U.S. Department
of Transportation

**National Highway
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DOT HS 809 700 **May 2004**

Class 8 Truck Tractor Braking Performance Improvement Study

Report – 1

Straight Line Stopping Performance on a High Coefficient of Friction Surface

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 809 700		

4. Title and Subtitle Class 8 Truck Tractor Braking Performance Improvement Study, Report 1, Straight Line Stopping Performance on a High Coefficient of Friction Surface	5. Report Date May 2004 6. Performing Organization Code NHTSA/NVS-312
7. Author(s) Ashley L. (Al) Dunn and Richard L. (Dick) Hoover, Transportation Research Center Inc.	8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box 37 East Liberty, OH 43319	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 400 Seventh Street, S.W. Washington, D.C. 20590	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Four configurations of pneumatic foundation brakes were evaluated and compared for high-speed stopping performance on two Class-8 6x4 truck tractors. The brake configurations include:

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

Both tractors were tested bobtail (lightly loaded vehicle weight – LLVW) and at tractor gross vehicle weight rating (GVWR, using an unbraked control trailer). The stops were from 96.6 kph (60 mph) on a dry concrete surface.

Compared to a possible 30% reduction in current FMVSS No. 121 standards at LLVW, margins of compliance for the minimum stopping distance (of six stops) at the LLVW load exceeded 10% for all non-standard brake configurations. Margins of compliance for the “hybrid-disc” and “all-disc” configurations exceeded 20% for both tractors at LLVW. Versus a possible 30% reduction in current GVWR standards, only one tractor-brake configuration (all disc) had a margin of compliance that exceeded 10%. Other brake configurations tested at GVWR had low or nonexistent margins of compliance for the possibly reduced standard.

Statistical analyses indicate significantly different mean stopping distances between all foundation brake configurations. Combining results for both tractors tested, an “all disc brake” configuration could yield a 20% improvement in stopping distance at GVWR over standard “all S-cam” brakes, and a 16% improvement at LLVW. With the hybrid disc brakes, the improvements were 12% and 19% for GVWR and LLVW, respectively. For the hybrid drum brakes, the improvements were 10% for both GVWR and LLVW.

17. Key Words	18. Distribution Statement
Heavy Truck Braking, Air Disc Brakes, Stopping Distance, Hybrid Brake Systems, FMVSS 121, Class-8 Truck Tractor, Brake Performance	Document is available to the public from the National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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 type effects on dry high-speed stopping performance of Class-8 (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. The extended full report on foundation brake testing covering stopping distance, stability, and trailer brake compatibility on wet and dry surfaces, will be completed fall 2004.

Different foundation brake configurations were field retrofitted to each of two truck tractor's existing pneumatic actuation and control systems. The tractors' actuation and control systems were not optimized for each brake type. 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 (also referred to as "X-large steer")
c) Hybrid disc: air disc brakes on steer, standard S-cam drums on drive axles (also referred to as "disc steer")
d) Air disc brakes on steer and drive axles

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. The stops were performed from 96.6 kph (60 mph) on a dry concrete skid pad (with nominal peak/slide surface friction coefficient measurements of 98/84).

Analyses of the minimum stopping distance (of six consecutive stops) at the LLVW load showed that margins of compliance (assuming a 30% reduction in the current standard for tractors at LLVW) for any modified foundation brake configuration (for either truck tractor) exceeded 10%. Margins of compliance for the "hybrid-disc" or "all-disc" configurations exceeded 20% for both tractors.

However, at GVWR load, only the Peterbilt tractor in the “all-disc” brake configuration had a minimum stopping distance that exceeded a 10% margin of compliance over the proposed minimum; that margin was 12.5%. The corresponding margin of compliance for the Volvo tractor was only 5.6%.

At both load conditions, stopping distances for the Peterbilt tractor with modified foundation brakes improved far better (over the standard “all S-cam” brakes) than did those for the Volvo tractor. Refer to section 3.1 for further discussion of minimum stopping distance results.

Also for this report, Analysis of Variance (ANOVA) was used to compare the effects of the four foundation brake configurations on the high-speed stopping performance of the two Class-8 truck tractors. Statistical analyses of the stopping distance results are discussed in sections 3.3, 3.4, and 3.5. Those conclusions indicate statistically different stopping distance means between all foundation brake configurations, whether the results for both weight configurations were combined or analyzed separately. Combining the results for both tractors tested, an “all disc brake” configuration could yield a 20% improvement in stopping distance at GVWR over the standard “all S-cam” brake configuration on dry pavement, and a 16% improvement at LLVW. With “hybrid disc” brakes, the improvements were 12% and 19% for GVWR and LLVW, respectively. For “hybrid drum” brakes, the improvements were 10% for both GVWR and LLVW.

Stopping distance means for all configurations, including traditional S-cam drums on all axles, were capable of achieving a 30% improvement over the current FMVSS No. 121 standard in the lightly loaded (LLVW) condition (from 335 ft. to 235 ft. for unloaded tractors).

As tested, only the “all disc brake” configuration could achieve a 30% improvement (in mean stopping distance) over the current FMVSS No. 121 standard at GVWR (from 355 ft. to 249 ft. for tractors loaded to GVWR). However, it is believed that further tuning development of the control and actuation systems might result in both hybrid systems being able to reach the 30% improvement.

Due to good statistical grouping, margins of compliance for stopping distance means were of similar magnitude to those for the minimum stopping distances.

Dry braking results for three peer vehicles in various configurations are included at the end of this report for comparison.

1 BACKGROUND AND PURPOSE

Current FMVSS No. 121 regulations allow longer stopping distances for pneumatically braked heavy vehicles than for passenger cars or motorcycles. NHTSA believes that improving the discrepancy in stopping distances is very important in reducing heavy truck related fatalities in North America. Currently, pneumatically braked truck tractors are required to stop from 96.6 kph (60 mph) in 108 m (355 ft.) at GVWR, whereas the FMVSS No. 135 requirement for passenger cars is 65 m (216 ft.) Actual stopping distances seen in the field vary significantly for both groups. Potential changes to FMVSS No. 121 include reducing stopping distances for heavy trucks by 30%, in both LLVW and GVWR load configurations. These changes are shown in Figure 1, compared graphically to existing standards for light vehicles.

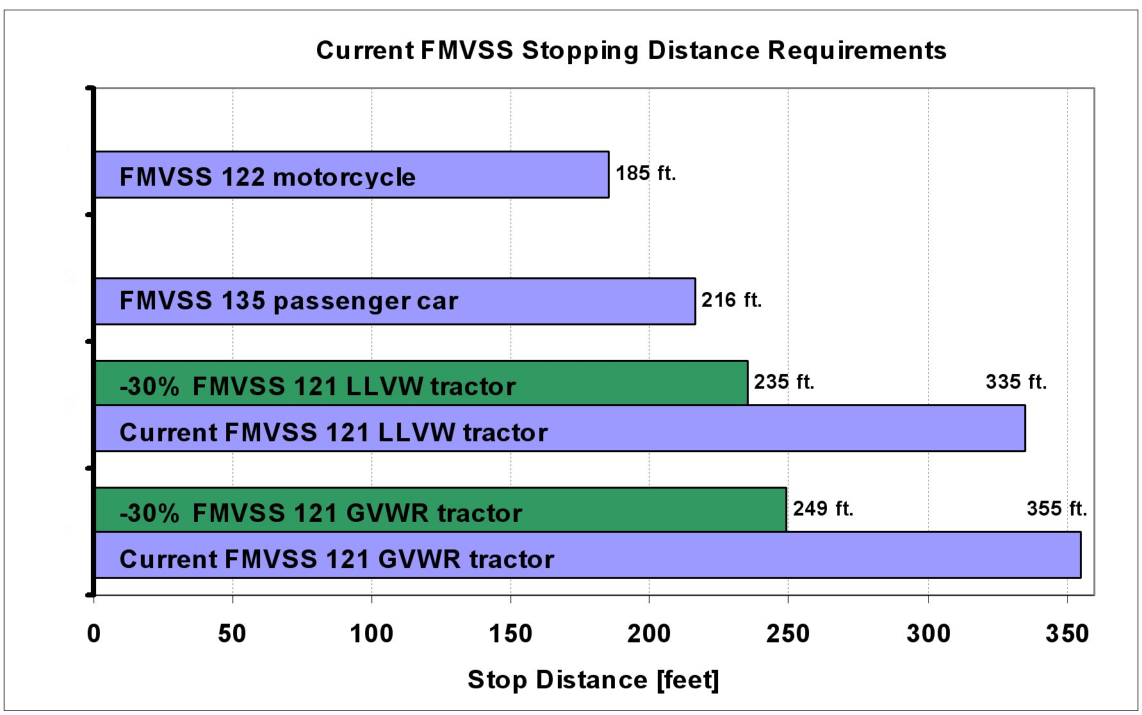

Figure 1: Comparison of current FMVSS stopping distance regulations, compared to 30% reduction in heavy truck stopping distances.

This study has been performed by NHTSA's Vehicle Research and Test Center (VRTC) in support of rulemaking activity for commercial vehicles with pneumatically operated braking systems, which are covered by FMVSS No. 121. In 2002, NHTSA decided that testing would be conducted at VRTC to evaluate and understand the effects of various modern foundation brake systems on Class-8 truck tractors and semitrailers. Consequently, VRTC has been testing many combinations of truck tractors, semitrailers, and foundation brake systems on various surfaces to better understand the effects of substituting traditional S-cam drum brakes with various configurations of pneumatic brakes having higher-than-traditional torque output. This report summarizes the findings for full-treadle, high-speed stopping distances on dry pavement for tractors only.

The purpose of this report is two-fold. The first purpose is to present the margins of compliance of minimum stopping distances (versus a 30% reduction in current standards) for each brake configuration. The second purpose is to communicate the statistically meaningful differences between various foundation brake configurations on two different truck tractors. These results provide a sound estimate of the braking performance achievable with various modern Class-8 tractor brake configurations when fitted to modern conventional tractors.

