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Class 8 Mack Straight Truck Emulating a Refuse Hauler – Braking Improvement Study

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15. Abstract

The effect of higher output foundation brakes were determined for a Class 8, Mack 6x4 MR-688-S straight truck which emulated a McNeilus refuse hauler. Four brake types studied included: original hybrid S-cam drums, big S-cam drums, hybrid disc, and all-disc. In order to simulate the completed refuse hauler, the mock-up truck was loaded in three configurations: fully laden at GVWR, at LLVW simulating an unloaded refuse hauler, and empty (MT) for comparison to other chassis-cab test trucks.

The results show that the chassis-cab mock-up truck with hybrid S-cam brakes produced performance data similar to that obtained from the McNeilus refuse hauler for most tests, which indicated that the mock-up was realistic in loading configuration and in braking capability. At GVWR, the test truck stopped in 298 feet, which correlated to the 302 feet obtained by the refuse hauler. By installing higher output brakes, the service brake stopping distances shortened dramatically. The all-disc brakes performed the best (228 feet), followed closely by the hybrid disc brakes (245 feet) and the big S-cam drum brakes (248 feet).

For baseline brake-in-a-curve (BIC) tests, all four brake configurations met the minimum stability and control test requirement; therefore, increasing the brake output made little change in stability on the low-coefficient-of-friction surface. Additional loads of GVWR and MT produced similar results at the 75-percent of drive-through “target speed” for four-of-four tests. For limit-speed tests, the highest lateral acceleration performance quotient (LAPQ) values were achieved by the hybrid S-cam and big S-cam brake configurations.

Each load and brake configuration applied to the chassis-cab mock-up truck met the 5-minute parking brake holding requirement of the FMVSS No. 121 on the 20-percent grade, which was also found previously for the refuse hauler. This pass/fail test could not distinguish any differences in brake type installed on this vehicle. However, the drawbar parking brake force test showed large differences in parking brake holding ability. The 2005 test results showed that the refuse hauler failed the drawbar test for the rearward pull direction on the rear axle by over one percent. However, the mock-up vehicle met the minimum required drawbar force. The higher output all-disc and big S-cam brakes produced drawbar margins of compliance ranging from 35 to 105 percent, with the big S-cam brakes producing the largest margins in the rearward pull direction.

Split-mu tests showed little difference in stopping distances or decelerations between the four brake types tested. The decelerations did indicate a side-to-side bias in total vehicle response to the stops on this surface, which were substantiated by driver comments and handwheel angle data. When loaded to GVWR and LLVW, the big S-cam brakes required the biggest driver handwheel inputs of the four brake types indicating that wider S-cam brakes are more sensitive to side-to-side brake imbalance issues.

16. Key Words	17. Distribution Statement
All-Disc Brakes, Hybrid Disc Brakes, Hybrid S-Cam Brakes, Big S-Cam Brakes, ABS Braking , Stopping Distance, FMVSS No. 121, Mack MR-688-S, BIC, Target Speed, Limit Speed, LAPQ, Drawbar, and 20-Percent Grade	Document is available to the public from the National Technical Information Service www.ntis.gov

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The National Highway Traffic Safety Administration issued stringent new braking requirements for heavy truck tractors in a July 27, 2009, release of a Final Rule, which updated the Federal Motor Vehicle Safety Standard (FMVSS) No. 121. NHTSA has expanded the review of FMVSS No. 121 air brake performance specifications to single-unit trucks (SUT), including straight trucks and buses. Recent brake performance improvement testing was conducted at the Transportation Research Center in East Liberty, Ohio, by NHTSA's Vehicle Research and Test Center (VRTC) on a 6x4 chassis-cab straight-truck test bed.

The premise of this study was to retrofit a straight truck (which was emulating a commercial vehicle that previous testing had found to only marginally meet the current FMVSS No. 121 requirements) with higher-torque (output) foundation brakes, without modifying or tuning the suspension or antilock braking system (ABS), to determine their effect on stopping distance and vehicle stability. In order to narrow the scope, individual variations in lining friction codes, lubrications, brake drum material or weight, chamber stroke or diameter, slack adjuster length, or application pressures were not explored; only large changes in foundation brake systems were compared.

This report presents the results of brake performance tests conducted on a Class 8 Mack chassis-cab straight truck. An abbreviated FMVSS No. 121 test sequence was conducted for each brake/load configuration, along with additional research tests. Use of Brake Group names that were established in previous heavy truck and tractor reports were applied here (see superset of configuration codes in **Error! Reference source not found.**). The truck was tested with four brake configurations:

1. "Hybrid S-Cam" – "X" - large 16.5 x 6-inch S-cam drum brakes on the steer axle and traditional S-cam drums on the drive axles; these were also standard on the McNeilus refuse hauler truck that was previously tested.

2. "Big S-Cam" – "B" - wider shoes and drums at all wheel positions, compared to the hybrid S-cam;

3. "Hybrid Disc" – "H" - air-disc brakes on the steer axle and traditional S-cam drums on the drive axles; and

4. "All-Disc" – "D" – air-disc brakes on all wheel positions.

The chassis-cab truck was tested in three load conditions: gross vehicle weight rating (GVWR), lightly loaded vehicle weight (LLVW), and empty (MT) where all ballast blocks were removed from the load frame. The "empty load" test data was correlated to that of the LLVW condition, and can be applied for future comparison to other chassis-cab trucks.

A 2005 brake performance test showed that a Class 8, Mack 6x4 straight truck (completed with a McNeilus refuse body) would stop in 302 feet on a high-coefficient-of-friction surface. With a margin of compliance of 2.6 percent to the FMVSS No. 121 standard requiring a stop in less than

310 feet, NHTSA determined that this truck configuration was a candidate for inclusion in a brake performance improvement study; therefore NHTSA purchased a chassis-cab truck similar to the McNeilus refuse hauler for a comparative brake test bed.

The minimum stopping distance attained at GVWR for the Mack MR-688-S mock-up truck (298 feet) was nearly the same as that of the McNeilus refuse hauler (302 feet) in standard FMVSS No. 121 brake performance tests. When the brake configuration was changed to a different combination of foundation brakes on the mock-up, its stopping distance shortened incrementally each time the brake output was increased. The minimum stopping distances were: all-disc, 228 feet; hybrid disc, 245 feet; big S-cam, 248 feet; and original hybrid S-cam, 298 feet. The all-disc brake configuration showed an improvement of more than 70 feet (or 24%) compared to the refuse hauler, and was 26.5-percent shorter than the standard requirement of 310 feet.

In the LLVW condition, all four brake configurations on the mock-up met the minimum stopping distance requirement of 335 feet with margins of compliance ranging from 29 to 44 percent.

The chassis cab truck was also tested in a third mode, with no ballast added to the load frame (MT load condition), such that the data obtained could be used to compare to other chassis-cab trucks that were not yet fitted with secondary-manufacturer bodies. In this empty load condition, the normal force was low on the drive axles resulting in the intermediate axle experiencing frequent lockups, especially with the higher output rear brakes, but the driver was able to maintain the vehicle stably throughout the stops. All four brake configurations produced minimum stops within a 7-foot window between 178 and 185 feet; therefore, there was no distinguishable stopping performance attributed to any one brake type at this load condition.

ANOVA analysis showed that for all of the brake stops performed using the chassis-cab mock-up truck, the treatments significantly attributing to the stopping distance result were: *load* – 69 percent; *brake* type – 20 percent; and *stop* iteration – 1 percent; with combined treatments *brake*load* – 7 percent and *brake*stop* – 1 percent.

Wheel slip histogram plots showed that the steer axle brakes tended to be torque limited for all four brake configurations at GVWR. As the loads were reduced, the slip values increased, dispersing somewhat over a larger range of wheel slips, but still remained relatively low in average percent-slip. At the lighter loads, the steer disc brakes did show some subtle indication of periodic higher, but controlled, slip. The drive wheel brakes produced a broader spectrum of wheel slip than the steers for each brake and load condition. The percent slip curves were relatively normal in distribution with some positive skewness. At GVWR, the large rear S-cams (big S-cam configuration) and the rear disc (all-disc configuration) produced somewhat higher percentages of slip, with broader percent-slip dispersion, and without experiencing any strong tendency toward wheel lock.

In general, for the failed systems tests on the Mack truck, trends observed for the service brake tests repeated, where the hybrid S-cam configuration stopped the longest and the all-disc configuration stopped the shortest.

However when comparing the two trucks with the same hybrid S-cam brake configurations, both primary and secondary failed reservoir tests for the Mack MR-688-S produced stops ranging from 38 to 50 percent longer than for the McNeilus refuse hauler. This shows the variability that is inherent in the failed systems test procedures, as driver style and brake application, and reservoir depletion rate combine to determine the initial residual air pressure remaining in the failed-reservoir at brake application. If a driver waits until the end of the 5-second window allotted before applying the service brake, the available pressure will be lower than for a driver who opts to apply the brake just after the low-pressure warning sounds; both cases are acceptable by FMVSS No. 121 as the goal is to stop the truck with whatever available air that remains in the reservoirs. The standard also does not specify a standard orifice diameter to use to establish the flow rate of the air being vented from the reservoir. A larger dump valve will also lower the initial pressure at the time of brake application. Lower pressure in a failed reservoir tends to produce longer stops. If the reservoir is totally depleted of air at the moment of brake application, the maximum measured brake stop may occur, unless the spring brakes apply and add to the available braking torque.

All four of the brake configurations met the minimum stability and control test requirement on a low coefficient-of-friction surface (500-foot radius curve of water-wetted Jennite) for the baseline brake-in-a-curve (BIC) tests. Only a few ballast blocks were attached to the load frame in order to simulate the required LLVW load condition, which represented the weight of an unloaded refuse hauler. The BIC tests were repeated for two more loads, GVWR and MT (with all ballast blocks removed from the mock-up truck load frame), which also showed that the truck stayed in the lane at the 75-percent of drive-through "target speed" for four-of-four braking tests.

Limit speed handling tests were performed for each brake configuration and load condition to expand upon the minimum go/no-go status required by FMVSS No. 121 in order to better differentiate the stability performance differences between the configurations. With a minimum acceptable lateral acceleration performance quotient (LAPQ) of 56 percent (for the 75% target speed), all 12 brake/load configuration exceeded 72 percent for LAPQ. It was noted that the all-disc brake configuration produced LAPQ values lower than the other brakes, which may be due in part to the lower coefficient-of-friction surface for tests conducted on this configuration and the big S-cam brake configuration. Overall, the two brake configurations with S-cam brakes on all wheel positions handled somewhat better than those with disc brakes.

In the parking brake evaluation, the brakes held the vehicle stationary on the 20-percent grade for each of the four brake configurations and in each of the three load conditions for the minimum 5-minute requirement. The big S-cam brake configuration required approximately half as much service brake pressure to hold the vehicle on the grade (compared to the other three brake types) and none of the tests required more than 43 psi.

The second parking brake evaluation was performed in response to the observation that the McNeilus refuse test truck had passed the 20-percent grade test in 2005, but failed the drawbar force test. For each of the 23,000 lb-rated axles, the minimum drawbar force requirement was 6,440 lbf. Each brake type met the FMVSS No. 121 requirement for both forward and rearward pulls. The lowest recorded drawbar force of 7,155 lbf occurred on the rearward pull on the rear drive axle while using hybrid S-cam brakes. This coincided with the same axle and draw direction that had failed the drawbar test performed during the 2005 refuse hauler test. The three higher output brake configurations produced considerably higher drawbar forces. The all-disc produced margins of compliance nearly two-to-one higher than the original hybrid S-cam configuration, but the big S-cam output was slightly higher than the all-disc. The S-cams on the hybrid disc performed somewhat better than those of the hybrid S-cam.

ANOVA analysis was applied to the drawbar test data. The omega-squared values indicated that *brake* was the primary influence on drawbar force. *Direction* and *axle* were each significant, but to a much lesser extent.

The laterally split-coefficient-of-friction tests showed that the two hybrid brake configurations stopped shorter and with more repeatability than the higher output big S-cam or all-disc brake configurations. The laden condition produced the most repeatable stopping distances, with the standard deviations increasing as the loads were reduced. ANOVA showed that *direction* traveled on the split-mu test pad was most critical with an omega-squared representation of 32 percent, followed by *brake, load,* and then test *iteration*. Other significant findings were from the combined effects of *brake*load* and *brake*direction*. The total model accounted for 89 percent determination of the resulting effect upon the stopping distances as compared to the R-squared value of 98 percent.

Computed deceleration values complemented the split-mu stopping distances and indicated that the average decelerations ranged between 0.29 and 0.34 g, but with 0.01 to 0.04 g higher decelerations for the stops performed in one specific direction, east-to-west (E-W). This indicated that the combined brake control system and truck suspension geometry appeared to bias the stopping capability of the truck in a side-to-side fashion. This phenomenon may explain some of the unknown variance from the ANOVA.

The driver commented that it was necessary to counter-steer into the direction of the lower coefficient-of-friction in order to maintain the truck stopping within the 12-foot width of the lane and that the E-W direction required larger inputs than the west-to-east (W-E) direction. The handwheel angle data corroborated these comments and also agreed with the deceleration variances as to side-to-side brake bias. The big S-cam brake configuration required the most driver handwheel input when loaded to GVWR and LLVW, compared to the other three brake types. The driver also noted that while a 60-degree handwheel input was not overly taxing, each of the split-mu stops that required handwheel inputs ranging anywhere from 30 to 70 degrees required a quick initial handwheel correction in order to maintain the truck in the lane.

1.0 BACKGROUND AND OBJECTIVES

The National Highway Traffic Safety Administration issued stringent new shorter stopping distance braking requirements for heavy truck tractors in a July 27, 2009, release of a Final Rule, which updated FMVSS No. 121.[1 2] NHTSA has expanded the review of FMVSS No. 121 air brake performance specifications to single-unit trucks, which includes straight trucks and buses. Presently, FMVSS No. 121 allows pneumatically braked SUTs to have significantly longer stopping distances than passenger cars. NHTSA believes that this discrepancy in stopping distance is a contributor to the number of heavy-truck crashes and fatalities. NHTSA's goal is to review the current stopping distance criteria for single-unit trucks and correlate these findings to the criteria proposed for shorter stopping distances for truck tractors.[3]

Testing was conducted on the Transportation Research Center Inc. (TRC) test track in East Liberty, Ohio, by the NHTSA Vehicle Research and Test Center (VRTC). VRTC has tested a variety of vehicles, including Class 8 truck tractors with different combinations of trailers, Class 8 straight trucks, a Class 7 school bus, and numerous light- and medium-duty commercial trucks. Brake group names and summary results for some of the recently completed tests are described in several References.[4 5 6 7]

The premise of this study was to retrofit a straight truck (which was emulating a commercial SUT that previous testing had found to only marginally meet the current FMVSS No. 121 requirements) with higher-torque (output) foundation brakes, without modifying or tuning the suspension or ABS; and to determine the effect on braking performance and vehicle stability. This report presents the results of a Class 8 Mack chassis-cab straight truck that was tested at VRTC. Standard testing (to TP-121V-05, Laboratory Test Procedures) included service brake stops from 60 mph, failed systems, brake-in-a-curve (BIC), and parking brake holding performance.[8] Added research tests included BIC limit tests and service brake stops on a laterally split-mu test surface. Each test sequence was repeated for four different foundation brake configurations. These results were then compared to the braking results from an actual, previously tested "completed" refuse hauler truck with a similar chassis.

2.0 TEST PROGRAM

The test program called for obtaining a test-bed vehicle to emulate a real-world truck that only marginally met the requirements of FMVSS No. 121 in recent compliance-type baseline brake tests. The brakes were modified, using commercial “off-the-shelf” brake hardware to try to improve the braking performance. This section details the brake components used, basic truck parameters and equipment, instrumentation, test conditions, and test methodologies. Comparison is made to highlights from the previous brake tests performed on a 2004 McNeilus refuse hauler tested in NHTSA report, “A Summary of Baseline Braking Tests on Medium and Heavy Duty Trucks” (Heitz & Barickman, in press; Report No. DOT HS 810 683).[9]

2.1 Description and Overview of the Test Vehicle

A Mack MR-688-S Chassis-Cab 2007 model, 6x4 straight truck was purchased from new dealer stock (Figure 2.1). The vehicle was equipped with pneumatically controlled and applied S-cam service brakes, which were ABS-modulated through a four-channel electronic control units (ECU).

Figure 2.1. Mack MR-688-S Chassis-Cab Truck Loaded to GVWR With Concrete Blocks to Simulate a McNeilus Refuse Hauler

The truck was tested in three load configurations to represent gross vehicle weight rating (GVWR); lightly loaded vehicle weight (LLVW), or intermediate vehicle weight (IVW) that emulated an empty refuse hauler; and empty (MT) that was the chassis-cab with an empty load frame, but no refuse body. Basic weight and distribution parameters are listed in Table 2.1. Measurements from the previous McNeilus refuse hauler are included for comparison.

Table 2.1. Overall Vehicle Weights and Measures

Vehicle	Mack Chassis-Cab Truck			McNeilus Refuse Hauler	
Configuration	**MT**	**LLVW**	**GVWR**	**LLVW**	**GVWR**
Placard Vehicle Weights (lb)*	d.n.a.	d.n.a.	66,000	d.n.a.	66,000
Measured Vehicle Weights (lb)	22,350 * / 22,220 avg**	38,558 avg**	65,735 avg**	38,700**	65,480**
Wheelbase (in)	210			210	
Track Width – Front/Rear (in)	85.3 / 72.5			85.3 / 72.5	
CG Vertical Distance Above Ground (in)	36.7 *	47.8 ***	70.3 ***	N.A.	66.7 ****

* - Chassis-Cab Truck MT (with load frame only) weights and CG's measured by TARDEC ref# 00253 [10]

** - Measured TRC test weight for brake tests

*** - Calculated CG height

**** - Estimated CG height (CG of added ballast was 94.0 inches above ground)

Longitudinal CG's were calculated from the measured static axle weights Table 2.2. A pictorial of ballast block placement is detailed in Figure 2.2 for the all-disc brake configuration.

Table 2.2. Longitudinal CG Calculations From Static Axle Weights

Truck	Foundation Brakes	Load Condition	Steer Axle (lbs)	Tandem Drive Axles (lbs)	Total Weight (lbs)	Longitudinal CG * (in)
Mack Chassis-Cab **	Hybrid Disc	MT	12,130	10,220	22,350	96.03
Mack Chassis-Cab ***	Averages of All Four Configurations	GVWR	19,735	46,000	65,735	146.95
		LLVW	18,703	19,855	38,558	108.14
		MT	12,205	10,015	22,220	94.65
McNeilus Refuse Hauler	Hybrid S-Cam	GVWR	19,900	45,580	65,480	146.18
		LLVW ****	19,500	19,200	38,700	104.19

Note * - longitudinal CG is measured from the centerline of the steer axle.
Note ** - This test was performed on a VIPER system at TARDEC in Michigan.[10]
Note *** - For individual CG calculations *by brake configuration* - see Appendix A, Table 6.1.
Note **** - The completed vehicle Refuse hauler in the LLVW load condition was comparable to the partially loaded Chassis-Cab in the LLVW load condition.
Both trucks had 210-inch wheelbases.

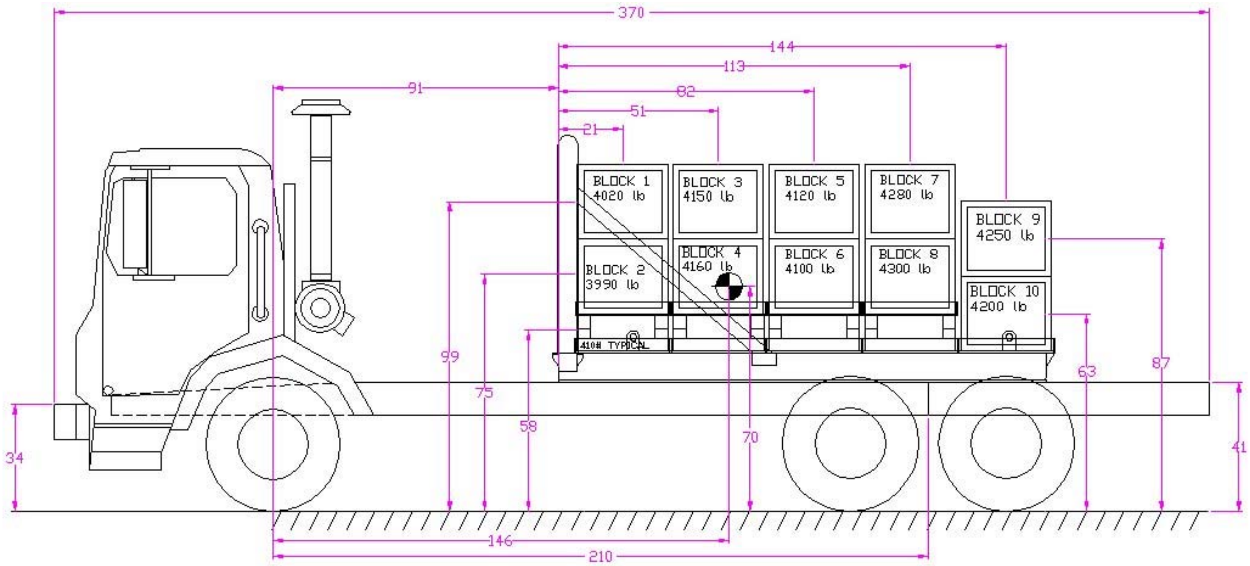

Figure 2.2. Mack Chassis-Cab All-Disc Brake Loading Configuration for Emulating a Laden Refuse Hauler

The antilock brake system ECU of the chassis-cab truck and the refuse hauler were similar, as were the tires and suspension systems. (Table 2.3).

