that relates steering amplitude to vehicle wheelbase. An example that has been tested success by BCVS is shown below:

$$\delta_h = 34.5(l) + 30.94$$

Where

δ_h = steering angle in degrees
l = vehicle wheelbase in meters

Method 2

The steering amplitude is determined on a dry asphalt surface using a slowly increasing steer test at a constant speed of 30 mph. The handwheel angle will be determined such that 0.5 g of lateral acceleration is achieved using a bobtail tractor at a speed of 30 mph.

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[16] The range of handwheel rates was estimated as a function of wheelbase of three tractors. The actual range may be larger when considering either shorter or longer wheelbases.

Discussion

Using method 1 as described in this test procedure, the following table documents the magnitude of steering angle to be used for test with our current tractors..

Tractor	Wheelbase (in.)	Wheelbase (m)	Steer Angle (deg)
2006 Volvo	211	5.36	216
2006 Freightliner	215	5.46	219
2008 Sterling	160	4.06	171

Since a time is specified in this test plan for the initial ramp of the steer angle, a steering rate can be calculated. Below are steering rates for a 1-2 second increase steering ramp (1t) time.

Angle	Freightliner 219	Volvo 215	Sterling 171
time(seconds)	rate (deg/sec)	rate (deg/sec)	rate (deg/sec)
1	219.35	215.86	171.15
1.1	199.40	196.24	155.59
1.2	182.79	179.89	142.62
1.3	168.73	166.05	131.65
1.4	156.68	154.19	122.25
1.5	146.23	143.91	114.10
1.6	137.09	134.91	106.97
1.7	129.03	126.98	100.68
1.8	121.86	119.92	95.08
1.9	115.44	113.61	90.08
2	109.67	107.93	85.57

Ramp Steer Maneuver (RSM)

Test Overview

The RSM is very similar to a J-Turn however it is performed using a steering controller to remove driver variability. Severity of the maneuver is controlled by incrementally increasing speed.

To normalize test vehicles steering to lateral acceleration gain, a Slowly Increasing Steer (SIS) maneuver is performed to determine the magnitude of the steering input for test conduct.

Test Method

Number of Tests	14 test runs (maximum)
Control Trailer	TBD
Loading	(1) 80K – CG 88” above ground (2) Tractor GAWR – CG as close to deck as possible (121 style load)
Outrigger	Yes
Test Throttle Condition	Drop Throttle (Clutch Pedal In)
Test Speed	20 mph start; increment each test by 2 mph
HW Angle	Determined by SIS maneuver
HW Rate	175 - 450 deg/sec
Steering Controller	Yes
Gear Selection	Not relevant since clutch is disengaged
Surface	Asphalt; High mu

Candidate Maneuvers Compared and Contrasted

Three candidate performance maneuvers are shown in Table 1. The table provides defined inputs and load configurations utilized for the duration of a test series. Though the table shows lots of differences with respect to input definitions all three maneuvers are essentially J-Turns with very similar paths and radii. These maneuvers are comparatively discussed by the categories listed in the first row of Table 1.

Table 1: Comparison of investigated maneuvers for Class 8 Truck Tractor stability control performance metric research.

Maneuver	Speed (mph)	Throttle Position	Steering Amplitude	Steering Rate	Load Configuration
RSM	20-40	Drop Throttle / Clutch Disengaged	SIS @ 0.3g	175 - 450 deg/sec	High CG Low CG FMVSS 121
RSCT	30	Increased to Full	SIS @ 0.5g Or Calculated	Approx. 85 – 220 deg/sec	Low CG FMVSS 121
DCR V2	30	Maintain Speed	Calculated	Calculated	Low CG FMVSS 121

Maneuvers

Both the RSM and the RSCT maneuvers utilize a steering controller to control steering amplitude, rate and duration. For these two maneuvers the steering wheel input is ramped to specified amplitude from 0 degrees at either a given constant steering rate or a given amount of time by an automated steering controller. The DCR maneuver is in one version of the procedure a path-following maneuver that is defined in the previous sections. This is fundamentally different maneuver from the RSMs in that the driver is given the freedom to either increase\decrease the amplitude, the rate or duration of the steering input to follow a defined path. In a second version of the DCR, use of a steering controller is mentioned.

