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Class 8 Truck Tractor Braking Performance Improvement Study

Low Coefficient of Friction Performance and Stability Plus Parking Brake Evaluations of Four Foundation Brake Configurations

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16. Abstract

Four configurations of pneumatic foundation brakes were evaluated and compared for wet brake-in-curve and wet split-coefficient braking performance on two Class-8 6x4 truck tractors. Parking brake performance was also evaluated. Tested at two load conditions, LLVW (bobtail) and GVWR, the brake configurations included:

a. Standard S-Cam drums on steer and drive axles
b. Hybrid drum: larger capacity S-Cam drums on steer, standard S-Cam drums on drive axles
c. Hybrid disc: air disc brakes on steer, standard S-Cam drums on drive axles
d. Air disc brakes on steer and drive axles

Wet braking stability was evaluated as per FMVSS No. 121 guidelines; entry speeds were then increased to evaluate the trucks' maximum brake-in-curve speed under each load-brake condition. Test results indicated a slightly reduced margin of compliance in brake-in-curve performance for the hybrid drum and hybrid disc configurations.

The truck-brake configurations were also evaluated for stopping performance and stability on a straight, wet split-coefficient surface. The air disc brake configuration showed better performance in this test over the other configurations for stopping efficiency. Since the brake systems were not torque limited on this surface, these findings indicate that air disc brakes may have inherent advantages in operating efficiency, compared to S-Cam drum brakes.

The S-Cam and air disc drive axle brakes were evaluated for parking brake effectiveness, as per the FMVSS No. 121 grade holding test and drawbar procedures, and using the SAE drawbar procedure. At LLVW on a 20% grade, all brake configurations evaluated generally proved capable of holding the grade. At GVWR, all brake configurations evaluated on a single drive axle failed to hold the grade. All tractor-brake configurations passed the drawbar tests with acceptable margins. Peak forces were higher for the air disc brakes than for the S-Cam brakes.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (°F - 32)	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (°C) + 32°F	Fahrenheit	°F

DISCLAIMER

NOTE REGARDING COMPLIANCE WITH AMERICANS WITH DISABILITIES ACT SECTION 508

For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided for graphical images contained in this report to satisfy Section 508 of the Americans With Disabilities Act (ADA).

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EXECUTIVE SUMMARY

This report covers an extensive comparison of foundation brake types and their effects on low speed wet braking and stability performance of two Class-8 (having a GVWR greater than 33,000 lbs.) truck tractors. The testing and this report support a rulemaking effort to reduce stopping distances for heavy truck tractors.

Different foundation brake configurations were field retrofitted to each of two truck tractors' existing pneumatic actuation and control systems. The tractors' control, actuation, and ABS (antilock brake control) systems were not optimized for each brake configuration. The brake configurations included:

a) **Standard S-Cam** drums on all steer and drive axles
b) **Hybrid drum**: larger capacity S-Cam drums on steer, standard S-Cam drums on drive axles
c) **Hybrid disc**: air disc brakes on steer, standard S-Cam drums on drive axles
d) **Air disc** brakes on all steer and drive axles.

For the wet surface stopping performance and stability, both tractors (1996 Peterbilt 377 and a 1991 Volvo WIA64T) were tested bobtail (lightly loaded vehicle weight – LLVW) and at tractor gross vehicle weight rating (GVWR, plus the 4,500-lb axle weight of the unbraked control trailer).

Wet braking stability was tested as per FMVSS No. 121 guidelines (§571.121, S. 5.3.6). That test was expanded to evaluate the trucks' maximum brake-in-curve speed under each load-brake condition. The results of the brake-in-curve stability testing indicated a smaller margin of compliance in brake-in-curve performance for both the hybrid drum and hybrid disc configurations. Aside from the fact that these brake configurations were field-installed retrofits, the authors cannot at this time identify the reason why the hybrid brake configurations performed slightly less effectively than the other two configurations.

The truck-brake configurations were also evaluated for stopping performance and stability on a straight, wet laterally split-μ (i.e., split coefficient of friction) surface. Several analyses led to the conclusion that the air disc brakes had a performance advantage over the other foundation brake configurations for stopping efficiency on the split-μ surface. Since none of the air brake systems were torque limited on this surface, these findings would indicate that the air disc brake configuration has inherent advantages in operating efficiency, as compared to the S-Cam drum brakes. All indications are that the foundation brake configuration had little effect on vehicle stability while making the straight-ahead stops on the wetted split-μ surfaces.

Finally, both foundation brake types used on the drive axles of the truck tractors tested were evaluated for parking brake effectiveness, under the FMVSS No. 121 grade holding test (using a 20% grade) and the FMVSS drawbar pull procedure (FMVSS No. 121, Section 5.6 and No. 121-V test procedure , Section 10.3). The brake configurations (S-Cam and air disc) were also tested as per the SAE J1626 drawbar procedure, which allows the parking brakes to be set while full-treadle braking pressure is applied – a technique of setting the parking brake which is not allowed under current FMVSS No. 121 guidelines.

For the grade holding tests at the LLVW load condition, all brake configurations evaluated proved capable of holding the grade if the tires had sufficient normal force. At the GVWR load condition (50,000 pounds plus the unbraked control trailer), all brake configurations evaluated on a single drive axle failed to hold the grade. The only configuration which held at GVWR was an all S-Cam foundation brake configuration on one tractor, which had parking brakes on both drive axles (as received by VRTC) instead of on only the intermediate drive axle, as did all other configurations. All tractor-brake configurations passed the FMVSS No. 121 drawbar tests with acceptable margins over the ratio of 0.14 of peak drawbar force / tractor GVWR, required by the FMVSS procedure; drawbar forces were higher for the air-disc parking brakes. The drawbar peak forces were generally higher using the SAE procedure.

1 BACKGROUND AND PURPOSE

This report is part of a series that covers extensive testing of various truck tractor foundation brake systems in support of rulemaking by the National Highway Traffic Safety Administration (NHTSA). A full discussion of the background and purpose for this testing can be found in [1].

2 TEST VEHICLES AND METHODOLOGY

2.1 Description of Test Vehicles and Test Brake Configurations

Two conventional truck tractors were each evaluated with four different foundation brake configurations. Both vehicles used pneumatically controlled and actuated brake systems for all testing. One vehicle was a 1991 Volvo WIA64T 6x4 (referred to as “Volvo” in this report) which has been used extensively at the NHTSA Vehicle Research and Test Center (VRTC) for heavy truck dynamics and stability testing. The other vehicle was a 1996 Peterbilt Model 377 6x4 (referred to as “Peterbilt” in this report), leased to VRTC by Dana Corporation. A full description of the two truck tractors used, and the foundation brake configurations evaluated on them, can be found in [1].

The truck tractors modified for this study used foundation brake configurations that were experimental in nature and intended to quantify the potential improvements in stopping performance that might be expected from various brake configurations. When tested with modified foundation brake systems, the performance of these vehicles is not necessarily representative of similarly configured production vehicles. Therefore, while truck manufacturers’ names are used in this report to identify the vehicles and avoid reader confusion, and test results should in no way be construed as criticism or endorsement of those vehicles.

2.2 Test Methodology and Driver Instructions

Three general test procedures were applied – two followed FMVSS No. 121 specifications (low coefficient stability and parking brake tests). The third procedure compared the brake types for straight-line braking performance and stability on a laterally split coefficient of friction surface.

2.2.1 Brake-in-Curve Stability Testing

The foundation brake types were compared for performance as per the brake-in-curve stopping stability procedures outlined in Section 5.3.6 of FMVSS No. 121 [2], and in Section 10.3-D of the FMVSS No. 121 Laboratory Test Procedures [3].

Following completion of the brake-in-curve stability procedure as prescribed by FMVSS No. 121, the brake-in-curve stability evaluation was expanded to find the limit initial (i.e., curve entry) speed at which the vehicle could physically remain within the 12-ft. lane (3.66 m) while braking in the curve. To determine that limit, the maneuver initial speed was increased by 1 mph (1.6 kph) increments above the terminal speed determined during the FMVSS No. 121 brake-in-curve stability testing, up to the speed at which the vehicle repeatably slid out of the lane during the brake-in-curve maneuver. Initial braking speed and stopping distance were recorded by the driver for all tests. The approximate location and number of lane-marking traffic pylons hit by the vehicle were recorded by trackside observers and stationary video equipment. An on-board data acquisition system recorded vehicle dynamic behavior, brake pressures and temperatures, driver steering and braking inputs, and other information as required by the test engineers.

The full-treadle braking tests discussed were performed on a wetted Jennite surface at the Transportation Research Center Inc. A single 12-ft. (3.66 m) wide lane was marked with pylons on a 500-ft. radius curve. The nominal peak friction coefficient of the surface was 0.30, however measured values averaged around 0.38 (slide traction was not monitored on the surface during this testing). The test surface was wetted within one minute before each braking run by a water spreading vehicle. Initial Brake pad and/or lining Temperature (I.B.T.) was nominally 150-200 °F (65.5-93.3 °C) before initiating each braking run. Inner and outer (disc) brake pad and leading and trailing (drum) brake lining temperatures were monitored as outlined in Section 10.3-D of the FMVSS No. 121 test procedure [3].

The professional test driver was instructed to establish the test speed after the initial brake temperature was reached, while approaching the wetted brake surface on a constant radius curve. Upon reaching a traffic pylon positioned such that the entire vehicle would be on the wetted test surface at brake initiation, the driver would attempt to maintain lane position with the vehicle centered in the 12-ft. (3.66 m) lane, while fully opening the brake treadle foot valve within 0.2 seconds, as outlined in the FMVSS No. 121 test procedure. The brakes remained fully applied until the vehicle came to rest unless the driver noticed an extended full brake lockup, which might indicate an ABS problem and could result in tire damage or loss of control. The location of each stop in a given series was kept consistent.