Table 2.3. ABS, Suspension, and Tires

	Mack Chassis-Cab Truck	McNeilus Refuse Hauler
ABS Configuration	Bosch 4s/4m (rear axle sensing)	Bosch 4s/4m (rear axle sensing)
Front Suspension	FAW20 - 20,000 lb leaf spring with no shock absorbers	20,000 lb leaf springs with no shock absorbers
Rear Suspension	S462 - 46,000-lb tandem camelback leaf springs with no shock absorbers	46,000-lb trunnion leaf spring with no shock absorbers
Steer Axle Tire	425/65R22.5 LR L Goodyear G286	425/65R22.5 LR L Goodyear G286
Drive Axle Tire	11R/22.5 14PR LR G Goodyear G164 RTD	11R/22.5 14PR LR G Goodyear G164 RTD

2.2 Brake Configurations

The chassis-cab truck was tested in the following four foundation brake configurations:

1. "X" - Baseline original high-output extra-large steer axle S-cam drum brakes as received on the new truck - Labeled "Hybrid S-Cam" in the tables and figures;
2. "B" - Big S-cam drum brakes (one inch or more wider than baseline brakes) installed at each wheel position - Labeled "Big S-Cam" in the tables and figures;

3. “H” - Hybrid of air-disc brakes on the steer axle and traditional standard S-cam drums on the drive axles - Labeled “Hybrid Disc” in the tables and figures; and
4. “D” - Air-disc brakes on all wheel positions - Labeled “All-Disc” in the tables and figures.

Brake specifications are listed in Tables 2.4 to 2.5 for each brake configuration. ArvinMeritor performed the drive axle retrofit when the all-disc brakes were installed. All other brake configurations were installed by TRC.

Table 2.4. Brake Specifications for Steer-Axle Foundation Brake Configurations

Brake Components	Foundation Brake Type				
	McNeilus Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All-Disc
Air Chamber	MGM 24	Haldex T24L	Haldex SC30L 3-inch stroke	MGM 1428075 C24L3	MGM 1428075 C24L3
Slack Adjuster	Haldex 5.5-inch auto	Haldex 5.5-inch auto	Haldex 5.5-inch auto	Internal auto	Internal auto
Brake Lining/Pad	R403 GG	R403 GG 4715	R403 GG 4707D	EX-225 PAD 741 DA	EX-225 PAD 741 DA
Brake Drum/Rotor	Gunite	Gunite 3687	Gunite 3796	Meritor 17.09-inch	Meritor 17.09-inch
Brake Type	Meritor Q-plus 16.5" x 6"	Meritor Q-plus 16.5" x 6"	Meritor Q-plus 16.5" x 7"	Meritor Disc EX225H202 XXX	Meritor Disc EX225H202 XXX

Table 2.5. Brake Specifications for Drive-Axle Foundation Brake Configurations

Brake Components	Foundation Brake Type				
	McNeilus Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All-Disc
Air Chamber	MGM 30/30	Haldex T30/30L	Haldex T30/30L	Haldex T30/30L	Meritor 20/24-LD2
Slack Adjuster	Haldex 6.0-inch auto	Haldex 6.0-inch auto	Haldex 6.0-inch auto	Haldex 6.0-inch auto	Internal auto
Brake Lining/Pad	R301 FF	R301 FF 4707D	R403 GG 4718D	MA312 FF 4707D	EX-225 PAD 741 DA
Brake Drum/Rotor	Gunite	Gunite 3401	Gunite 3796	Gunite 3401	Meritor 17.09-inch
Brake Type	Meritor Q-plus 16.5" x 7"	Meritor Q-plus 16.5" x 7"	Meritor Q-plus 16.5" x 8"	Meritor Q-plus 16.5" x 7"	Meritor EX225H202 DA000

2.3 Test Conditions and Methodology

Tests were performed by VRTC at the TRC test track in East Liberty, Ohio, and were conducted as prescribed in the FMVSS No. 121 and the associated test procedure TP-121V-05.[2] [8] Additional, non-FMVSS No. 121 tests were performed for research purposes. Unless otherwise noted, similar tests were performed for each brake configuration and loading condition.

Before testing each brake configuration, all friction materials were changed, including drums and rotors, pads and shoes, and the tires; however, the antilock brake system, suspension, brake controls, and brake application methods were not modified or "tuned" between brake configurations. For the all-disc brake tests, a duplicate drive axle assembly with modified end fittings was used to facilitate installation of the disc brake assemblies. Once configured, each new brake set was pre-conditioned (prior to testing) using a 500-snub burnish procedure as prescribed in Section 6.1.8 of FMVSS No. 121.[2] Each snub was made from 40 to 20 mph, while maintaining a constant deceleration rate of 10 ft/sec/sec. Pressure repeatability was maintained using an added constant pressure reservoir system. Temperature history plots are included in Appendix A, Figures 6.1 through 6.4, for the respective four brake configurations.

2.3.1 Instrumentation

Time history data was taken for each test. Descriptions of the channels are outlined below.

- Brake pad/shoe temperatures were monitored and recorded as outlined in the FMVSS No. 121 and the test procedure.[2] [8] The ambient temperature was also recorded.
- Stopping distances were measured with a ground-contact 5th wheel assembly, mounted on the rearmost part of the vehicle. Stopping distances and vehicle speed were both recorded from a Labeco TrackTest Fifth Wheel System Performance Monitor, which

displayed initial braking speed and integrated stopping distance. All measured stopping distances were corrected using the standard method described in SAE J299; therefore, all stopping distances were normalized to the targeted initial braking speeds.[11]

- Individual wheel speeds were measured by passing the signals from added tone ring wheel speed sensors, through frequency-to-voltage (F/V) converters, to the data system.
- Chamber pressures were measured and recorded for each brake position at the brake chambers. Treadle and reservoir pressures were measured for the primary and secondary circuits. Parking brake chamber pressure was also measured for one brake position at each drive axle (this truck was equipped with parking brakes on both drive axles.)
- Steering handwheel angle was measured with a string potentiometer.
- Using a three-axis inertial measurement device, linear acceleration and angular rates (in all three axes) were measured and recorded. This unit was located near the GVWR CG.
- A fast-acting tape switch was attached to the service brake foot pedal to trigger the data acquisition system. This signal, along with brake light voltage and ABS electronic control unit voltages, were also recorded with the data acquisition system. A tabbed-microswitch was added to identify the full displacement of the treadle pedal, and was used to identify the first movement during release of the treadle (foot) pedal for timing tests.

2.3.2 Standard FMVSS No. 121 Tests

The chassis-cab truck tested for this program was purchased from regular dealer stock, and was assumed to have already met full FMVSS No. 121 compliance criteria. Therefore, only critical performance tests were performed for this program. Standard FMVSS No. 121-type tests performed included:

- Full service brake stops from 60 mph on a high-coefficient-of-friction surface;
- Failed systems tests;
- Brake-in-a-curve tests of a low-coefficient-of-friction surface, plus developmental limit tests; and
- Both drawbar and 20-percent grade holding tests for the parking brake system.

2.3.2.1 Driver Instructions

One driver was used for the entire brake test program – to reduce the variation in the collected results. The driver was instructed to warm or cool the brakes (before each brake run) such that the respective pad or shoe temperatures were within the specified initial brake temperature (IBT) range of 150 to 200 ºF (66 to 93 ºC). This truck was equipped with an automatic transmission; therefore, all burnish and brake performance tests were performed “in-gear.”

The individual tests were begun by accelerating the vehicle to a few mph over the initial braking speed (IBS) of 60 mph (for skid tests) and then allowing the vehicle to coast down to 60 mph, while the driver maintained the vehicle in the center of the lane. At IBS, the service brake treadle valve (foot brake) was applied within 0.2 seconds, as outlined in the FMVSS No. 121 and TP-121V-05.[2, 8] The brake pedal was held fully applied until the vehicle came to rest, unless the driver noticed an extended full lockup and needed to modulate the brakes to safely stop and assess why the wheels were locking. Unless otherwise noted, the general location on the test pad used for beginning each stop in a given test series was kept consistent.

2.3.2.2 Dry Stopping Performance Tests

Stopping performance tests were conducted according to the procedures outlined in Section 5.3.1 of FMVSS No. 121.[2] Full-treadle brake application straight-line stops were performed from 60 mph on a dry surface with a high coefficient of friction. Nominally, six stops were made on the TRC concrete skid pad. The surface had nominal peak and slide coefficients-of-friction of 0.98 and 0.87, respectively.

2.3.2.3 Emergency Brake System Testing

Emergency brake system tests were performed according to the procedures outlined in Section 5.7 of FMVSS No. 121. Three separate failed systems tests were performed, including a failed primary reservoir, a failed secondary reservoir, and a failed primary control line. The failed primary and secondary reservoirs were separately simulated by having the driver vent the air pressure in one of the selected tanks, to atmospheric pressure, through a remotely operated solenoid valve. A full-treadle brake application was then made within 5 seconds after the low-pressure warning alarm activated (nominally at 60 psi). The primary control line failure was simulated by removal of the primary pneumatic control signal from the drive axle relay valves, thus simulating a failure of the control signal to reach the drive axle brakes, while still operating the steer axle brakes. A full-treadle brake application was then made. Six stops from 60 mph were performed for each failed system test on the skid pad. The skid pad had nominal peak and slide coefficients of friction of 0.98 and 0.87, respectively. This test was repeated for each of the three load conditions.

2.3.2.4 Brake-In-a-Curve Stability Testing

FMVSS No. 121 requires straight trucks to pass the BIC test on a low-coefficient-of-friction surface, only in the LLVW load condition. However, since this truck was a chassis-cab (with no secondary manufacturer’s body attached), it was tested in all three load conditions. This allowed for comparison of braking stability results of the baseline chassis system to an emulated empty refuse hauler, and to a fully laden truck.

Stability tests were performed using the brake-in-a-curve procedure outlined in Section 5.3.6 of FMVSS No. 121. First, a drive-through speed was established. This was defined as the highest speed in which the vehicle could maintain the 12-foot lane throughout the 500-foot radius path. Then, at a *target* speed equivalent to 75 percent of the drive-through speed, full treadle application brake stops were made. The stops were initiated once the vehicle was established in the center of the 12-foot lane, and after it traveled for at least 60 feet into the 500-foot radius curve. Four stops were made on the water-wetted Jennite surface on the TRC vehicle dynamics area (VDA).

To further test the braking stability of the vehicle, *limit* stability and control maneuvers were performed for research purposes. (Note: These *limit* tests were run from speeds higher than required for the target-speed tests and were not required in the FMVSS No. 121 standard, but were run to identify the actual upper handling *limit* on this surface.) The entry speed of the vehicle was increased in 1 mph increments, until the driver could not maintain the vehicle in the lane while performing a full treadle brake application. The highest speed attained, while maintaining the lane, was considered the *limit* brake-in-a-curve speed.

To normalize the test data (in order to reduce the effect of periodic variation in surface coefficient-of-friction) lateral acceleration performance quotients (LAPQ) were computed. The LAPQ was originally developed and implemented for tractors in a Class 8 Truck Tractor, Brake Performance Improvement Study.[5] LAPQ was applied to this SUT's *limit* braking performance as a ratio of the maximum attainable lateral acceleration (as calculated by curve radius and entry speed during the brake-in-a-curve maneuver) to the maximum drive-through lateral acceleration (with no braking). Rationalizing the performance in this manner normalized the brake-in-a-curve *limit* speed as a function of the maximum drive-through speed. Since both evaluations were performed on the same test day, the effect of the surface traction coefficient was largely mitigated. Therefore, for each brake-load configuration, the square of the speed ratio of the brake-in-a-curve *limit* speed to drive-through speed produced the performance quotients for the Mack straight truck, using Equation 1 (EQ-1).

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

where,

V_{limit} = *Maximum speed attained, while braking and maintaining the 12 – ft lane*; *and*

$V_{drive-through}$ = *Maximum speed attained, while not braking and maintaining 12 – ft lane.*

2.3.2.5 Parking Brake Testing

The foundation brake configurations were compared for static retardation force and grade-holding ability following the procedures outlined in Section 5.6 FMVSS No. 121, and in Sections 10.3-G, H, and I of the TP-121V-05, Laboratory Test Procedures, with the following exceptions or additions.[2 8]

a) Grade holding tests were performed at GVWR, LLVW, and MT load conditions, for each brake configuration. This test was performed on a 20-percent grade with the vehicle facing uphill, and then downhill. Only a minimal pressure was applied to the service brake to stop and hold the truck on the grade until the parking brake could be set. Then the service brake was released and the five-minute holding period begun.

b) A series of four static retardation tests were performed for each pull direction and for each individual drive axle. To prevent the occurrence of tire traction-limitation, the tests were only run at the GVWR load condition. A Hunter Plate Brake Tester was used to record the maximum vertical and horizontal (pull) forces, in addition to the primary force logged from the standard, drawbar load cell.[12] In order to avoid compounding, the parking brake was applied with no prior service brake application.

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

2.3.3 Additional Non-FMVSS No. 121 - Research Tests

For research and development purposes, an additional test, which was not required in the FMVSS No. 121 standard, was performed. Split-μ stopping performance tests were straight-ahead full-treadle service brake application stops performed on a laterally split coefficient-of-friction surface (water sprayed, asphalt and Jennite, split-μ) from 30 mph. For test efficiency, one stop was made in one direction (west-east), and then in the other direction (east-west), before repeating the cycle. A total of 12 stops were conducted for each set of tests (6 in each direction).

3.0 TEST RESULTS AND DISCUSSION

This section includes tables, graphs, and figures that present the findings from the standard-type FMVSS No. 121 tests, as well as from the exploratory research tests. Tests included panic stops from 60 mph, single failed-systems emergency braking performance using three different failure modes, handling during low coefficient-of-friction stops on a 500-foot radius curve, parking brake holding, and an experimental stability series on a laterally split-mu surface. Supplementary data is contained in the appendix at the end of the report (Figures 6.1 through 6.4 show plots of the temperatures logged per wheel during each of the 500 brake conditioning burnish snubs).

The Mack MR-688-S chassis-cab truck was fitted with a steel load frame for holding various configurations of ballast. Figure 3.1 shows the truck emulating a fully laden refuse hauler at GVWR. The 10 concrete blocks, each nominally weighing 2 tons, were bolted and chained to the load frame to prevent movement during brake testing. The first four stacks of blocks were elevated by one foot in order to better simulate the higher CG of a laden refuse hauler.

Figure 3.1. Mack MR-688-S Performing a Service Brake Stop

The original blocks and pedestals were replaced by a smaller array of blocks to emulate a lightly loaded refuse hauler, which is referred to as the lightly loaded vehicle weight (LLVW) condition in this report. When all of the blocks were removed from the load frame, the load reference was termed empty (referenced as MT for this report). The MT load condition data might be used as baseline performance upon which other secondary-manufacturer body configurations could be added.

3.1 Dry Stopping Performance Test Results

Standard brake performance tests were performed using the FMVSS No. 121 test procedures. Table 3.1 shows the results from the individual stops performed on the high coefficient-of-friction concrete surface at the TRC skid pad. Each row depicts a different brake configuration, with the first entry being a comparison of the actual McNeilus refuse hauler tested in the Heitz and Barickman NHTSA report (DOT HS 810 683, in press).[9] In multi-columnar format are the dry stopping distance data. The first six columns list the stopping distances logged for individual stops after being corrected to an equivalent entry speed of 60 mph using the SAE J299, Equation 1.[11] These are followed by the minimum (Min) stopping distance and margin of compliance relative to the current FMVSS No. 121 requirement of 310 feet. Next are the maximum and mean stopping distance values, and ending with the stopping distance standard deviations and 95-percent confidence range.

Table 3.1. Statistics for Service Brake Stops at GVW From 60 mph

Configuration	Dry Stopping Distance (ft)											
	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min	Margin of Compliance	Max	Mean	Std Dev	95% Confidence Range
McNeilus	321	317	327	302	314	324	302	2.6%	327	318	9	310, 325
Hybrid S-Cam	337	334	316	317	298	300	298	3.9%	337	317	16	304, 330
Big S-Cam	280	256	258	257	294	248	248	20.0%	294	266	18	251, 280
Hybrid Disc	264	255	272	257	245	258	245	21.0%	272	259	9	251, 266
All	238	233	247	232	228	236	228	26.5%	247	236	7	230, 241

Upon comparing the minimum stopping distances attained for each vehicle and brake type, the result for the Mack MR-688-S mock-up matched that of the McNeilus refuse hauler at approximately 300 feet. As higher output brakes were installed on the mock-up truck, the stopping distances shortened incrementally with each brake type. The all-disc brake configuration stopped in the shortest distance at 228 feet. This was an improvement of more than 70 feet (or 24 percent) compared to the refuse hauler, and 26.5 percent shorter than the standard of 310 feet.

Figure 3.2 plots the data described in Table 3.1. Here, the y-axis lists the vehicle and brake configuration. The x-axis portrays stopping distance, which ranges from 200 to 350 feet. Data are plotted in horizontal bar format, increasing from the left axis. Green dots indicate the actual data points for each stop. A red diamond indicates the mean stopping distance and the magnitude is labeled above each symbol. Two blue vertical line segments mark the 95-percent confidence limits. Vertical reference lines on the graph represent the current stopping distance limit of 310 feet, and three comparative improvement levels, each indicating 10-percent incremental improvements in stopping distance.

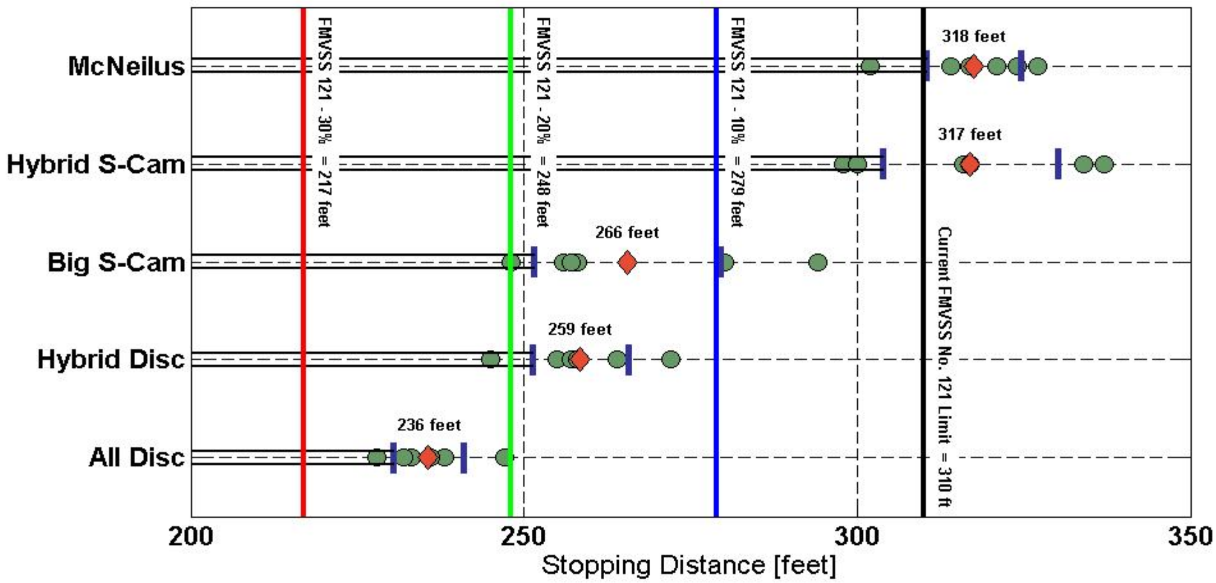

Figure 3.2. Service Brake Stops From 60 mph at GVW

After reducing the load to the intermediate load configuration, the mock-up weighed approximately the same as the refuse hauler in the LLVW load condition. Service brake stops were repeated for the same array of vehicle and brake conditions as in the GVWR tests.

Table 3.2 shows a similar trend for the LLVW tests as was seen in the GVWR tests, where the higher output brakes produced incrementally shorter stopping distances. However, the LLVW margins of compliance were considerably higher for all brake types. At LLVW, the mock-up stopped shorter than the refuse hauler; although both had similar brake types (hybrid S-cam). While the ballast blocks were stacked to produce a relatively high CG, similar to the unloaded refuse hauler, the mock-up still produced shorter stops. By increasing the size (width) of the S-cam brakes on all axles to the big S-cam brake configuration, there was an increase in the margin of compliance of over 7 percent. Adding disc brakes to the steer axle (hybrid disc) boosted the margin by another 5 percent, but the shortest stops were attained by the all-disc brakes.