Steering Wheel Amplitude

Steering Amplitude:	**RSM**	**SIS @ 0.3 g**
	RSCT	**SIS @ 0.5 g or Calculated**
	DCR V2	**Calculated**

The steering wheel amplitude for the RSM is calculated from RSM SIS test data. The RSM SIS is performed for each load configuration tested and is therefore is characterized by the tractor/trailer combination being evaluated. The RSCT steering wheel amplitude is derived in either of two ways. It can be calculated with an equation based on wheelbase or calculated from the RSCT SIS maneuver. Once research for these candidate maneuvers is complete, it is envisioned that one of these options will be selected, should either the RSM or the RSCT be the preferred performance maneuver. The version 1 of the DCR is a path following maneuver; therefore, steering wheel angle amplitude is dependent upon maneuver entrances speed, vehicle, and driver.

In general and from test track experience, tight control over steering inputs increases test repeatability. Therefore researchers see maneuvers that are conducted with automated steering controllers as advantageous for performance/compliance test implementation. Version 2 of the DCR test makes reference to using a steering controller. As previously stated, it is difficult to determine the theoretical steering input and rate needed to follow the path as prescribed using an open loop steering controller. It is believed that the main purpose of the decreasing radius is to have the test vehicle experience a range of lateral accelerations within a single test maneuver. Given this assumption, it is believed that steering profile can be generated that meets this test goal.

Figure 1 shows example steering profiles for all candidate maneuvers for a given tractor. To get an idea of the steering profile that the DCR requires, tests were performed using a test driver. The driver was instructed to follow the path (by cones) described in the DCR test. As can be seen in Figure 1, this steering data is actually quite similar. It should be noted that the dip in hand wheel angle observed from 2 – 6 seconds is due to ESC activation. The driver had to counter steer to maintain the prescribed path.