2 TEST VEHICLES AND METHODOLOGY

2.1 Test Vehicle Description

Two conventional 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" or "R5" in this report) which has been used extensively at VRTC for heavy truck dynamics and stability testing. The other vehicle was a 1996 Peterbilt Model 377 6x4 (referred to as "Peterbilt" or "R4" in this report), leased to VRTC by DANA corporation. The vehicle specifications are tabulated in Table 1. Note that "rear side" control ABS indicates that brake pressure chambers on either side of the rear tandem are controlled together, with wheel speed feedback from the rear axle only. Similarly, "intermediate side" control indicates that wheel speed control feedback is from the intermediate (or lead) drive axle only, from which both sides of the tandem are controlled together.

Table 1: Overview of Peterbilt and Volvo Test Tractors

	1996 Peterbilt 377	**1991 Volvo WIA64T**
Gross Vehicle Weight Rating (GVWR, lb)	50,000	50,000
Unloaded Curb Weight (lb)	20,460	19,070
Wheelbase (in)	235.0	189.5
Track width f/r (in)	82/72	82/72
Front suspension	12k# 2 Leaf spring	12k# Leaf spring
Rear suspension	38k# Pneumatic	38k# 4-leaf spring parabolic
ABS system	Eaton 4S4M w/ rear side control	2001 Meritor 4S4M type-D w/ intermediate side control
CG location (x, in), unloaded	106.0 behind steer axle c.l.	103.6 behind steer axle c.l.
CG location (x, in), GVWR	178.6 behind steer axle c.l.	144.0 behind steer axle c.l.
Steer axle tire	295/75R22.5 G-14 Bridgestone R299 rib	275/80R24.5 G-14 Michelin Pilot XZA-1+
Drive Axle Tire	295/75R22.5 G-14 Bridgestone M711 lug	275/80R24.5 G-14 Michelin Pilot XDA-2

2.2 Foundation Brake Configurations Tested

The foundation brake configurations tested included the following:

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 (also referred to as "X-large steer")

c) Hybrid disc: air disc brakes on steer, standard S-cam drums on drive axles (also referred to as "disc steer")

d) Air disc brakes on steer and drive axles

Although the foundation brake configurations were the same for both tractors tested, the manufacturer and consequently specific parts of the foundation brakes were different from tractor to tractor. Brake configuration details are presented in Tables 2 through 5. Each table lists part specifications for a specific configuration of foundation brakes. Air chamber sizes were based on the brake manufacturers' recommendations. The foundation brake configurations evaluated on the Peterbilt were exclusively Dana brake packages, and the brake configurations on the Volvo were exclusively Meritor brake packages.

Table 2: Brake Specifications for the Standard S-cam Drum Brake Configuration (S-cam drums)

	1996 Peterbilt		1991 Volvo	
	Steer axle	**Drive axle**	**Steer axle**	**Drive axle**
Air chamber	Grau type 20	MGM 30/30	type 20S	30/30
Slack adjuster	5.5" auto	5.5" auto	5.5" auto	5.5" auto
Brake shoe	ES-1504L	ES-1657	SMA2124702QP	SMA2124707QP
Brake lining	ES-420	ES-410	MA 212	MA 212
Brake drum/rotor	Gunite 3721	Gunite 3600A	Meritor15156323	Meritor14156751
Brake type	Dana 15 x 4	Dana 16.5 x 7	Meritor 15x4 Q Plus	Meritor 16.5x7 Q Plus

Table 3: Brake Specifications, High-output S-cam Drums on Steer Axle Configuration (Hybrid Drum)

	1996 Peterbilt		1991 Volvo	
	Steer axle	**Drive axle**	**Steer axle**	**Drive axle**
Air chamber	type 30L3	MGM 30/30	type 20S	30/30
Slack adjuster	5.5" auto	5.5" auto	5.5" auto	5.5" auto
Brake shoe	ES-1656	ES-1657	SMA2104720QP	SMA2104707QP
Brake lining	ES-670	ES-410	MA 210	MA 210
Brake drum/rotor	Gunite 3687	Gunite 3600A	Meritor85123370	Meritor85123207
Brake type	Dana 16.5 x 6	Dana 16.5 x 7	Meritor 16.5 x 5 Q Plus	Meritor 16.5 x 7 Q Plus

Table 4: Brake Specifications, Air Disc Brakes on Steer Axle Configuration (Hybrid disc – ADB on steer axle only)

	1996 Peterbilt		1991 Volvo	
	Steer axle	**Drive axle**	**Steer axle**	**Drive axle**
Air chamber	Grau type 24	MGM 30/30	MGM 20L 1621016 (2.5" stroke)	Maxibrake N36330A-212K type 30/30
Slack adjuster	Internal control arm	5.5" auto	3.5" control arm	5.5" auto
Brake shoe/pad	ESD 1550	ES-1657	70200060	SMA2124707QP
Brake lining	AD1550	ES-410	MA 703	MA 212
Brake drum/rotor	Webb 16.93"O.D. x 1.77"	Gunite 3600A	Webb 16.54"O.D. x 1.77"	Meritor1415675107
Brake type	Dana ESD 225	Dana 16.5 x 7	Meritor DX225	Meritor 16.5 x 7 Q Plus

Table 5: Brake specifications, Full air disc brakes configuration (all disc brakes – ADB on all axles)

	1996 Peterbilt		1991 Volvo	
	Steer axle	**Drive axle**	**Steer axle**	**Drive axle**
Air chamber	Grau type 24	Grau type 24	MGM 20L 1621016 (2.5" stroke)	MGM 24L/30
Slack adjuster	Internal control arm	Internal control arm	3.5" control arm	3.5" control arm
Brake pad	ESD 1550	ESD 1550	DiscPlus	DiscPlus
Brake lining	AD1550	AD1550	MA 703	MA 703
Brake drum/rotor	Webb 16.93"O.D. x 1.77"	Webb 16.93"O.D. x 1.77"	Webb 16.54"O.D. x 1.77"	Webb 16.54"O.D. x 1.77"
Brake caliper	Dana ESD 225	Dana ESD 225	Meritor DX225	Meritor DX225

2.3 Test Methodology

The full-treadle braking tests discussed herein were performed on the dry concrete skid pad at the Transportation Research Center, Inc., having nominal peak and slide surface friction coefficients of 98 and 84, respectfully. Initial brake pad and/or lining temperature (I.B.T.) was nominally 150-200 °F before initiating each braking run. Brake pad temperatures were monitored as outlined in the FMVSS No. 121 test procedure.

The stopping distances were measured with a 5th wheel assembly, mounted on the rearmost part of the tractor frame. Stopping distances were recorded from a Labeco Tracktest Fifth Wheel System Performance Monitor, which displays initial speed and integrated stopping distance.

All measured stopping distances were corrected via the standard method as prescribed by SAE J299 (re: SAE Handbook); all stopping distances were normalized to the intended initial speed (for these tests 96.6 kph, or 60 mph). Nominally, six consecutive repetitions for each tractor-brake-load configuration were performed.

2.3.1 Driver Instructions

The professional test driver, having over a decade experience in testing heavy trucks, was instructed to establish the test speed after the minimum brake temperature was reached. Using the same lane on the skid pad for each stop, the driver would maintain lane position while fully opening the brake treadle valve within 0.5 seconds, as outlined in FMVSS No. 121 test procedure. The brake pedal remained fully applied until the vehicle came to rest unless the driver noticed an extended full brake lockup, which might signal an ABS problem and could result in severe tire damage or loss of control. The location of each stop in a given series was kept consistent.

3 RESULTS AND ANALYSES

3.1 Full Service Brake System Minimum and Mean Stopping Distances

Tables 6 through 9 contain comparisons of stopping distances with different foundation brake types for the two test tractors. The minimum of six stops is shown for each brake type along with their corresponding margins of compliance, based on a 30 percent reduction of the current FMVSS No. 121 requirement. The mean for each brake type is also shown, along with its difference from the proposed 30 percent reductions. Note that for most configurations, the difference and margin of compliance are within a few percent.

Tables 6 and 7 show stopping distance results for each tractor at the LLVW (bobtail) load condition. Figures 2 and 3 graphically illustrate minimum, maximum and mean stopping distances for the LLVW load condition, corresponding to Tables 6 and 7. Likewise, Tables 8 and 9 (as well as Figures 4 and 5) compare brake configurations for both tractors at the GVWR load condition.

For the LLVW load configuration, all brake configurations produced a minimum stopping distance under a proposed 30% reduction in the current FMVSS No. 121 standard. All modified (i.e., non-standard) brake configurations resulted in minimum stopping distances with substantial margins of compliance (greater than 10%) over the proposed reduction. The smallest margin of compliance for any non-standard brake configuration was 14.7%. The “hybrid disc” and “all-disc” brake configurations yielded similar margins of compliance (over 20%) for both tractors in the LLVW load configuration.