The stopping distances were measured with a 5th wheel assembly, mounted on the rearmost part of the tractor frame (LLVW) or under the front midsection of the unbraked control trailer (GVWR condition). Stopping distances were recorded from a Labeco Tracktest Fifth Wheel System Performance Monitor, which displays initial speed and integrated stopping distance. Stopping distances were corrected for initial braking speed for the 75% target speed (compliance) tests, but not for the elevated speed (limit) tests.

2.2.2 Straight-line Stopping on Wet Split-Coefficient Surface

These full-treadle application braking tests were performed on a wetted laterally split-μ (i.e., split-coefficient of friction) surface at the Transportation Research Center Inc. The wetted test surface consists of one half lane of untreated asphalt and the other half lane of Jennite. The nominal peak and slide friction coefficients of the surfaces were 0.30 (peak)

/ 0.10 (slide) for the wet Jennite and 0.85 / 0.65 for the wet untreated asphalt. Measured values for the same surfaces were generally near 0.35 / 0.10 for the wet Jennite and 0.86 / 0.60 for the wet untreated asphalt. Initial Brake pad and/or lining Temperature (I.B.T.) was nominally 150-200 °F (65.5-93.3 °C) before initiating each braking run. Brake pad temperatures were monitored as outlined in the FMVSS No. 121 test procedure [3].

For test efficiency, a stop from an initial speed of 30 mph (48.2 kph) was made in one direction (east-to-west), then the opposite direction (west-to-east) after turnaround. Nominally six stops were performed at each test condition, three in each direction.

The test driver was instructed to establish the test speed after the brake temperature was within the required limits, while approaching the wetted brake surface on a straight-ahead approach. Upon reaching a traffic pylon positioned such that the entire vehicle would be on the wetted surface at brake initiation, the driver would attempt to maintain lane position while fully opening the brake treadle foot valve within 0.2 seconds. Steering input was permitted as required to keep the vehicle path centered along the division between the two surfaces of the split-μ section. The treadle foot valve (brake pedal) remained fully applied until the vehicle came to rest unless the driver noticed an extended full brake lockup, which might indicate an ABS problem and could result in tire damage or loss of control. The location of each stop in a given series was kept consistent.

Stopping distances and on-board vehicle data were recorded as discussed in the previous section. All measured stopping distances were corrected via the standard method as prescribed by SAE J299 [4] to be normalized to the intended initial speed.

2.2.3 Parking Brake Effectiveness Testing

The foundation brake types were compared for static retardation force and grade holding ability as per the procedures outlined in Section 5.6 of FMVSS No. 121 [2], and in Sections 10.3-G, H, & I of the FMVSS No. 121 Laboratory Test Procedures [3], with the following exceptions or additions:

a) Static retardation tests were performed at gross vehicle weight rating (GVWR) only on a Hunter Plate Brake Tester [5], and the maximum vertical and horizontal forces from the brake tester were recorded.

b) A series of four static retardation tests were performed with the parking brake applied with no service brake pressure (as per FMVSS No. 121 guidelines), then repeated with the parking brake being applied while the service brakes are at full-treadle application, as per the SAE J1626 procedure [6].

c) Four static retardation tests were performed per braked axle, per direction, per initial service brake application mode.

d) During the static retardation tests, the following were recorded with a digital data acquisition system: drawbar tension (via 25,000-lb. load cell), the distance the vehicle moved, parking brake chamber pressure, primary and secondary treadle pressures, brake reservoir pressures, and brake temperatures. The highest forces for each of the four 90 degree pulls were recorded on a data sheet. The maximum of all four pulls was recorded as the maximum parking brake force for that given direction.

e) Grade holding tests were performed at lightly loaded vehicle weight (LLVW) and GVWR load conditions.

3 RESULTS AND ANALYSES

3.1 Wet Brake-in-Curve Stability as per FMVSS No. 121

Table 1 shows the results for the FMVSS No. 121 stability testing to compare the four foundation brake configurations on both test tractors in the LLVW load condition. The term "Drive-Through Speed" refers to the maximum speed at which the curve could be negotiated with no braking – without departing the 12-ft lane – under that condition. To achieve a "passing" grade, the truck must remain within the lane during a full-treadle brake-in-curve maneuver, for 3 out of 4 consecutive attempts. The initial braking speed was established as 75% of the maximum drive-through speed that could be repeatably attained. The measured peak surface coefficient (as per ASTM Method E1337-90) that most closely corresponds to the actual test date is included for reference as the "Measured Peak Skid Number." The measured peak skid numbers are presented as percentages, not coefficients (i.e., 42 instead of 0.42).

Table 1: FMVSS No. 121 Stability and Control Test results for both truck tractors at LLVW

Tractor	Brake Configuration	Drive-Through Speed (mph)	Target Speed @ 75% Drive-Through (mph)	No. of Stops Passed	Measured Peak Skid Number
Peterbilt	All S-Cam	33	25	4	42
	Hybrid drum	37	28	4	45
	Hybrid disc	36	27	4	45
	All Disc	33	25	4	34
Volvo	All S-Cam	31	23	4	30
	Hybrid drum	32	24	3	32
	Hybrid disc	33	25	3	34
	All Disc	34	26	4	37

All foundation brake configurations passed the qualification procedure. Although the significance cannot be determined with the given information, brake-in-curve stability for the Volvo tractor may have suffered slightly when outfitted with the "hybrid drum" and "hybrid disc" configurations – as compared to either the "all S-Cam" or "all-disc" foundation brake configurations. The fact that both hybrid brake configurations, on the Volvo tractor at LLVW, passed only 3 out of the 4 trials suggests those configurations had a detrimental effect on brake-in-curve performance for that tractor, versus the "all-S-Cam" or "all-disc" brake configurations.

Table 2 shows the FMVSS No. 121 brake-in-curve stability results in the GVWR load condition. As with the LLVW condition, all brake configurations for both trucks passed the qualification test. Note, however, that the "hybrid disc" configurations on both trucks only passed the minimum required 3 out of 4 trials.

Table 2: FMVSS No. 121 Stability and Control Test results for both truck tractors at GVWR

Tractor	Brake Configuration	Drive-Through Speed (mph)	Target Speed @ 75% Drive-Through (mph)	No. of Stops Passed	Measured Peak Skid Number
Peterbilt	All S-Cam	33	25	4	37
	Hybrid drum	35	26	4	44
	Hybrid disc	39	29	3	46
	All Disc	33	25	4	36
Volvo	All S-Cam	30	23	4	30
	Hybrid drum	31	23	4	32
	Hybrid disc	33	25	3	32
	All Disc	34	26	4	38

3.1.1 Wet Brake-in-Curve Stability – Beyond FMVSS No. 121

After qualifying each tractor-brake configuration for the pass/fail brake-in-curve criteria specified in FMVSS No. 121, the test series was continued for each condition by increasing the entry speed into the brake-in-curve maneuver by 1-mph increments to determine the highest maneuver execution speed for which the vehicle could maintain position within the 12-ft. (3.66 m) lane while braking at full treadle. Table 3 shows the results for that testing and a ratio of the limit braking speed to the limit drive-through speed. Peak surface coefficient measurements (as per ASTM Method E1337-90) are given in the last column to aid in comparison of the data. Peak measurements only were taken because the surface – along a 500-ft. (152.4 m) radius of curvature – cannot be tested for longitudinal peak and slide during a single traction test sequence.

Due to the time required to change vehicle brake systems, this test series took well over a year to complete. Hence, the surface coefficient evolved significantly during the course of the testing. This evolution was further complicated by an unavoidable resurfacing that took place before the testing was complete. If the data were collected in a way such that multiple runs (repeats) existed, then statistical methods that took the measured skid numbers into account as covariates could have been employed. However, the test could not be efficiently structured to include repeats of the same condition.

As another way to normalize the vehicles' limit performance for comparison, the vehicle limit performance is expressed as a "lateral acceleration performance quotient" (referred to as "LAPQ"). LAPQ is expressed as the ratio of the maximum attainable lateral acceleration (as calculated by curve radius and entry speed) during the brake-in-curve maneuver to the maximum drive-through lateral acceleration (with no braking). Rationalizing the performance in this way normalizes the limit brake-in-curve speed as a function of the limit drive-through speed. Since both evaluations were performed on the same test day, the effect of the surface traction coefficient is largely mitigated. The performance quotient was calculated as shown in equation (1).

$$LAPQ = \frac{V_{limit}^2}{V_{drive-through}^2} \times 100 \qquad (1)$$

where:

V_{limit} = limit speed attainable for brake-in-curve maneuver

$V_{drive-through}$ = limit speed attainable during drive-through

Table 3: Wet Brake-in-Curve limit stability results

Load Condition	Tractor	Brake Type	Drive-Through Speed (mph)	Limit BIC Speed (mph)	Speed Ratio (%)	LAPQ (%)	Peak Skid Number
LLVW	Peterbilt	All S-Cam	33	34	103	106	42
		Hybrid	37	34	92	84	45
		Hybrid disc	36	31	86	74	45
		All Disc	33	33	100	100	34
	Volvo	All S-Cam	31	25	81	65	30
		Hybrid	32	26	81	66	32
		Hybrid disc	33	25	76	57	34
		All Disc	34	31	91	83	37
GVWR	Peterbilt	All S-Cam	33	34	103	106	37
		Hybrid	35	35	100	100	44
		Hybrid disc	39	32	82	67	46
		All Disc	33	29	88	77	36
	Volvo	All S-Cam	30	28	93	87	30
		Hybrid	31	24	77	60	32
		Hybrid disc	33	28	85	72	32
		All Disc	34	34	100	100	38

Figure 1 graphically presents the brake-in-curve limit test performance quotients computed at the LLVW condition and presented in Table 3. In Figure 1, the “hybrid disc” foundation brake configuration had the lowest quotient (versus the other three brake configurations) as tested on both tractors. Furthermore, there does not appear to be a direct correlation with the ranking of the limit brake-in-curve performance and the measured peak skid numbers. This result corroborates the findings for the FMVSS No. 121 “brake-in-curve stability” results at the LLVW condition, discussed in the previous section.

