<u>NHTSA's Class 8 Truck-Tractor Stability Control Test Track Effectiveness</u>

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ABSTRACT

Statistical analyses of crash data in the United States show that a large percentage of heavy truck crashes are rollover related. To evaluate roll stability for truck tractors, the National Highway Traffic Safety Administration (NHTSA) has performed test maneuvers with several Class 8 combination truck tractor/trailers on a test track. Stability Control interventions have been observed with all test track maneuvers conducted on dry pavement. Rollover events have been observed to be mitigated by stability control interventions in tests conducted with the truck tractor/trailer combinations loaded with a High Center of Gravity (CG) load.

This paper discusses the initial test track observations and test maneuvers NHTSA evaluated. Test maneuvers included constant radius increasing velocity tests, J-turn tests, and double lane change maneuvers. These tests were conducted with and without tractor and trailer stability control systems enabled. Tests were conducted under different loading conditions and on high coefficient of friction surface.

INTRODUCTION

According to the Large Truck Crash Facts 2006, there were 4,321 large trucks involved in fatal crashes during 2006. A total of 221 fatal crashes attributed rollover as the first harmful event [1]. Depending on the effectiveness of a stability control system, some number of these may possibly have be prevented.

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 per year [2]. Recognizing the safety potential of this technology, NHTSA has mandated that all vehicles less than 10,000 lbs. be equipped with ESC by model year 2012 [3].

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. 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.

TRUCK TRACTOR STABILTY

Truck tractors that pull a semi-trailer in service are subject to many different loading conditions. Often these loads can dramatically change the handling characteristics of combination units. A combination vehicle can be loaded so that the CG is raised significantly. In these conditions the vehicle is more prone to roll instability. Tank trailers carrying fuel or liquids have been measured to have CG heights of over 193 centimeters from the ground where as a conventional flat bed trailer may have CG of just over half that. Since the same truck tractor may be in service pulling either type of trailer, a safety beneficial stability system must be able to adapt to either condition.

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

- Trailer-based Roll Stability Control (RSC).
- Tractor-based RSC.
- Tractor based Electronic Stability Control (ESC).

Trailer-based RSC is capable of generating torque at the trailer axle brakes only. These systems generally do not have as much stability margin 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 generally have a larger stability margin than the trailer based systems. This is because they are able to electronically reduce engine torque on the tractor in addition to the trailer and therefore apply more braking torque than trailer-based systems. 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. The stability system can reduce engine torque by electronically removing the drivers 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 additions of these capabilities, the ESC system can not only assist drivers in mitigating roll events but also yaw instability events.

TEST TRACK PERFORMANCE STUDY

To gain a better understanding about the performance of heavy vehicle stability systems, a test track study was conducted. The study evaluated stability control performance of two truck tractors pulling a semi-trailer under a variety of different loading conditions and test maneuvers.

Tests were conducted with a 2006 Freightliner Century Class 6x4, a 2006 Volvo VNL64T630, and 1999 Fruehauf 53 ft. (16m) van trailer. Both of the 6x4 tractors were modified with an external roll bar for the driver's protection. The van trailer was modified to support outriggers and a load frame so that the trailer could be ballasted safely. These structures are included in the base weight and CG measurements for each vehicle. Table 1 describes the basic platform characteristics for each test vehicle:

Table 1. Base vehicle parameters.