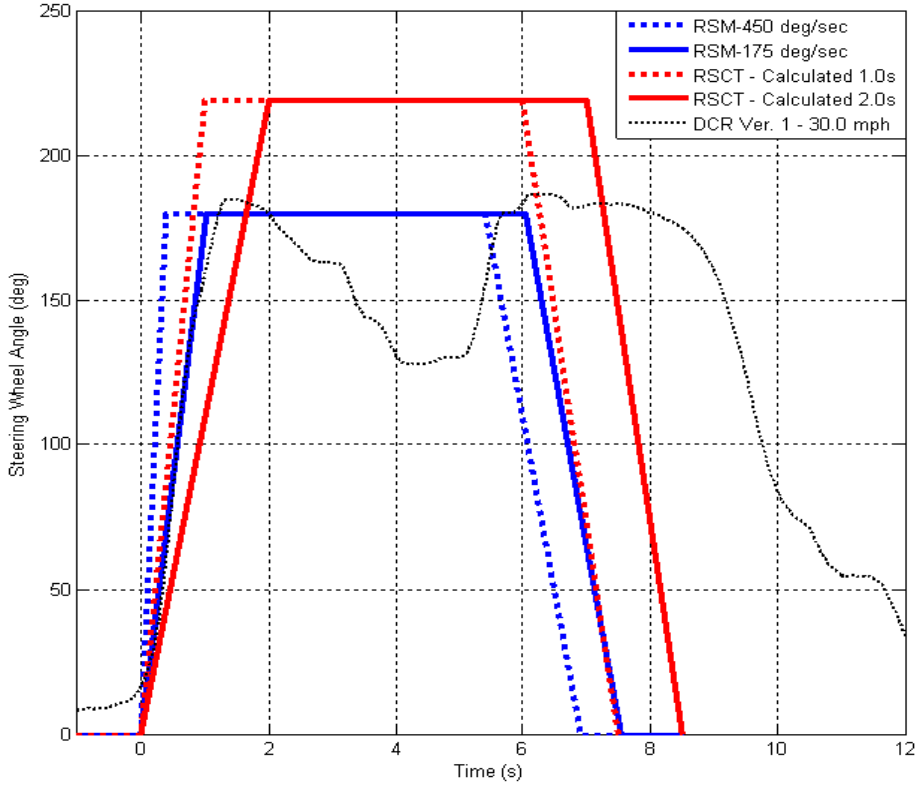

Figure 1: Example of automated steering wheel inputs for the RSM and RSCT for a given Class 8 tractor.

Steering Wheel Rate

Steering Rate:	**RSM**	**175 or 450 deg/sec**
	RSCT	**85 – 250 deg/sec**
	DCR	**Speed and Vehicle Dependant**

The steering wheel rate for the RSM is 175 and/or 450 deg/sec. This was derived from the analysis of driver steering inputs into multiple 150-foot J-Turn test series with two tractors and multiple load configurations (observed rates were 50 to 450 deg/sec). The RSM uses the higher rates tested because it is similar to a step input to the tractor system. It is believed that the higher rate test not only evaluates RSC, but potentially may evaluate a yaw stability system performance. The RSCT uses a fixed time to steering wheel amplitude of 1 to 2s. Depending on the time chosen, this will change the steering rate as demonstrated in a previous section. The DCR V2 maneuver procedure does not put any bounds on steering rate; it is allowed to fluctuate with amplitude and is dependent upon maneuver entrance speed and vehicle. Observing Figure 1, it can be seen that the steering profiles for all three maneuvers are all very similar in magnitude and rate.

Speed Input

Speed Inputs:	**RSM**	**20.0-40.0 mph**
	RSCT	**30.0 mph**
	DCR	**30.0 mph**

A range of maneuver speeds will be employed for the RSM candidate performance maneuver. For driver safety; the maneuver entrance speed will be incremented up from 20.0 mph by 2.0 mph increments during the RSM test series. Maneuver entrance speed is incremented up until either the maximum test speed is reached or a test terminating event[17] has occurred. Comparatively the RSCT and DCR maneuvers are conducted at a single maneuver entrance speed.

Throttle Input

Throttle Inputs:	**RSM**	**Drop**
	RSCT	**Full**
	DCR	**Variable**

Prior to initiating a test for any one of the candidate performance maneuvers the driver is given the freedom to increase/decrease the throttle input to achieve the desired maneuver entrance speed. Once the maneuver has been initiated each candidate performance maneuver utilizes a different assignment for the throttle input. The RSM test specifies that the throttle be dropped just prior to initiating the maneuver. The RSCT specifies that the throttle be increased to open at the start of the test maneuver. The DCR procedure requires the driver to use the throttle as needed to try and maintain a constant speed. The advantages to dropping the throttle are increased test repeatability and procedure simplicity. The advantage to applying full or partial throttle is that throttle control can now be observed during the maneuver as the initial step in ESC intervention.

Load Configuration

Configuration:	**RSM**	**High CG (86.00 in) and/or FMVSS121v**
	RSCT	**Low CG or FMVSS 121v**
	DCR	**Low CG or FMVSS 121v**

The three candidate maneuvers utilize a variety of different load configurations. The RSM procedure employs a loaded control trailer with the Center of Gravity located at approximately 86.00 inches above the ground plane; it is referred to as the High CG load Configuration. A 2nd configuration with the center of gravity of the load as close to the control trailer deck as possible (FMVSS 121V, Ver. 1999). The RSCT and DCR procedure calls for a control trailer to be loaded to GVWR with the load placed as low to the trailer deck as possible. The 2nd configuration for those two maneuvers would be very similar to that required by FMVSS No. 121. Where the truck tractor is loaded to

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[17] Test terminating events include wheel lift arrested by outriggers; articulation angle arrested by ant-jackknife cables or repeated observation of severe understeer. Exact maneuver procedures can be found in previous sections, which also details the procedures used if a tests terminating event is observed.