Table 6 **Stopping Distances for each brake type on the Peterbilt tractor in the LLVW load configuration showing the minimum and mean of 6 stops. Margins of compliance are based on a 30 percent reduction of the current FMVSS No. 121 requirement.**

	Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Foundation Brake Type	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
All S-cam Drums	222	5.4%	230	2.0%
Hybrid Drums	191	18.9%	192	18.5%
Hybrid Disc	177	24.5%	178	24.1%
All Disc	176	25.2%	181	23.2%

Table 7 **Stopping Distances for each brake type on the Volvo tractor in the LLVW load configuration showing the minimum and mean of 6 stops. Margins of compliance are based on a 30 percent reduction of the current FMVSS No. 121 requirement.**

	Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Foundation Brake Type	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
All S-cam Drums	203	13.7%	212	10.0%
Hybrid Drums	200	14.7%	205	12.6%
Hybrid Disc	177	24.6%	181	22.9%
All Disc	181	22.9%	188	19.9%

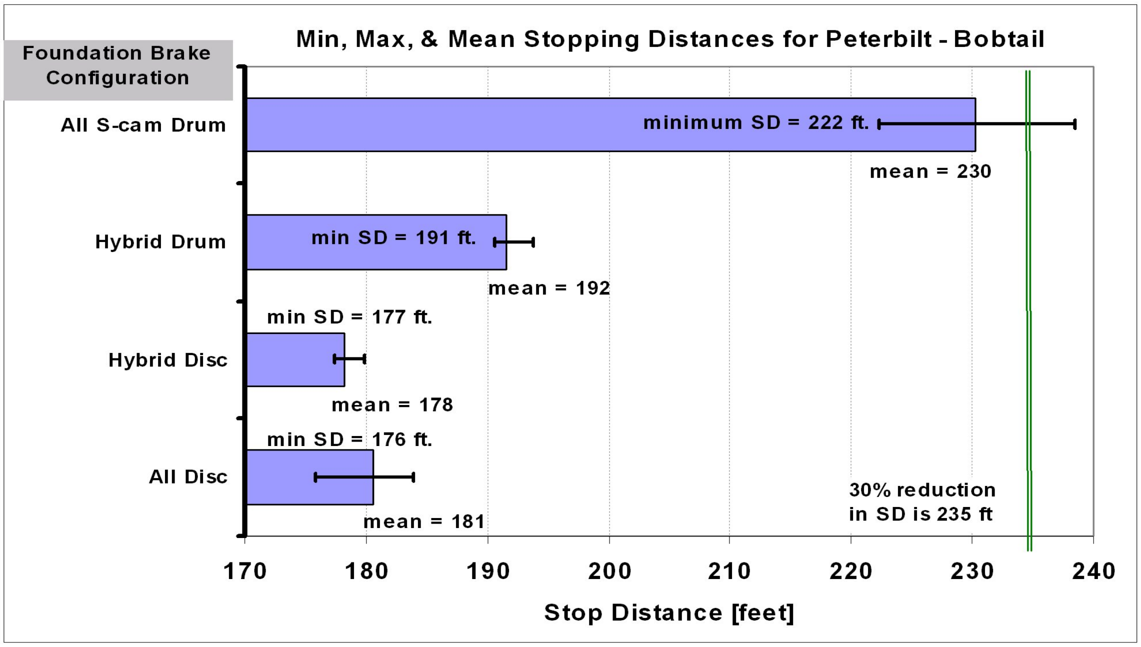

Figure 2: Stopping distance for foundation brake configurations on the Peterbilt tractor at the LLVW load. Histobars show the mean of six consecutive stops – the mean is printed at the end of each histobar. Variance bars show the minimum and maximum of the six stops – the numeric value for the minimum stopping distance is also shown. A 30% reduction in the current FMVSS No. 121 limit is shown at the right.

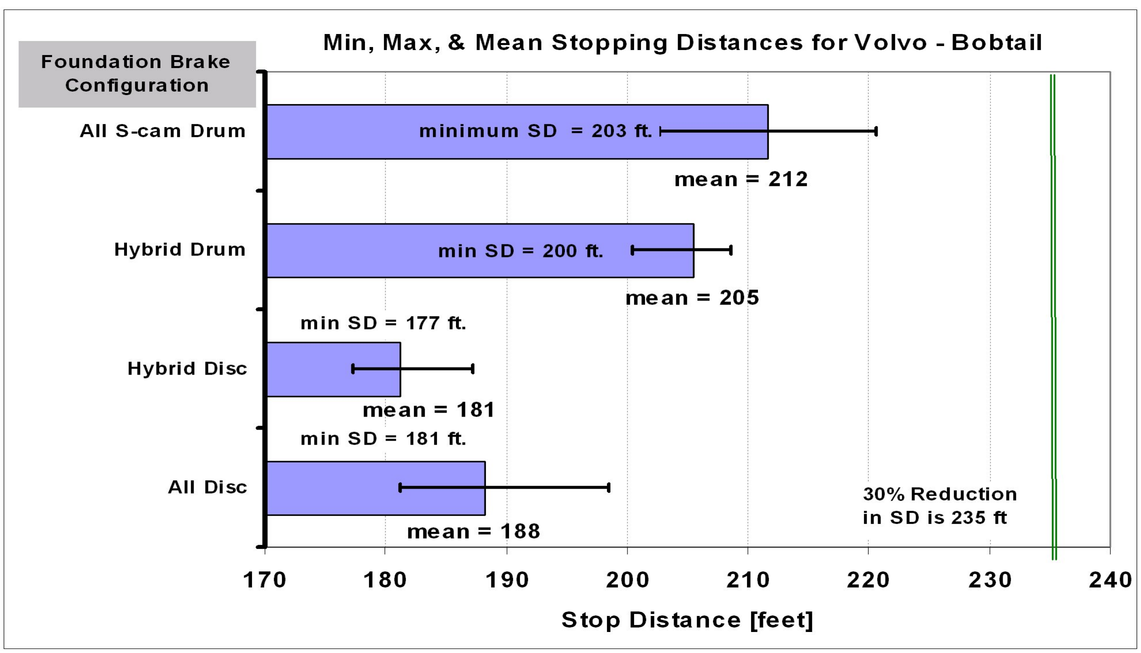

Figure 3: Comparison of stopping distance for foundation brake configurations on the Volvo tractor at the LLVW (bobtail) load condition. Refer to Figure 2 for plot formatting and conventions.

The margins of compliance at GVWR were different than those for the LLVW condition. For both tractors, a proposed 30% reduction in minimum stopping distance was not met when fully loaded in the standard (“full S-cam”) brake configuration or the with “hybrid drum” brake configuration. Margins of compliance at GVWR were unacceptably thin (or nonexistent) for both truck tractors in the “hybrid disc” brake configuration. With air disc brakes on all brake positions, the Peterbilt had a significant margin of compliance (i.e., over 10%). The margin of compliance for the Volvo with “all disc” brakes was only 5.6% for the minimum stopping distance. Note that for both tractors, margins of compliance for the minimum of six stops were usually similar to the “difference from minimum requirement” for the mean stopping distance.

Table 8 **Stopping Distances for each brake type on the Peterbilt tractor in the GVWR load configuration showing the minimum and mean of 6 stops. Margins of compliance are based on a 30 percent reduction of the current FMVSS No. 121 requirement.**

	Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Foundation Brake Type	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
All S-cam Drums	307	-23.4%	317	-27.3%
Hybrid Drums	250	-0.3%	252	-1.3%
Hybrid Disc	234	6.2%	247	0.8%
All Disc	218	12.5%	222	10.7%

Table 9 **Stopping Distances for each brake type on the Volvo tractor in the GVWR load configuration showing the minimum and mean of 6 stops. Margins of compliance are based on a 30 percent reduction of the current FMVSS No. 121 requirement.**

	Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Foundation Brake Type	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
All S-cam Drums	260	-4.3%	264	-6.2%
Hybrid Drums	264	-5.8%	269	-7.9%
Hybrid Disc	249	0.1%	263	-5.6%
All Disc	235	5.6%	241	3.3%

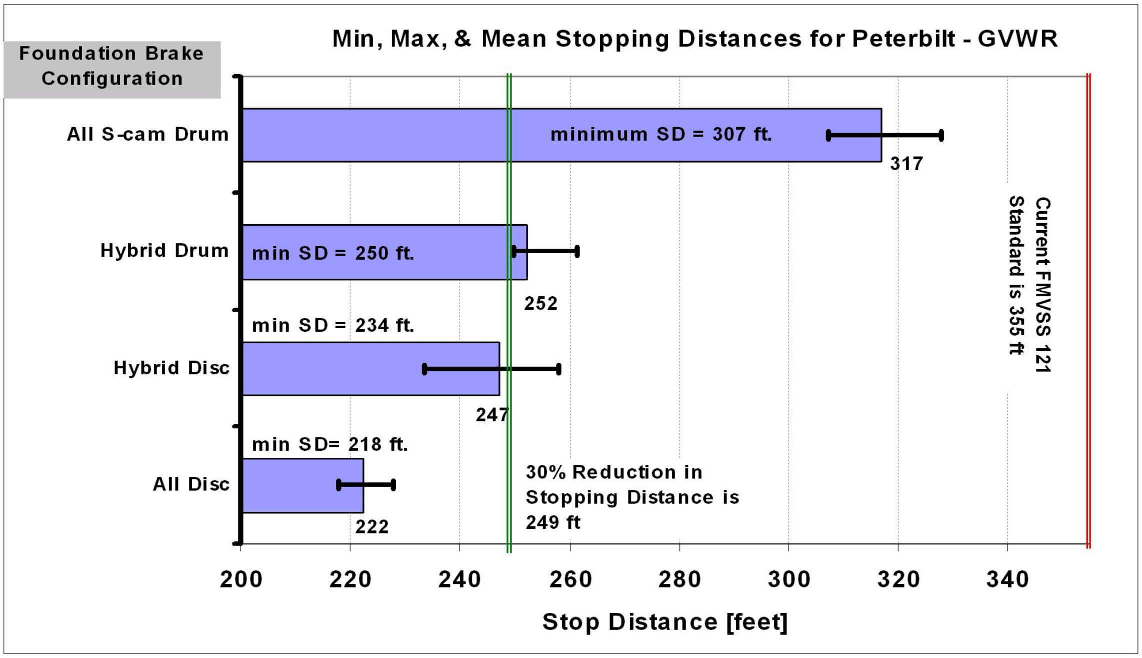

Figure 4: Comparison of stopping distance for foundation brake configurations on the Peterbilt tractor at the GVWR load condition. Refer to Figure 2 for plot formatting and conventions. Current and proposed FMVSS No. 121 limits at GVWR are shown by vertical lines.