Table 3.2. Statistics for Service Brake Stops at LLVW From 60 mph

Configuration	Dry Stopping Distance (ft)											
	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min	Margin of Compliance	Max	Mean	Std Dev	95% Confidence Range
McNeilus	261	260	272	263	266	267	260	22.4%	272	265	4	261, 268
Hybrid S-Cam	255	253	239	240	244	243	239	28.7%	255	246	7	240, 251
Big S-Cam	230	223	228	216	223	214	214	36.1%	230	222	6	217, 227
Hybrid Disc	211	201	202	205	196	199	196	41.5%	211	202	5	198, 207
All	201	193	190	190	188	192	188	43.9%	201	192	5	189, 196

The graph in Figure 3.3 plots the data described in Table 3.2. The graph shows the distinct reduction in stopping distance attained for each improvement in brake output applied. At the LLVW load condition, the baseline brakes (hybrid S-cams) produced stops that were 20 to 30 percent shorter than the current standard limit of 335 feet. Each of the three higher-output brake configurations produced margins of compliance exceeding 35 percent.

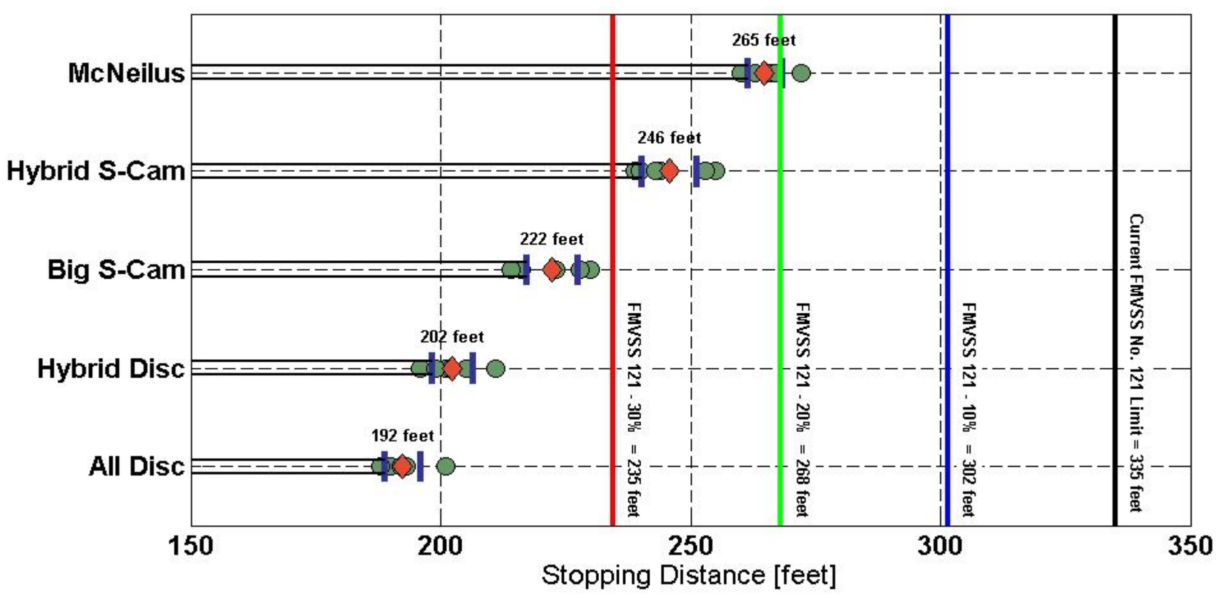

Figure 3.3. Service Brake Stops From 60 mph at LLVW

A third MT load configuration was tested only on the chassis-cab truck, as the refuse hauler body could not be removed from the McNeilus refuse hauler. All ballast blocks were removed from the load frame for baseline testing of the chassis-cab truck, to provide data for direct comparison to other chassis-cab trucks that are tested without the addition of secondary manufacturer bodies or appliances.

In the unballasted MT load condition, the stopping distances were very similar for each of the four brake types tested. The minimum stopping distance margins of compliance to the LLVW standard limit requirement of 335 feet ranged from 45 to 47 percent (Table 3.3). When plotting this data in Figure 3.4, the data groups fall in a relatively vertical pattern, indicating similar output between the brake types for this load condition. This data indicates that slightly shorter average stopping distances may be achieved using disc brakes on at least the steer axle, rather than S-cam brakes.

Table 3.3. Statistics for Service Brake Stops at MT From 60 mph

Configuration	Dry Stopping Distance (ft)											
	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min	Margin of Compliance	Max	Mean	Std Dev	95% Confidence Range
Hybrid S-Cam	211	201	198	185	189	191	185	44.8%	211	196	9	188, 203
Big S-Cam	186	178	189	192	205	186	178	46.9%	205	189	9	182, 197
Hybrid Disc	188	180	180	180	181	180	180	46.3%	188	182	3	179, 184
All	180	186	193	182	187	187	180	46.3%	193	186	5	182, 189

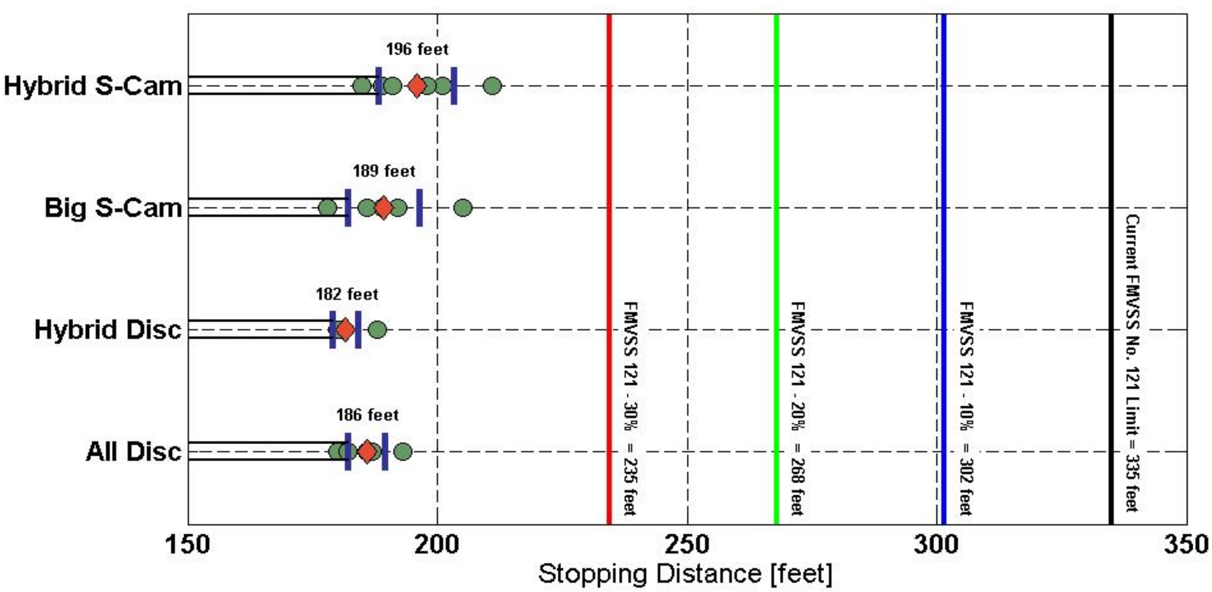

Figure 3.4. Service Brake Stops From 60 mph With MT Load Frame

3.1.1 Stopping Distance ANOVA Results

Analysis of variance (ANOVA) computations were performed using the Statistical Analysis Package of MatLab. Data from the mock-up were analyzed comparing the stopping distances for each of the six brake-test stops performed. Applied treatments of brake type, loading condition, and stop repetition were studied for their effect on the dependent variable stopping distance.

Table 3.4 lists columnar data as treatment (Effect), degrees of freedom (DF), the Fisher (F) value, probability factor, significance, and the magnitude of the effect of the treatment applied. Corresponding rows include the three input parameters: brake, load, and stop number, followed by pairings of these inputs. The table rows conclude with the magnitude of the undefined error, totals for degrees of freedom and treatment effects, and finally the R-squared fit of the model.

Table 3.4. ANOVA Results for All Brakes, Loads, and Repetitions for the Mock-Up Truck

Effect	DF	F value	Prob>F	Significant	Magnitude of Treatment Effect ω^2
Brake	3	152.72	< 0.0001	Yes	0.1971
Load	2	793.30	< 0.0001	Yes	0.6862
Stop	5	4.35	0.0043	Yes	0.0072
Brake*Load	6	27.08	< 0.0001	Yes	0.0678
Brake*Stop	15	2.81	0.0079	Yes	0.0117
Load*Stop	10	0.71	0.7058	No	-0.0012
Error	30				
Total	71				**0.9688**
R^2	**0.9870**				

The analysis shows that Brake, Load, and Stop repetition were all significant factors in this model, as were the interaction effects of Brake*Load and Brake*Stop. The interaction effect of Load*Stop was not significant. Load was by far the most significant factor with an ω^2 value of 0.6862 (or 69 percent). Brake was second most apparent at 20 percent. As for Stop, it was declared significant, but only contributed less than 1 percent to the total result. The broader dispersion in the S-cam data (compared to the all-disc data) caused Stop to become a significant, but limited factor.

An additional ANOVA analysis was performed using Brake and Load to determine the effect on mean stopping distance. By averaging each group stopping distance data set before running the ANOVA, the effect of dispersion in the S-cam brake data was nullified. The remaining effects show that Load was significant and accounted for 68 percent of the model response, where brake was no longer significant in this lower sensitivity model.

Table 3.5. ANOVA Results for Mean Stopping Distances Using Four Brake Types and Three Loading Conditions for the Mock-Up Truck

Effect	DF	F value	Prob>F	Significant	Magnitude of Treatment Effect ω^2
Brake	3	4.54	0.0549	No	0.1483
Load	2	25.50	0.0012	Yes	0.6841
Error	6				
Total	11				**0.8324**
R^2	**0.9150**				

Next are plots of wheel slip for the panic stops performed from an initial velocity of 60 mph on the high-coefficient-of-friction surface.

3.1.2 Wheel Slip Histogram Plots

Wheel slip histogram plots show the percentage of time that the wheel encountered specific ranges of longitudinal slip. Longitudinal wheel slip is the ratio between an individual wheel speed and vehicle speed. Wheel slip varied with brake type, brake conditioning, tire-to-roadway surface coefficient-of-friction, brake temperature, vehicle loading, and braking input applied. The tires were new for each test and the test surface was the same for each test series. During brake tests, the brakes were heated/cooled to an initial brake temperature range of 150 to 200 degrees Fahrenheit just prior to each test run. Upon actual brake application, a full treadle input was applied. Each of these initial preparations normalized variations in their effects so the effects of loading and brake type on wheel slip could be examined independently from these other effects.

The wheel orientation for the slip tests used the conventional VRTC pattern of driver's left-front wheel as number one, with numbers increasing to the right, and from front to rear on the truck (Figure 3.5).

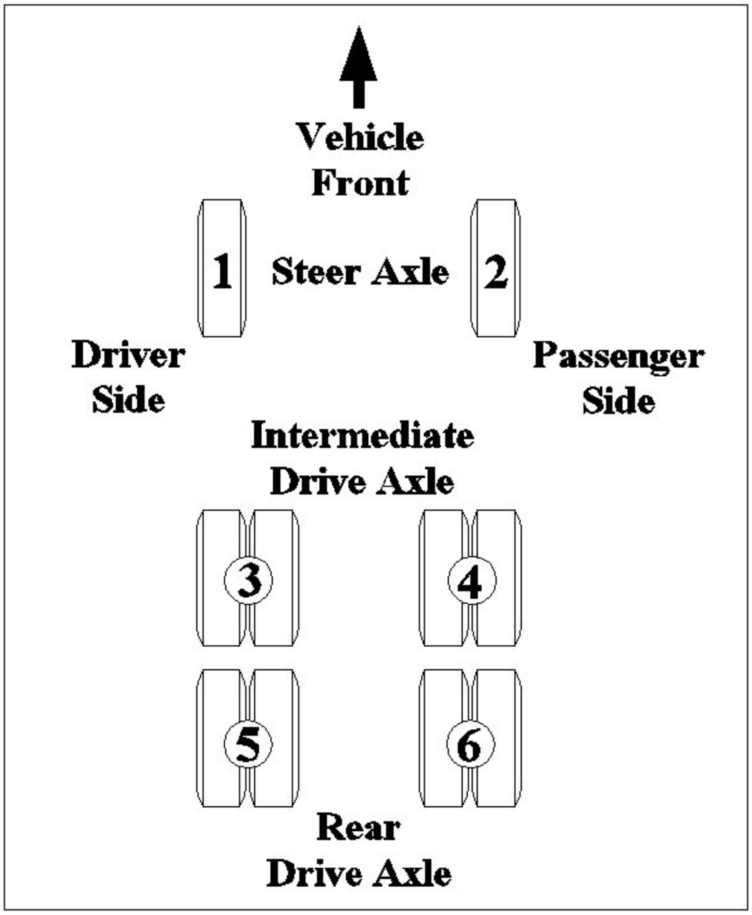

Figure 3.5. Brake Positions for Both Mack 6x4 Trucks

For each of the three loading conditions, the slip dynamics of the four brake types are compared on single pages. Figures 3.6 through 3.17 each show six wheel slip histograms corresponding to the wheel positions portrayed in Figure 3.5. Each slip histogram shows the average slip ratios of up to six stops for each load and brake configuration. Each vertical data bar represents a 2-percent wide "bin" segment of the whole range of wheel slips from 0 to 100 percent. The magnitudes are the averages of the data bars from the individual tests for each percent slip range. Figures 3.6 through 3.9 include plots of the slip ratios for the fully laden chassis-cab truck at GVWR.

Figure 3.6 shows that the standard hybrid S-cam brakes were considerably torque limited as the wheel speeds nearly matched the vehicle speed during the entire stop. At this GVWR loading condition, the tires provided sufficient traction, but the brakes were somewhat low in output compared to a higher output brake (which would be characterized by a more optimal wheel slip of 10 to 15%). The steer axle brakes showed most braking occurring in the 0 to 4-percent slip range, while the drive axle brakes ranged mostly in the 3- to 6-percent slip band.

When using the larger big S-cam brakes on all axles, Figure 3.7 shows a slight improvement in steer braking (with 0- to 6-percent slip) and a distributed slip range of 5- to 16 percent for most of the braking for the drive axles. This was noted by a 16-percent reduction in average stopping distance (Table 3.1) compared to the original hybrid S-cam brakes.

The hybrid disc brake configuration showed an even shorter stopping distance than the big S-cam brakes (Table 3.1) with a 19-percent reduction in average stopping distance when referenced to the hybrid S-cam brakes. Figure 3.8 shows that the steer axle disc brakes provided more output than the earlier S-cam brakes. Here, the hybrid disc slip ratios ranged from 0 to 8 percent for the steers. The slip ratio bands appear more closely bunched (less distributed) for the drive axles (similar to the same S-cam brakes used for the original hybrid S-cam drive brakes) but with a little more slip induced, producing a slip range of 0 to 12 percent, with the highest concentration in the 5- to 10-percent range.

With all-disc brakes (Figure 3.9), all slip ratio bands widened - became more dispersed - than in the previous brake groups. The steer axle brakes ranged from 0- to 10-percent slip and the drive from 0- to 16-percent slip, with most slip in the 5- to 12-percent range. The higher percentages of slip resulted from higher torque generated in the brakes, which produced much shorter stopping distances (Table 3.1 shows an average stopping distance reduction of 24 percent compared to the original hybrid S-cam brakes).

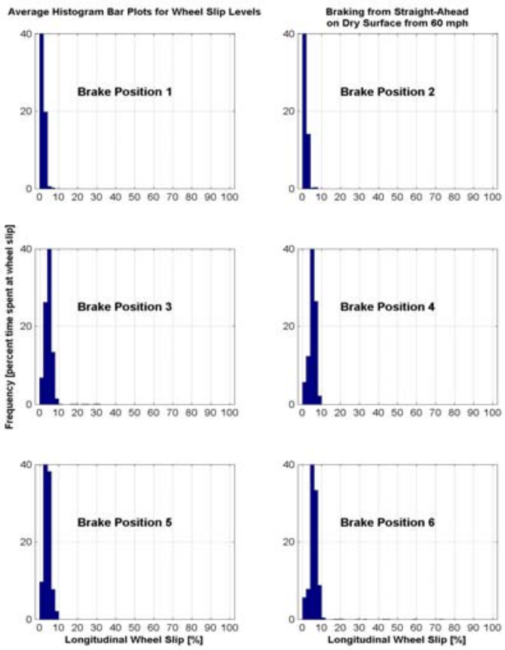

Figure 3.6. Wheel Slip for Hybrid S-Cam Brakes and GVW Load

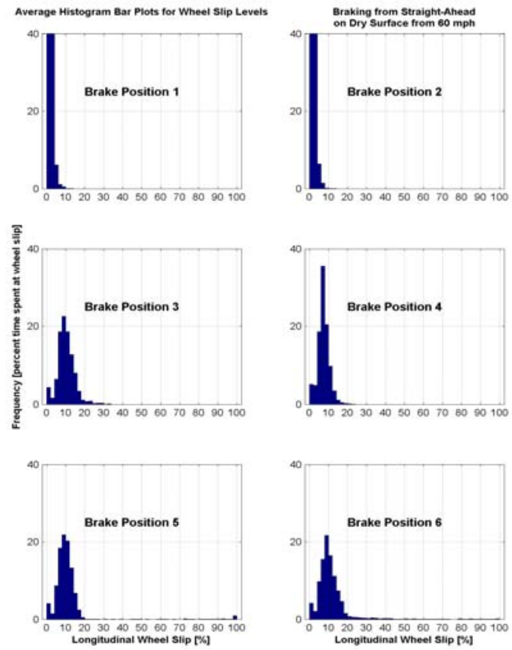

Figure 3.7. Wheel Slip for Big S-Cam Brakes and GVW Load

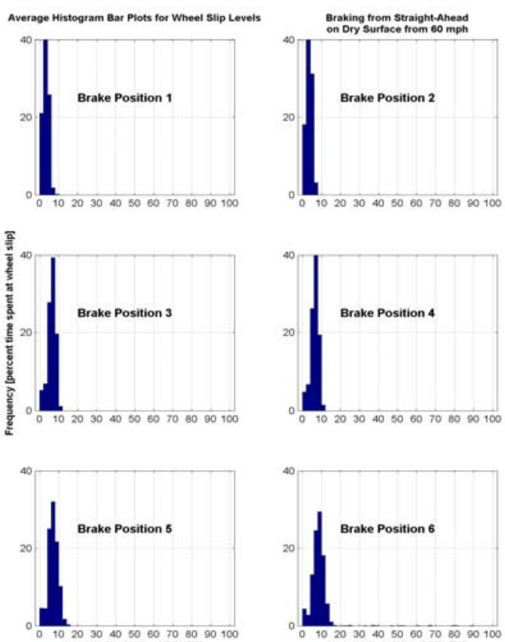

Figure 3.8. Wheel Slip for Hybrid Disc Brakes and GVW Load

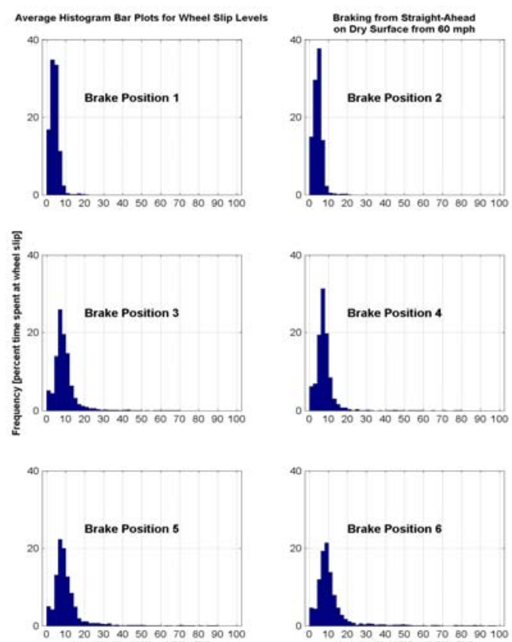

Figure 3.9. Wheel Slip for All-Disc Brakes and GVW Load

When the load was reduced to LLVW, the graphs for the steer axle resembled the percent slip graphs obtained from the previous GVWR load condition. However, for the drive axle graphs, the curves produced had widened out to show higher slip levels and the largest frequency magnitudes of the percent bins (bars) reduced by nearly half.

In Figure 3.10, the tire slip was mostly concentrated in the 0- to 6-percent range for the hybrid S-cam-braked steers. This again shows that the front brakes were torque limited as they didn't cause much reduction in wheel speed below that of the vehicle speed. The plot for Brake Position 1 shows no slip data; which was due to the wheel speed sensor that had failed early in the test series. On the drive axle, the tire percent slip had broadened out somewhat from the plot seen for the GVWR load. The broad spectrum of slip ranged from 0 to 30 percent, with a concentration between 9- and 14-percent slip.

The brakes were changed to big S-cams for Figure 3.11. The steer brakes ranged 0- to 12-percent slip, with a focus in the 0- to 6-percent slip range. The drives were much broader in slip response with a range of 0- to over 40-percent slip. The concentration of slip occurred in the 9- to 14-percent range and the magnitudes for nearly all of the bins were less than 20 percent in frequency of occurrence.

For the hybrid disc brake configuration, a circuit malfunction occurred in the pre-filter circuit to the six wheel speed sensors, thus causing noisy data that erroneously indicated high slip responses; therefore these data were not plotted. However, the vehicle speed and other more critical data parameters were collected satisfactorily; thus a repeat test was not performed for this data set.