	Freightliner	**Volvo**	**Fruehauf**
Configuration	6x4 Tractor	6x4 Tractor	53 ft' Van
Wheel Base	546 cm	536 cm	n/a
Base Weight	8,854 kg	8,763 kg	7,820 kg
Vertical CG	91 cm	100 cm	120 cm
Length	810 cm	803 cm	1,605 cm
Width	231 cm	234 cm	257 cm
Height	292 cm	381 cm	409 cm
Brake Type	Air Disc	S-Cam	S-Cam
Stability System	ESC	ESC	RSC

All tests were conducted with a tractor pulling the Fruehauf 53 ft. van trailer under three different loading conditions. These conditions included, a lightly loaded vehicle weight (LLVW), a low CG gross vehicle weight rating (GVWR), and a high CG GVWR. LLVW was defined as the base vehicle weight that included outriggers, roll bar, instrumentation, etc. without adding any ballast to the trailer. The low and high GVWR conditions were setup to achieve close to a 5,443 kg (12K lb) steer axle, 15,422 kg (34K lb) drive axle, and 15,422 kg (34K lb) trailer axle combined weight. The low CG condition was limited by placing blocks directly on the floor of the trailer while the high CG was created by raising the ballast.

Ballasting the trailer was accomplished by using cement blocks that were fastened by chains and binders to the floor of the trailer. Each cement block weighed approximately 1,900 kg, and was 61 cm x 61 cm x 183 cm. Blocks were placed directly over the kingpin and trailer axles to achieve desired axle weight ratings. To elevate the vertical CG of the trailer, loading tables that accept the cement blocks were used. The ballast blocks and tables can be used in various configurations to achieve different loading conditions. Table 2 documents the loading conditions used to perform this testing.

Tests were conducted on the vehicle dynamics area (VDA) at the Transportation Research Center, Inc. Although the coefficient of friction does change over time on the VDA, the average peak and slide coefficients of friction were measured at 0.97 and 0.86 for this time period.

Table 2. Trailer loading for different test conditions.

LLVW		Trailer Vertical CG = 154 cm from ground.	
	Steer (kg)	Drive (kg)	Trailer (kg)
Freightliner	4984	6586	5443
Volvo	5025	6309	5279
Low CG		Trailer Vertical CG = 152 cm from ground	
	Steer (kg)	Drive (kg)	Trailer (kg)
Freightliner	5316	15159	15295
Volvo	5384	15140	15299
High CG		Trailer Vertical CG = 219 cm from ground	
	Steer (kg)	Drive (kg)	Trailer (kg)
Freightliner	5302	15413	15345
Volvo	5307	15118	15404

For each vehicle and loading combination, three handling maneuvers were performed. The matrix displayed in Table 3 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.

Table 3. Test matrix conducted for each test maneuver.

	Speed (KM/H) at Critical Event					
	LLVW		**~GVWR**			
			Low CG		**High CG**	
	Trailer RSC		**Trailer RSC**		**Trailer RSC**	
	OFF	**ON**	**OFF**	**ON**	**OFF**	**ON**
Freightliner						
ESC OFF						
ESC ON						
Volvo						
ESC OFF						
ESC ON						

Based on the experience from previous NHTSA light vehicle research, several maneuvers were chosen to evaluate combination unit truck stability control performance on a high coefficient of friction surface [4]. These maneuvers included the following:

- Constant radius circle with increasing velocity
- J- turn with constant radius
- Double Lane Change Maneuver

Testing was conducted both clockwise and counter-clockwise for each maneuver. Very minor asymmetries were observed. For purposes of this paper, direction will not explicitly be discussed. Results will be combined showing both clockwise and counterclockwise maneuvers, unless otherwise noted.

Constant radius circles with increasing velocity tests were conducted on the 45 m and 61 m 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 5 cm off the ground (outriggers making contact with the test surface).

J-turn tests with a constant radius were conducted using a 45 m and 61 m radius located on the center of the VDA. For purposes of this paper, only the 45 m 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 32 km/h and were incremented by 3 km/h 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 80 km/h was achieved. 80 km/h was chosen for a maximum test entrance speed based on available test area and design of the safety support equipment (outriggers, roll bar, etc.)

Double lane change tests were performed on the VDA. Gates were setup 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 32 km/h and were incremented by 3 km/h 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 80 km/h was achieved.