GVAR via a control trailer and ballast distributed evenly about the kingpin; so that minimal load is carried by the trailer axles.

Comparatively the elevated center of gravity loads simulate reduced roll stability configurations, which researchers have observed during maneuver development testing. The Low CG or FMVSS 121 variants have been observed to simulate reduced yaw stability and/or roll stability depending on the tractor, trailer type and maneuver.

Further research is needed using low center of gravity load configurations to determine its merit for RSC performance testing. It is understood that current ESC systems are not capable of determining load CG. It is understood that the total weight of the load is estimated from engine torque. From this load estimation, the CG is assumed from a look up table. Given this fact, a tractor should perform no different using an 80K Low CG load compared to using an 80K High CG load. Depending on the MOP developed, Low CG testing may be reasonable and desirable.

Additionally, while it may or may not merit use for RSC performance testing there appears to be certain Low CG trailers in which reduced yaw stability is observed; making it a candidate maneuver for ESC performance testing. Again more research is needed in this area.

Gear Selection Criteria

Gear Selection:	**RSM**	**N/A**
	RSCT	**Not Specified**
	DCR	**Not Specified**

The RSM test is conducted off-throttle and with the clutch disengaged. This negates any effects that gear ratio and RPM may have on test performance. If a test is to be conducted on throttle, it is believed that gear selection may be important, since limited testing has shown drivers have the option of using 4 different transmission gears to sustain a maneuver entrance speed. Allowing multiple gear selection options will decrease test repeatability. Therefore, to increase test repeatability manual gear selection criteria would have to be developed.

Proposed Test Program:

Based on the analysis of candidate tests, it is proposed that the following test matrix and test procedure be used to generate a well defined set of test data that can be used to develop an effective MOP. The test exercises the tractor trailer system through a variety of lateral acceleration levels that will allow different metrics (subtle to severe) to be evaluated.

From this data, a performance test and success criteria can be defined. It is envisioned that the performance test generated will be similar to the procedure outlined below, however it will be conducted with a single control trailer, using 1 or 2 loading conditions, and will be conducted at a single speed. If all the cells in the proposed matrix are completed below, a large common dataset can be collected to enable a more comprehensive analysis and will help determine the best MOP.

Proposed Test Matrix:

		Trailer					
		Dry Box Van		Flatbed			Tanker
Tractor	Load	53ft. Fruehauf	53ft. Strick	48ft. Spread Axle	48ft. Tandem Axle	28ft. FMVSS 121 Control Trailer	9200 Gallon (4 comp.)
2006 Freightliner 6X4 - ESC	**Low CG**						
	High CG						
2006 Freightliner 6X4 - RSC	**Low CG**						
	High CG						
2006 Volvo 6X4 – ESC	**Low CG**						
	High CG						
2008 Sterling 4X2 – RSC	**Low CG**						
	High CG						

Proposed Test:

It is recommended that the test matrix be completed using a modified RSC Test maneuver as described by the RSCT test (candidate test No. 2) test procedure. All maneuvers are to be performed without the use of test trailer brakes. Trailers will be loaded in either a High CG or Low CG condition. The High CG condition should load the truck tractor/trailer combination to the maximum road legal load condition. For most 6X4 tractor-trailer configurations this should by a 12K, 34K, 34K type load. The CG height of the loaded trailer should be >= 80 inches above the ground. The Low CG condition should load the tractor trailer combination to XX (some percentage of GVWR). The CG of the load should be placed as close to the deck of the test trailer as possible. The CG of the load should not exceed 32" above the deck of the trailer. If alternate loads are used, they should be documented.