For the all-disc brake configuration (Figure 3.12), the slip plots appeared nearly the same as for the big S-cam brake tests in this LLVW load condition. The peak magnitudes for the steer had reduced to less than 15 percent in frequency of occurrence for each bin, and the spectrum ranged from 0- to 12-percent slip with a concentration in the 3- to 10-percent range. For the drive wheels, the magnitudes were all less than 20 percent, and ranged from 0 to 50 percent. The primary focus was from 9- to 16-percent slip. Wheel Position 3 showed a tendency toward frequent partial lock-ups and this repeated for Wheel Position 4 to a lesser extent.

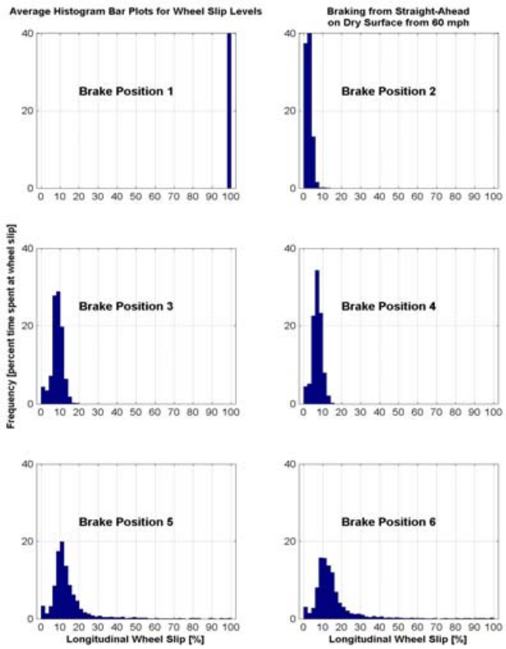

Figure 3.10. Wheel Slip for Hybrid S-Cam Brakes and LLVW Load

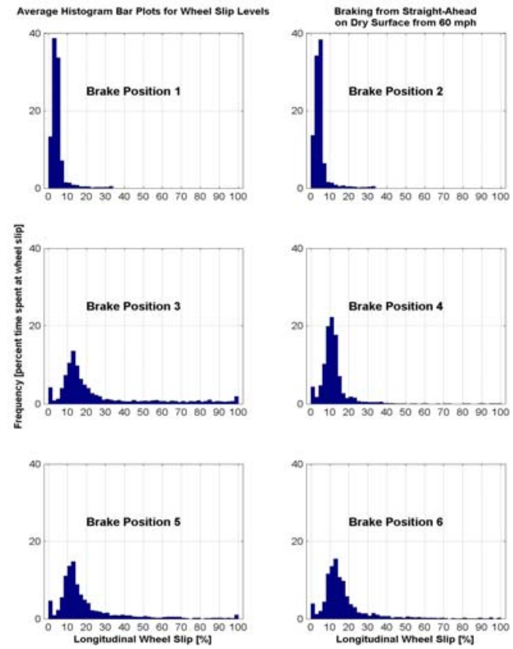

Figure 3.11. Wheel Slip for Big S-Cam Brakes and LLVW Load

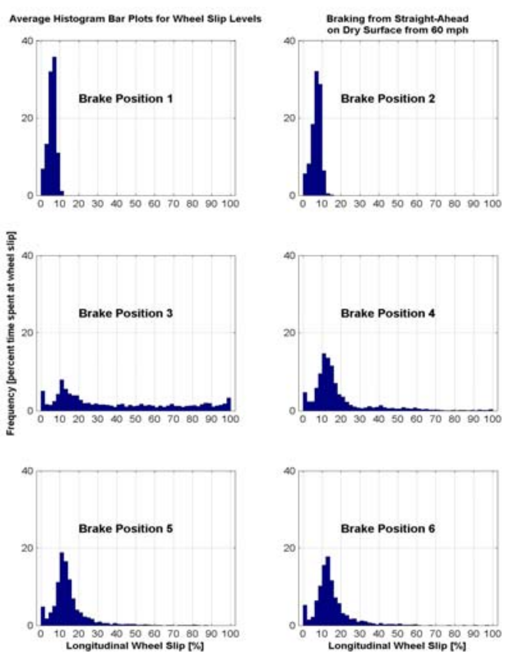

Figure 3.12. Wheel Slip for All-Disc Brakes and LLVW Load

The third load configuration used the MT load where all ballast blocks were removed from the load frame. Both steer and drive wheel slip plots showed increased dispersion in response to the reduced normal force of the vehicle. The steers showed high peaks and a continued sharp cut-off after 12-percent slip for the original hybrid S-cam brake configuration, which showed torque limiting at the brake; whereas the steers on the three higher-output brake configurations showed percent-slip values as high as 50 to 100 percent, indicating no torque limiting.

Figure 3.13 shows the hybrid S-cam steers with a tight band of slip response ranging from 0- to 12-percent slip, and focused between 3 and 10-percent slip. The drive axles saw no peaks above 12-percent frequency, but did see data dispersed from 0- to over 40-percent slip, with some concentration between 8- and 16-percent slip. Both wheels on the intermediate axle showed some tendency toward lockup.

For the big S-cam steer brakes in Figure 3.14, the percent slip was less focused than the hybrid S-cam by seeing frequency of occurrence peaks only around 20 percent and broader ranges of slip (0 to over 24 percent with a concentration between 5- and 12-percent slip). The drives were similar to the previous hybrid S-cam brakes, but with considerable lockups on the left intermediate wheel. The measured slip broadly ranged from 0 to 50 percent and concentrated in the 9- to 16-percent slip range.

With disc brakes on the front axle, Figure 3.15 shows a broad, almost flat response for the steer axle. The frequency magnitudes were less than 14 percent. The data ranged from 0- to 40-percent slip; however, the main group of data appeared as a block with a range from 3 to 18 percent. On the drive axles, the data was more normally distributed with a broad range from 0- to 40-percent slip and centered around 11- to 20-percent slip - which presented the highest slip average for the brakes tested thus far.

In Figure 3.16, the slip distributions resembled the big S-cam plots in Figure 3.14. The steer slip ranged from 0 to 26 with an emphasis between 5- and 15-percent slip, and no frequency magnitudes exceeded 17 percent. The data from the drive axles were somewhat dispersed ranging from 0 to 40 percent and concentrated between 9- and 16-percent slip. Wheel Position 3 saw considerable lockup during the stops and the plot shows very low-slip activity for that wheel.

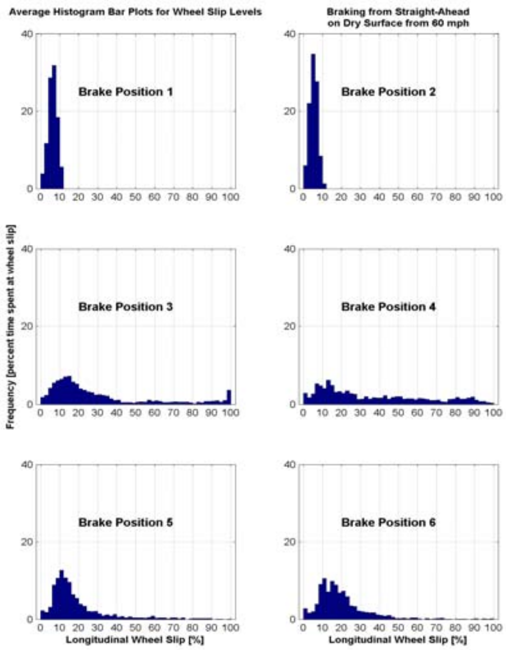

Figure 3.13. Wheel Slip for Hybrid S-Cam Brakes and Empty Load

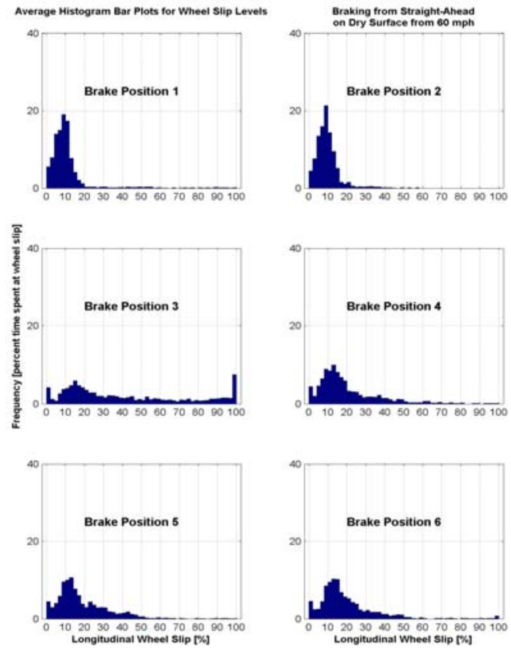

Figure 3.14. Wheel Slip for Big S-Cam Brakes and Empty Load

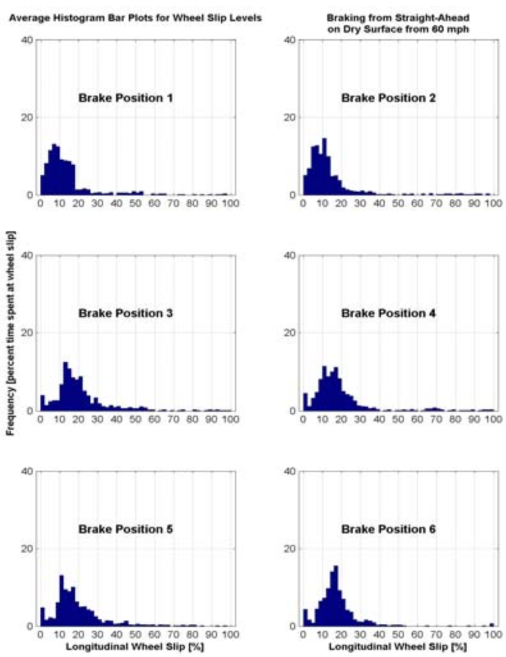

Figure 3.15. Wheel Slip for Hybrid Disc Brakes and Empty Load

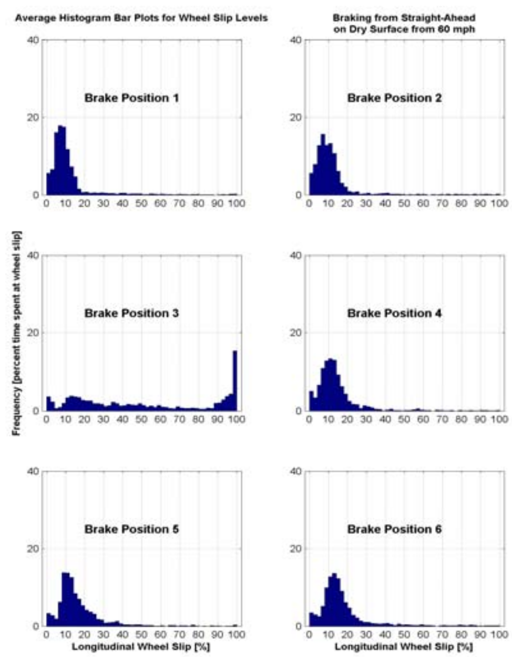

Figure 3.16. Wheel Slip for All-Disc Brakes and Empty Load

3.1.3 Wheel Slip Histogram Summary

The slip data for the steer axle shows that the original hybrid S-cam brakes in all three load conditions were mostly torque limited, with little or no indication of wheel slip. This indicates that a higher output steer-axle brake may provide beneficial stopping power to the vehicle. When the larger (wider) S-cam drum or disc brakes were substituted, the percent-slip distribution broadened somewhat, while remaining relatively normal, and showed no signs of lockup. At LLVW, a similar response repeated the GVWR results, only with additional dispersion in the data. The biggest change was seen for the higher-output brakes in the MT load condition. The steer disc brakes produced lower magnitude frequency-of-occurrence peaks for each incremental 2-percent bin than for either S-cam steer brake. The steer discs did show some higher levels of wheel slip, but only with very infrequent occurrence, indicating that they still provided sufficient wheel speed control that would ensure lateral vehicle stability.

The drive wheel brakes produced a broader spectrum of wheel slip than the steers for each brake and load condition. The percent slip curves were relatively normal in distribution with some positive skewness to the side of higher slip. At GVWR, the large rear S-cams (big S-cam configuration) and the rear disc (all-disc configuration) produced somewhat higher percentages of slip, with broader percent-slip dispersion, and without experiencing any strong tendency toward wheel lock. In the LLVW load condition, the higher output rear brakes showed higher percentages of slip in contrast to the original hybrid S-cam which still appeared to be torque limited. In the MT load condition, the rear brakes produced considerable wheel slip for each type of brake. The drive axle brakes saw frequent activations of the ABS while attempting to minimize wheel lockup. The intermediate axle wheels periodically locked due to being the un-sensed drive axle.

3.2 Emergency Stopping Capability With Failed Systems Test Results

Standard failed systems brake stopping distance tests were performed using the FMVSS No. 121 test procedures. Emergency braking systems were tested as specified in FMVSS No. 121 by simulating failed primary reservoir, failed secondary reservoir, and failed primary control line malfunctions. The full treadle brake applications made in this test series produced periodic wheel lockup with the lighter loads, but did not flat-spot the tires, nor did the truck experience any lane departures; therefore, it was not necessary for the driver to modulate the brake pedal.

Table 3.6 shows the results from the individual stops performed on the high coefficient-of-friction concrete surface of the TRC skid pad. Each row depicts a different brake configuration and load condition. In multi-columnar format are the dry stopping distance data for the failed primary reservoir tests. The first six columns list the stopping distances logged for individual stops after being corrected to an equivalent entry speed of 60 mph using the SAE J299, Equation 1.[11] These are followed by the minimum (Min) stopping distance and margin of compliance relative to the current FMVSS No. 121 requirement of 613 feet. Next are the maximum and mean stopping distance values, and ending with the stopping distance standard deviations and 95-percent confidence limits.

Table 3.6. Statistics for Failed Primary Reservoir Tests

Failed Primary Reservoir Test	Stopping Distance (ft)											
Configuration	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min (ft)	Margin of Compliance (%)	Max (ft)	Mean (ft)	Std Dev	95% Conf Range
GVWR McNeilus S-Cam	368	374	353	354	350	369	350	43.0	374	361	10	353, 369
GVWR Hybrid S-Cam	491	484	495	517	514	519	484	21.0	519	503	15	491, 515
GVWR Big S-Cam	350	347	359	344	350	350	344	43.9	359	350	5	346, 354
GVWR Hybrid Disc	336	334	342	336	335	350	334	45.5	350	339	6	334, 344
GVWR All Disc	298	289	289	287	291	288	287	53.2	298	290	4	287, 293
LLVW McNeilus S-Cam	349	331	328	327	311	322	311	49.3	349	328	13	318, 338
LLVW Hybrid S-Cam	268	262	271	266	269	268	262	57.2	271	267	3	265, 270
LLVW Big S-Cam	252	250	256	254	256	258	250	59.2	258	254	3	252, 256
LLVW Hybrid Disc	216	220	218	223	225	220	216	64.7	225	220	3	218, 223
LLVW All Disc	205	209	206	206	212	204	204	66.7	212	207	3	205, 209
MT Hybrid S-Cam	248	230	225	258	232	232	225	63.2	258	238	13	227, 248
MT Big S-Cam	200	209	211	232	218	219	200	67.3	232	215	11	206, 223
MT Hybrid Disc	207	206	218	204	227	216	204	66.7	227	213	9	206, 220
MT All Disc	193	197	201	209	209	201	193	68.6	209	202	7	196, 207

%MC = Percent Margin of Compliance - Current FMVSS No. 121 Limit is 613 feet

The minimum stopping distances attained for each vehicle and brake type within each load condition were compared. With the exception of the GVWR hybrid S-cam, the Mack MR-688-S mock-up had shorter stopping distances than the McNeilus refuse hauler. As higher output brakes were installed on the mock-up truck, the stopping distances shortened incrementally with each brake type. The MT all-disc brake configuration stopped in the shortest distance overall at 193 feet. In the LLVW tests the Mack MR-688-S mock-up had shorter stopping distances than the McNeilus hybrid S-cam in all brake configurations by a margin of 49 to 107 feet.

Figure 3.17 shows plots of the data described in Table 3.6. Here, the y-axis lists the vehicle, brake, and load configuration. The x-axis portrays stopping distance, which ranges from 100 to 650 feet. Data are plotted in horizontal bar format, increasing from the left axis. Green dots indicate the actual data points for each stop. A red diamond indicates the mean stopping distance and the magnitude is labeled to the right of the symbols. Two blue vertical line segments mark the 95-percent confidence limits. A vertical reference line on the graph represents the current stopping distance limit of 613 feet. The trend of shorter stopping distances resulting from the application of higher output brakes is indicated in the plot with the exception of the GVWR Mack MR-688-S with hybrid S-cams. All configurations tested with the failed primary reservoir malfunction met the current FMVSS No. 121 requirement of not more than 613 feet.

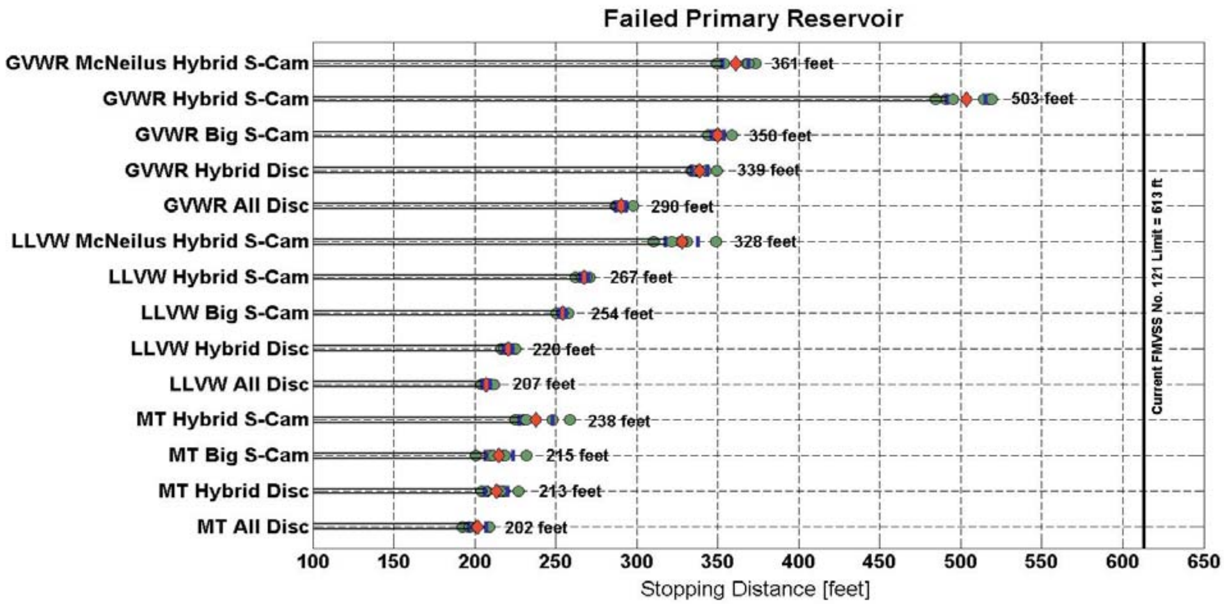

Figure 3.17. Failed Primary Reservoir Tests

Table 3.7 contains the data from the failed secondary reservoir tests. The minimum stopping distances attained for each vehicle and brake type within each load condition again were compared. The LLVW McNeilus refuse hauler had the shortest stopping distance of all the failed secondary reservoir tests at 257 feet. The percentage margin of compliance for the McNeilus refuse hauler in both the GVWR and the LLVW tests was greater than all other configurations and loads tested for the failed secondary reservoir malfunction. All of the failed secondary reservoir tests met the current FMVSS No. 121 requirement of not more than 613 feet.

Table 3.7. Failed Secondary Reservoir Tests

Failed Secondary Reservoir Test	Stopping Distance (ft)											
Configuration	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min (ft)	Margin of Compliance (%)	Max (ft)	Mean (ft)	Std Dev	95% Conf Range
GVWR McNeilus S-Cam	364	384	371	354	363	356	354	42.3	384	365	11	357, 374
GVWR Hybrid S-Cam	567	557	544	532	530	533	530	13.5	567	544	15	532, 556
GVWR Big S-Cam	386	423	388	398	386	396	386	37.0	423	396	14	385, 407
GVWR Hybrid Disc	468	493	472	489	461	468	461	24.7	493	475	13	465, 485
GVWR All Disc	396	392	422	385	400	402	385	37.2	422	400	13	389, 410
LLVW McNeilus S-Cam	257	277	271	258	264	271	257	58.2	277	266	8	260, 273
LLVW Hybrid S-Cam	406	430	415	418	405	415	405	34.0	430	415	9	408, 422
LLVW Big S-Cam	386	380	387	397	387	383	380	37.9	397	387	6	382, 391
LLVW Hybrid Disc	419	430	420	415	430	424	415	32.3	430	423	6	418, 428
LLVW All Disc	388	375	386	386	392	390	375	38.8	392	386	6	382, 391
MT Hybrid S-Cam	384	391	390	404	407	391	384	37.4	407	394	9	387, 402
MT Big S-Cam	400	381	383	372	376	390	372	39.3	400	384	10	376, 392
MT Hybrid Disc	384	386	400	406	407	398	384	37.3	407	397	10	389, 405
MT All Disc	410	398	397	407	424	398	397	35.2	424	406	10	397, 414

%MC = Percent Margin of Compliance - Current FMVSS No. 121 Limit is 613 feet

Figure 3.18 plots the data described in Table 3.7. Instead of the trend of incrementally shorter stopping distances resulting from the application of the higher output service brakes, this plot shows a band of similar stopping distance results in the mid to upper 300 foot range for most failed secondary reservoir stops. In the lightly loaded condition, there was little difference between most brake configurations. All of the Mack chassis-cab truck tests were performed by one driver using one brake application timing method and reservoir venting solenoid orifice size; a different driver using different solenoid valves performed the McNeilus tests. Varying any of these parameters often produces different stopping distances for failed-systems tests.