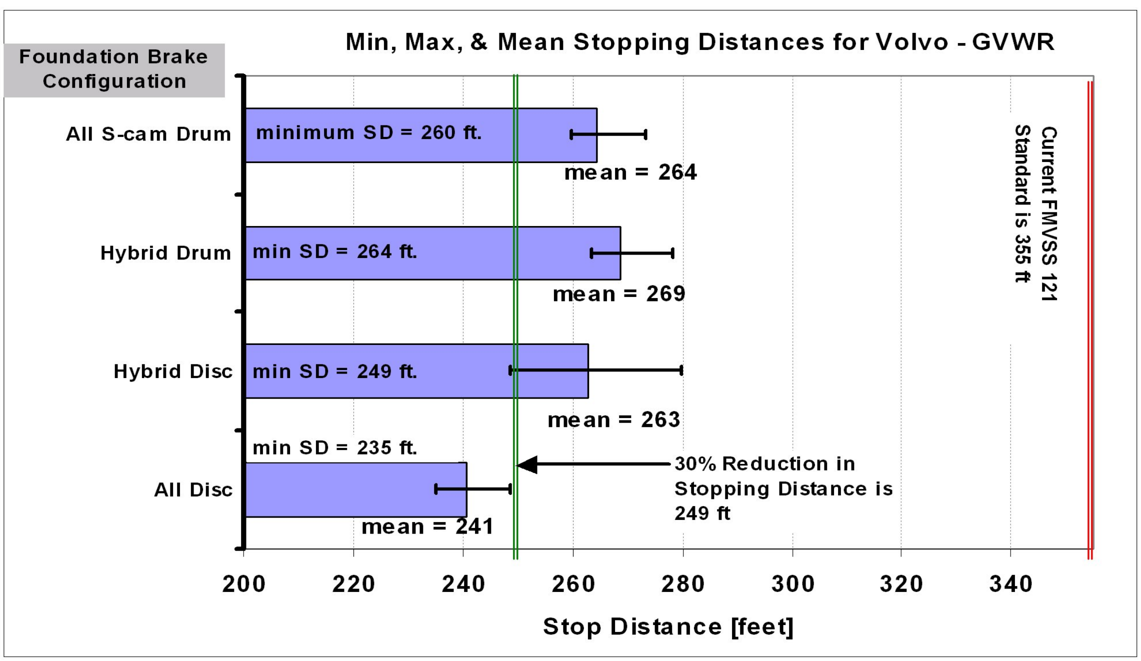

Figure 5: Comparison of stopping distance for foundation brake configurations on the Volvo tractor at the GVWR load condition. Refer to Figure 2 for plot formatting and conventions.

3.2 Failed Systems Testing Minimum and Mean Stopping Distances

Emergency braking systems were tested as specified in FMVSS No. 121 by simulating the following system malfunctions:

a. Failed primary control line

b. Failed primary reservoir

c. Failed secondary reservoir

Primary control line failure was simulated by removal of the primary pneumatic control signal from the relay valves for the drive axle brakes, thus simulating a failure of the control signal to reach the drive axle brakes while still operating the steer axle brakes. The failed primary and secondary reservoirs were separately simulated by having the driver vent the air pressure in the selected reservoir to atmospheric pressure, via remotely operated solenoid valves. A full pedal service brake application was then made within 5 seconds after the low-pressure warning alarm activated (nominally at 60 psi). The stopping distance testing was otherwise performed as described in Section 2.3.

Minimum stopping distances and their corresponding margins of compliance, relative to a 30% reduction in the current minimum requirement, are presented in Tables 10 through 12. The means (of nominally six stops) and their margins relative to the same proposed 30% reduction in the minimum are also presented. Graphic results were not compiled for the failed systems data.

Table 10 Failed Primary Control Line Stopping Distances for each brake type on both truck tractors in the LLVW load configuration.

		Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Tractor	**Foundation Brake Type**	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
Peterbilt	All S-cam Drums	225	68.7%	232	67.7%
	Hybrid Drums	186	74.1	190	73.6
	Hybrid Disc	176	75.5	179	75.1
	All Disc	175	75.7	180	75.0
Volvo	All S-cam Drums	207	71.3%	214	70.3%
	Hybrid Drums	201	72.1	204	71.7
	Hybrid Disc	179	75.1	183	74.6
	All Disc	184	74.4	185	74.3

Table 11 Failed Primary Reservoir Stopping Distances for each brake type on both truck tractors in the LLVW load configuration.

		Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Tractor	**Foundation Brake Type**	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
Peterbilt	All S-cam Drums	636	11.7%	666	7.5%
	Hybrid Drums	363	49.6	384	46.7
	Hybrid Disc	276	61.6	283	60.7
	All Disc	294	59.2	300	58.4
Volvo	All S-cam Drums	432	40.0%	451	37.3%
	Hybrid Drums	365	49.4	404	43.9
	Hybrid Disc	300	58.3	312	56.7
	All Disc	303	57.9	315	56.3

Table 12 Failed Secondary Reservoir Stopping Distances for each brake type on both truck tractors in the LLVW load configuration.

		Minimum Stopping Distance		Mean Stopping Distance (of 6)	
Tractor	**Foundation Brake Type**	**Minimum (ft.)**	**Margin of compliance**	**Mean (ft.)**	**Difference versus 30% reduction**
Peterbilt	All S-cam Drums	386	46.4%	391	45.7%
	Hybrid Drums	389	46.0	412	42.8
	Hybrid Disc	396	45.0	405	43.7
	All Disc	419	41.8	430	40.2
Volvo	All S-cam Drums	386	46.4%	392	45.5%
	Hybrid Drums	381	47.1	386	46.3
	Hybrid Disc	372	48.3	384	46.6
	All Disc	392	45.6	408	43.4

3.3 Statistical Analyses Overview

Analysis of Variance (ANOVA) analyses were performed using the Statistical Analysis Software package (S.A.S.) with the corrected stopping distance data as the dependent measure. Nominally, six repetitions for each tractor-brake-load configuration were analyzed. ANOVA analyses are used to gauge main and interaction effects of independent treatments (in this case *brake type, tractor*, or *load*) on a dependant variable (*stopping distance*). ANOVA analyses provide for the comparison of the means without assuming linear relationships. A “Pr > F” of 0.05 was used as the limit for statistical significance for all analyses.

3.4 Statistical Analyses of the Full Service Brake System Stops

Statistical analyses were conducted and the findings are listed in their respective subheadings below. All three analyses used *stopping distance* as the only dependent variable. The first of the three separate analyses covers all tractor-brake-load configurations combined, with *brake type*, *tractor*, and *load* being the independent variables. Although the means are not as meaningful since stopping distance results are combined for varying loads and truck tractor, the analyses are important if one seeks the effect of brake type on entire data set. The second of the three analyses breaks the tractor-brake configurations out by load (i.e., LLVW and GVWR), thereby making the stopping distance comparisons to field testing more meaningful. Here, the independent variables are *brake type* and *tractor*, while the dependent variable remains *stopping distance*. The final analyses are of the failed systems (as required by FMVSS No. 121) and are conducted at the LLVW load condition only; *brake type* and *tractor* are the only independent variables.

3.4.1 All tractor-brake-load configurations combined

Before breaking out the data by load, the ANOVA model used *brake type, tractor*, and *load* as independent variables and *stopping distance* as the dependent measure. Observations of the combined results analysis, presented in Table 13, are as follows:

a. Stopping distance was found to be significantly different for all brake configurations. Factors of *load* and *brake type* were found to be statistically significant, as were interactions of "*tractor* $\times$ *brake*" and "*brake* $\times$ *load*."

b. When added as an independent measure to the above model, *replication number* was found to have no significant trend (i.e., there was no indication that for any foundation brake configuration, stopping distance was a function of stop order).

c. The effect of "*tractor*" had an insignificant influence on stopping distance. This indicates that – statistically speaking – differences in stopping distance could not be attributed to whether the test tractor was the Peterbilt or Volvo.

Table 13 ANOVA Results table for the both load conditions combined

Effect	DF	F value	Pr > F
Replication	5	0.36	0.8730
Tractor	1	0.05	0.8177
Brake	3	167.74	<0.001
Load	1	1576.90	<0.001
Tractor x Brake	3	56.14	<0.001
Brake x Load	3	15.24	<0.001

3.4.2 All tractor-brake configurations combined, analyzed per load

This analysis was performed to allow the means for the LLVW or "no load" and GVWR conditions to be presented separately, which provides more meaningful stopping distance means when compared to current standards and stopping distance measurements. The ANOVA model used *brake type* and *tractor*, as independent variables and *stopping distance* as the dependent measure. Results for the unloaded and loaded conditions are given in Tables 14 and 15, respectively.

Table 14: ANOVA Results table for the LLVW (bobtail) condition

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1,47	0.95	0.3348	Not significant
Brake	3,47	247.02	<.0001	.83
Tractor x Brake	3,47	34.68	<.0001	.11

Table 15: ANOVA Results table for the GVWR (fully loaded) condition

Effect	DF	F value	Pr > F	Magnitude of Treatment Effect ω^2
Tractor	1,47	0.05	0.8295	Not significant
Brake	3,47	160.15	<.0001	.62
Tractor x Brake	3,47	81.11	<.0001	.31

A very small "Pr > F" value indicates a statistically significant effect for that treatment on the model. I.e., for Table 14, the effect of *tractor* is not significant ("Pr > F" = 0.3348), whereas the effect of *brake* is significant ("Pr > F" < 0.0001). Conversely larger values for ω^2 indicate stronger normalized influence of the treatment on the response. The findings are discussed below:

a. All brake configurations were found to result in significantly different mean stopping distances for the LLVW (bobtail) load condition. The LLVW rankings are illustrated at full and zoomed-in scales in Figures 6 and 7, respectively. The 95% confidence intervals for brake types of "all-disc" and "hybrid disc" (in Figures 6 and 7) just meet at 181 ft.

b. Brake configurations of "hybrid disc" and "hybrid drum" were found by post-hoc analysis to be statistically similar for the GVWR condition. "All disc" and "all S-cam" configurations were statistically separate. The GVWR rankings are illustrated at full and zoomed-in scales in Figures 8 and 9, respectively. Note again that the 95% confidence intervals shown in Figures 8 and 9 agree with the ANOVA and post-hoc analyses.

c. The "*tractor* × *brake*" interaction was significantly stronger for the loaded condition than for the unloaded condition (re: Tables 14 and 15).

d. The ANOVA model accounted for 97% of the observed variance in stopping distance, which indicates a very good "fit" for the model.

e. To understand stopping distance variability within each *brake type*, the standard deviation for each set of stops (for each brake configuration) were normalized by their respective mean. This method normalizes the effect of the magnitude of the mean on the variance. Analyses (presented in Table 16) indicate that there is more variation (as a percentage of the mean) for the loaded condition versus the unloaded condition. The normalized standard deviation for the "standard S-cam" configuration was found to have the most variation for both "loaded" and "unloaded" conditions. The minimum normalized variation belonged to the "hybrid disc" configuration for the unloaded condition, and to the "hybrid drum" configuration for the loaded condition.