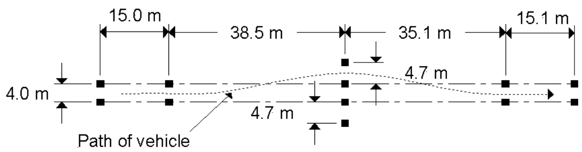

Figure 1. Double lane change maneuver.

MEASURES

Each tractor and the trailer were instrumented with a variety of sensors to measure the vehicles' dynamics and state of stability control system. Table 4 and 5 list the measures that were collected on the tractors and trailer respectively.

Table 4. Tractor based measures.

Measure	**Units**
Lateral Acceleration	G's
Longitudinal Acceleration	G's
Vertical Acceleration	G's
Yaw Angular Rate	Deg/sec
Roll Angular Rate	Deg/sec
Pitch Angular Rate	Deg/sec
Throttle Position	% displaced
Brake Treadle Switch	On/Off
Steering Wheel Angle	Deg.
Frame Rail Height @ approx long. CG	L/R cm
Rear Drive Axle Height	L/R cm
Brake Chamber Pressures (6)	kPa
Glad Hand Pressure	kPa
Wheel Speeds (6)	KM/H
Tractor Ground Speed	KM/H
J1939 VDC1 CAN MSG	RSC/ESC Status

Table 5. Trailer based measures.

Measure	**Units**
Lateral Acceleration	G's
Longitudinal Acceleration	G's
Yaw Angular Rate	Deg/sec
Roll Angular Rate	Deg/sec
Outrigger Height (Left and Right)	cm
Rear Trailer Axle Height (Left and Right)	cm
Brake Chamber Pressures (4)	kPa
Wheel Speeds (4)	KM/H

While most of the measures collected are self-explanatory, a short discussion about how wheel lift was calculated and how stability control activation was determined is described.

Rear drive axle height on the tractor and rear axle height on the trailer are both measured with sensors mounted on the left and right of the relevant axles. Data are processed and analyzed for determining if wheel lift has occurred. It should be noted for purposes of this study, wheel lift is considered to be greater than 5 cm. The value of 5 cm is used because it has been demonstrated that at this height, it can be visually confirmed.

The brake treadle switch, glad hand pressure, and brake chamber pressures were all measured to determine the source of brake activation. Under the given test protocol, the driver should not be braking during a maneuver. If this does occur the test is invalid. Monitoring the trailer brakes and glad hand pressure, confirms if the trailer RSC activated. If there was no glad hand pressure (trailer air brake command) and pressure was observed at the chambers, then Trailer RSC intervention was inferred. Tractor ESC braking was confirmed by observing pressures build in the tractor brake chambers while their treadle pressure was at zero. In cases where both the tractor and trailer based systems were enabled, the tractor system dominated the trailer system because it activated earlier and mitigated the instability before the trailer based system could activate. In the rare event that both systems engaged simultaneously, a difference between the glad hand pressure and trailer chamber pressures could be observed.

Using the SAE J1939 VDC1 CAN message available on both tractors, several status bits were observed to help determine the source of tractor stability activation. This message contains four bits that indicate the state of the stability system. These bits indicate if one of the following occurs:

- Engine torque reduction ESC
- Engine torque reduction RSC
- Brake activation ESC
- Brake activation RSC

RESULTS

Data from each test series was processed and analyzed. For purposes of this paper, results will be discussed in terms of the ground speed of the tractor at the start of the maneuver and the maximum lateral acceleration experienced at the CG of the tractor during the test maneuver. Results will also be discussed in terms of tests that resulted in trailer wheel lift greater than 5 cm and if the stability system activated during the maneuver.

Constant Radius Circle

Table 6 summarizes the results in terms of speed at the critical event during the maneuver. The speed was representative of all runs in a series including both left and right conditions. The critical event occurred when the stability system activated or for the case where stability control was disabled, the speed that wheel lift occurred. In some cases, the vehicle may not have had a critical event. The trailer RSC condition was tested with only the Volvo tractor.