Two notable exceptions are the GVWR Mack MR-688-S with hybrid S-cams that averaged 544 feet and the LLVW McNeilus refuse hauler that had the shortest stop at 257 feet. These range differences may be somewhat attributed to the variance between the two vehicle setups and the braking styles of the two drivers for this initial-pressure sensitive failed system test. If the driver applies the service brake soon after the low-pressure warning sounds, the residual pressure in the "failed" tank may be higher than for the test where the driver waits until the end of the 5-second brake application window (FMVSS No. 121 allows a driver discretionary 5-second lapse between low-pressure warning and service brake application). Similarly, if a smaller-orifice solenoid (dump valve) is used to vent the air from the "failed" reservoir, the residual air pressure in the tank will be higher at brake application than a reservoir that uses a larger solenoid orifice. Typically, higher initial braking pressure produce shorter stops. If the combined 5-second delay and large solenoid valve (so the reservoir was depleted of air at brake apply) were used at the same time, the stopping distance would approach the maximum obtainable for that failed system. The McNeilus tests used a ¼" solenoid and the Mack tests used a 3/8" solenoid.

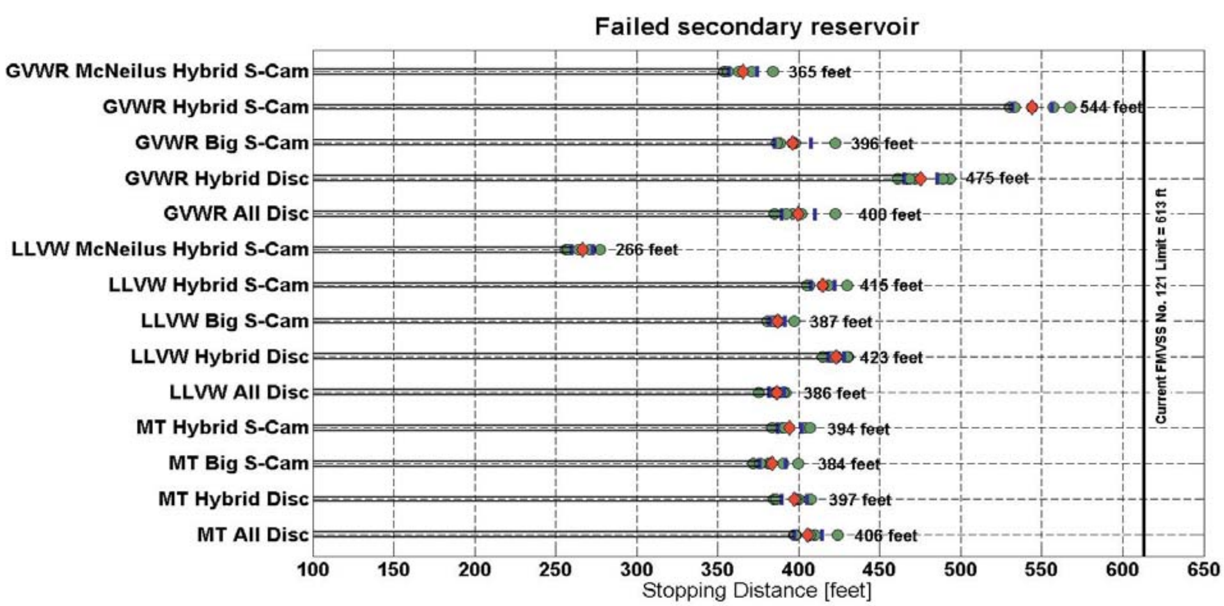

Figure 3.18. Failed Secondary Reservoir Tests

The results of the failed primary control line tests are found in Table 3.8. All of the brake stopping distances met the FMVSS No. 121 requirement of 613 feet or less. The minimum stopping distances ranged from the low of 178 feet by the MT big S-cam configuration on the Mack mock-up truck to the highest of 325 feet by the GVWR Mack MR-688-S with hybrid S-cams.

Table 3.8. Failed Primary Control Line Tests

Failed Primary Control Line Test	Stopping Distance (ft)											
Configuration	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6	Min (ft)	Margin of Compliance (%)	Max (ft)	Mean (ft)	Std Dev	95% Conf Range
GVWR McNeilus S-Cam	321	318	313	318	313	326	313	49.0	326	318	5	314, 322
GVWR Hybrid S-Cam	365	352	347	343	325	328	325	46.9	365	343	15	331, 355
GVWR Big S-Cam	288	264	268	270	269	279	264	56.9	288	273	9	266, 280
GVWR Hybrid Disc	256	262	262	262	264	263	256	58.3	264	261	3	259, 264
GVWR All Disc	239	246	245	238	236	240	236	61.6	246	240	4	237, 244
LLVW McNeilus S-Cam	280	271	270	269	280	301	269	56.1	301	278	12	269, 288
LLVW Hybrid S-Cam	268	256	253	246	249	249	246	59.9	268	253	8	247, 260
LLVW Big S-Cam	225	227	233	228	223	221	221	63.9	233	226	4	223, 230
LLVW Hybrid Disc	202	204	207	206	202	204	202	67.0	207	204	2	203, 206
LLVW All Disc	193	190	201	198	198	199	190	69.0	201	196	4	193, 200
MT Hybrid S-Cam	200	199	195	194	187	191	187	69.6	200	194	5	190, 198
MT Big S-Cam	200	178	190	193	190	189	178	70.9	200	190	7	184, 196
MT Hybrid Disc	188	188	184	193	185	185	184	70.0	193	187	3	184, 190
MT All Disc	196	184	186	191	189	190	184	70.0	196	189	4	186, 193

%MC = Percent Margin of Compliance - Current FMVSS No. 121 Limit is 613 feet

The data from Table 3.8 is plotted in Figure 3.19. The trend of incrementally reduced stopping distances (as the higher output brakes were applied) is similar to that of the failed primary reservoir tests. The GVWR Mack MR-688-S mock-up with hybrid S-cams again had the longest stop, but was much closer to the other configurations tested in the GVWR load condition. All met the FMVSS No. 121 standard with margins of compliance greater than 46 percent.

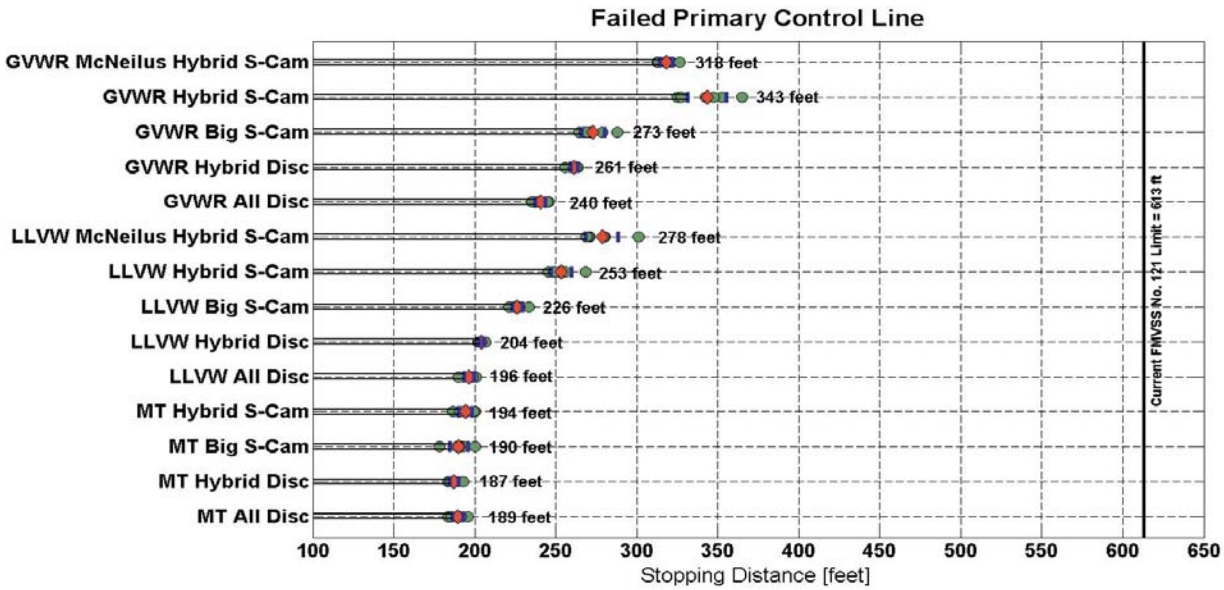

Figure 3.19. Failed Primary Control Line Tests

An overview of all failed system tests for the Mack MR-688-S Chassis Cab is shown graphically in Figure 3.20. The trends established by the service brake tests repeated for both the failed primary reservoir and failed primary control line tests. However in the failed secondary reservoir tests, the big S-cam configuration stopped considerably shorter than the hybrid disc configuration, thereby reversing the trend seen in the service brake tests.

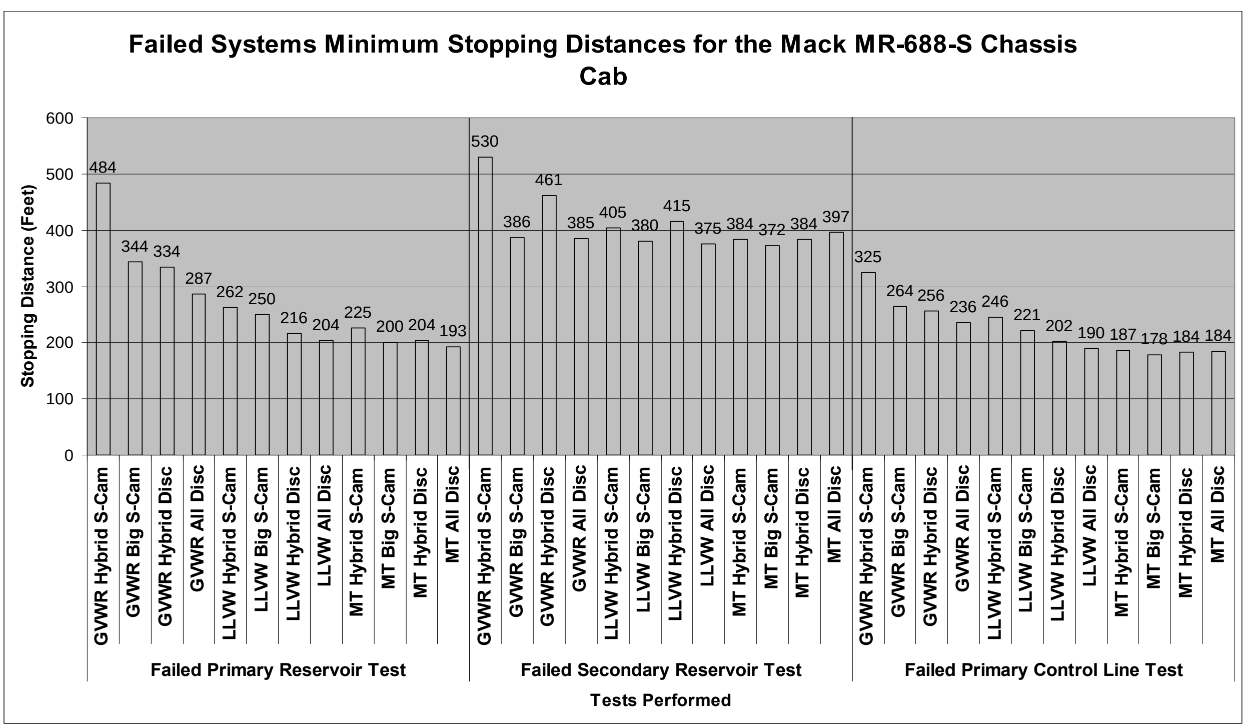

Figure 3.20. Minimum Stopping Distances for All Failed Systems Tests

The results of all of the straight line dry stopping tests for both the Mack MR-688- S Chassis Cab and the McNeilus refuse hauler, each equipped with hybrid S-cam brakes are shown in Figure 3.21 for GVWR and in Figure 3.22 for LLVW. The 60 mph Service Brake Stopping Tests were included for comparison. The vertical bar graphs are composed of four major groups of Test Series on the X-axis. These test groups from left to right are: failed primary reservoir, failed secondary reservoir, failed primary control line, and 60 mph service brake stopping performance tests. Each major test group is divided into a group for the McNeilus refuse hauler on the left and a group for the Mack MR-688-S Chassis Cab on the right. The result of each stop is represented by a colored vertical bar. Stopping distance is represented by the Y-axis with major grid line divisions every 100 feet. The scale is 0 to 600 feet.

With the addition of the service brake stops into the comparison it can be observed that most of the stopping distances at the GVWR load condition fall into a loose band across the chart. This band ranges from approximately 300 feet to about 360 feet. The two test sets that had significantly longer stops were the failed primary reservoir and the failed secondary tests with the Mack MR-688-S Chassis Cab.

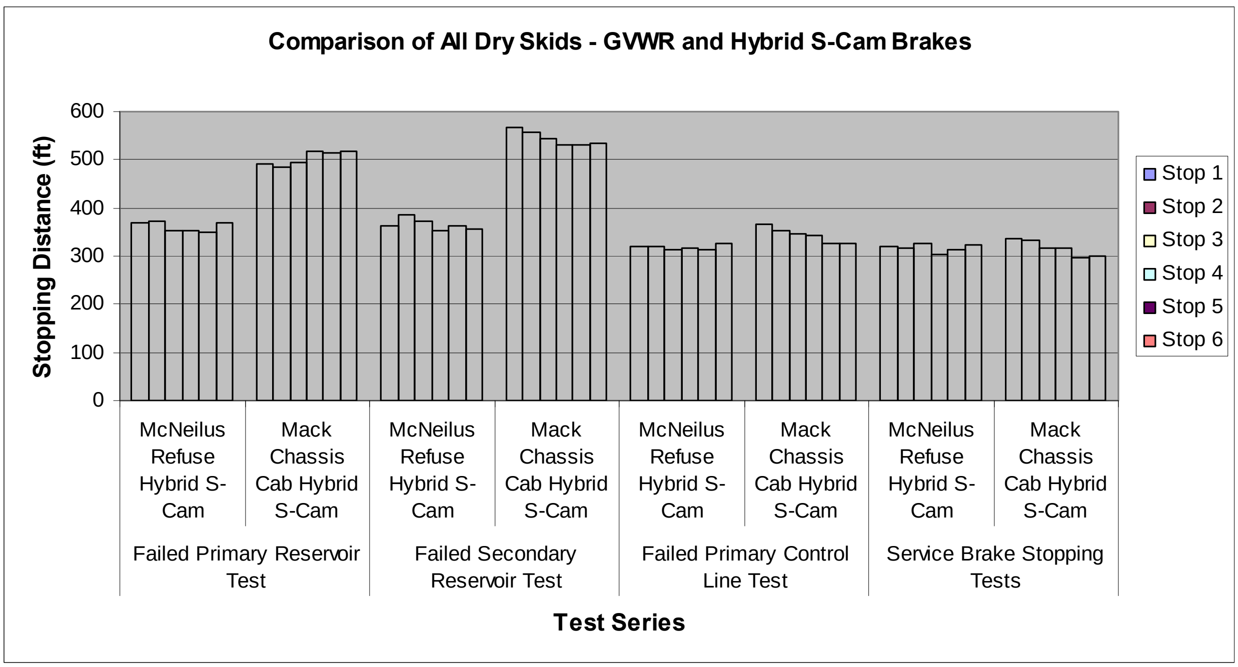

Figure 3.21. All Dry Skids – GVWR

Figure 3.22 is a graph of the same tests and configurations as in Figure 3.21 (GVWR dry skids), but for the LLVW load conditions. Again most of the stopping distances fall into a band mid-range on the graph. The Mack MR-688-S Chassis Cab failed secondary reservoir tests were longer than the other test set series by approximately 100 feet.

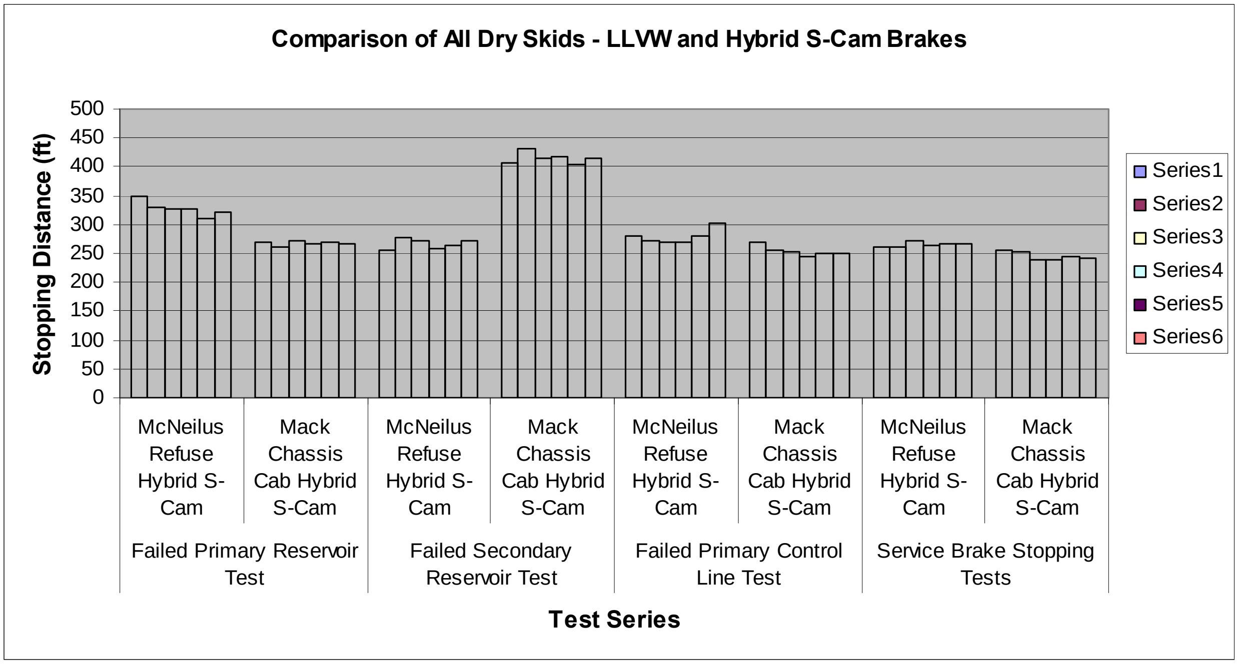

Figure 3.22. All Dry Skids – LLVW

3.3 Brake-in-a-Curve Stability Testing Results

The following results for the BIC stability tests include four standard *target* speed stops and a series of experimental *limit* speed stops, all of which were conducted on a water-wetted Jennite curve.

3.3.1 Stability and Control – Target Speed BIC Tests

For each brake configuration and load condition, a maximum drive-through speed was established. These drive-through speeds ranged from 33 to 37 mph. The corresponding 75-percent of drive-through "target" speeds ranged from 25 to 28 mph. The truck completed four-of-four stops from the target speed, in lane, for each of the three load conditions and for the four successive foundation brake configurations. This thereby indicated that changing the foundation brakes did not adversely affect the braking stability of the vehicle for the baseline BIC tests.

Table 3.9 shows the results of the basic FMVSS No. 121 - BIC tests. The data are grouped in columns by load condition and foundation brake configuration, followed by data: the drive-through speeds, the computed target speeds, the comparison of stops achieved in-the-lane to stops attempted, and a measurement of the Jennite test surface coefficient-of-friction (Mu).

Additionally, Figure 3.23 graphically compares the drive-through speed to the target speed for each foundation brake, grouped by load condition. Speed values are listed at the top of each data bar. For each data pair, the left (blue) bar represents the drive-through speed, while the right bar (violet) represents the target speed.