Figure 2 shows the limit test performance quotients for the GVWR condition presented in Table 3. Similar to the LLVW comparisons, one might conclude that there was a slight disadvantage for the “hybrid disc” configuration on the Peterbilt tractor and for both hybrid brake configurations (“hybrid drum” and “hybrid disc”) on the Volvo. The reader is reminded that although all four configurations passed the FMVSS No. 121 “brake-in-curve” ABS certification procedures, the “hybrid disc” configurations stood out on both tractors as they passed only 3 out of the 4 compliance runs (which is sufficient to pass the test). Although we can speculate that this difference might be due to the fact that the hybrid brake configurations may not have been as optimally tuned as the “all S-Cam” or “all disc” configurations, only further extensive testing will prove if a) an actual difference does exist, b) if so, to what extent, and c) what precisely is causing the difference?

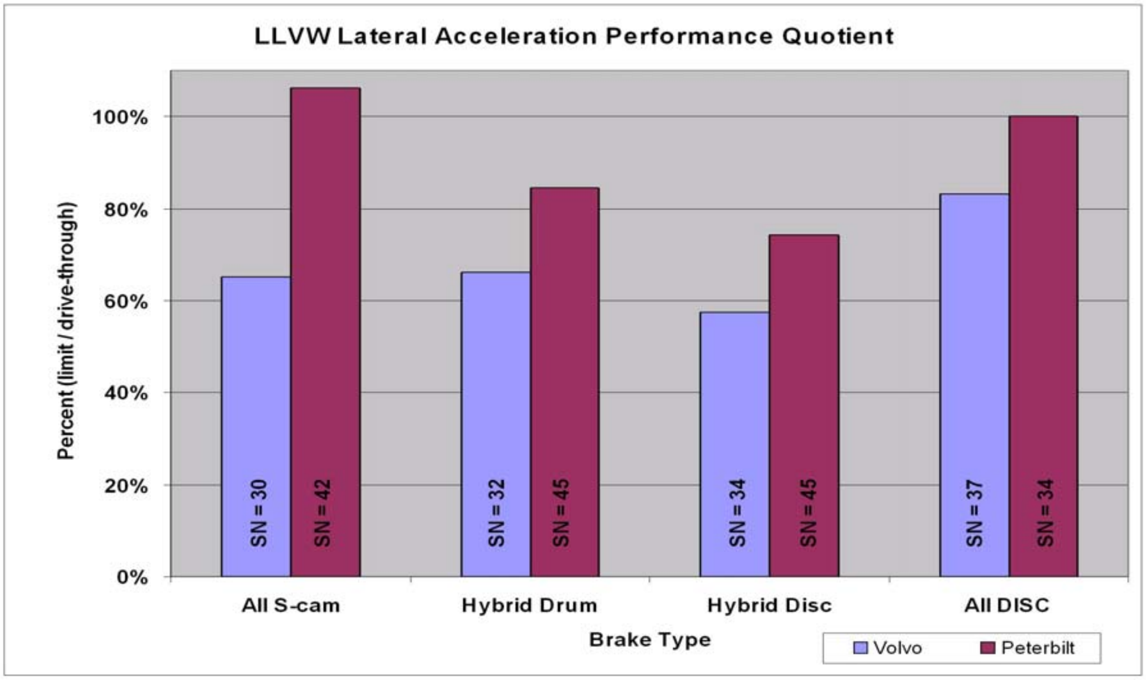

Figure 1: Lateral Acceleration Performance Quotients for both truck tractors at the LLVW load condition. Peak skid numbers corresponding to the surface at the time of each test series are presented within each histobar.

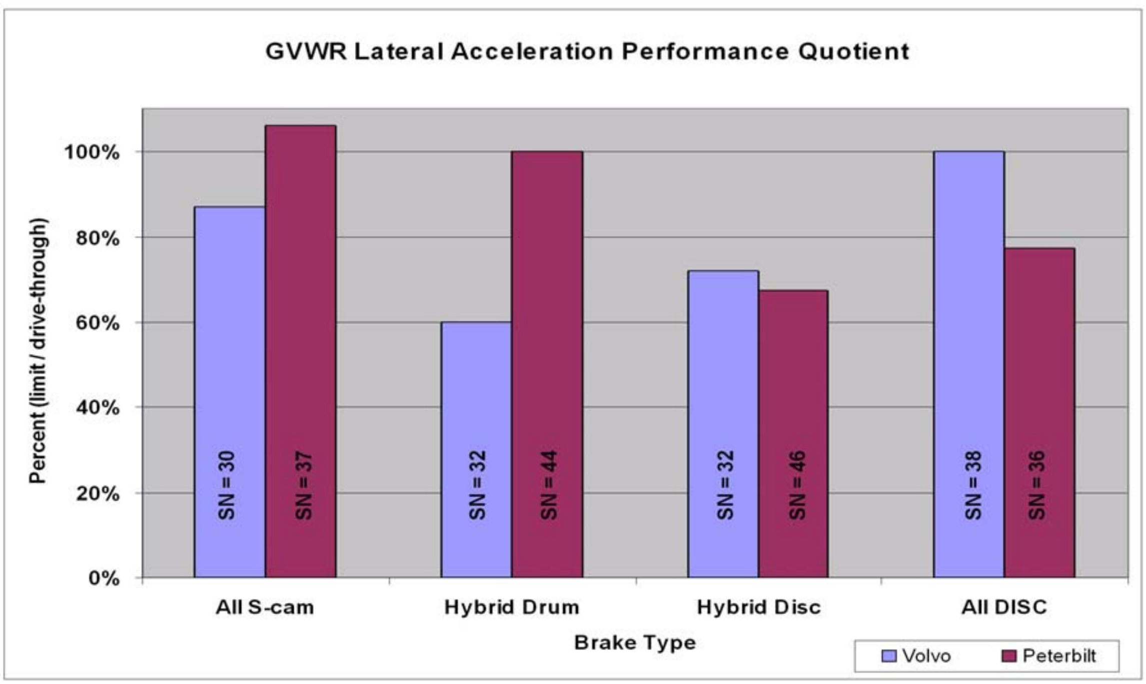

Figure 2: Lateral Acceleration Performance Quotients for both truck tractors at the GVWR load condition. Peak skid numbers corresponding to the surface at the time of each test series are presented within each histobar.

3.2 Wet Split-Coefficient Surface Stopping Distances and Stability

All truck-brake configurations were evaluated for their performance while stopping the truck tractors on a wetted split-μ (i.e., split coefficient) surface. All stops were performed straight-ahead, nominally from 30 mph (48.3 kph). The test data are presented in the following sections.

3.2.1 Stopping Distance Results: Tractor Means Combined

Stopping distances on the wetted split-μ surface were initially analyzed using the collective results for both tractors. Although these analyses could potentially introduce more “noise” into the analysis (due to combining the results from both tractors), it does have the advantage of giving a more representative comparison of foundation brake effects on a large and varied fleet of 6x4 tractors having otherwise different layouts, in terms of suspension design, wheelbase, ABS controls, and other important factors.

Table 4 contains some simple stopping distance statistics for the stopping distances of the two truck tractors combined, at the LLVW load condition. The standard deviation for the combined data at LLVW for the “hybrid drum” brake configuration is large due to the Peterbilt data, discussed in the following section. Table 5 compares foundation brake types tested at the GVWR load condition.

Figures 3 and 4 illustrate the results presented in Tables 4 and 5. When the data for both tractors are combined, the “all disc” brake configuration appears to have a slight advantage over the other three configurations at both LLVW and GVWR loads. Also at both loads, the other brake configurations appear to be statistically similar when compared using 95% confidence limits. More rigorous statistical analyses are presented in the following sections.

The authors note here that all of the brake configurations – at any load condition up to and including GVWR – were capable of locking the brakes on any axle at any time during these stops. Therefore, the apparent advantage in stopping ability on a low-µ surface for the “all disc” configurations should be attributed to efficiencies in their operation, which are beyond their ultimate torque capacity. This topic is covered and simulation comparisons are discussed at length in [7].

Table 4 **Combined wet split-µ stopping distances at LLVW for each brake type showing the mean, minimum, maximum, and standard deviation for 12 stops (6 per each truck tractor). Data from the Peterbilt and Volvo Tractors have been combined.**

Foundation Brake Type	Mean (ft.)	Minimum (ft.)	Maximum (ft.)	Standard Deviation (ft.)
All S-Cam Drums	106.1	99.7	114.1	5.0
Hybrid Drums	107.6	89.5	123.3	12.8
Hybrid Disc	104.4	100.2	112.4	3.6
All Disc	97.0	90.9	102.6	3.8

Table 5 **Combined wet split-µ stopping distances at GVWR for each brake type showing the mean, minimum, maximum, and standard deviation for 12 stops (6 per each truck tractor). Data from the Peterbilt and Volvo Tractors have been combined.**

Foundation Brake Type	Mean (ft.)	Minimum (ft.)	Maximum (ft.)	Standard Deviation (ft.)
All S-Cam Drums	99.4	87.1	107.0	6.7
Hybrid Drums	102.0	93.0	110.0	5.6
Hybrid Disc	102.1	98.8	105.6	2.0
All Disc	93.5	89.8	98.1	2.5