Test results show that tractor ESC as well as trailer based RSC were capable of mitigating wheel lift in this maneuver. When any of the stability systems were enabled, wheel lift was no longer observed.

With ESC completely disabled, both the LLVW and low CG conditions resulted in the vehicles severely under-steering before wheel lift occurred. The speeds where 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.

Table 6. Constant Radius maneuver speed at critical event test results.

	Speed (km/h) at Critical Event					
	LLVW		~GVWR			
			Low CG		High CG	
	Trailer RSC		Trailer RSC		Trailer RSC	
	OFF	ON	OFF	ON	OFF	ON
Freightliner						
ESC OFF	64^	X	56^	X	47*	42
ESC ON	48	49	43	42	41	40
Volvo						
ESC OFF	65^	49	55^	48	46*	42
ESC ON	58	49	38	39	36	37

* - Denotes wheel lift.
^ - Denotes no critical event.
X - Denotes not tested.

The effects of stability control can be observed by comparing maximum lateral acceleration vs. speed for each load and stability condition. Maximum lateral acceleration (Ay) vs. critical event speed data for the constant radius test are displayed in Figures 2 and 3, 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.

All test runs with trailer wheel lift occurred without stability control active. No cases of wheel lift were observed under the LLVW or low CG condition. Under these load conditions, both tractors would understeer and did not reach a velocity much greater than 65 and 55 km/h 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 0.45G.

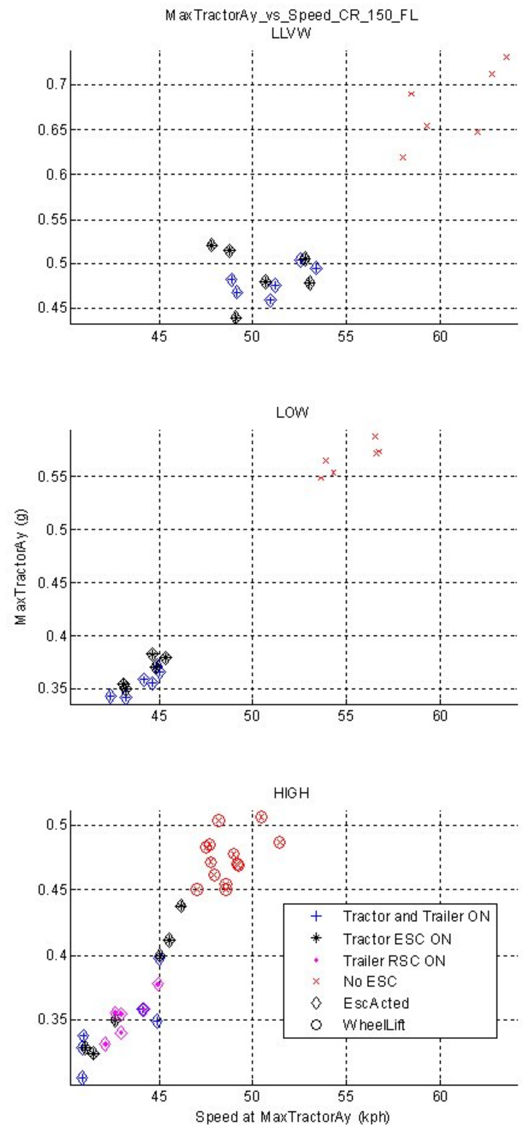

Figure 2. Freightliner maximum tractor Ay vs. speed during the 45 m constant radius test.

Truck tractor based stability control limited the maximum lateral acceleration of the tractor and prevented wheel lift for the different loads tested. Both tractors function in a similar manner, allowing higher maximum lateral accelerations for the LLVW as compared to the low and high CG conditions. There was little difference in peak lateral acceleration under the low and high CG conditions.