Table 3.9. FMVSS No. 121 Stability and Control Test Results

Load	Brake Configuration	Drive-Through Speed (mph)	Target Speed (mph)	Stops in Lane /Attempts	Measured Peak Mu
GVWR	Hybrid S-Cam	36	27	4 / 4	0.41
	Big S-Cam	36	27	4 / 4	0.28
	Hybrid Disc	37	28	4 / 4	0.43
	All-Disc	35	26	4 / 4	0.29
	McNeilus Truck	33	25	4 / 4	0.40
LLVW / Intermediate Load	Hybrid S-Cam	37	28	4 / 4	0.45
	Big S-Cam	37	28	4 / 4	0.28
	Hybrid Disc	37	28	4 / 4	0.46
	All-Disc	35	26	4 / 4	0.28
	McNeilus Truck *	34	26	4 / 4	0.40
MT	Hybrid S-Cam	36	27	4 / 4	0.41
	Big S-Cam	37	28	4 / 4	0.28
	Hybrid Disc	37	28	4 / 4	0.46
	All-Disc	35	26	4 / 4	0.28

*Note: Completed McNeilus Truck with front-loading refuse Body (tested previously) with no additional ballast

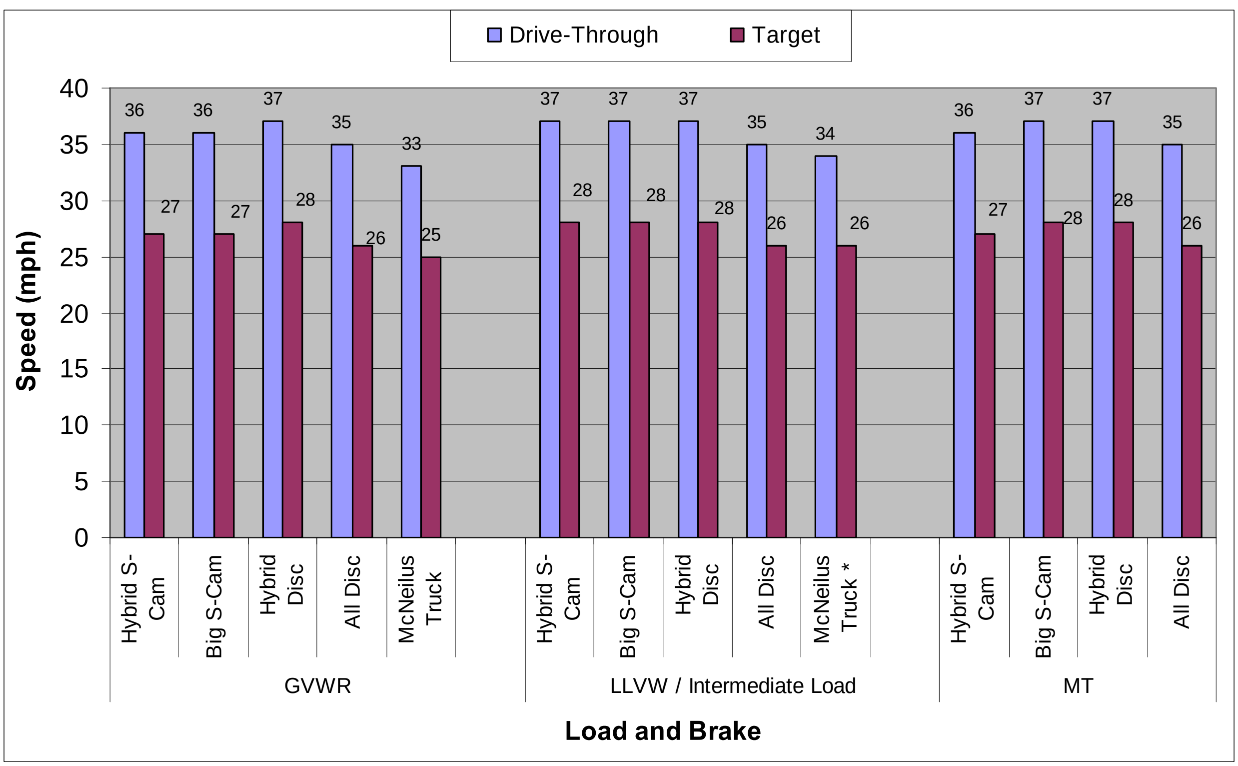

Figure 3.23. Comparison of Target Speeds for Each Load and Brake Configuration

3.3.2 Stability and Control – Developmental Limit Handling Speed

After the four compulsory target-speed stops were completed, the initial braking speeds were increased to determine the actual *limit* handling speed for stability and control during braking on the low-coefficient-of-friction surface. Once obtained, the limit handling speeds were compared to the drive-through speeds. To mitigate the effects of surface friction, LAPQ were computed.

The results are compiled in Table 3.10 for each brake-load configuration. The columnar data include loading condition, foundation brake configuration, and data sets: maximum drive-through speed, the maximum attained in-the-lane limit speed, a speed ratio comparing the limit speed to the drive-through (DT) speed, the computed LAPQ, and the measured coefficient-of-friction of the low-mu Jennite surface. Figure 3.24 graphically compares the drive-through speed to the limit speed for each foundation brake, grouped by load condition. Speed values are listed at the top of each data bar. For each data pair, the left (blue) bar represents the drive-through speed, while the right bar (violet) represents the limit speed.

Table 3.10. Limit Handling Tests for Brake-in-a-Curve

Mack 6x4 Truck Load	Brake Configuration	Drive-Through Speed (mph)	Limit Speed (mph)	Speed Ratio Limit/DT (%)	LAPQ (%)	Measured Peak Mu
GVWR	Hybrid S-Cam	36	33.7	94%	88%	0.41
	Big S-Cam	36	34.0	94%	89%	0.28
	Hybrid Disc	37	34.1	92%	85%	0.43
	All-Disc	35	31.2	89%	79%	0.29
LLVW / Intermediate Load	Hybrid S-Cam	37	34.4	93%	86%	0.45
	Big S-Cam	37	33.1	89%	80%	0.28
	Hybrid Disc	37	33.6	91%	82%	0.46
	All-Disc	35	30.0	86%	73%	0.28
MT	Hybrid S-Cam	36	34.0	94%	89%	0.41
	Big S-Cam	37	34.3	93%	86%	0.28
	Hybrid Disc	37	33.8	91%	83%	0.46
	All-Disc	35	31.8	91%	83%	0.28

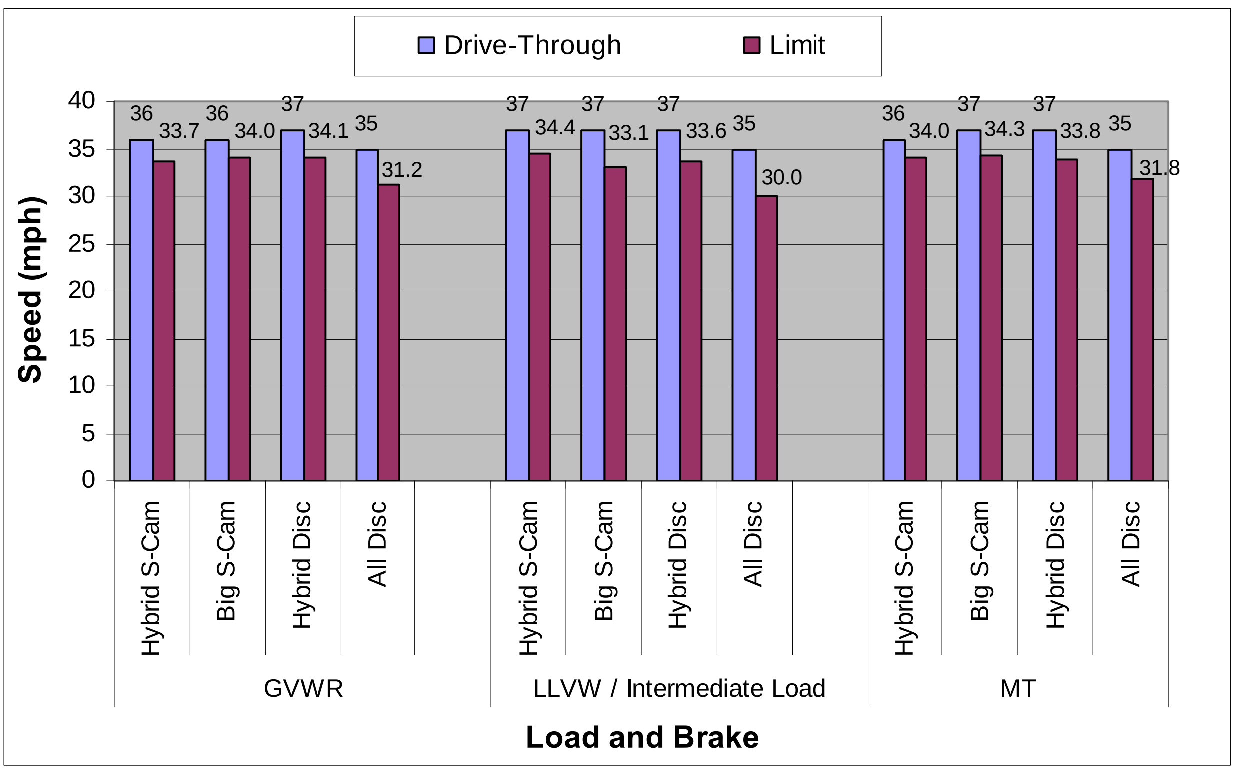

Figure 3.24. Comparison of Limit Speeds for Each Load and Brake Configuration

For comparison to a minimally acceptable performance where the speed ratio would be only 75 percent, the LAPQ would be 0.56, or 56 percent. Each of the brake configurations tested surpassed the minimum performance expectation and achieved somewhat similar LAPQ's. However, the S-cam configurations provided slightly better stability than those with disc brakes in the GVWR and MT load conditions, and the higher output brakes (big S-cam and all-disc) did not perform quite as well as the two hybrids at the LLVW load condition. This indicates that each of the brake configurations provided sufficient stability in the BIC test, but the best overall was the original hybrid S-cam brake configuration (Figure 3.25).

It was also noted that the surface coefficient-of-friction was considerably lower for the big S-cam and the all-disc brake configuration tests. While LAPQ mitigates small variations in surface friction from test-to-test, it does not account for the non-linear response to the inertial effect of a locked wheel. On a lower coefficient-of-friction surface, a slowed tire (in a high slip condition) takes longer to spin back up than one on a higher friction surface; therefore, the ABS build time tends to vary with the perceived longitudinal slip, thus allowing for slightly longer stops, but with better lateral control of the vehicle.

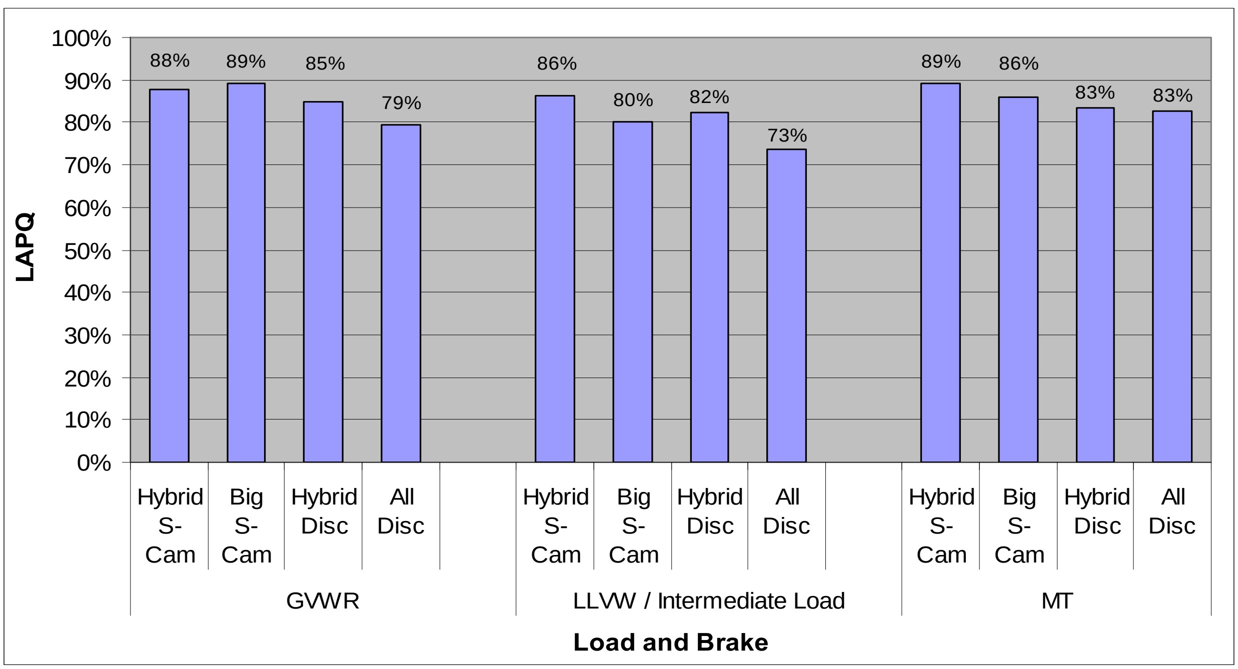

Figure 3.25. Lateral Acceleration Performance Quotients as Percentages

3.4 Parking Brake Test Results

The following results detail the parking brake tests performed. Both Grade Holding and Drawbar tests were conducted using the FMVSS No. 121 procedures.

3.4.1 20-Percent Grade Holding

The refuse hauler and the Mack chassis-cab truck both passed the 20-percent grade holding tests, for each load condition, direction (front of truck facing uphill or downhill), and brake configuration. While on the grade with the parking brake engaged, no movement was exhibited within the 5-minute holding period for either truck. Although FMVSS No. 121 does not specify a service brake application prior to applying the parking brake, Table 3.11 shows the minimum treadle pressures applied (in psi) to stop and hold the vehicles stationary on the 20-percent grade, until the parking brake was engaged. The columns of data are categorized by vehicle, load, and brake type. The rows differentiate the direction of travel of the vehicles on the grade and the loads applied.

Table 3.11. 20-Percent Grade Tests – Minimum Treadle Pressures to Stop on the Grade

Direction	Load	McNeilus	Mack Chassis-Cab			
		Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All Disc
uphill	GVWR	40	42	20	38	36
downhill	GVWR	43	38	16	35	34
uphill	LLVW	25	23	17	16	20
downhill	LLVW	25	18	14	17	18
uphill	MT	d.n.a.	33	9	18	14
downhill	MT	d.n.a.	24	12	17	25

Note: all pressures in psi

Figure 3.26 shows the data from Table 3.11 graphed in a vertical bar format. Each vehicle/brake group displayed on the x-axis contains up to six data bars (except the McNeilus truck only shows its four data bars). The labels for the data bars follow the first two columns of the table data, where alternate bars repeat for the directions of pull uphill, then downhill, followed by the three load configurations, GVWR, LLVW, and MT.

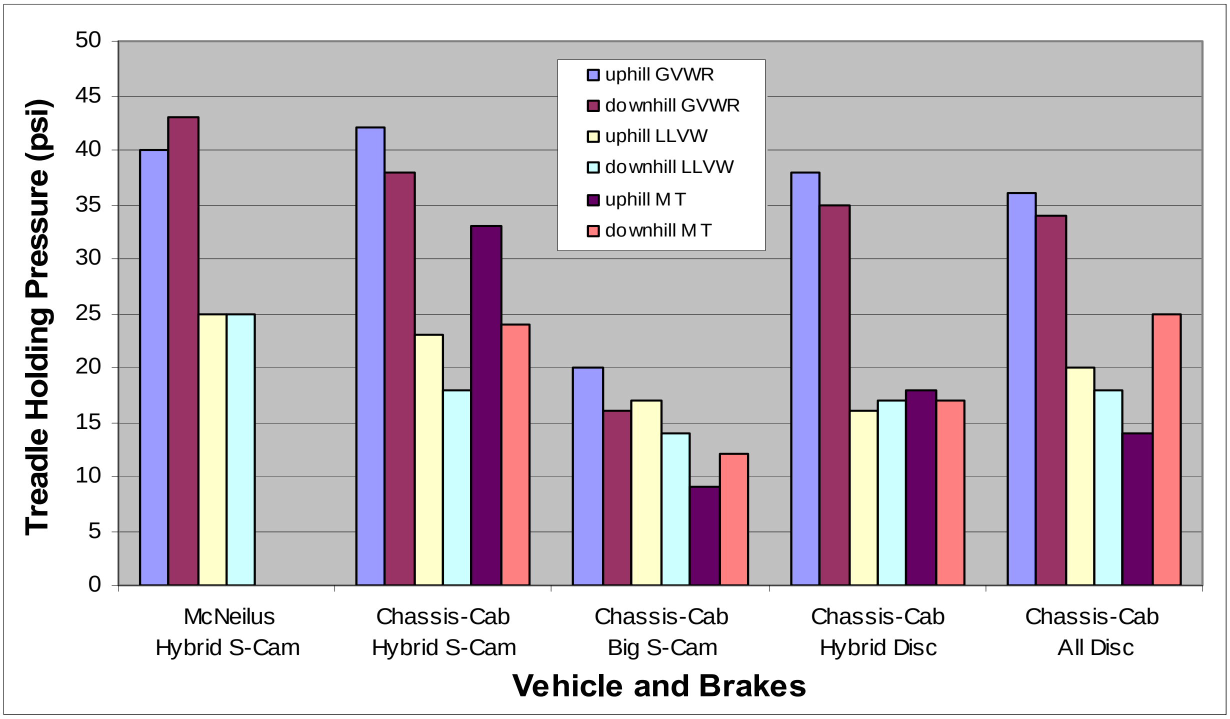

Figure 3.26. 20-Percent Grade Tests – Minimum Treadle Pressures to Stop on the Grade

For most of the tests at GVWR, the initial holding pressures were similar for each brake type, ranging from 34 to 43 psi. However, the big S-cam brake stopped the truck on the grade with only 16 to 20 psi applied to the service brakes, which was less than half of the holding pressure required for the other brake configurations, prior to setting the parking brake.

For the LLVW condition, all of the initial holding pressures were lower than for the GVWR loads. At the MT loading condition for the chassis-cab truck, a few holding pressures were slightly higher than at the LLVW load condition, while the others were the same or lower. The big S-cam brake configuration continued to hold at lower pressures than any of the other brakes.

In Figure 3.27, the data from Table 3.11 is re-plotted after re-sorting the categories to emphasize the trend in reducing pressure as the load was reduced. The vertical-columnar groups are arranged by direction and load. The magnitude of the bars in each grouping correspond to the treadle holding pressures required to hold the truck on the grade for a given truck with a specified type of brake (i.e., each brake configuration is presented in a separate group). In this sorting format, both the McNeilus truck and the chassis-cab with hybrid S-cam brakes at GVWR required more initial holding pressure compared to the higher output brakes (which required somewhat less holding pressure). This trend continued for the LLVW condition as well. The big S-cam brake configuration required the least holding pressure for five of the six load/direction comparisons. The reducing pressure trend did not hold for the chassis-cab in the empty load condition with either hybrid S-cam or all-disc brakes, as there was a slight upturn in pressure needed to stop the truck on the grade.

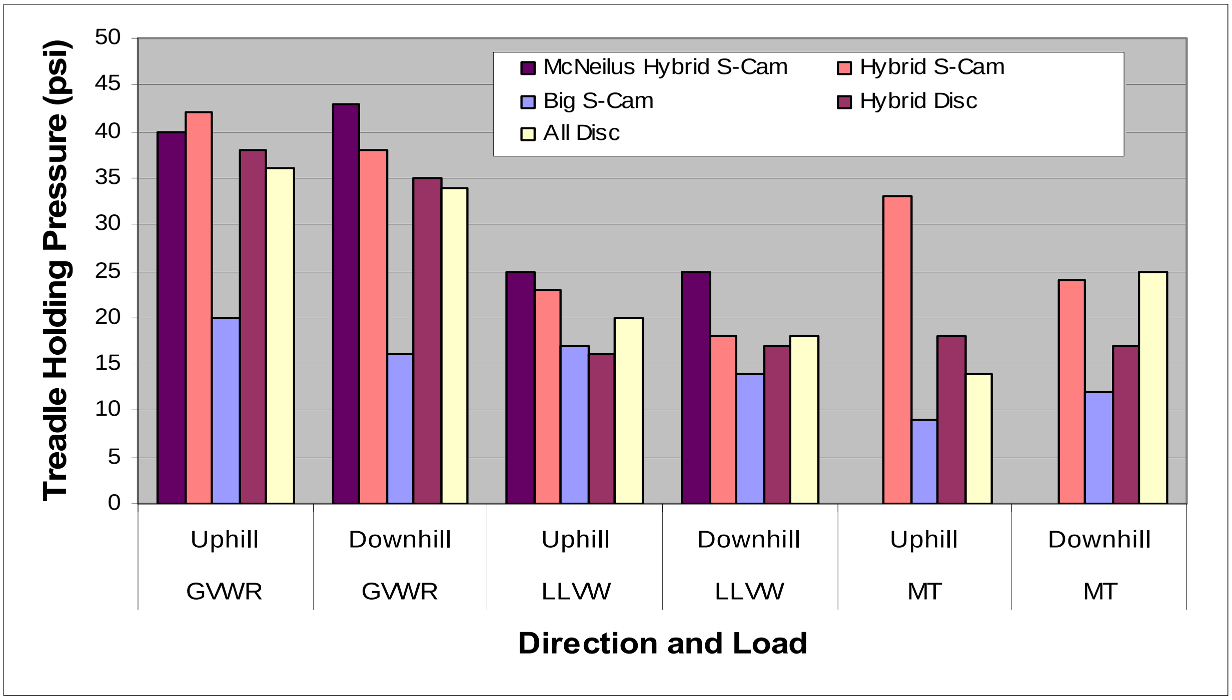

Figure 3.27. 20-Percent Grade Tests – Minimum Treadle Pressures Re-Grouped

3.4.2 Drawbar Test Results

After seeing both trucks hold on the 20-percent grade satisfactorily, the results of the drawbar tests were expected to be equally positive; however, one configuration failed to meet the minimum drawbar force when testing one axle. In general, the parking brake drawbar test results for the forward pulls were consistently higher than for the rearward pulls. Some believe this phenomenon was caused by the brakes being burnished while the vehicle was being driven in the forward direction. Because of this, the brakes became more effective in the forward direction; and therefore, resulted in higher margins of compliance, in the forward direction.