Table 16: Mean normalized standard deviations for stopping distances

Brake configuration	Unloaded	GVWR
All S-cam	.0512	.0961
Hybrid Drum	.0375	.0374
Hybrid Disc	.0103	.0490
All disc	.0325	.0455
Mean	.0329	.0570

f. A noticeable outlier in these analyses is the disparity in means for the "standard S-cam" setup run at GVWR on both test tractors. The mean of six stops for this configuration was 264 ft. for Volvo. The mean for the Peterbilt, under the same condition and brake type, was 317 ft. Stopping distances at the GVWR load condition are broken out by tractor in Figures 10 and 11, with the Peterbilt shown in Figure 10 and the Volvo shown in Figure 11. As compared using Figures 10 and 11, the mean of 264 ft. for the Volvo (with all S-cam brakes) appears "out of place" versus the other results for both tractors. However, when the results for both tractors were combined for the ANOVA analyses, this disparity in means for the two "all S-cam" configurations did not result in the loss of statistical validity of the comparison of brake configurations at the GVWR condition. Note that this disparity is driving the importance of the *tractor* $\times$ *brake* interaction term in Table 15.

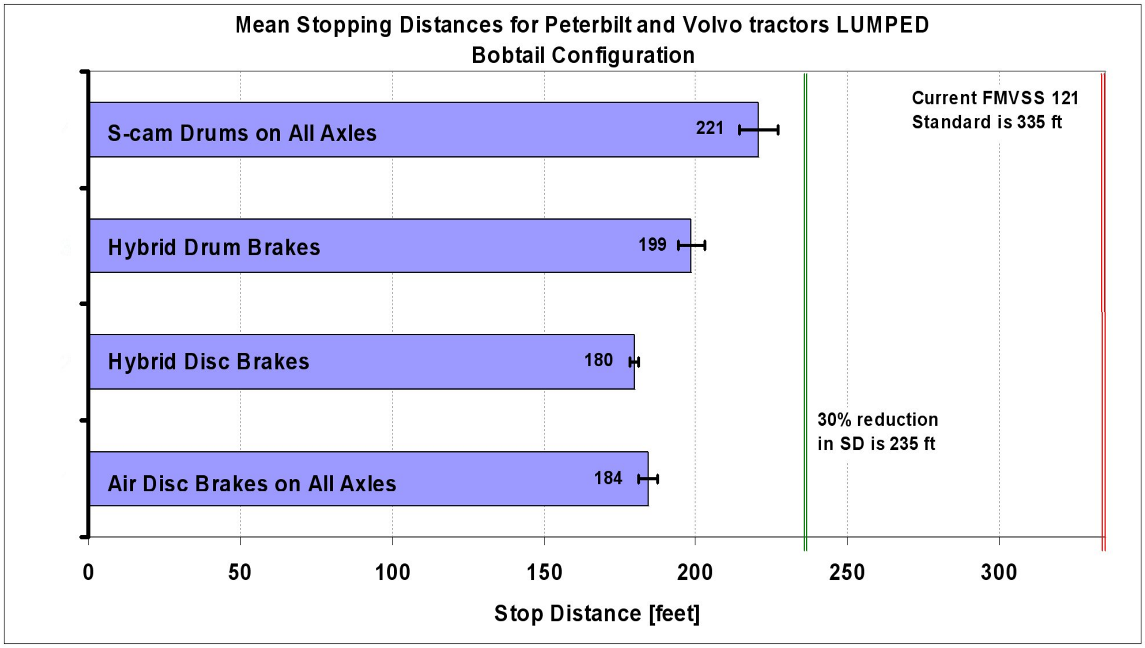

Figure 6: Full-scale comparison of stopping distance means for the both tractors combined at LLVW condition. 95% confidence intervals for the means are plotted at the end of the histobars. Current and 30% reduced FMVSS No. 121 limits are shown.

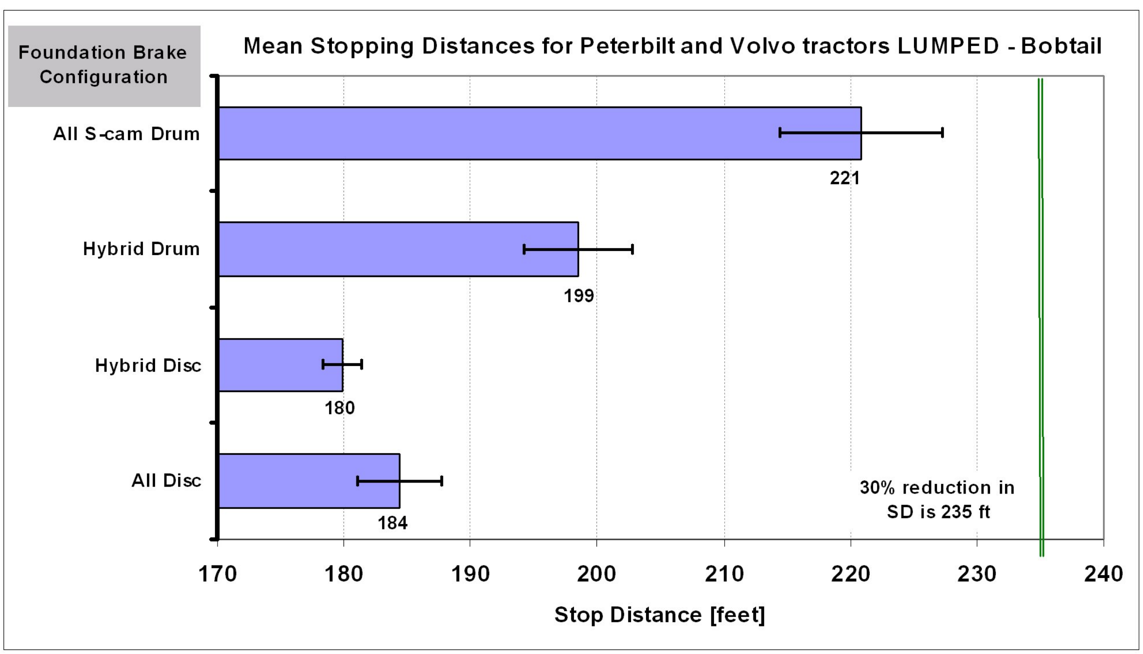

Figure 7: Zoomed-in view of stopping distance means comparison for the both tractors combined at LLVW condition. 95% confidence intervals for the means are plotted at the end of the histobars. A 30% reduction in the FMVSS No. 121 limit is shown at the right of the chart.

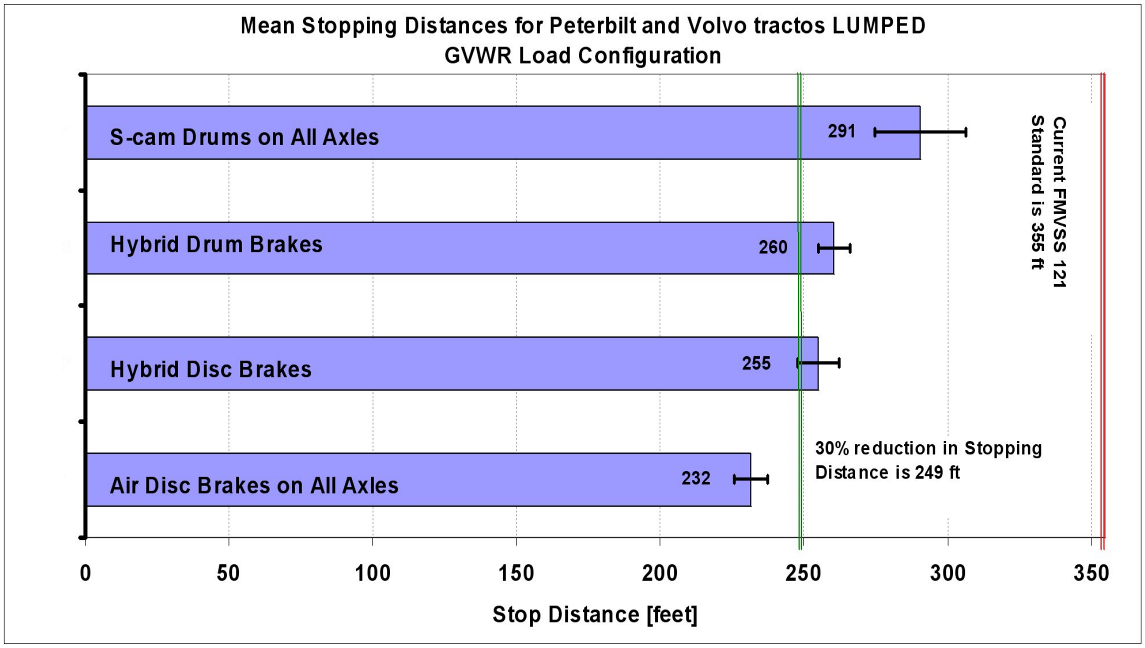

Figure 8: Full-scale comparison of stopping distance means for the both tractors combined at the GVWR load condition. 95% confidence intervals are plotted at the end of the histobars. Current and 30% reduced FMVSS No. 121 limits are shown.