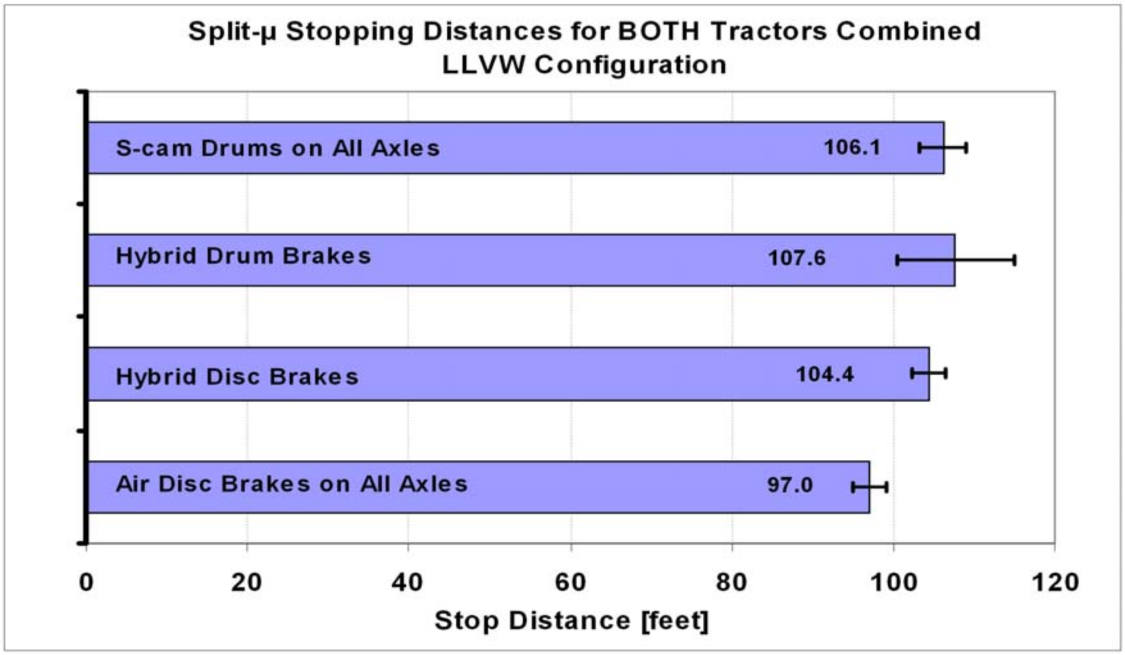

Figure 3: **Split-µ stopping distances for both tractors (Peterbilt and Volvo) combined, at the LLVW (bobtail) load condition. Histobars show the mean of twelve stops – the numeric value of the mean (in ft.) is printed near the end of each histobar. Variance bars show the upper and lower 95% confidence intervals about the means.**

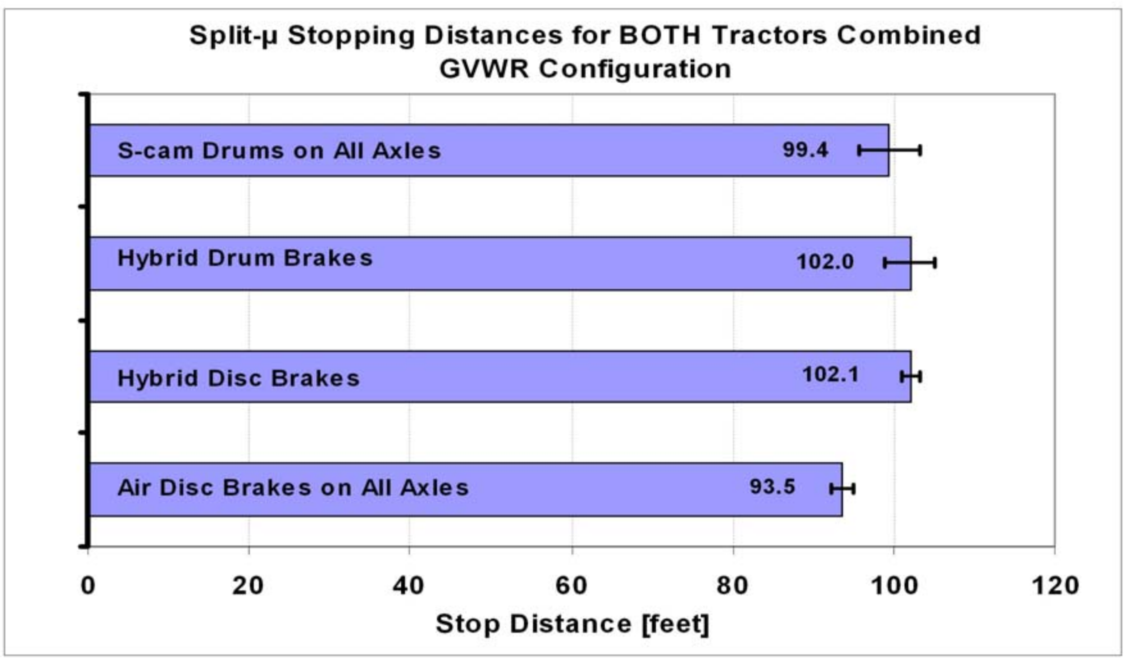

Figure 4: **Split-µ stopping distances for both tractors (Peterbilt and Volvo) combined, at the GVWR load condition. Refer to Figure 3 for plot formatting and conventions.**

3.2.2 Split-Coefficient Stopping Distance Results: Tractors Analyzed Separately

Table 6 contains results for both truck tractors in the LLVW (bobtail) load configuration. In Table 6, all four foundation brake types can be compared for the mean, minimum, maximum, and standard deviation of the six stops nominally performed for each type. Also presented are the ASTM peak and slide traction measurements taken from both test surfaces on or near the day of testing. Traction numbers are presented as percentages, not coefficients (i.e., 85 instead of 0.85). If the ASTM traction measurement did not occur on the same day as the actual tractor testing, a linear interpolation of the traction data was used to estimate the ASTM measurement for that day. Inclusion of the ASTM measurements is provided to help the reader reach conclusions about the influence of the inevitably varying surface traction during the rather long test series. More rigorous statistical evaluations of the effects of peak and slide traction levels are presented in the following section.

Table 7 contains data for both truck tractors at GVWR.

Table 6 Wet split-μ stopping distances at LLVW for each truck tractor and each brake type showing the mean, minimum, maximum, and standard deviation (Std. Dev.) for 6 stops. Peak and slide traction levels for both surfaces, measured on or near the day of test are shown.

Tractor	Brake Configuration	Stopping Distance Statistics (ft)				Asphalt Peak / Slide Traction	Jennite Peak / Slide Traction
		Mean	Min.	Max	Std. Dev.		
Peterbilt	All S-Cam	109.0	103.6	114.1	4.6	86 / 57	32 / 10
	Hybrid drum	105.4	89.5	123.3	17.0	86 / 58	37 / 11
	Hybrid disc	104.2	100.8	106.3	2.0	84 / 56	36 / 11
	All Disc	96.5	90.9	101.3	4.0	84 / 59	33 / 11
Volvo	All S-Cam	102.6	99.7	105.2	2.0	81 / 59	29 / 09
	Hybrid drum	109.9	100.6	118.3	7.8	80 / 55	27 / 10
	Hybrid disc	104.5	100.2	112.4	5.0	79 / 50	34 / 10
	All Disc	97.6	91.6	102.6	3.9	87 / 59	35 / 11

Table 7 Wet split-μ stopping distances at GVWR for each truck tractor and each brake type showing the mean, minimum, maximum, and standard deviation (Std. Dev.) for 6 stops. Peak and slide traction levels for both surfaces, measured on or near the day of test are shown.

Tractor	Brake configuration	Stopping Distance Statistics (ft)				Asphalt Peak / Slide Traction	Jennite Peak / Slide Traction
		Mean	Min.	Max	Std. Dev.		
Peterbilt	All S-Cam	94.1	87.1	101.5	5.3	87 / 59	35 / 11
	Hybrid drum	101.8	93.0	110.0	7.4	86 / 58	35 / 11
	Hybrid disc	102.5	98.8	105.6	2.2	84 / 57	37 / 11
	All disc	93.3	89.8	98.1	3.2	87 / 61	35 / 11
Volvo	All S-Cam	104.7	102.0	107.0	1.9	80 / 57	30 / 08
	Hybrid drum	102.2	98.1	107.0	3.7	77 / 53	28 / 10
	Hybrid disc	101.7	99.3	104.9	1.9	81 / 53	29 / 09
	All disc	93.8	91.2	96.6	1.9	87 / 61	35 / 11

Figures 5 through 8 graphically compare each tractor's stopping distance performance on the wetted split-µ surface at each load condition. Each graph contains histobars that represent the mean of each group of six stops. The numeric results for the mean are also presented on each histogram. Variance bars (or "error bars") represent ± 95% confidence intervals about each mean.

Figures 5 and 6 show results for each tractor at the LLVW load condition. Figure 5 shows the Peterbilt stopping distance results on the split-µ surface, comparing the four foundation brake types. The data for the "hybrid drum" brake configuration on the Peterbilt had a great deal of variance, due largely to an apparent dependence on direction of the stop. Although the "all disc brake" configuration was slightly better for stopping distance than the "all S-Cam" or "hybrid disc" configurations, the improvement was marginal. Had the variance in the "hybrid drum" configuration been more consistent with the other groups (and therefore lower), the "all disc brake" configuration may have shown to be slightly superior to that configuration as well.

In Figure 6, the "all disc" brake configuration for the Volvo at the LLVW load condition is also superior to the other configurations by a slim margin. If the superior stopping distance of the "all disc" brakes on either tractor has statistical significance, that difference might be attributed to the disc brakes' ability to react more rapidly to quickly changing dynamic commands that originate from the antilock braking system (ABS). This phenomenon has been modeled, and the results of simulated differences in brake hysteresis are discussed at length in [7].

Figures 7 and 8 show stopping distance comparisons on the same split-µ surface with both truck tractors at the GVWR load condition. Figure 7 shows results for the Peterbilt tractor. The means for the two hybrid brake configurations are slightly higher than those for the "all S-Cam" or "all disc" configurations. For the Volvo tractor (Figure 8), the "all disc" configuration slightly outperforms the other configurations.