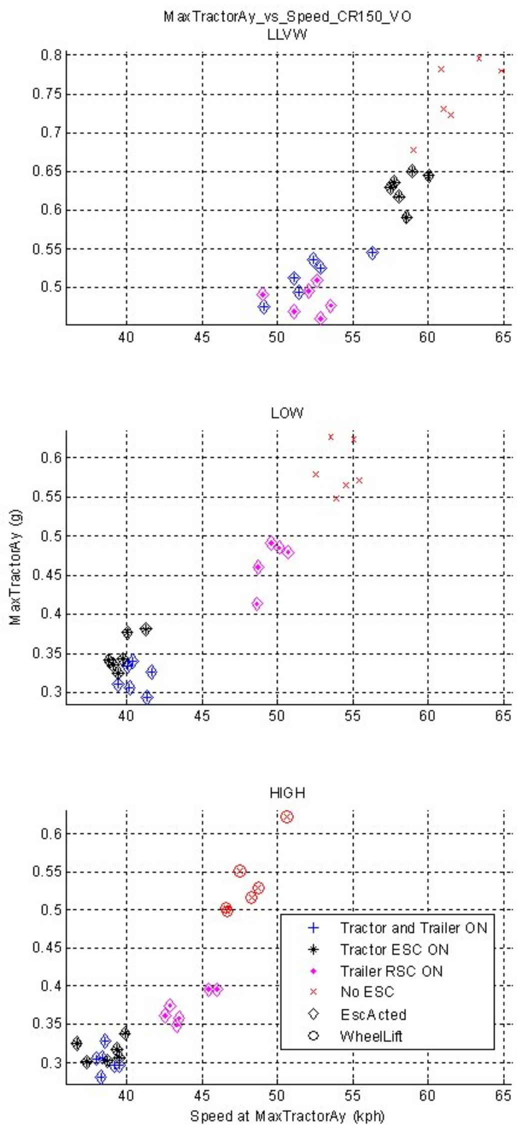

Figure 3. Volvo maximum tractor Ay vs. speed during the 45 m constant radius test.

Trailer based RSC was observed to limit maximum lateral acceleration and mitigate wheel lift with the different loads tested. 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 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. In comparison, the truck tractor based systems were observed to be more adaptive as the load increases.

45 m J-turn

Table 7 summarizes the test results for the 45 m J-turn maneuver in terms of maneuver entrance speed at which a critical event 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. The critical event occurred when the stability control system activates, or for the cases where stability control was disabled, the speed that wheel lift occurred. In some cases, the vehicle may not have encountered a critical event. The trailer RSC condition was tested with only the Volvo tractor.

For all tests with tractor based ESC, no cases of trailer wheel lift were observed for the J-turn maneuver. For both tractors in the low and high CG loading conditions, tractor based ESC intervened with braking at a speed well before the speed observed to produce trailer wheel lift. In the LLVW conditions the Freightliner's ESC system activated braking approximately 12 km/h sooner than the Volvo's.

Table 7. 45 m J-turn maneuver speed at critical event test results.

	Speed (km/h) at Critical Event					
	LLVW		~GVWR			
			Low CG		High CG	
	Trailer RSC		Trailer RSC		Trailer RSC	
	OFF	ON	OFF	ON	OFF	ON
Freightliner						
ESC OFF	81^	X	61*	X	49*	X
ESC ON	49	49	44	43	44	43
Volvo						
ESC OFF	77*	60	60*	45	50*	45
ESC ON	61	60	40	40	40	40

* - Denotes wheel lift.
^ - Denotes no critical event.
X – Denotes not tested.

Trailer based RSC was also observed to improve the base combination vehicle's roll propensity. From Table 7, the trailer system was observed to activate at similar speeds as the tractor based system for the LLVW load condition. When the Low and High CG load conditions were tested at GVWR the tractor based system was observed to activate at approximately 5 km/h sooner. For this maneuver, when both systems were enabled, the tractor based system was observed to dominate the trailer system.