Tests will be conducted drop throttle, clutch in. It is understood that RSC systems can cut the throttle and engage the engine and/or exhaust brake to reduce engine torque and decrease vehicle speed. These are helpful in situations where mild deceleration is needed. In many crash eminent or more severe cases, braking will dominate the event and generate far more deceleration. Secondly, since a variety of transmissions, gear ratios, and other factors may affect test performance, it is advantageous to reduce the number of factors that a test procedure may need to address. Testing off-throttle and with the clutch in reduces many of these factors and produces very repeatable results. Additionally, experience has shown a great deal of success triggering the steering controller from the speed signal. Using a comparator circuit built into the steering controller, the maneuver is triggered by the vehicle speed falling into the desired test speed. Drivers are instructed to accelerate the combinational vehicle to 1 mph above the desired test speed, at which then they drop the throttle and disengage the clutch. When vehicle speed decreases to the desired test speed, the steering program is initiated. This has lead to very tight control and repeatability in the speed at which tests are conducted. Since the ultimate goal is to develop a compliance test, it is critical to be able to test in this repeatable manner.

Minimum Preferred Dataset

Tractor:

1. Lateral Acceleration
2. Yaw Angular Rate
3. Throttle Position
4. Longitudinal Acceleration
5. Pitch Angular Rate
6. Tractor Speed
7. Vertical Acceleration
8. Steering Wheel Angle
9. VDC1 Message from J1939
10. Roll Angular Rate
11. Brake Treadle Application

12. Frame Rail Height (L/R) (to determine roll)
13. Glad hand valve pressure

Trailer:

1. Lateral Acceleration
2. Roll Angular Rate
3. Rear Axle Height (L/R)
4. Longitudinal Acceleration
5. Yaw Angular Rate
6. Outrigger Height (L/R) (to determine roll)
7. Vertical Acceleration
8. Pitch Angular Rate,

Vehicle Pre-test Conditioning

The vehicle pre-test conditioning is performed as the following describes:

1) Tire warm-up
    a) Two circles clockwise and two circles counter-clockwise at a speed that result in 0.1 g lateral acceleration. (Approximate 150-foot radius at 20 mph.)
2) Brake warm-up
    a) Use 40-20 mph burnish (0.3 g decel.) bring tractor brake temperatures to a minimum of 150-200 degrees F [FMVSS 121]
3) Mass estimation drive cycle
    a) The electronic stability control system should be enabled.
    b) From stop accelerate to 40 mph
    c) Decelerate at 0.3 to 0.4 g to a stop.
    d) Ignition cycle will require new mass estimation drive cycle.

Test Procedure

SIS Characterization Maneuver

The SIS characterization maneuver is performed as the following describes:

1) Vehicle Pre-test conditioning
2) Test (3 tests in the clockwise direction and 3 test in the counter-clockwise direction – Bobtail)
    a) Speed = 30 mph
    b) Steering = steering magnitude increases from 0 to 270 degrees @ 13.5 deg/sec. (Note: According to TruckSim higher handwheel angles may be needed for long wheel base-high steering ratio tractors.)
3) Test End
    a) Steering magnitude = 270 deg
    b) Tractor wheel lift is observed.
    c) Test driver feels it's unsafe to continue.
4) Calculate RSM [illegible]

RSM [illegible] is calculated per the test procedure provided by RSCT.

Test	Event Point (count)	MES [mph]	Steer Direction	AY End of Range (g)	Angle @ 0.3g [degree]	Steering Gain	R-Squared
1	201	24.1	Right	0.300	**191.7**	0.001538	0.993
2	197	25.3	Right	0.300	**186.5**	0.001645	0.997
3	200	24.3	Right	0.300	**178.8**	0.001675	0.980
4	202	25.8	Left	-0.300	**-193.5**	0.001446	0.993
5	203	25.9	Left	-0.300	**-191.0**	0.001536	0.997
6	203	24.8	Left	-0.300	**-181.8**	0.001652	0.999
	Averages	25.0		0.300	**187.2**	0.001582	0.993

From 6 SIS tests the Steering Angle Output ranged from 179 to 194 degrees. The average value of 187 would be used to define δ^{Test}.