The fact that any one configuration would outperform another in this test should be better understood. For all of the tractor-brake configurations tested, none of the brake configurations were torque limited, as might be seen on a high-μ (i.e., dry) surface at high speeds. For this reason, the authors stress that the mechanical properties – inherent to the design of the air disc brake assemblies – were probably a root cause for their slightly superior performance on these low-to-mid-μ surfaces. The disc brake assemblies were of two different designs and supplied by two independent suppliers.

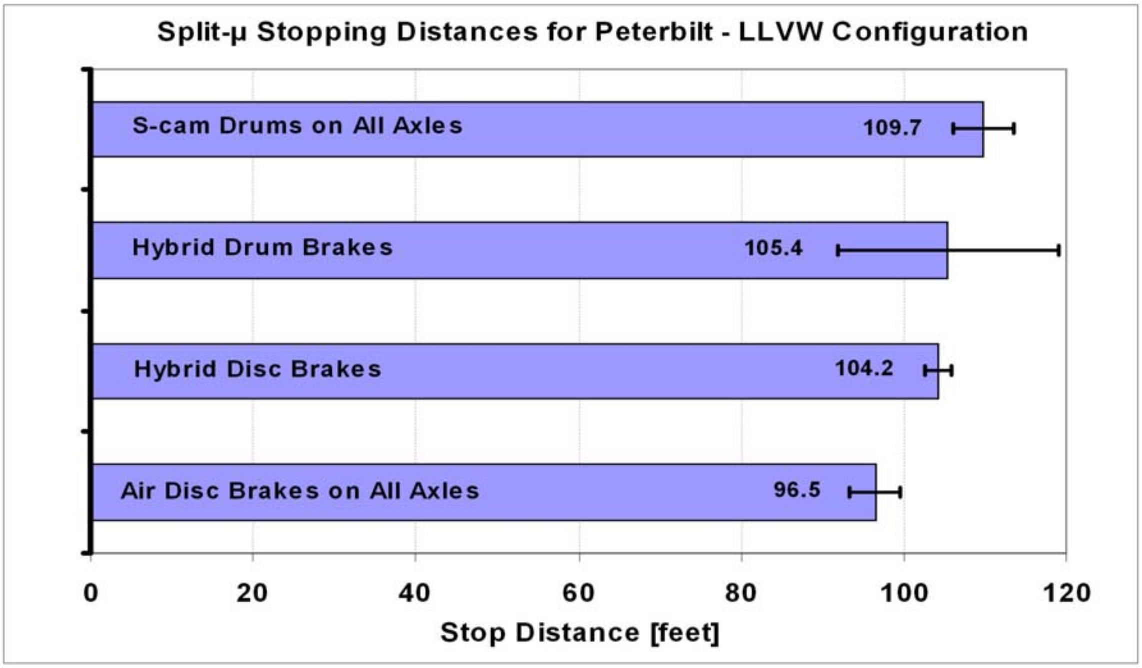

Figure 5: **Split-μ stopping distances for the Peterbilt tractor at the LLVW (bobtail) load condition. Four foundation brake configurations are compared. Histobars show the mean (in ft.) of six consecutive stops – the numeric value of the mean is printed near the end of each histobar. Variance bars show the upper and lower 95% confidence intervals about the means.**

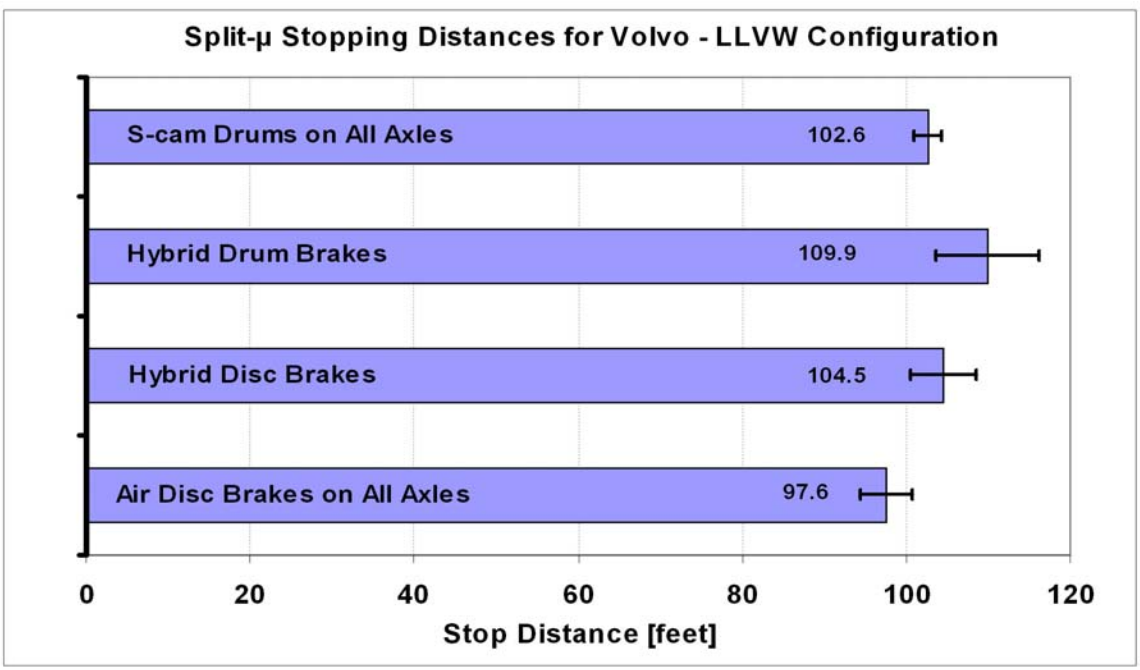

Figure 6: **Split-μ stopping distances for the Volvo tractor at the LLVW (bobtail) load condition. Refer to Figure 5 for plot formatting and conventions.**

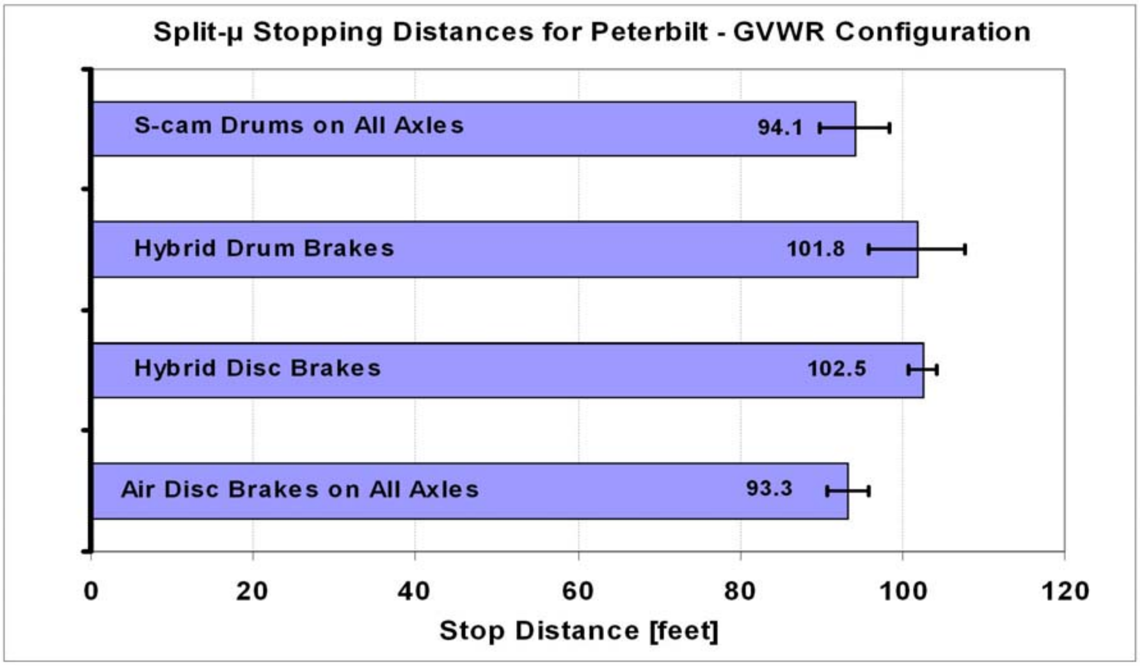

Figure 7: **Split-µ stopping distances for the Peterbilt tractor at the GVWR load condition. Refer to Figure 5 for plot formatting and conventions.**

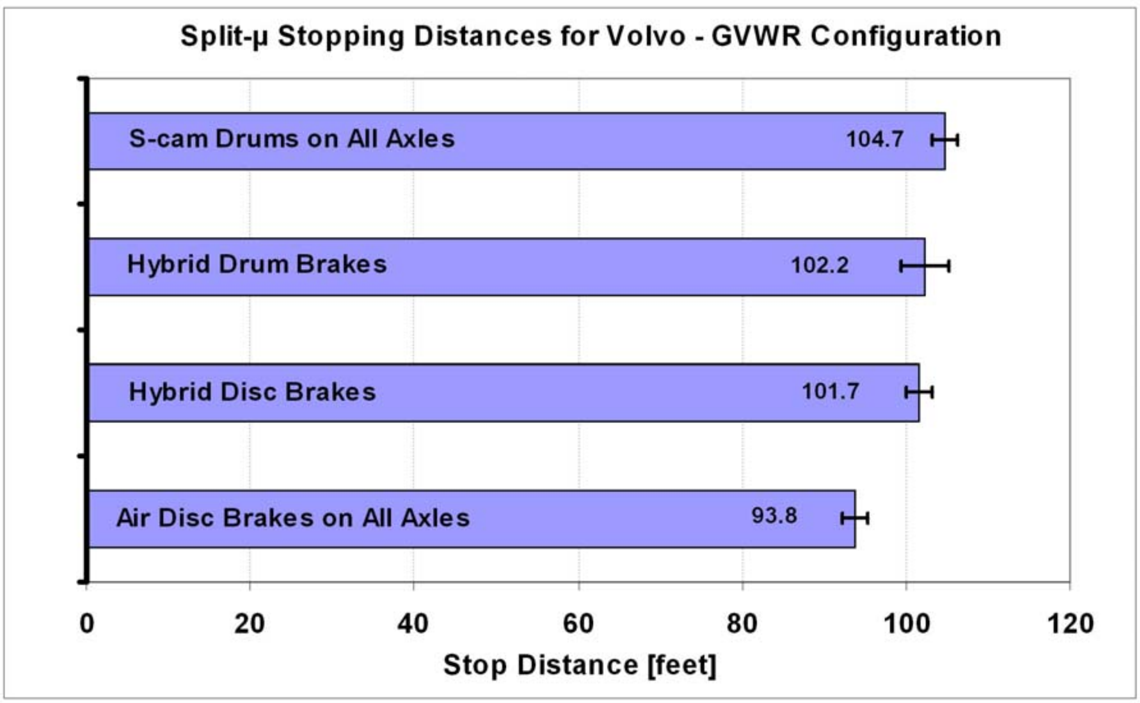

Figure 8: **Split-µ stopping distances for the Volvo tractor at the GVWR load condition. Refer to Figure 5 for plot formatting and conventions.**