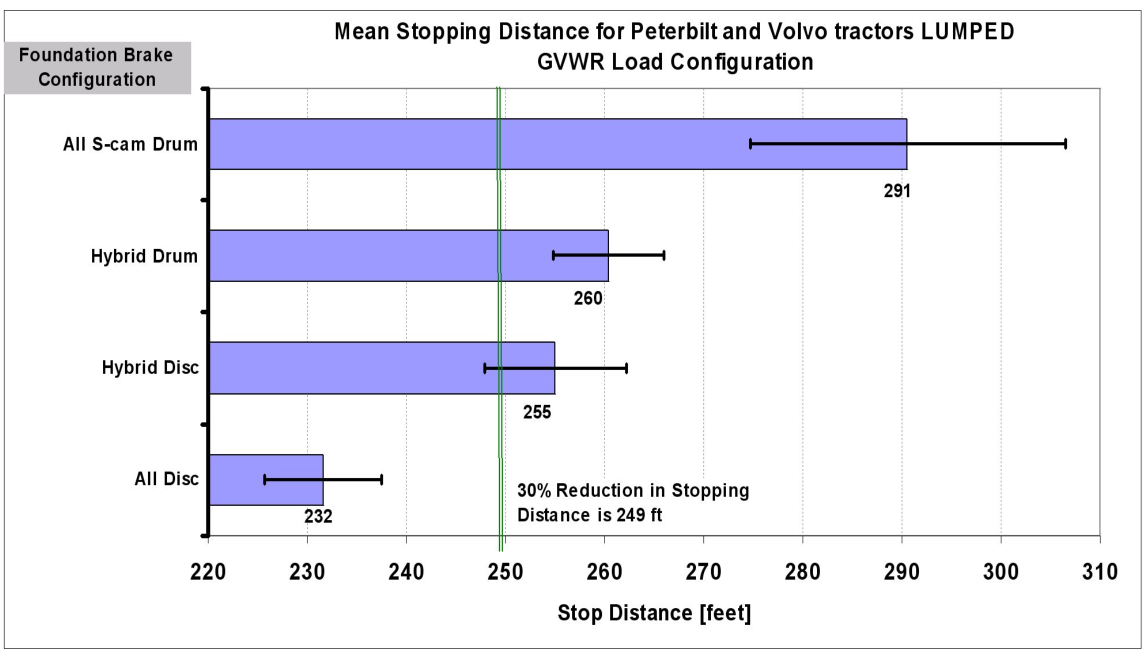

Figure 9: Zoomed-in view of stopping distance means comparison for the both tractors combined at the GVWR load condition. 95% confidence intervals are plotted at the end of the histobars. A 30% reduction in the FMVSS No. 121 limit is shown.

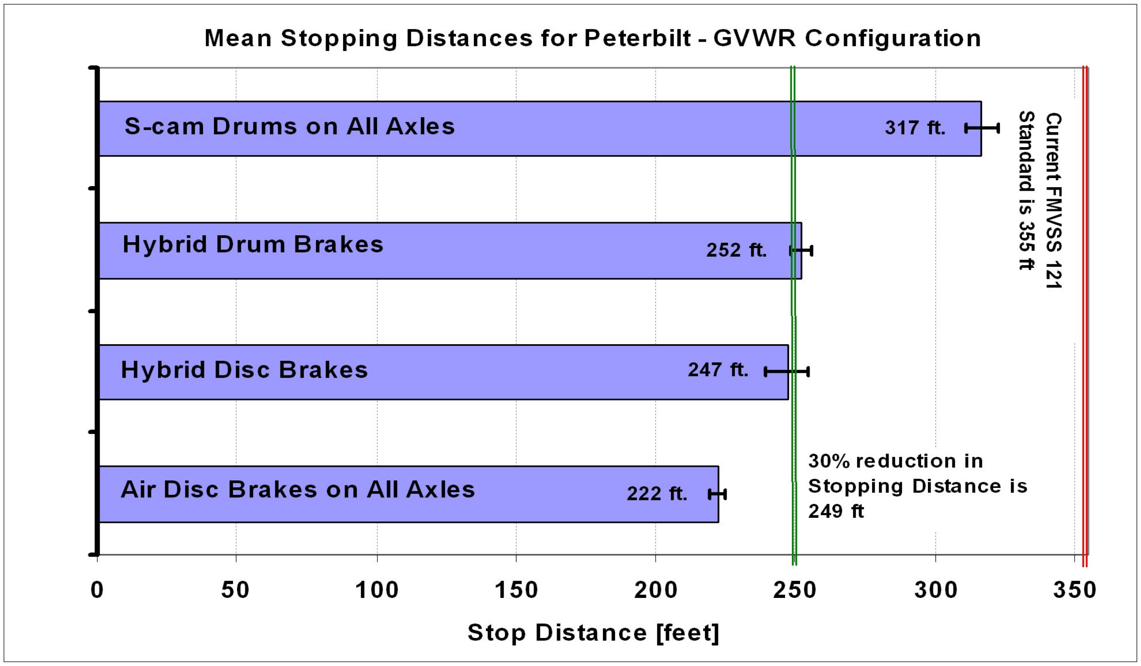

Figure 10: Full-scale comparison of stopping distance means for the Peterbilt tractor at the GVWR load. 95% confidence intervals for the means are plotted at the end of the histobars. Current and proposed FMVSS No. 121 limits are shown.

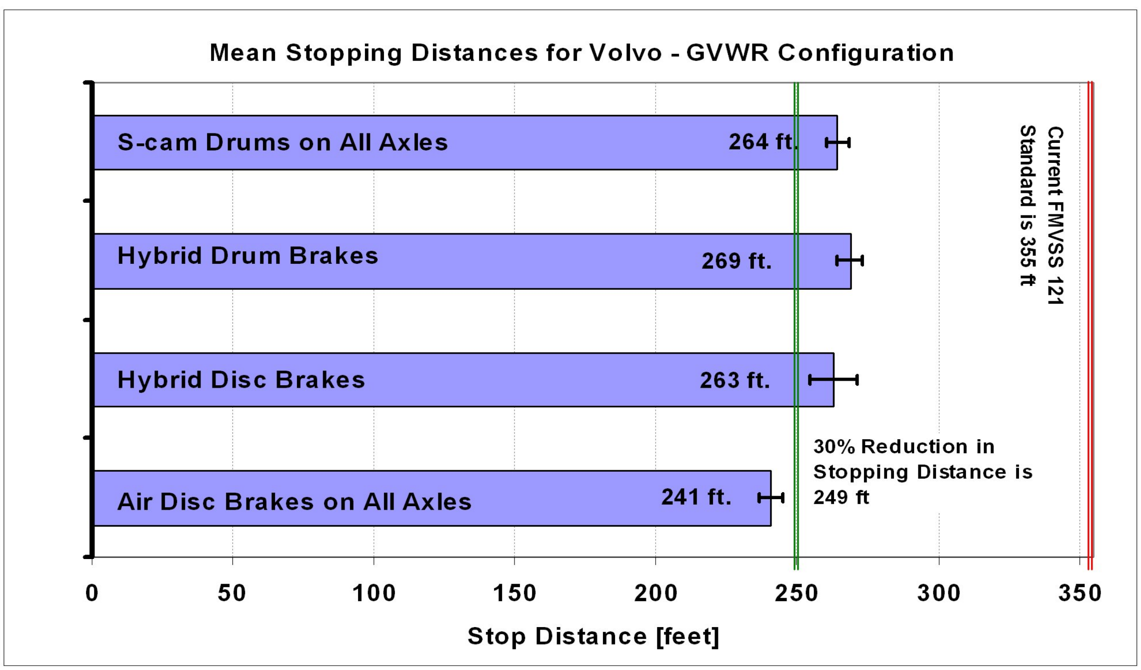

Figure 11: Full-scale comparison of stopping distance means for the Volvo tractor at the GVWR load. 95% confidence intervals for the means are plotted at the end of the histobars. Current and proposed FMVSS No. 121 limits are shown.

3.5 Statistical Analyses of the Failed System Stops

ANOVA analyses were also conducted on three failed systems configurations:

a. Failed primary control line

b. Failed primary reservoir

c. Failed secondary reservoir

The summaries of the analyses of the failed systems are given below in Tables 17 and 18. Table 17 contains the ANOVA results for all failed system tests. Table 18 contains model fit quality and degrees of freedom. The ANOVA results provide the following conclusions:

a. For the condition of failed primary control line, *brake type* was found to have a statistically significant effect on stopping distance.

b. There was generally little or no difference in stopping distance associated with the primary control line failure mode, versus the baseline (full functional system) condition run at LLVW. Refer to Figure 12.

c. Differences due to *tractor* were considerably more important in the "Secondary Reservoir Failure" mode than for the other two modes of failure.