NOTE: It is unclear if 0.3 vs. 0.5 g should be used as the steer point at this time. It seems reasonable that it should be somewhere in this range and that conducting the maneuver bobtail, as the RSCT suggests, is a logical method. More analysis is needed to determine the optimum lateral acceleration that should be used.

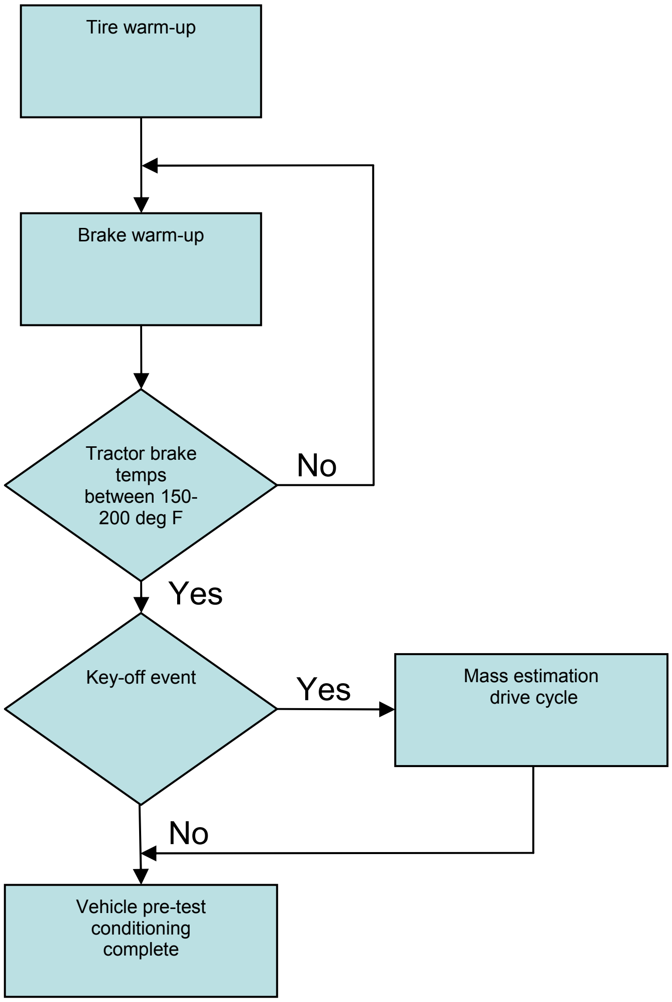
RSC Performance Maneuver

1) Vehicle pre-test conditioning
2) Test (per each load condition)
   a) steering magnitude = δ^{Test}
   b) steering rate = 175 deg/sec
   c) speed = 20 mph
   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 speed for each test @ 2 mph until one of the following conditions occur.
   a) Speed = 50 mph – Test Complete
   b) Tractor or Trailer wheel lift occurs
      i) Wheel lift 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 wheel lift occurred, test should be decremented by 2 mph.
   a) Repeat test at major wheel lift speed – 2 mph.
   b) Repeat test at major wheel lift speed – 1 mph.
   c) Repeat test at major wheel lift speed
   d) If wheel lift has not occurred, continue to increment speed by 1 mph until wheel lift occurs.
   e) Test is complete when wheel lift occurs (jump step 6).
5) Test is complete when wheel lift has occurred 2 times or condition 3a has been met.
6) Test Complete