3.3 Wet Split-Coefficient Stopping Distance: ANOVA Analysis

Analysis of Variance (ANOVA) were performed using the Statistical Analysis Software package (S.A.S.) with the speed-corrected stopping distance data as the dependent measure. Nominally, six repetitions for each tractor-brake-load configuration were analyzed. ANOVA analysis is used to gauge main and interaction effects of independent treatments (here, *brake type, tractor,* or *direction*) on a dependant variable (*stopping distance*).

In utilizing Tables 8 through 13, several items are notable. First, "DF" refers to the degrees of freedom for a particular independent treatment. "F-value" is the measure of distance between individual distributions, or means. Higher F-values indicate less overlap and therefore a higher degree of statistical separation. A "Probability greater than F" ("Pr > F") of 0.05 was used as the criterion for statistical significance for a specific treatment on the outcome of stopping distance – treatments with Pr>F values greater than 0.05 were considered not significant. The "Magnitude of Treatment Effect," or "ω^2" term, estimates the percentage of total model variance that can be attributed to that treatment. The higher the number, the more important that treatment. The sum of the "ω^2" terms (listed in the bottom row in each table) alludes to the total amount of variance in the data that can be described by that statistical model. The complement to that number is the amount of variance unexplained by the model. The sum of the "ω^2" terms usually agree to within a few percent of the model overall "$\mathbf{R^2}$" value; the closer to 1.0, the better. The term "n.s." indicates that treatment was not significant.

All of the analyses used *stopping distance* as the only dependent variable. The first of the two separate analyses covers all *tractor-brake* configurations combined and analyzed by *load*, with *tractor*, *brake type*, and *test direction* being the independent variables. The results are shown in Table 8 for the LLVW load condition and Table 9 for the GVWR load condition.

3.3.1 All Tractor-Brake Configurations Combined, Analyzed per Load

Table 8: ANOVA results table for the LLVW (bobtail) condition, test directions combined.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	0.07	0.7869	n.s.
Brake	3	18.27	<0.0001	0.236
Tractor x Brake	3	4.85	0.0063	0.053
Direction	1	42.75	<0.0001	0.190
Tractor x Direction	1	0.00	0.9640	n.s.
Brake x Direction	3	23.80	<0.0001	0.312
Total Percent of Variance Accounted for in the Model				0.781

Table 9: ANOVA results table for the GVWR (fully loaded) condition, test directions combined.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	11.37	0.0018	0.049
Brake	3	26.27	<0.0001	0.362
Tractor x Brake	3	11.56	<0.0001	0.151
Direction	1	8.12	0.0073	0.034
Tractor x Direction	1	0.30	0.5867	n.s.
Brake x Direction	3	13.41	<0.0001	0.178
Total Percent of Variance Accounted for in the Model				0.771

Significant effects resulting from *test direction* at both loads (in Tables 8 and 9) motivated further subdivision of the dataset by *load*, then *test direction*.

The results from the ANOVA analysis, after being further subdivided into groups by *test direction*, are in Tables 10 through 13.

Table 10: ANOVA results table for the LLVW (bobtail) condition, East-to-West direction.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	0.11	0.7449	n.s.
Brake	3	65.75	<0.0001	0.537
Tractor x Brake	3	49.19	<0.0001	0.399
Total Percent of Variance Accounted for in the Model				0.934

Table 11: ANOVA results table for the LLVW (bobtail) condition, West-to-East direction.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	0.11	0.7483	n.s.
Brake	3	56.18	<0.0001	0.857
Tractor x Brake	3	2.48	0.0982	n.s.
Total Percent of Variance Accounted for in the Model				0.857

Table 12: ANOVA results table for the GVWR condition, East-to-West direction.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	16.95	0.0008	0.114
Brake	3	31.32	<0.0001	0.650
Tractor x Brake	3	3.98	0.0270	0.064
Total Percent of Variance Accounted for in the Model				0.828

Table 13: ANOVA results table for the GVWR condition, West-to-East direction.

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1	4.11	0.0595	n.s.
Brake	3	26.30	<0.0001	0.531
Tractor x Brake	3	14.28	<0.0001	0.279
Total Percent of Variance Accounted for in the Model				0.810

3.3.2 Observations Drawn from Analyses

In Tables 8 and 9, the treatments are *tractor*, *brake type*, *direction*, and their first-order interactions. *Direction* refers to the direction on the test surface that a particular stop was run (three were run in one direction, three in the opposite direction for efficiency). The only dependant variable is *stopping distance.*

In Tables 8 and 9, where the data taken at both *test directions* are analyzed in a common set, the model explains about 78% of the total variance. *Direction* accounts for a significant 19% of the variance for the LLVW load (see the right-hand column in Table 8) and about 3% for the GVWR load (Table 9). The effect of *tractor* was not significant at LLVW, but was significant at GVWR, accounting for about 5% of the total variance. *Brake type* was significant, accounting for 24% of variance at LLVW and 36% at GVWR. The interaction of *brake x tractor* accounted for more variance at GVWR than at LLVW.

Analyses results from splitting the dataset further by *load* and *direction* can be seen in Tables 10 through 13. Eliminating test *direction* as an effect in the model allows the model to explain much more of the total variance (improving to 88% to 93%). At LLVW, the effect of *tractor* remains insignificant for both directions, while the effect of *brake* is significant (accounting for 86% of the model in the "W-E" direction, Table 11). Datasets split by *direction* explained about 82% of the model variance at the GVWR condition. Unlike the LLVW condition, *tractor* was found to have marginal significance at GVWR (accounting for only 0-11% of the experimental variance), although it was significant (for that test direction), unlike for the LLVW load condition. *Brake* configuration was significant for both directions and the interaction of *brake x tractor* were significant for one direction only.

3.3.2.1 Brake Type Rankings (Table 14):

Table 14 presents the post-hoc analyses, showing relative rankings for each brake type for various combinations of condition. The table containing the corresponding basic analysis of variance is listed in the right-hand column. The bottom line is that the all-disc setup showed significantly lower stopping distances, no matter how the model was split up.

Table 14: Post-Hoc analyses and brake type rankings.

Load	Direction	Ranking of Stop Distance	Associated ANOVA Results Table
Combined	E-W	(SC = HD) > HS > AD 104.6 101.9 96.9 93.3	not applicable
Combined	W-E	HS > HD > SC > AD 112.8 104.6 100.9 97.3	not applicable
LLVW	Combined	(HS = SC = HD) > AD 107.7 106.2 104.4 97.0	Table 8
GVWR	Combined	(HS = HD) > SC > AD 102.1 102.0 99.4 93.5	Table 9
LLVW	E-W	SC > HD > HS > AD 107.6 102.7 96.5 94.0	Table 10
LLVW	W-E	HS > (HD = SC) > AD 118.8 106.0 104.7 100.0	Table 11
GVWR	E-W	(SC = HD) > HS > AD 101.7 101.0 97.3 92.6	Table 12
GVWR	W-E	HS > HD > (SC = AD) 106.7 103.2 97.2 94.5	Table 13

<u>Legend for Table 14</u>:
SC = standard S-Cam brake setup, all brake positions
HS = (hybrid S-Cam) all S-Cam, with oversized steer axle brakes
HD = (hybrid disc) air disc brakes on the steer axle, S-Cam drum brakes on drive axles
AD = air disc brakes on all axles.

In addition, stopping distances were quite different depending upon *direction* (discussed in the previous section). When combining *loads*, there were many reversals in the rankings. When combining *directions*, reversals (in the *brake* rankings) reduced significantly; basically all the non-all-disc setups were grouped at roughly 8% longer stopping distances vs. the all-disc. Stopping distances with the HS brakes ("hybrid S-Cam drum" configuration, having oversized S-Cam brakes on the steer axle) were consistently longer than the other three configurations, for reasons yet to be understood.

Splitting out all *loads* and *directions* resulted in some reversals in ranking order, but the "all-disc" setup remained significantly better for all analyses.

Table 15 shows the mean normalized standard deviations for each configuration, which indicates that there was less variance in the disc-braked vehicle stopping distances than with the drum brakes. Note that this conclusion was reached using the same method of analysis for the corresponding dry braking comparisons, presented in [1].

Table 15: Mean normalized standard deviations for stopping distances on the split-μ surface at the LLVW and GVWR load configurations, showing both test directions for each load.