Tables 3.12 through 3.14 list the drawbar-pull test results for both the McNeilus refuse hauler and the chassis-cab truck in the four different brake configurations. The FMVSS No. 121 standard required that the maximum drawbar force/GAWR ratio be greater than or equal to 0.28, for each parking-brake-equipped axle on a straight truck. These trucks were configured with two 23,000 pound (GAWR) drive axles that were individually required to meet or exceed a drawbar force of 6,440 pounds; therefore, the drawbar tests were repeated for each axle one at a time. The resulting Table 3.12 compares maximum drawbar forces measured from the four required pulls which correlate to each pull direction, axle, and brake configuration. The parking brake force for each pull test exceeded the minimum 6,440 lbf requirement except the in-use truck (McNeilus) rearward pull on the rear drive axle (highlighted in **bold**). It was approximately 1.2 percent low.

Table 3.12. Drawbar - Maximum Parking Brake Forces (in lbf)

Pull Direction	Drive Axle	McNeilus	MR-688-S Chassis-Cab			
		Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All Disc
Forward	Intermediate	8,100	9,917	13,159	10,220	12,752
	Rear	6,821	7,906	11,247	8,753	11,044
Rearward	Intermediate	7,114	8,005	12,441	8,195	8,725
	Rear	**6,360**	7,155	12,241	9,117	9,326

The parking brake drawbar forces from Table 3.12 are plotted in vertical column format in Figure 3.28. The data are grouped by type of brake configuration and vehicle. Each group contains data columns that correspond to the direction of pull (forward and rearward), to the axle position on the truck (intermediate or rear), and to the minimum parking brake force requirement to exceed (requirement) for reference. The Y-axis is graduated in lbf to depict parking brake drawbar force and ranges from 0 at the bottom, to 15,000 at the top. Each vertical column displays the magnitude of the force at the top. Midway vertically, there is a bold line extending horizontally to the limits of the graph and with a constant magnitude equivalent to the minimum required drawbar force (labeled “y = 6440”).

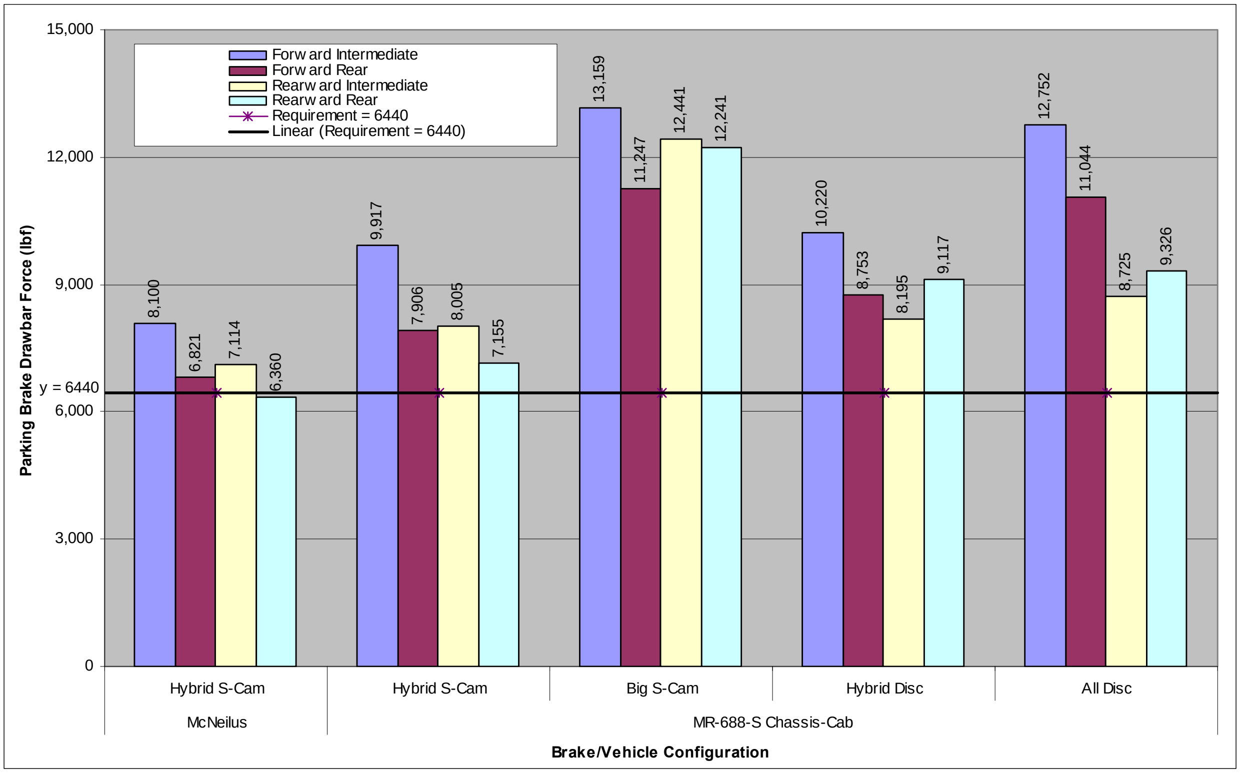

Figure 3.28. Parking Brake Drawbar Forces

In order to obtain an easier comparison of the parking brake forces, the minimum requirement of 6,440 lbf was subtracted from each value in Table 3.12 and the differences listed in Table 3.13. The margins of safety values in Table 3.13 ranged from -80 to +6,719 lbf. The parking brake forces measured for the chassis-cab truck with baseline hybrid S-cam brakes were lower than for the other higher-output brakes tested, but were somewhat higher than for the in-use truck (McNeilus with similar brake components).

Table 3.13. Drawbar – Reserve Parking Brake Forces Beyond Minimum Requirement

Pull Direction	Drive Axle	McNeilus	MR-688-S Chassis-Cab			
		Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All Disc
Forward	Intermediate	1,660	3,477	6,719	3,780	6,312
	Rear	381	1,466	4,807	2,313	4,604
Rearward	Intermediate	674	1,565	6,001	1,755	2,285
	Rear	**-80**	715	5,801	2,677	2,886

Note: McNeilus rearward pull parking brake force for the rear drive axle was below minimum requirement by 80 lbf, but truck had held satisfactorily on the 20-percent grade test.

When examining the chassis-cab truck parking brake outputs from the separate axles in the forward pull direction, the parking brakes of the intermediate axle produced between 1.4 to 2.4 times higher force margins than those of the rear axle. In the rearward pull direction, the hybrid S-cam produced a similar output ratio (2.2:1), the big S-cam showed the axles produced nearly the same forces for each pull direction, but the hybrid disc and the all-disc saw a reversal to where the output from the intermediate axle parking brake was lower, or approximately 70 to 80 percent of the output of the rear axle parking brakes.

For a given axle, the margin ratios of the forward force divided by the rearward force (Fwd/Rwd) produced results somewhat similar to the previous axle comparisons. For the parking brakes on the intermediate axle, the Fwd/Rwd ratios ranged from 2.8:1 to 2.2:1 for each brake, except the big S-cam whose ratio was just 1.1:1. For the rear axle parking brakes, the margin ratios reduced and some actually reversed. The output ratio for the hybrid S-cam lowered to 2:1, and for the all-disc, to 1.6:1. For the big S-cam and the hybrid disc, the ratios reversed to 0.8:1 to 0.9:1, respectively, indicating higher output in the rearward direction.

Table 3.14 shows the percent margins of compliance computed for the maximum measured parking brake forces. A margin of compliance value is calculated by taking the margin values (from Table 3.13) and dividing by the minimum drawbar requirement of 0.28 times GAWR (6,440 lbf for this example), and then multiplying by 100 percent.

Table 3.14. Drawbar – Margins of Compliance

Pull Direction	Drive Axle	McNeilus	MR-688-S Chassis-Cab			
		Hybrid S-Cam	Hybrid S-Cam	Big S-Cam	Hybrid Disc	All Disc
Forward	Intermediate	26%	54%	104%	59%	98%
	Rear	6%	23%	75%	36%	71%
Rearward	Intermediate	10%	24%	93%	27%	35%
	Rear	**-1%**	11%	90%	42%	45%

Note: McNeilus rearward pull parking brake force was below minimum requirement by 1% for rear axle, but passed on the intermediate axle by 10%. The parking brake force of the two axles combined was sufficient to permit the vehicle to hold satisfactorily on the 20-percent grade.

A parking brake force with a 10- to 15-percent margin of compliance provides a comfortable margin of safety beyond the basic requirement. For the chassis-cab truck, each of the parking brake forces produced such a margin and confirmed the ability of the parking brakes to hold the truck on the 20-percent grade. The area of concern during this test series was the rearward pull value measured for the rear axle on the in-use McNeilus truck with hybrid S-cam brakes. The margin of compliance was -1 percent. This indicated that if this test were run for compliance purposes on a new truck with this parking brake capability, the rear axle brake would not be compliant and that the truck may not hold on the 20-percent grade.

Multivariate analysis was performed to determine the effect of the three input parameters upon the dependent variable of Drawbar Force. Since each test was performed using the same brake warm-up schedule, the same friction surface, and the same nominal drawbar tensioning rate, the variances from comparing the effects of brake temperature, roadway surface, and near static rotational velocity were mitigated. Therefore, the ANOVA analysis focused on the input parameters of *Brake* configuration, *Direction* of pull, and *Axle* under test.

The analysis showed that *Brake* was the primary input that influenced drawbar Force, with an $\boldsymbol{\omega^2}$ value of 0.6675 (or 67 percent). *Direction* of pull was the next most significant factor with an $\boldsymbol{\omega^2}$ value of 0.11 (11 percent). *Axle* was also significant, but to a much limited extent at 0.05 (5 percent). Two sets of interaction effects (*Brake*Direction* and *Direction*Axle*) were somewhat significant with respective $\boldsymbol{\omega^2}$ values of 0.08 (8 percent) and 0.06 (6 percent). The interaction effect of *Brake*Axle* was not significant (Table 3.15). This ANOVA model predicts drawbar Force effectively using the three specified input parameters, as the total $\boldsymbol{\omega^2}$ value (0.9762) was nearly the same as the R-Squared value (0.9955).

Upon analyzing the population means of the primary control input *Brake*, there was some overlap in the deviations about the hybrid S-cam brake and the hybrid disc brake. However, the deviations for the big S-cam and the all-disc brakes were each significantly different than the other brakes, thus showing their independent effects upon the measured drawbar Forces.

Table 3.15. ANOVA Results Comparing Three Parameters Affecting Drawbar Force

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F	Significant?	Magnitude of Treatment Effect,ω^2
Brake	37258091	3	12419364	150.8949	0.0009	yes	0.6675
Direction	5993928	1	5993928	72.8260	0.0034	yes	0.1066
Axle	2743164	1	2743164	33.3294	0.0103	yes	0.0480
Brake*Direction	4738995	3	1579665	19.1929	0.0184	yes	0.0810
Brake*Axle	798921	3	266307	3.2356	0.1803	no	0.0100
Direction*Axle	3582503	1	3582503	43.5273	0.0071	yes	0.0631
Error	246914	3	82305				
Total	55362515	15					**0.9762**
R^2	**0.9955**						

Note: VR7 Chassis-Cab PB Drawbar Tests with 4 brakes, 2 directions, and 2 axles.

3.5 Split-Mu Stopping Performance Results

Each brake and load configuration of the Mack MR-688-S chassis-cab truck was tested on the Split-Mu surface using an initial braking speed of 30 mph. The completed McNeilus refuse hauler was not submitted for this experimental test procedure as it was only subjected to the standard FMVSS No. 121 tests.

Stopping distance performance test results from the water-wetted, lateral split-coefficient-of-friction surface (split-Mu) are displayed in Table 3.16. The data are categorized in rows, showing the three load configurations, the four foundation brake configurations per load, and the stopping distance data - which was comprised of minimum value, mean value, maximum value, computed standard deviation, and 95-percent confidence range. Each data point was derived using the cumulative data collected from three stops for each of the two directions traversed on the test pad during the test series (six total tests for each datum). A complete list of all individual stops recorded is compiled in Appendix A, Table 6.2.

Table 3.16. Highlights of Split-Mu Tests

Load	Brake	Stopping Distances (ft)				
		Min	Mean	Max	Std. Dev.	95% Conf. Range
GVWR	Hybrid S-Cam	91	95	98	2.64	93, 97
	Big S-Cam	90	97	104	6.57	91, 102
	Hybrid Disc	88	92	96	2.76	90, 94
	All-Disc	89	97	107	6.35	92, 102
LLVW	Hybrid S-Cam	91	96	102	3.87	93, 99
	Big S-Cam	94	101	109	6.95	95, 106
	Hybrid Disc	89	96	100	3.97	93, 99
	All-Disc	95	104	111	7.31	98, 110
MT	Hybrid S-Cam	81	89	94	4.85	85, 92
	Big S-Cam	87	96	107	8.80	89, 103
	Hybrid Disc	85	90	94	3.74	87, 93
	All-Disc	93	102	110	7.65	96, 108

The data show that there was only a small difference in the minimum stopping distances measured at the GVWR loading condition for the four different foundation brake systems; however, the stopping distance standard deviations and confidence limits show interesting details. For the two hybrids, the smaller standard deviations showed less dispersion between stops indicating that these stops were more repeatable than for the two higher output big-S-cam and all-disc brakes. The 95-percent confidence intervals show that each of the brake configurations performed most repeatedly at the GVWR loading condition and less repeatedly when all of the ballast blocks were removed for the MT load condition.

The mean stopping distances calculated in Table 3.16 are plotted in the following Figure 3.29. The horizontal bar chart shows the Load and Brake Configurations on the y-axis and the Mean Stopping Distances on the x-axis. The magnitude of each data point is labeled at the right "upper" end of each bar.

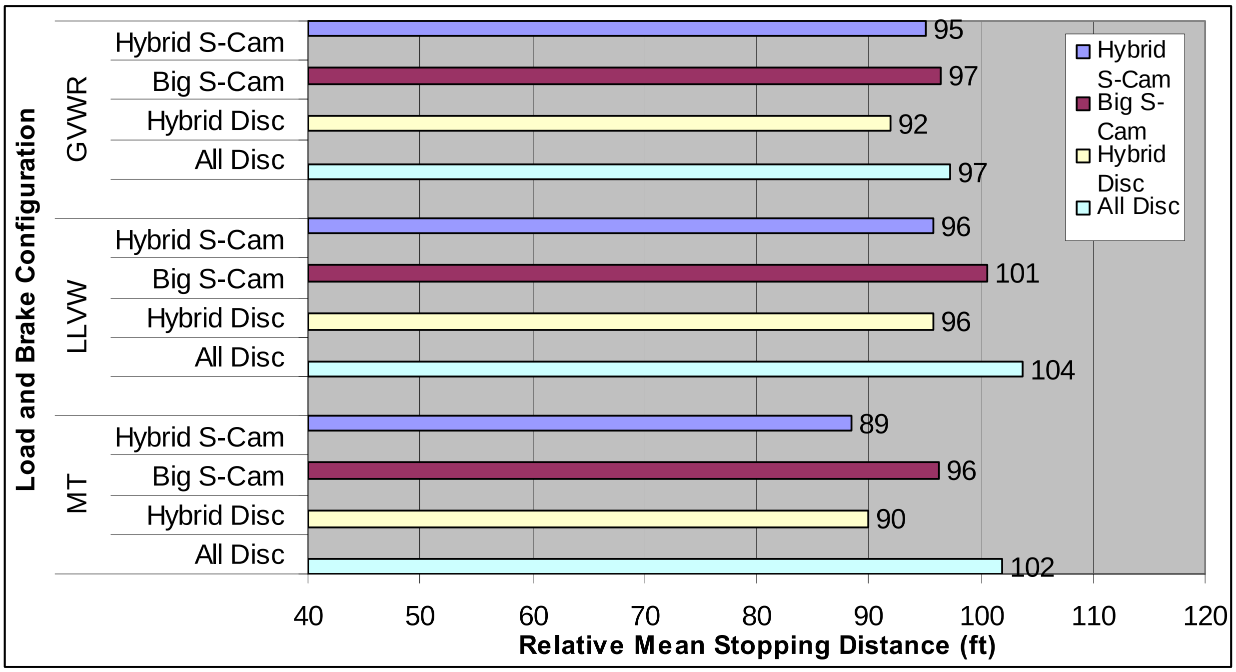

Figure 3.29. Comparison of Mean Stopping Distances on Split-Mu Surface

For a more detailed analysis of the stopping distance data, ANOVA was applied to decipher the effect of each input parameter: *Brake*, *Load*, *Direction*, and *Iteration* (Table 3.17). *Brake* was expected to be the predominant control in this Split-Mu test; however, the non-linear response generated side-to-side caused *Direction* to be the major factor in determining the stopping distance with an ω^2 value of 0.32. Approximately ¼ of the total effect resulted by influence of the type of foundation *Brake*. The *Load* was somewhat significant with 9 percent, and while the iteration was significant, it only accounted for 4 percent of the total variance. Two groups of interaction effects were significant: *Brake*Direction* with more influence at 10 percent than the *Load* by itself, and *Brake*Load* at 5 percent. The other interaction effects were not significant factors in affecting the stopping distance.

Table 3.17. ANOVA Results for 30 mph Service Brake Stops on Split-Mu Surface

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F	Significant?	Magnitude of Treatment Effect, ω^2
Brake	847	3	282	55.80	<0.0001	yes	0.2469
Load	303	2	152	29.95	<0.0001	yes	0.0870
Direction	1097	1	1097	216.73	<0.0001	yes	0.3240
Iteration	135	2	68	13.35	0.0009	yes	0.0371
Brake*Load	194	6	32	6.39	0.0033	yes	0.0485
Brake*Direction	361	3	120	23.75	<0.0001	yes	0.1025
Brake*Iteration	27	6	4	0.88	0.5404	no	-0.0011
Load*Direction	32	2	16	3.13	0.0805	no	0.0064
Load*Iteration	44	4	11	2.19	0.1317	no	0.0072
Direction*Iteration	10	2	5	1.02	0.3886	no	0.0001
Brake*Load*Direction	38	6	6	1.24	0.3542	no	0.0021
Brake*Load*Iteration	158	12	13	2.61	0.0552	no	0.0290
Brake*Direction*Iteration	44	6	7	1.43	0.2798	no	0.0039
Load*Direction*Iteration	14	4	4	0.71	0.6000	no	-0.0017
Error	61	12	5				
Total	3364	71					**0.8919**
R^2	**0.9819**						

Table 3.18 was generated to show the attained decelerations in the Split-Mu tests. The data in this table are in columns showing the three Loading conditions, the four foundation Brake configuration per load, the Mean Stopping Distance, the calculated Average Deceleration, and the individual peak and slide coefficients-of-friction for the two water-wetted surfaces, Asphalt and Jennite. A simplified comparison of the vehicle decelerations were obtained using Equation 2 (EQ-2).

$$Decel_g = \frac{(V_{mph})^2 * (88_{fps} / 60_{mph})^2}{2 * S_f * 32.174_{fpsps/g}} \qquad \text{(EQ-2)}$$

where,

V_{mph} = *Initial braking speed of* 30 *mph*.

S_f = *Stopping distance in feet*.

The last four columns list the corresponding peak and slide surface coefficients-of friction for both surfaces, which were measured on or near the test date.

Table 3.18. Stopping Distances and Deceleration Capability Compared to Split-Mu Surface Variations in Coefficient-of-Friction During Life Cycle of Test Program

Load	Brake Configuration	Mean S.D. (ft)	Avg. Decel (g)	Wet Asphalt		Wet Jennite	
				Peak Mu	Slide Mu	Peak Mu	Slide Mu
GVWR	Hybrid S-Cam	95	0.32	0.84	0.57	0.42	0.17
	Big S-Cam	97	0.31	0.90	0.60	0.29	0.15
	Hybrid Disc	92	0.33	0.88	0.55	0.45	0.18
	All-Disc	97	0.31	0.90	0.65	0.29	0.11
LLVW	Hybrid S-Cam	96	0.31	0.82	0.55	0.42	0.18
	Big S-Cam	101	0.30	0.90	0.60	0.29	0.15
	Hybrid Disc	96	0.31	0.81	0.56	0.44	0.18
	All-Disc	104	0.29	0.90	0.63	0.29	0.13
MT	Hybrid S-Cam	89	0.34	0.84	0.57	0.42	0.17
	Big S-Cam	96	0.31	0.90	0.60	0.29	0.15
	Hybrid Disc	90	0.33	0.81	0.56	0.44	0.18
	All-Disc	102	0.30	0.90	0.64	0.29	0.12

The average decelerations were nearly the same for each brake, but the variations in actual deceleration due to the response of the ABS slip control varied over the duration of the stop. By splitting the deceleration averages into Direction components, Figure 3.30 shows the dependence upon the Direction traveled during the tests on the laterally Split-Mu surface. All but one brake and load group showed a range of 0.01 to 0.04 g higher output (higher decelerations) in the E-W direction than in the W-E direction. Therefore, the side-to-side bias of the truck brake control system did have a more significant effect on the stopping distance than any of the other factors, thus limiting the value of this Split-Mu test for comparing stopping capability and vehicle stability while braking on this surface.