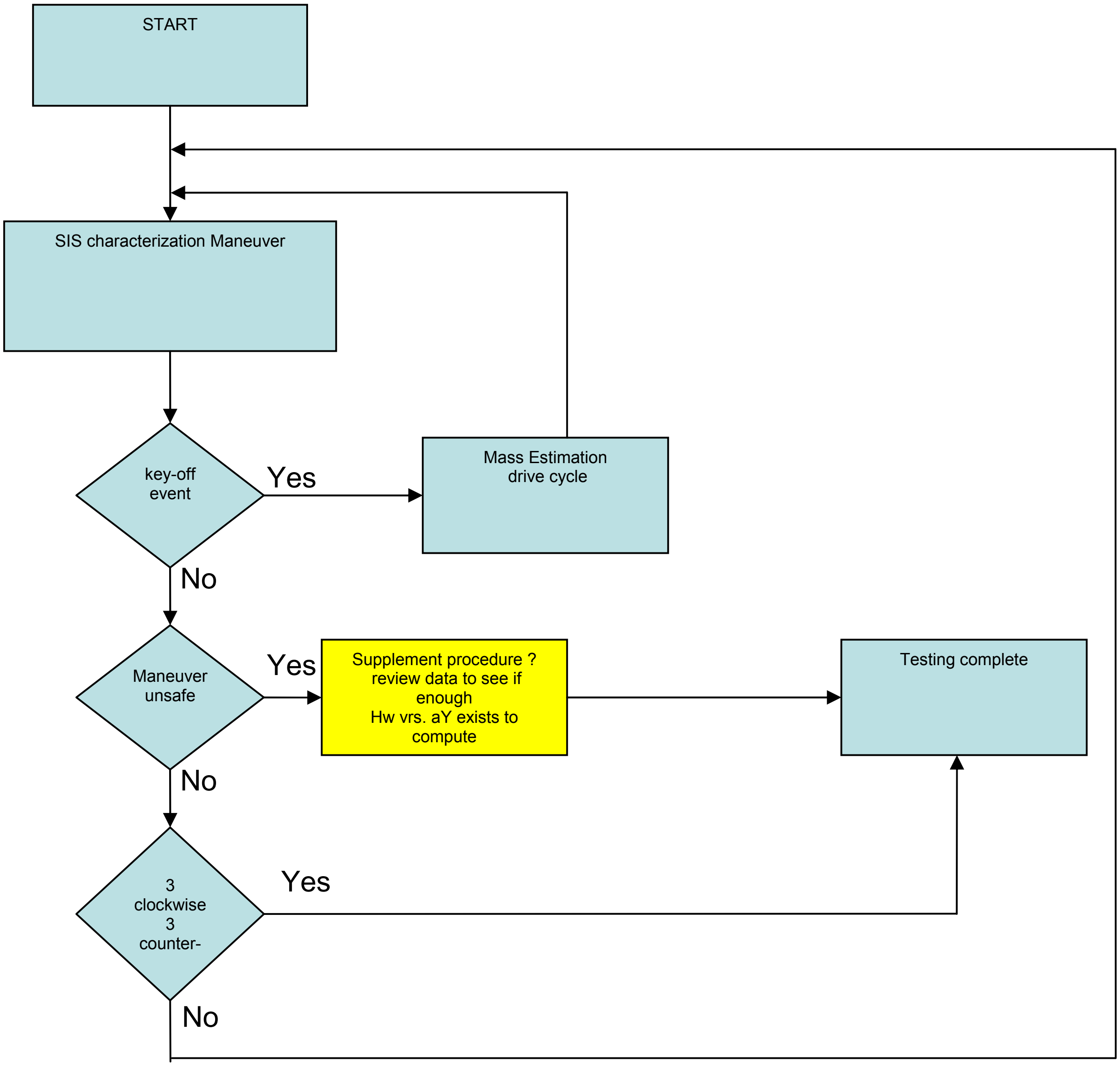
Note: All tests are conducted to the left. Test drivers should be sensitive to this issue and make right turns when returning to the test start point so as not to bias any learning algorithms that a system may have. The number of left turns and right turns should be balanced as much as possible.