Brake configuration	LLVW		GVWR	
	East-West	West-East	East-West	West-East
All S-Cam	6.4%	1.6%	4.2%	8.4%
Hybrid Drum	7.6%	2.4%	2.8%	2.6%
Hybrid Disc	2.0%	3.9%	1.6%	1.9%
All disc	2.7%	1.9%	1.1%	3.5%

The ANOVA and post-hoc analyses therefore indicate that *brake type* did have a significant effect on the outcome of stopping distance on the wet split-μ surface. Furthermore, the all-disc configured truck tractors could be counted on for a 3-8% improvement in low-speed, medium-μ stopping distances. Further indications are that *tractor* type was not significant at LLVW but was at GVWR. The effect of *test direction* was significant, adding variance to the overall dataset.

4 PARKING BRAKE TESTING RESULTS AND COMPARISONS

The tractor parking brake effectiveness was tested as outlined in FMVSS No. 121, Section 5.6 (and No. 121-V Laboratory Test Procedure , Section 10.3). Grade holding and draw bar tests were performed on both the S-Cam and air disc configurations on both tractors. The Peterbilt tractor was tested with parking brakes on both the intermediate and rear drive axles in the standard S-Cam configuration. All other configurations (Peterbilt with air disc and Volvo with S-Cam and air disc) had parking brake capability on the intermediate drive axle only.

The truck tractors were evaluated for grade holding on a 20% grade at their GVWR of 50,000 pounds (plus a 4,500-lb. control unbraked control trailer) and at LLVW (as per FMVSS No. 121 procedures). Each brake type (air disc and S-Cam) was evaluated with the vehicle facing uphill, then downhill. The results of these tests are in Table 16. At the LLVW load condition, all brake configurations passed with the one exception of the Peterbilt with the air disc brakes on the intermediate drive axle. The failure mode was one noticed in past NHTSA testing, wherein the bobtail tractor did not generate enough normal load on the tires for the brakes to hold, i.e. the braked tires just slid on the pavement. The same configuration held on the grade when facing uphill, placing slightly more normal load on the rear tires. Many configurations failed to hold on the 20% grade at the GVWR condition. The only passing configuration was the S-Cam brakes on the Peterbilt, which were on both drive axles instead of only one (as was the case for other parking brake configurations tested). The authors believe that these results make a strong argument for inclusion of parking brake capability on both drive axles of 6x4 tractors in the future.

The drawbar tests were performed as specified in FMVSS No. 121 as well as the SAE J1626 Recommended Practice [6]. The drawbar tests were intended to measure the peak static braking force that the vehicle parking brakes can develop by pulling the vehicle with an inline load cell to measure drawbar or cable tension. Current FMVSS No. 121 standards require the ratio of the drawbar force to vehicle GVWR to be no less than 0.14 (for 3-axle truck tractors). The results from the drawbar pulls are shown in Tables 17 through 20. All brake configurations passed the FMVSS test with acceptable margins, including the Peterbilt / air disc combination, which failed the grade-holding test.

As is often the case, the drawbar pull force measured during the SAE procedure met or exceeded that seen for the FMVSS No. 121 tests. This result occurs frequently due to the "preset" (resulting from the full treadle application of the service brakes prior to the parking brake being engaged) obtained during the SAE procedure. This preset is not obtained for the FMVSS No. 121 procedure as no treadle application is allowed (thus simulating the parking brake capability with at least one failure in the service brake system).

Note that the air disc brake configurations provided significantly higher drawbar force quotients than the standard S-Cam setups on either truck tractor.

Table 16: 20% grade-holding parking brake test results

Load Condition	Tractor	Brake Type	Direction of Nose of Tractor on Grade	Pressure to First Stop Vehicle on Grade (psi)	Pressure Used to Hold Vehicle on Grade (psi)	Hold Time on Grade (sec)	Pass/Fail Status
LLVW	Peterbilt	S-Cam	Uphill	17	17	>300	Pass
			Downhill	17	17	>300	Pass
		Disc	Uphill	16	71	>300	Pass
			Downhill	28	n.a.	0	Fail 1
	Volvo	S-Cam	Uphill	13	37	>300	Pass
			Downhill	33	33	>300	Pass
		Disc	Uphill	13	22	>300	Pass
			Downhill	19	25	>300	Pass
GVWR	Peterbilt	S-Cam	Uphill	34	38	>300	Pass 1
			Downhill	27	42	>300	Pass 1
		Disc	Uphill	n.a.	105*	0	Fail 2
			Downhill	n.a.	105*	0	Fail 2
	Volvo	S-Cam	Uphill	20	41	0	Fail 2
			Downhill	39	46	0	Fail 2
		Disc	Uphill	n.a.	30	0	Fail 2,3
			Downhill	72	49	0	Fail 2,3

Notes for Table 16:

105* = pressure information was manually logged, and was higher than needed to stop vehicle; data file not available for this actual test.

LLVW = bobtail, no ballast added.
GVWR = w/control trailer front loaded to tractor GVWR + 4500-lb trailer axle.
Pass 1 = only parking brake configuration with spring brakes on both drive axles.
Fail 1 = tires slid on hill, insufficient normal force (very low axle load).
Fail 2 = parking brakes slipped allowing creep and/or runaway.
Fail 3 = upon **re-application** of treadle after parking brakes initially failed, the parking brakes held the grade for a period of time exceeding 300 seconds.

Anti-Compounding was active for all 20% Grade Tests.
FMVSS No. 121 does not allow for re-application of the service brake once the parking brake withstand begins.

Table 17: Parking brake drawbar results from NHTSA and SAE procedure pulls on the Volvo tractor with air disc brakes on the intermediate drive axle

NHTSA Procedure - 0 psi Treadle Pressure, Rearward					NHTSA Procedure - 0 psi Treadle Pressure, Forward				
Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)
90º	9386	0.188	33.25	0.50	90º	12973	0.259	35.00	0.53
180º	9758	0.195	33.00	0.54	180º	12921	0.258	33.75	0.52
270º	9804	0.196	33.75	0.55	270º	13081	0.262	34.50	0.55
360º	9603	0.192	33.50	0.60	360º	12409	0.248	34.00	0.59
	max	**0.196**				**max**	**0.262**		
SAE Procedure -Max Cut-Out Treadle Pressure, Rearward					**SAE Procedure -Max Cut-Out Treadle Pressure, Forward**				
Turn	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**	**Turn**	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**
90º	10388	0.208	33.00	0.56	90º	12953	0.259	34.75	0.48
180º	9887	0.198	33.00	0.61	180º	13062	0.261	34.00	0.48
270º	10035	0.201	33.75	0.58	270º	12879	0.258	34.50	0.60
360º	10270	0.205	33.00	0.50	360º	12745	0.255	33.75	0.54
	max	**0.208**				**max**	**0.261**		

Table 18: Parking brake drawbar results from NHTSA and SAE procedure pulls on the Volvo tractor with S-Cam brakes on the intermediate drive axle

NHTSA Procedure - 0 psi Treadle Pressure, Rearward					NHTSA Procedure - 0 psi Treadle Pressure, Forward				
Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)
90º	8300	0.166	33.00	0.79	90º	8917	0.178	34.00	0.50
180º	8241	0.165	32.75	0.81	180º	8558	0.171	33.25	0.43
270º	8910	0.178	33.00	0.59	270º	8907	0.178	33.63	0.56
360º	8818	0.176	34.00	0.59	360º	8928	0.179	33.38	0.52
	max	**0.178**				**max**	**0.179**		
SAE Procedure -Max Cut-Out Treadle Pressure, Rearward					**SAE Procedure - Max Cut-Out Treadle Pressure, Forward**				
Turn	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**	**Turn**	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**
90º	9381	0.188	33.00	0.72	90º	10248	0.205	33.63	0.44
180º	9592	0.192	33.13	0.59	180º	9730	0.195	33.63	0.48
270º	9757	0.195	33.13	0.47	270º	9822	0.196	33.38	0.46
360º	10015	0.200	34.00	0.47	360º	9778	0.196	33.38	0.45
	max	**0.200**				**max**	**0.205**		

Table 19: Parking brake drawbar results from NHTSA and SAE procedure pulls on the Peterbilt tractor with air disc brakes on the intermediate drive axle

NHTSA Procedure - 0 psi Treadle Pressure, Rearward					NHTSA Procedure - 0 psi Treadle Pressure, Forward				
Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	Steady State Rate of Pull(in/sec)
90º	10035	0.201	36.00	0.48	90º	11016	0.220	21.00	0.32
180º	10314	0.206	29.75	0.52	180º	11400	0.228	29.50	0.62
270º	10144	0.203	19.30	0.65	270º	11061	0.221	9.25	0.57
360º	10127	0.203	27.50	0.54	360º	11561	0.231	33.20	0.64
	max	**0.206**				**max**	**0.231**		
SAE Procedure - Max Cut-Out Treadle Pressure, Rearward					**SAE Procedure - Max Cut-Out Treadle Pressure, Forward**				
Turn	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**	**Turn**	**Draw Force**	**Force-GVWR Ratio**	**Draw Distance**	**Steady State Rate of Pull(in/sec)**
90º	10300	0.206	36.00	0.61	90º	12040	0.241	35.50	0.41
180º	10885	0.218	29.20	0.44	180º	12303	0.246	34.50	0.68
270º	10595	0.212	33.90	0.59	270º	12862	0.257	34.00	0.54
360º	10473	0.209	30.00	0.52	360º	12210	0.244	32.00	0.63
	max	**0.218**				**max**	**0.257**		

Table 20: Parking brake drawbar results from NHTSA and SAE procedure pulls on the Peterbilt tractor with S-Cam drum brakes on the intermediate and rear drive axles