The effects of stability control can be observed by comparing maximum Ay vs. maneuver entrance speed for each load and stability condition. This data for the J-turn maneuver are displayed in Figures 4 and 5 for the Freightliner and Volvo. As previously mentioned each subplot represents one of the three loading conditions, they are labeled LLVW, Low and High.

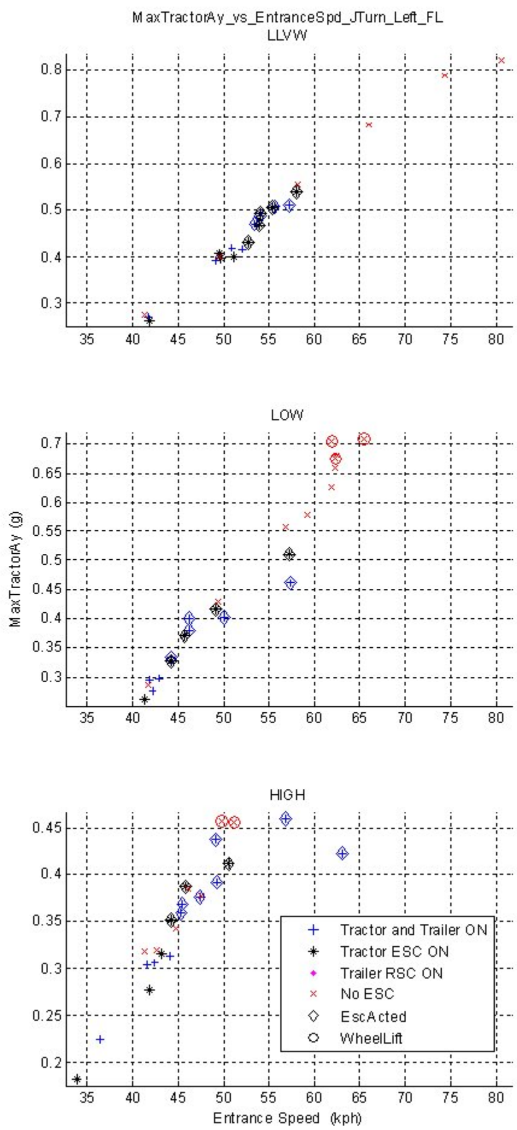

Figure 4. Freightliner maximum tractor Ay vs. speed during the J-turn drop throttle maneuver.