F. FLOW CHARTS (APPENDIX F)

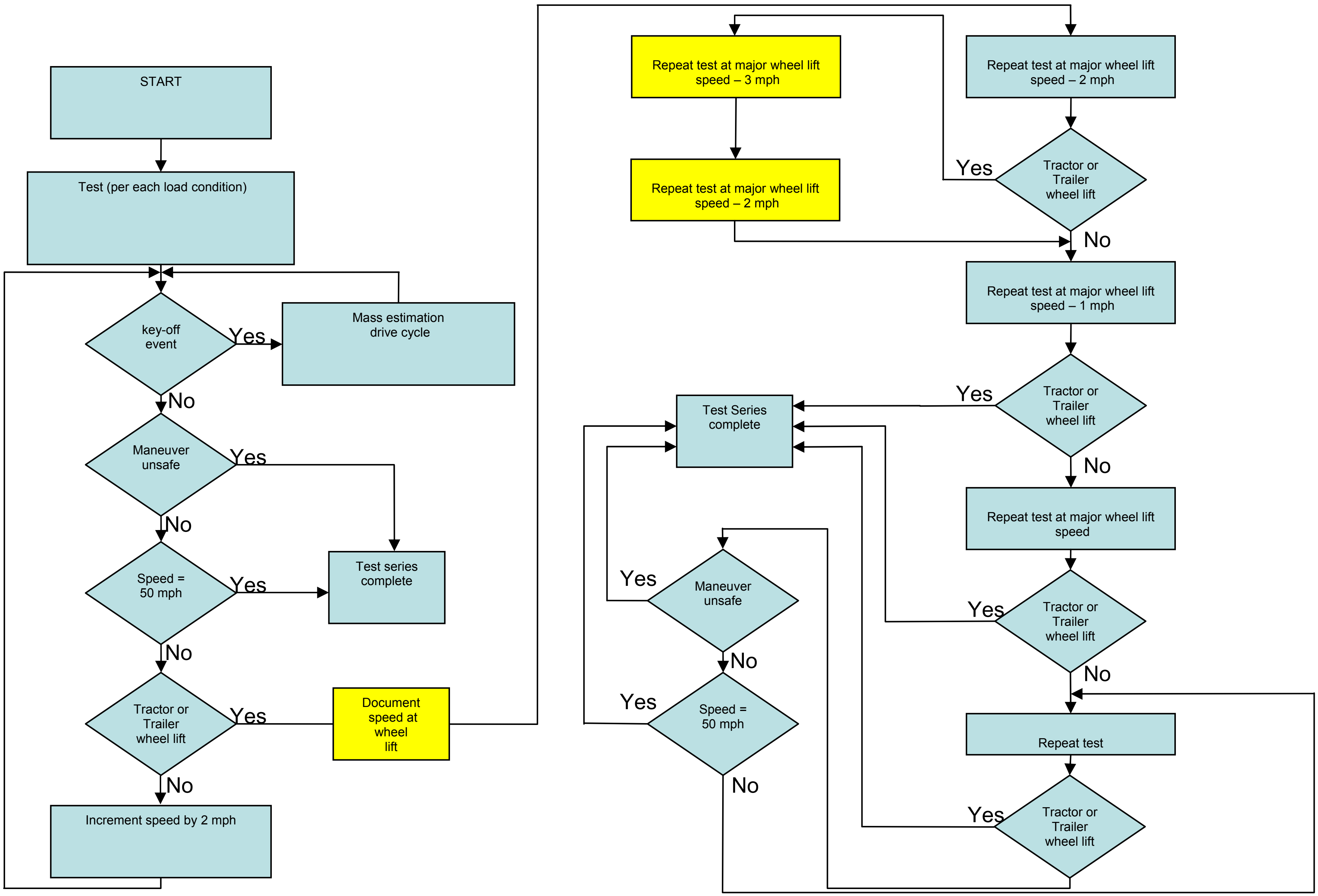
Vehicle Pre-Test Conditioning Procedure Flow Chart



SIS Characterization Maneuver Procedure Flow Chart



RSC Performance Maneuver Procedure Flow Chart



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