Table 17: ANOVA Results table for the Failed System Testing, LLVW

	Failed Primary Cntrl. Line			**Failed Primary Reservoir**			**Failed Secondary Reservoir**		
Effect	**F**	**Pr > F**	ω^2	**F**	**Pr > F**	ω^2	**F**	**Pr > F**	ω^2
Tractor	1.80	0.32	Not significant	80.32	<0.0001	.03	43.37	<0.0001	.25
Brake	323.7	<0.0001	.86	624.33	<0.0001	.76	23.34	<0.0001	.39
Tractor × Brake	39.50	<0.0001	.10	152.46	<0.0001	.19	5.74	0.0024	.08

Table 18: Model Correlation Coefficient and degrees of freedom for the Failed Primary Reservoir Tests, LLVW

	Failure Mode		
	Primary Control Line	Primary Reservoir	Secondary Reservoir
Model R^2	.96	.98	.77
Number of trials (dof)	47	47	48

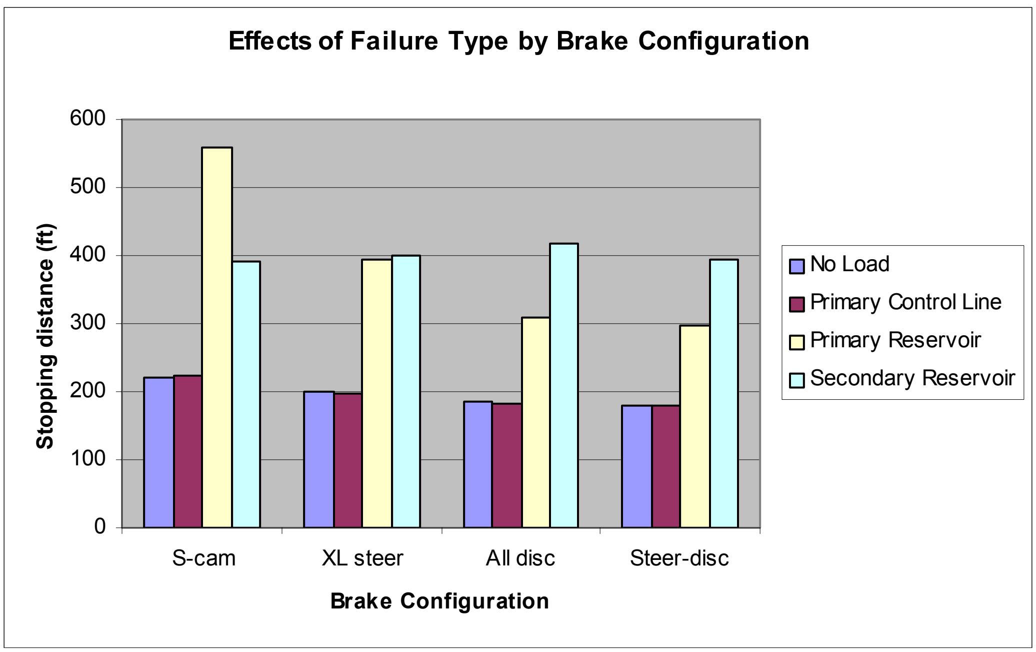

Figure 12: Combined means comparing each evaluated brake system failure mode and the fully functional system (labeled "No Load"). All tests were at LLVW (bobtail).

4 COMPARISON OF MINIMUM AND MEAN MEASUREMENTS

The current FMVSS No. 121 Road Test Procedures call for the minimum measurement of six stops to not exceed the prescribed limit. This procedure, conceived before FMVSS No. 121 made antilock brake systems (ABS) mandatory for air braked vehicles, was developed to recognize the driver's best effort stop from a group of stops that could have significant deviation. In the ensuing decade, antilock braking system proficiency has developed to the point that a group of six stops using the full service brake system will generally have a small standard deviation about their mean.

The results presented herein suggest that prediction and comparison of dry braking performance of a population of truck tractors is better achieved by specifying the mean (of an appropriate number of stops) with their appropriate confidence interval, as opposed to the current practice of specifying the minimum stopping distance of a group of stops. Sample minimums, which by definition might be "outliers," could provide significantly optimistic predictions. Recent testing indicates that contemporary truck tractor brake and ABS control systems provide for very good statistical grouping for stopping distances. Figures 13 and 14 illustrate how the two analyses of the same data could yield different results, based on the two methods. Comparison of Figures 13 and 14 shows that using minimum stopping distance as the criterion, the "hybrid disc" configuration *would* meet a 30% reduction in stopping distance limits, whereas using the mean (of six stops) with 95% confidence intervals, the same configuration *would not* meet a 30% reduction.

The tight groupings for stopping distances discussed herein suggest a difference that was generally around 2% (and not exceeding 6%) between the minimum and mean of each group of six stops, corresponding to approximately 5 ft. Considerable further investigation would be necessary to deduce an appropriate number of repetitions and confidence interval procedure. Extensive historical data is available at VRTC that would be useful in such future investigations.

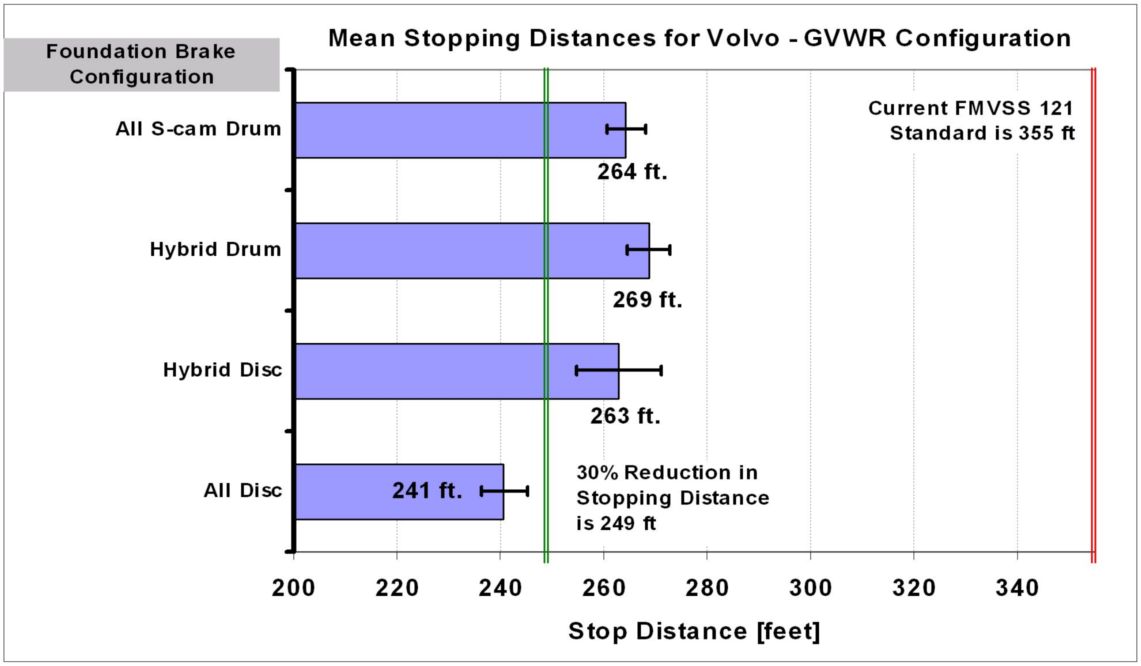

Figure 13: Comparison of mean stopping distance for the four foundation brake configurations on the Volvo tractor at GVWR showing 95% confidence intervals, using variance bars, about the mean of six stops.

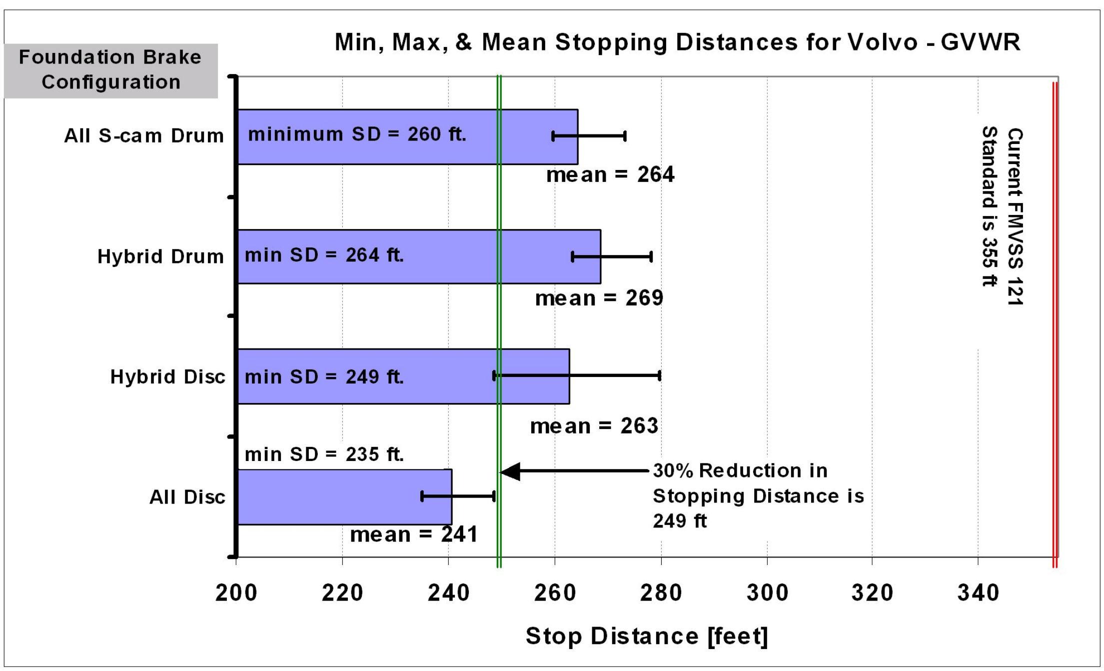

Figure 14: Comparison of stopping distance for foundation brake configurations on the Volvo tractor at the GVWR load condition. The histobars represent the mean of six stops with the minimum and maximum indicated by the variance bar limits.