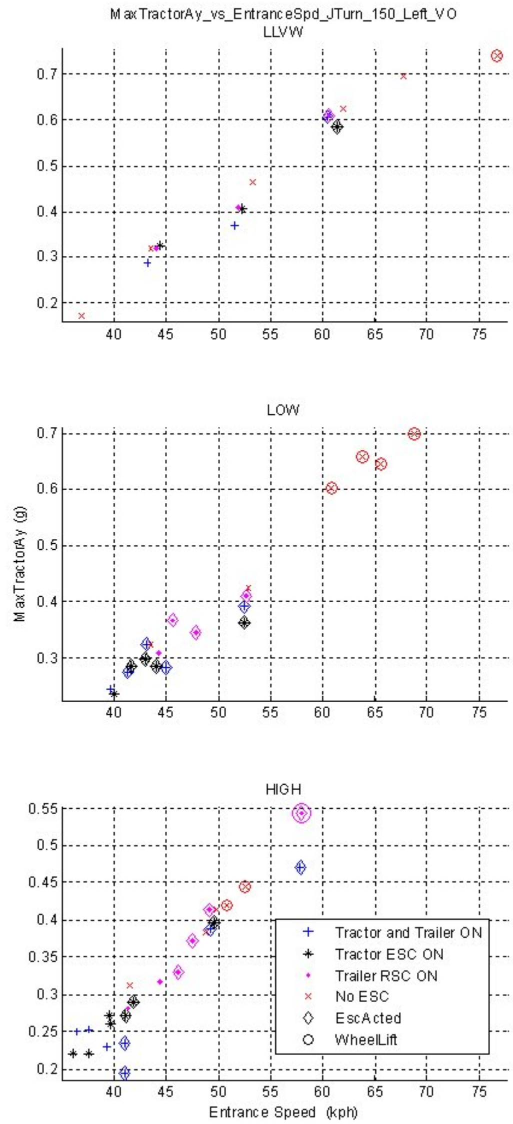

Figure 5. Volvo maximum tractor Ay vs. speed during the J-turn drop throttle maneuver.

For both 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 loaded in the LLVW load condition tractor maximum lateral accelerations were limited to approximately 0.6 G in the Freightliner and the Volvo did not appear to be limited. When loaded in the Low or High CG condition, tractor lateral accelerations were limited to 0.5 and 0.4 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 57 km/h. Though wheel lift was observed at speeds above 57 km/h 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 50-53 km/h.

Double Lane Change (DLC)

Table 8 summarizes the results in terms of maneuver entrance speed at which a critical event was observed during the DLC maneuver. The critical event was when the stability control system activated or for the cases where stability control was disabled, the speed that wheel lift occurred. In several cases both critical events were observed, and in such cases both speeds are reported. 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 80 km/h. Only results for only the High CG condition are reported.

As shown in Table 8, 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 systems disabled, instances of wheel lift were observed at 66 KM/H with the Freightliner and 73 KM/H with the Volvo.

When 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 49 and 53 KM/H for the Freightliner and Volvo. Then wheel lift was observed at maneuver entrance speeds of 66 and 80 KM/H 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 8, the Freightliner's stability control system activated at 45 KM/H and then was overdriven at 82 KM/H (trailer wheel lift observed.) The Volvo's stability control system activated at 45 KM/H with no instances of trailer wheel lift at the subsequent higher test speeds.

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 52 KM/H and then was overdriven at 82 KM/H (trailer wheel lift observed.) Stability control activation was observed at 46 KM/H with the Volvo. Trailer wheel lift was not observed for the range of speeds evaluated in this combination and maneuver.

Table 8. DLC maneuver speed at critical event test results.

	Entrance Speed (KM/H) at Critical Event	
	~GVWR High CG	
	Trailer RSC	
	OFF	ON
Freightliner		
ESC OFF	66*	49 66*
ESC ON	45 82*	52 82*
Volvo		
ESC OFF	73*	53 80*
ESC ON	45	46

* - Denotes wheel lift.

When the truck tractor based ESC systems were active, instances of wheel lift were no longer observed for test speeds less than 80 KM/H. The minimum speed observed to activate the truck tractor systems in the DLC maneuver was 45 KM/H for both truck tractor systems. The truck stability systems were observed to be activating at speeds 4 to 8 KM/H lower than the trailer based stability control system.

The effects of stability control can be observed by comparing maximum truck tractor lateral acceleration (Ay) vs. maneuver entrance speed for each testing condition. These data for the DLC maneuver are displayed in Figures 6 and 7 for the Freightliner and Volvo.

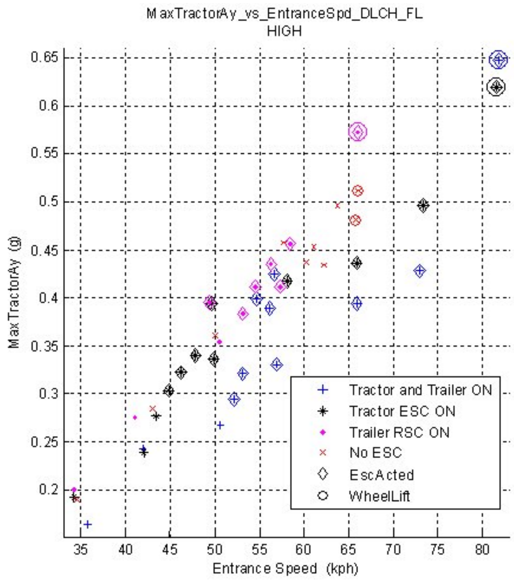

Figure 6. Freightliner maximum tractor Ay vs. speed during the DLC maneuver.