	NHTSA Procedure - 0 psi Treadle Pressure, Rearward					NHTSA Procedure - 0 psi Treadle Pressure, Forward				
	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)
Intermediate Drive Axle	90º	7206	0.144	32.00	0.54	90º	7802	0.156	32.50	0.44
	180º	7041	0.141	32.00	0.53	180º	7511	0.150	32.75	0.40
	270º	7646	0.153	31.75	0.41	270º	7479	0.150	32.75	0.44
	360º	7331	0.147	32.25	0.38	360º	7603	0.152	32.75	0.44
		max	**0.153**				**max**	**0.156**		
	SAE Procedure -Max Cut-Out Treadle Pressure, Rearward					**SAE Procedure -Max Cut-Out Treadle Pressure, Forward**				
	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)
	90º	8154	0.163	32.00	0.46	90º	8345	0.167	33.25	0.49
	180º	7848	0.157	32.50	0.50	180º	8522	0.170	33.25	0.54
	270º	8041	0.161	31.50	0.51	270º	8449	0.169	33.75	0.55
	360º	8184	0.164	32.25	0.65	360º	8708	0.174	33.25	0.49
		max	**0.164**				**max**	**0.174**		
	NHTSA Test - 0 psi Treadle Pressure Rearward					**NHTSA Test - 0 psi Treadle Pressure Forward**				
	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)
Rear Drive Axle	90º	8685	0.174	32.25	0.45	90º	7862	0.157	32.00	0.41
	180º	8328	0.167	32.00	0.49	180º	8335	0.167	33.50	0.43
	270º	8298	0.166	32.00	0.43	270º	8706	0.174	32.75	0.46
	360º	8603	0.172	32.00	0.46	360º	8730	0.175	32.75	0.54
		max	**0.174**				**max**	**0.175**		
	SAE Procedure -Max Cut-Out Treadle Pressure, Rearward					**SAE Procedure -Max Cut-Out Treadle Pressure, Forward**				
	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)	Turn	Draw Force	Force-GVWR Ratio	Draw Distance	S.S. Rate of Pull(in/sec)
	90º	9316	0.186	32.00	0.43	90º	9213	0.184	32.75	0.49
	180º	9408	0.188	32.00	0.52	180º	9969	0.199	33.50	0.52
	270º	9406	0.188	31.75	0.48	270º	10001	0.200	33.75	0.46
	360º	9270	0.185	32.25	0.74	360º	10415	0.208	33.50	0.47
		max	**0.188**				**max**	**0.208**		

5 CONCLUSIONS AND RECOMMENDATIONS

The test results presented herein summarize an evaluation of four foundation brake configurations on two Class 8 truck tractors for wet braking performance and stability, as well as parking brake effectiveness. The foundation brakes were field-installed retrofits performed at NHTSA's Vehicle Research and Test Center (VRTC). The existing pneumatic control, actuation, and ABS control systems were retained without any revision. This wet braking stability testing was performed in tandem with comparisons of the various foundation brake configurations for dry high speed braking performance. The results of the dry testing are covered in a separate report [1].

Four brake configurations were tested on each of two 6x4 truck tractors. The configurations were:

a) Standard S-Cam brakes on steer and drive axles,
b) Hybrid drum: Higher capacity S-Cam drum brakes on the steer axle, standard S-Cam drums on the drive axles,
c) Hybrid disc: Air disc brakes on the steer axle, standard S-Cam drums on the drive axles, and
d) All disc: Air disc brakes on all axles.

Conclusions and recommendations are as follows:

1. For the FMVSS No. 121 braking stability tests, the hybrid disc brake systems were the only configuration that did not consistently accomplish all of the four required lane-holding maneuvers while braking within the 500-ft (152.4 m) radius curve at an target initial speed of 75 percent of drive-through speed. That said, all brake configurations were capable of completing 3 out of 4 attempts, as required by current FMVSS No. 121 standards to pass this maneuver.

2. FMVSS No. 121 brake-in-curve stability tests were expanded in that each test was continued beyond the four runs required at 75 percent of the drive-through speed by increasing initial braking speed until the tractor could not maintain the lane while braking in the 500-ft. (152.4 m) radius curve. During this part of the evaluation, normalized results indicate that both the hybrid brake systems showed a drop in limit performance versus the standard all-S-Cam system or the all air-

disc configurations. The increase in relative braking power on the front axle for both hybrid configurations may have caused the vehicle to understeer more severely under braking with the hybrid configurations. This trend existed at both LLVW and GVWR load configurations, and was most pronounced for the “hybrid disc” configuration.

3. The brake configurations were also compared for stopping distance and stability while performing straight-ahead, full-treadle stops on a wetted, laterally split-μ surface. These data were analyzed in various ways to fully understand the influence of the braking systems on the vehicle’s performance during this test. Subjective driver feedback and analysis of vehicle dynamic responses (examining steering, yaw rate, and lateral acceleration during these maneuvers) do not indicate a significant effect of any brake configuration on stability for either truck tractor.

4. In-depth analyses of the split-μ stopping distance performance of each brake type leads to the conclusion that both truck tractors experienced a 3-8% improvement in stopping performance with the all-disc brake configuration, regardless of load. These results lead to the conclusion that mechanical properties of the air disc brake assemblies might have inherent advantages over the traditional S-Cam brake, in terms of cycling efficiency during ABS-assisted stops. The authors believe that the effects of air disc brakes on low-coefficient stopping performance should be explored further on a consistent (non split-μ) surface at high speeds.

5. Furthermore, differences in wet stopping distances could be attributed more to “brake type” than any other effect studied.

6. It was also clear for the split-μ stops that the direction of braking was indeed a significant effect on stopping distance, adding significant amounts of variance to the test.

7. Some tractor-brake configurations had difficulty holding the 20% grade at the LLVW load condition due to the tires sliding on the surface. All tractor-brake configurations failed to hold the hill at GVWR with the exception of one, which had S-Cam parking brakes on both drive axles instead of only the intermediate drive axle, which is how the remainder of the parking brake configurations were

tested. These results make a strong argument for inclusion of parking brake capability on both drive axles of 6x4 tractors in the future. All brake configurations passed the FMVSS No. 121 drawbar tests at GVWR.

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7. Dunn, Ashley L., “Jackknife Stability of Articulated Tractor Semitrailer Vehicles with High Output Brakes and Jackknife Detection on Low Coefficient Surfaces,” Ph.D. dissertation, The Ohio State University, 2003, pp. 58-63.

Appendix of Data Tables

In this appendix are data tables listing the individual data for each speed-corrected stopping distance as measured during the wet split-coefficient (i.e., wet split-μ) testing of all foundation brake configurations. For "Stop Direction," the label "W-E" indicates that stop was performed in the west-to-east direction. For the label "E-W," the stop was performed in the east-to-west direction. The test directions were alternated for test efficiency.

Table 21: Individual stopping distance data for the Peterbilt Tractor at the LLVW load condition.

Foundation Brake Configuration	Stop Direction	Replication	Stopping Distance (ft.)
All Disc	W-E	1	98.7
	E-W	2	95.0
	W-E	3	101.3
	E-W	4	93.6
	W-E	5	99.4
	E-W	6	90.9
Hybrid Disc	W-E	1	100.8
	E-W	2	104.4
	W-E	3	106.3
	E-W	4	105.7
	W-E	5	105.1
	E-W	6	103.2
Hybrid Drum	W-E	1	118.1
	E-W	2	90.3
	W-E	3	123.3
	E-W	4	90.1
	W-E	5	121.1
	E-W	6	89.5
S-Cam	W-E	1	107.5
	E-W	2	113.6
	W-E	3	105.7
	E-W	4	114.1
	W-E	5	103.6
	E-W	6	113.5

Table 22: Individual stopping distance data for the Volvo Tractor at the LLVW load condition.

Foundation Brake Configuration	Stop Direction	Replication	Stopping Distance (ft.)
All Disc	W-E	1	97.4
	E-W	2	97.9
	W-E	3	100.8
	E-W	4	95.2
	W-E	5	102.6
	E-W	6	91.6
Hybrid Disc	W-E	1	112.4
	E-W	2	101.0
	W-E	3	108.8
	E-W	4	101.8
	W-E	5	102.7
	E-W	6	100.2
Hybrid Drum	W-E	1	115.5
	E-W	2	105.6
	W-E	3	118.3
	E-W	4	102.8
	W-E	5	116.6
	E-W	6	100.6
S-Cam	W-E	1	103.3
	E-W	2	99.7
	W-E	3	105.2
	E-W	4	103.7
	W-E	5	103.1
	E-W	6	100.8

Table 23: Individual stopping distance data for the Peterbilt Tractor at the GVWR load condition.

Foundation Brake Configuration	Stop Direction	Replication	Stopping Distance (ft.)
All Disc	W-E	1	89.8
	E-W	2	92.1
	W-E	3	96.3
	E-W	4	91.7
	W-E	5	98.1
	E-W	6	92.0
Hybrid Disc	W-E	1	102.8
	E-W	2	98.8
	W-E	3	103.7
	E-W	4	101.7
	W-E	5	105.6
	E-W	6	102.4
Hybrid Drum	W-E	1	108.4
	E-W	2	93.0
	W-E	3	110.0
	E-W	4	95.4
	W-E	5	106.8
	E-W	6	97.2
S-Cam	W-E	1	90.7
	E-W	2	95.4
	W-E	3	87.1
	E-W	4	98.2
	W-E	5	92.0
	E-W	6	101.5

Table 24: Individual stopping distance data for the Volvo Tractor at the GVWR load condition.

Foundation Brake Configuration	Stop Direction	Replication	Stopping Distance (ft.)
All Disc	W-E	1	94.8
	E-W	2	92.0
	W-E	3	96.6
	E-W	4	93.9
	W-E	5	91.2
	E-W	6	94.0
Hybrid Disc	W-E	1	104.9
	E-W	2	99.3
	W-E	3	101.1
	E-W	4	101.1
	W-E	5	100.9
	E-W	6	102.6
Hybrid Drum	W-E	1	101.6
	E-W	2	98.1
	W-E	3	107.0
	E-W	4	99.4
	W-E	5	106.6
	E-W	6	100.6
S-Cam	W-E	1	102.0
	E-W	2	103.2
	W-E	3	106.5
	E-W	4	107.0
	W-E	5	104.6
	E-W	6	105.0

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