5 PEER VEHICLE COMPARISON

The three peer vehicles tested each had less than 50,000 miles on them. The following peer vehicles are included for reference and comparison to the performance of the focus vehicles (Peterbilt and Volvo tractors):

1. 1998 Freightliner Argosy 6x4 prototype tractor with ABS, equipped with:
    a. Steer axle brakes: 14.88 x 1.77 Meritor DX195 Air Disk Brakes & ECBS
    b. Drive axle brakes: 14.88 x 1.77 Meritor DX195 Air Disk Brakes & ECBS
    c. 22.5" steer axle tires / 19.5" drive axle tires
2. 2001 Mack 6x4 tractor with ABS, equipped with:
    a. Steer axle brakes: 15x4 S-cam drum
    b. Drive axle brakes: 16.5x7 S-cam drum
    c. 22.5" steer and drive axle tires
3. 2000 Ford Sterling 4x2 tractor with ABS, equipped with:
    a. Steer axle brakes: 16.5x5 S-cam drum
    b. Drive axle brakes: 16.5x7 S-cam drum
    c. 295/75R22.5" steer and drive axle tires

The peer vehicles were tested at LLVW (bobtail) and GVWR conditions (with unbraked control trailer). Figures 15 and 16 illustrate the comparisons of stopping distance means, in the form of histograms. Test results from the focus vehicles (Peterbilt and Volvo) are included – in the "standard S-cam" configuration – for comparison.

As might be expected, the Freightliner Argosy prototype had better stopping distance performance as compared to other tractors with pneumatically controlled S-cam brakes. However, the mean stopping distances for the Argosy fell between the results for Peterbilt and Volvo tractors, as tested with pneumatically controlled Air Disc Brakes on all brake positions, for the GVWR load (see Table 19).

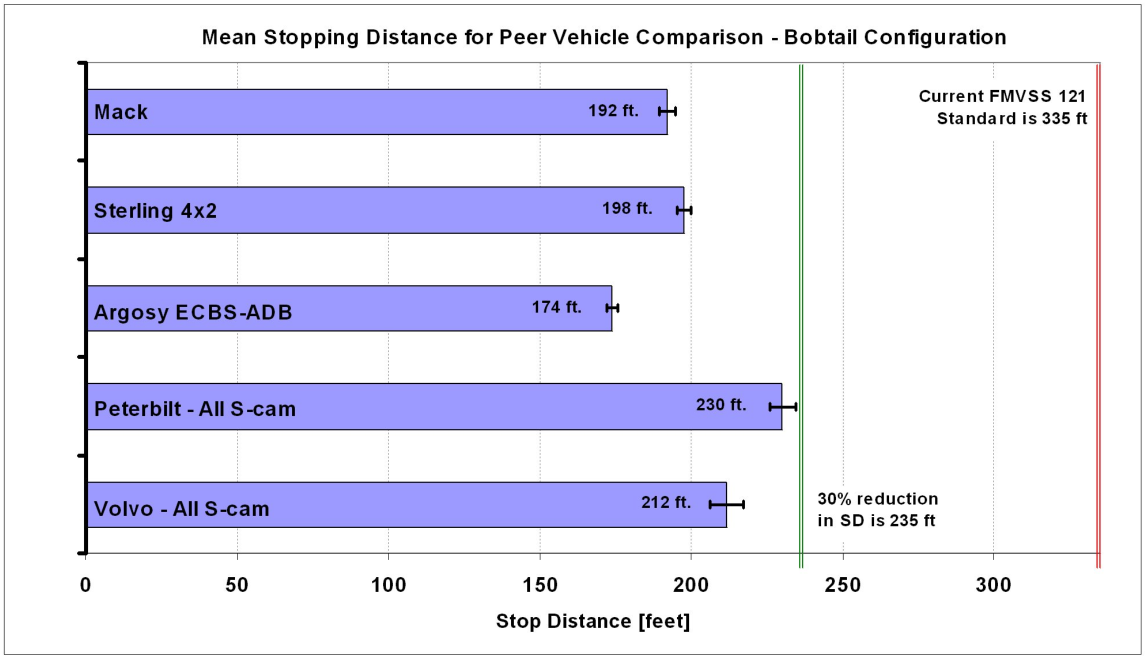

Figure 15: Mean stopping distances for the peer vehicles at LLVW load condition. The Peterbilt and Volvo test tractors are included in the "all S-cam" brake configuration. 95% confidence intervals are plotted via variance bars. Current and proposed FMVSS No. 121 limits are shown.

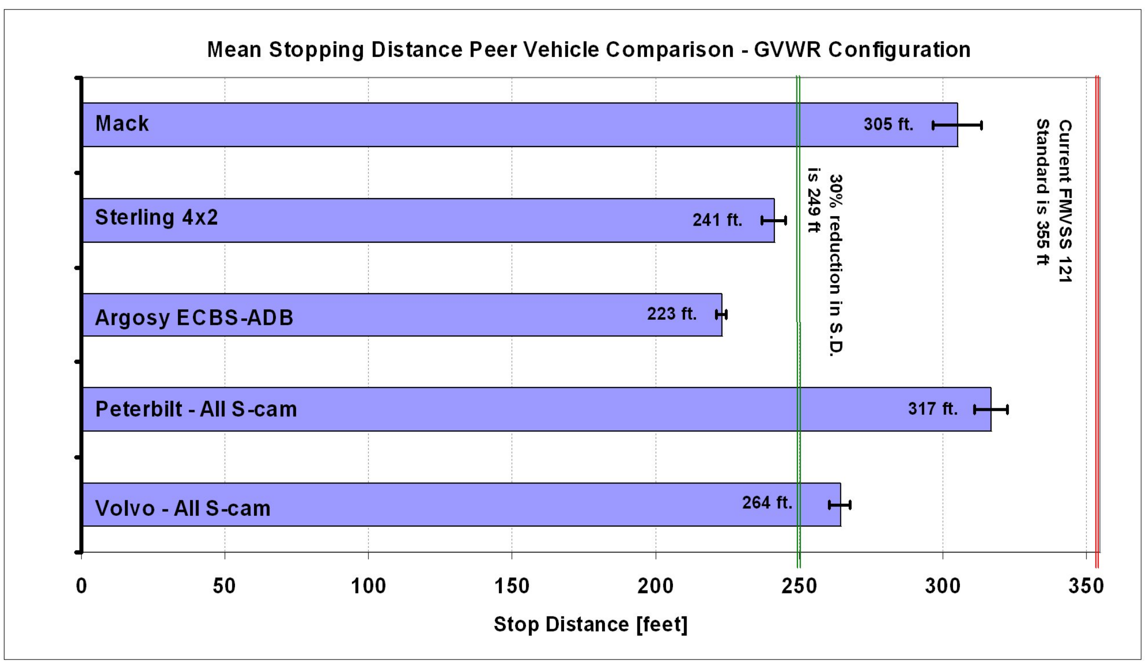

Figure 16: Mean stopping distances for the peer vehicles at GVWR load condition. The Peterbilt and Volvo test tractors are included in the "all S-cam" brake configuration. 95% confidence intervals are plotted via variance bars. Current and proposed FMVSS No. 121 limits are shown.

Table 19: Comparison of Argosy (equipped with ABS and ECBS) to the Peterbilt and Volvo test tractors, all tested with air disc brakes.

	Peterbilt with "all disc" brakes	**Volvo with "all disc" brakes**	**Argosy with ECBS-ADB**
LLVW (bobtail)	181 ft.	188 ft.	174 ft.
GVWR	222	241	223

6 CONCLUSIONS AND RECOMMENDATIONS

These test results are for two Class 8 truck tractors that were each tested with four different foundation brake systems. The foundation brakes were field-installed retrofits performed at VRTC. The existing pneumatic control and actuation systems were retained without any revision. With system development and tuning, some of the hybrid brake configurations, which in these tests (at GVWR) did not achieve the goal of improving stopping distance by 30% over current FMVSS No. 121 regulations, might otherwise achieve that goal. However, the margin of compliance would probably remain less than that seen with the "all-disc" brake configurations as tested. Individual conclusions and recommendations are as follows:

1. Versus a 30% reduction in current FMVSS No. 121 standards, margins of compliance for the minimum stopping distance (of six stops) at the LLVW load exceeded 10% for all non-standard brake configurations. Margins of compliance for the "hybrid disc" and "all disc" configurations exceeded 20% for both tractors at LLVW.
2. Versus a 30% reduction in current GVWR standards, the minimum stopping distance for only one tractor-brake configuration tested had a margin of compliance that exceeded 10% (Peterbilt tractor with "all-disc" brake configuration). Minimum stopping distances for the other brake configurations tested at GVWR had low or nonexistent margins of compliance.

3. In this study, the only foundation brake configuration that was found to be capable of meeting a 30% reduction in mean stopping distance at the GVWR configuration (50,000 lbs. for the tractors tested) is the "all-disc brake" configuration.
4. Stopping distance means for every brake configuration evaluated at LLVW (including peer vehicles) achieved at least a 30% improvement over current FMVSS No. 121 limits, although the margin of compliance for Peterbilt tractor with "standard all S-cam" brakes was insufficient.
5. As tested, the two hybrid brake configurations (using high-capacity S-cam drum or air disc brakes on the steer axle only, while leaving standard output S-cam drums on the drive axles), appear to not be capable of providing enough additional stopping power to comply with a proposed 30% reduction in stopping distance at GVWR. Note that with further developmental tuning for the control and actuation systems, these hybrid systems may indeed be capable of meeting the 30% reduction goal, but with a smaller margin of compliance than that shown by the air disc brake configuration.
6. Statistical analyses show that all three modified foundation brake configurations were found to significantly improve stopping distance performance over the standard S-cam configuration at LLVW. The same was true at GVWR, however the "hybrid" configurations (high-capacity drums or ADB on the steer axle only) were found to be statistically similar at GVWR.
7. Analyses of standard deviations show that the spread of the data for the standard "all S-cam" drum brake configurations to consistently be the highest. Grouping for the air disc brake setups were consistently tight, but did not yield the smallest standard deviations for all conditions. Also note that the standard deviations for the Argosy (having ECBS and ADB) were lower than either the Peterbilt or Volvo with the "all-disc" setup.
8. The results herein suggest that further research be initiated to understand the full impact of using group means and confidence intervals, as opposed to group minimums as predictors of truck stopping distance.