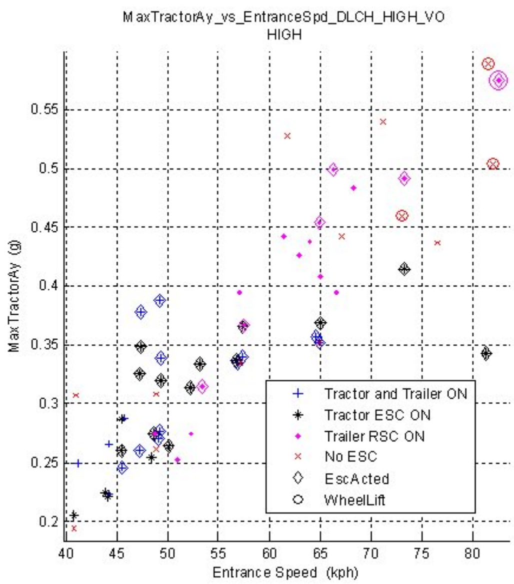

Figure 7. Volvo maximum tractor Ay vs. speed during the DLC maneuver.

As shown in Figure 6, the stability control activation in the Freightliner was first observed for a DLC maneuver that produced a maximum lateral acceleration of 0.3 G. The figure shows that when the systems were disabled wheel lift was not observed until a maximum tractor lateral acceleration of 0.45 G. The Freightliner's stability control system was observed to limit peak lateral acceleration to approximately 0.50 G, which, mitigated wheel lift at the trailer for tests performed under 80 km/h. Tests performed at speeds greater than 80 km/h resulted in maximum lateral accelerations that exceeded 0.6 G. Then trailer wheel lift was observed regardless of interventions by the tractors stability control system.

Figure 7 shows that the stability control system in the Volvo activated in a DLC maneuver at a tractor maximum lateral acceleration of 0.22 G. The Volvo's stability control system was then observed to limit tractor maximum lateral acceleration to approximately 0.40 G and mitigate wheel lift for all speeds evaluated in the DLC maneuver. When stability control systems were disabled with the Volvo, trailer wheel lift was observed when tractor maximum lateral acceleration reached 0.41 G.

For test series completed with only the trailer's stability control system enabled, the trailer system was observed to activate when maximum tractor lateral acceleration reached 0.38 G with the Freightliner (Figure 6) and 0.28 G with the Volvo (Figure 7). Trailer wheel lift was observed when a maximum tractor lateral acceleration of 0.57 G was reached with the Freightliner and 0.47 G with the Volvo. When all systems were disabled trailer wheel lift was observed at 0.45 G with the Freightliner and 0.41 G with the Volvo.

Maximum lateral acceleration from test series conducted with both tractor and trailer stability control systems enabled were similar to those test series conducted with the tractor stability control system enabled. For the Freightliner, activation was observed when the maximum tractor lateral acceleration first reached 0.3 G (tractor stability system enabled activated when maximum lateral acceleration reached 0.3 G). For the Volvo combination, activation was observed when the maximum tractor lateral acceleration first reached 0.20 G (tractor stability system enabled activated when maximum lateral acceleration reached 0.22 G)

Discussion

For both tractor based stability systems, changes in the tractor lateral acceleration when the stability systems activated were observed between the LLVW and GVWR 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 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 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 80 km/h 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. 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 80 km/h 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 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 successfully 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 successfully.

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.

Conclusions

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 a suitable to evaluate tractor and trailer stability control systems. However, further study of this type of maneuver is necessary to understand how stability control technology and other factors influence the dynamic response of heavy vehicles.

References

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