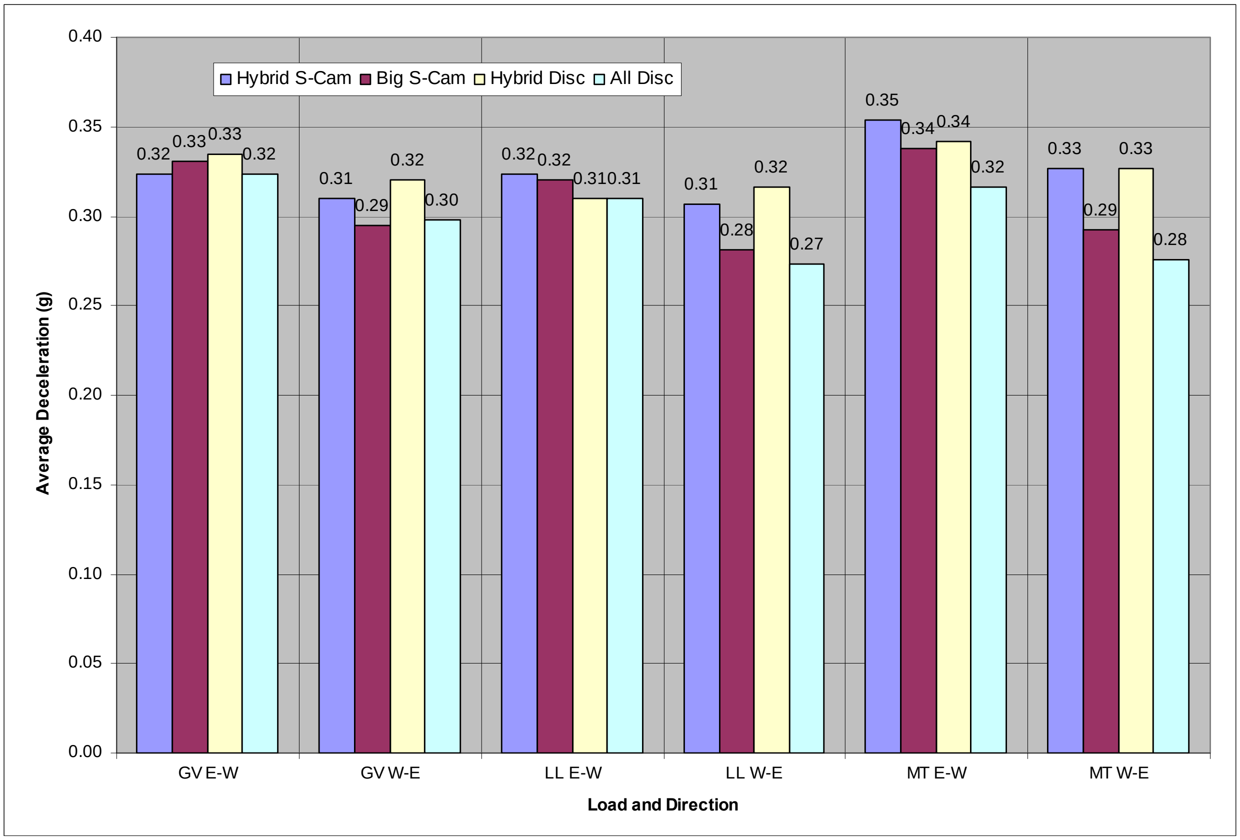

Figure 3.30. Computed Average Decelerations by Load and Direction for Split-Mu Stability Tests

One other indicator of stability was driver steering effort while attempting to maintain the vehicle in the lane while performing a stop. Therefore, handwheel angle was measured for each stop on the split-mu surface. The drive axle wheels on the higher coefficient-of-friction surface provided more braking force than the wheels on the low friction surface, and this imbalance in braking forces created a yaw moment acting on the truck's center of gravity. This caused the truck to yaw such that driver intervention was required to counter steer the truck in the direction of the lower coefficient-of-friction surface in order to maintain the truck in the lane during the stop.

The handwheel results were averaged for the three stops performed for each Load and Brake type, and compared by the Direction travelled in the lane. In Figure 3.31, the red bars plotted above the zero line represent the clockwise handwheel angle input by the driver while stopping the truck in an east-to-west (E-W) direction on the split-mu surface. While traveling in this direction on the test pad, hard braking caused the truck to yaw counter-clockwise, necessitating the driver's correction with a clockwise input to the right. When the truck was being driven in the opposite direction on the pad (W-E), the results were similar, except the directions of the yaw and driver correction were reversed (plotted as negative values below the x-axis).

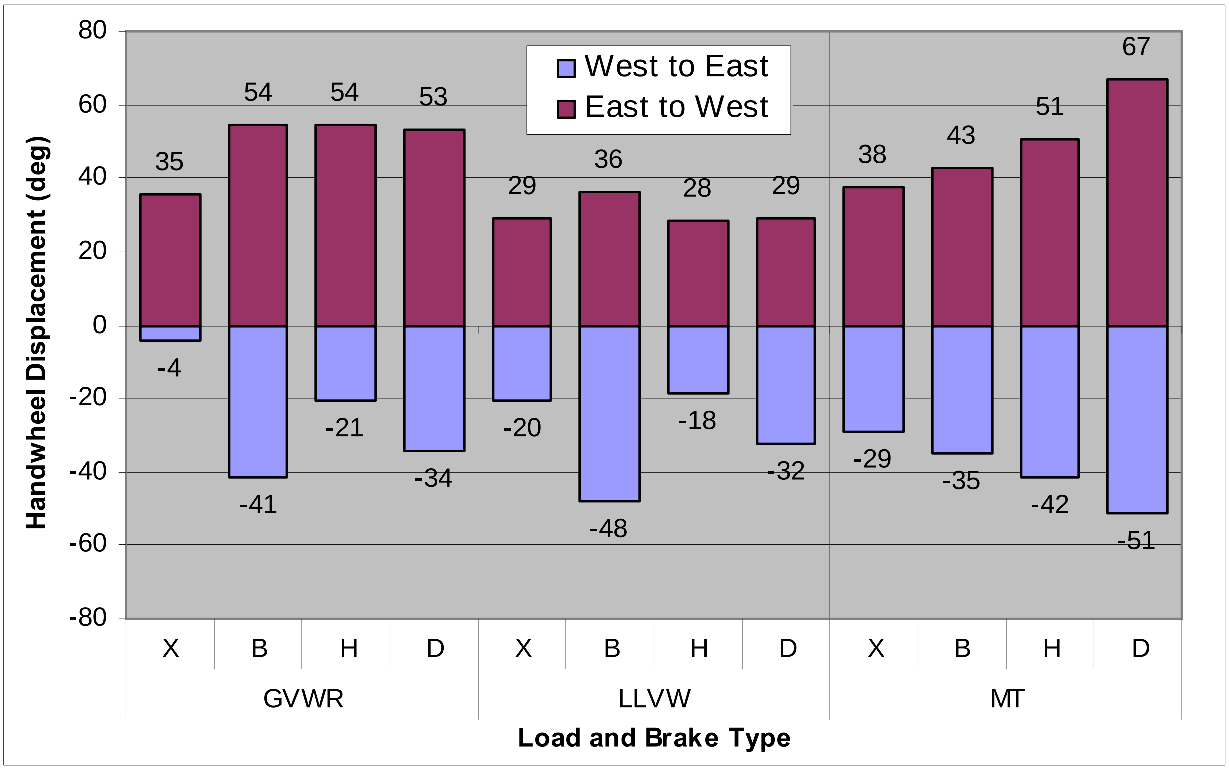

Figure 3.31. Driver Handwheel Effort for Stops on Laterally Split-Mu Surface

Positive Handwheel Displacement is clockwise to the right
X = Hybrid S-cam (with extra-large or high output steer axle brakes)
B = Big S-cam brakes at all locations
H = Hybrid disc brake configuration
D = Disc brakes at all wheel positions

Figure 3.31 shows that the GVWR load required the least driver correction when using the original hybrid S-cam brakes (X); however, there was considerable left-to-right disparity in the effort. The other three brake types required somewhat more effort (+19 degrees), but the driver indicated that this was not a burden for the duration of the short stops. These three brake types also responded more symmetrically than did the original X brake.

When most of the ballast blocks were removed (for the LLVW load) to simulate a complete refuse hauler carrying no load, all four brake types required much less driver steering effort during the stops and all of the handwheel inputs were relatively symmetrical. The big S-cam brake configuration required the most driver attention during the stops.

Upon removing all ballast blocks from the load frame, the MT load condition required the most handwheel inputs (side-to-side). With nearly a 2-to-1 increase in handwheel input over the heavier loads, the MT load configuration required larger counter-steering effort as the brake configurations progressed from the original S-cams, through the big S-cams, into the hybrid disc and all-disc setups.

The driver indicated that while even a 60-degree handwheel input was not overly taxing, each of the stops in the 30- to 70-degree range required a quick initial handwheel correction in order to maintain the truck within the 12-foot lane. The truck also appeared to self-regulate in maximum yaw angle as when the wheels running on the higher coefficient-of-friction surface translated onto the low-mu surface, the rear of the truck did not abruptly slide out of the lane. Then, as the truck continued to slow toward zero speed, the rear wheels tended to track back toward the center of the lane.

The handwheel input angle data confirms the side-to-side sensitivity of the truck braking system, as most of the E-W stops required more driver handwheel input than the W-E stops.

4.0 RESULTS AND CONCLUSIONS

4.1 Summary of Results

The 2005 brake performance test results showed that the Class 8, Mack 6x4 straight truck (completed with a McNeilus refuse body) stopped in 302 feet on a high-coefficient-of-friction surface. With a margin of compliance of 2.6 percent to the FMVSS No. 121 standard requiring a stop within 310 feet, NHTSA determined that this truck configuration was a candidate for inclusion in a brake performance improvement study.

NHTSA purchased a chassis-cab truck similar to the McNeilus refuse hauler for a comparative brake test bed. The truck was subjected to numerous FMVSS No. 121 "road tests," in three loading conditions: at placard GVWR, LLVW simulating a refuse hauler with no payload added, and MT with only a load frame instead of a full body attached; and with four different configurations of foundation brakes: original hybrid S-cam, big S-cam, hybrid disc, and all-disc.

In FMVSS No. 121 standard brake performance tests, the minimum stopping distances attained for the Mack MR-688-S mock-up matched that of the McNeilus refuse hauler at approximately 300 feet when both vehicles were loaded to GVWR. The mock-up truck's stopping distances shortened incrementally each time the brake output was increased with a different foundation brake type. The minimum stopping distances were: all-disc 228 feet; hybrid disc 245 feet; big S-cam 248 feet; and original hybrid S-cam 298 feet. The all-disc brake configuration's 228-foot stopping distance was an improvement of more than 70 feet (or 24 percent) compared to the refuse hauler, and was 26.5 percent shorter than the standard requirement of 310 feet.

In the LLVW condition, all four brake configurations on the mock-up met the minimum stopping distance requirement of 335 feet with margins of compliance ranging from 29 to 44 percent.

The chassis cab truck was also tested with no ballast added to the load frame (MT load condition), such that the data obtained could be used as a basis for adding future loads or body types. The intermediate axle experienced frequent lockups, especially with the higher output rear brakes, but the vehicle maintained stability throughout the stops. All four brake configurations produced minimum stops within a 7-foot window between 178 and 185 feet; therefore, there was no distinguishable stopping performance attributed to any one brake type at this load condition.

ANOVA analysis showed that for all of the brake stops performed using the chassis-cab mock-up truck, the treatments significantly attributing to the stopping distance result were: *load* – 69 percent; *brake* type – 20 percent; and *stop* iteration – 1 percent; with significant second order effects contributing as follows: *brake*load* – 7 percent and *brake*stop* – 1 percent.

Wheel slip histogram plots showed that the steer axle brakes tended to be torque limited for all four brake configurations at GVWR. As the loads were reduced, the slip values increased, dispersing somewhat over a larger range of wheel slips, but still remained relatively low in average percent-slip. At the lighter loads, the steer disc brakes did show some indication of periodic higher, but controlled, slip. The drive wheel brakes produced a broader spectrum of wheel slip than the steers for each brake and load condition. The percent slip curves were relatively normal in distribution with some positive skewness. At GVWR, the large rear S-cams (big S-cam configuration) and the rear disc (all-disc configuration) produced somewhat higher percentages of slip, with broader percent-slip dispersion, and without experiencing any strong tendency toward wheel lock.

The Mack MR-688-S Chassis Cab and McNeilus refuse hauler met the FMVSS No. 121 minimum stopping distance standard of 613 feet or less in each of the three different failed system Tests. These included tests in four different brake configurations and three different load conditions for the Mack MR-688-S Chassis Cab and two load conditions and just the hybrid S-cam for the McNeilus refuse hauler.

When comparing the minimum stopping distances in each of the nine different failed systems test-sets for the Mack MR-688-S Chassis Cab, typically the longest was the hybrid S-cam brake configuration. In the LLVW failed secondary reservoir tests the hybrid S-cam brake configuration had the second longest minimum stopping distance out of four load conditions and in the MT failed secondary reservoir tests the hybrid S-cam was the third longest minimum stop. In these instances, the range of the minimum stops was 40 feet for the LLVW load conditions and 25 feet for the MT load conditions. Generally, when the higher output brake configurations were applied the stopping distances decreased. Six of the Mack MR-688-S Chassis Cab test-sets (GVWR and LLVW tests) were performed with load conditions to simulate the McNeilus refuse hauler. The ranking of the best performing brake configurations from shortest stopping distance to longest stopping distance was: all-disc brakes, hybrid disc brakes, big S-cam brakes, and hybrid S-cam brakes. The one test grouping that differed from the other five was the LLVW failed secondary in which the order was (from shortest to longest): all-disc brakes, big S-cam brakes, hybrid S-cam brakes, and hybrid disc brakes.

When the Mack MR-688-S Chassis Cab and the McNeilus refuse hauler stopping distances were compared, each equipped with the hybrid S-cam brake configuration, the McNeilus refuse hauler had shorter minimum stopping distances in all three GVWR failed systems Tests and in the LLVW failed secondary reservoir Test. The Mack Chassis Cab had shorter minimum stopping distances in the failed primary reservoir and the failed primary Control Line Tests in the LLVW load condition.

For baseline Brake-In-a-Curve (BIC) tests, all four of the brake configurations met the minimum stability and control test requirement on a low coefficient-of-friction surface (500-foot radius curve of water-wetted Jennite). To simulate the required LLVW load condition, the load frame on the chassis-cab truck was only lightly loaded in order to simulate the weight of an un-loaded refuse hauler. The BIC tests were repeated for additional loads of GVWR and MT (with all ballast blocks removed from the mock-up truck load frame, which also showed that the truck stayed in the lane at the 75-percent of drive-through "target speed" for four-of-four tests, for all brake configurations tested.

Additional Limit Handling Speed tests were performed for each brake configuration and load condition to expand upon the go/no-go minimum FMVSS No. 121 requirement in order to determine the actual stability performance differences between the configurations. With a minimum acceptable LAPQ of 56 percent (for the 75-% target speed), all 12 brake/load configuration exceeded 72 percent for LAPQ. It was noted that the all-disc brake configuration produced LAPQ values lower than the other brakes; however, this configuration was tested with lower surface coefficient-of-friction. While LAPQ mitigates surface friction variance, it cannot compensate for the additional non-linear response associated with tire spin-up (inertial delay) associated with testing on the lower coefficient-of-friction surface as experienced by both the all-disc and the big S-cam brake configurations. Overall, the two brake configurations with S-cam brakes on all wheel position handled somewhat better than those with disc brakes.

In the parking brake evaluation, the brakes held the vehicle stationary on the 20-percent grade for each of the four brake configurations and in each of the three load conditions for the minimum 5-minute requirement. The big S-cam brake configuration required approximately half as much initial service brake pressure to stop and hold the vehicle on the grade while the parking brake was being set (compared to the other three brake types) and none of the tests required more than 43 psi.

The second parking brake evaluation was performed in response to the observation that the McNeilus refuse test truck had passed the 20-percent grade test in 2005, but failed the drawbar test. For each of the 23,000 lb-rated axles, the minimum drawbar force requirement was 6,440 lbf. Each brake type met the FMVSS No. 121 requirement for both forward and rearward pulls. The lowest recorded drawbar force of 7,155 lbf occurred on the rearward pull on the rear drive axle while using Hybrid S-cam brakes. This coincided with the same axle and draw direction that had failed the drawbar test performed during the 2005 refuse hauler test. The three higher output brake configurations produced considerably higher drawbar forces. The all-disc produced margins of compliance nearly two-to-one higher than the original hybrid S-cam configuration, but the big S-cam output was slightly higher than the all-disc. The S-cams on the Hybrid disc performed somewhat better than those of the hybrid S-cam.

ANOVA analysis was applied to the drawbar test data. The omega-squared values indicated that *brake* was the primary influence on drawbar force at 67 percent, followed by *direction* at 11 percent, and *axle* at 5 percent.

The laterally split-coefficient-of-friction tests showed that the two hybrid brake configurations stopped shorter and with more repeatability (lower standard deviations) than the higher output big S-cam or all-disc brake configurations. The laden condition produced the most repeatable stopping distances, with the standard deviations increasing as the loads were reduced. ANOVA showed that *direction* traveled on the split-mu test pad was most critical with an omega-squared representation of 32 percent, followed by brake at 25 percent, load at 9 percent, and test iteration at 4 percent. Other significant findings were from the interaction effects of brake*load at 5 percent and brake*direction at 1 percent. The total model accounted for 89 percent determination of the resulting effect upon the stopping distances as compared to the R-squared value of 98 percent.

Computed deceleration values complemented the split-mu stopping distances and indicated that the average decelerations ranged between 0.29 and 0.34 g, but with 0.01 to 0.04 g higher decelerations for the stops performed in one specific direction (E-W). This indicated that the combined brake control system and truck suspension geometry appeared to bias the stopping capability of the truck in a side-to-side fashion. This phenomenon may explain some of the unknown variance from the ANOVA.

The driver commented that it was necessary to counter-steer into the direction of the higher coefficient-of-friction in order to maintain the truck stopping within the 12-foot width of the lane and that the E-W direction required larger inputs than the W-E direction. The handwheel angle data corroborated these comments and also agreed with the deceleration variances as to side-to-side brake bias. The big S-cam brake configuration required the most driver handwheel input when loaded to GVWR and LLVW, compared to the other three brake types. The driver also noted that while a 60-degree handwheel input was not overly taxing, each of the split-mu stops that required handwheel inputs ranging anywhere from 30 to 70 degrees required a quick initial handwheel correction in order to maintain the truck in the lane.

4.2 Conclusions

The chassis-cab mock-up truck with hybrid S-cam brakes produced performance data similar to that obtained from the McNeilus refuse hauler for most tests, which indicated that the mock-up was realistic in both loading configuration and braking capability.

Overall, increasing the brake output shortened the service and emergency brake stopping distances over that obtained by the original hybrid S-cam brake configuration. The all-disc brakes performed the best, followed closely by the hybrid disc. By installing wider drums and shoes for the big S-cam brake configuration, stopping performance was improved over that of the hybrid S-cam configuration, but did not show as much improvement as the installations that included disc brakes on at least one axle (only on steers or on both steers and drives).

In general, for the failed systems tests on the Mack truck, trends observed for the service brake tests repeated, where the hybrid S-cam configuration stopped the longest and the all-disc configuration stopped the shortest.

However when comparing the two trucks with the same hybrid S-cam brake configurations, both primary and secondary failed reservoir tests for the Mack MR-688-S produced stops ranging from 38 to 50 percent longer than for the McNeilus refuse hauler. This shows the variability that is inherent in the failed systems test procedures, as driver style and brake application, and reservoir depletion rate combine to determine the initial residual air pressure remaining in the failed-reservoir at brake application. If a driver waits until the end of the 5-second window allotted before applying the service brake, the available pressure will be lower than for a driver who opts to apply the brake just after the low-pressure warning sounds; both cases are acceptable by FMVSS No. 121 as the goal is to stop the truck with whatever available air that remains in the reservoirs. The standard also does not specify a standard orifice diameter to use to establish the flow rate of the air being vented from the reservoir. A larger dump valve will also lower the initial pressure at the time of brake application. Lower pressure in a failed reservoir tends to produce longer stops. If the reservoir is totally depleted of air at the moment of brake application, the maximum measured brake stop may occur, unless the spring brakes apply and add to the available braking torque.

For BIC tests, all four brake configurations met the minimum stability and control test requirement for all loads; therefore, increasing the brake output made little change in stability on the low-coefficient-of-friction surface. For limit-speed tests, the highest LAPQ values were achieved by the hybrid S-cam and big S-cam brake configurations.

Each load and brake configuration applied to the chassis-cab mock-up truck met the 5-minute parking brake holding requirement of FMVSS No. 121 on the 20-percent grade. This test did not distinguish any differences between the brake types installed on this vehicle.

The hybrid S-cam drawbar test produced results similar to those from the 2005 refuse hauler test, for direction of pull and for each individual axle tested, but with a slightly higher output force produced from each drive-axle spring brake. Consequently, the mock-up vehicle met the minimum required drawbar force, where the refuse hauler failed one test by over 1 percent. The higher output all-disc and big S-cam brakes produced drawbar margins of compliance ranging from 35 to 105 percent, with the big S-cam brakes producing the largest margins in the rearward pull direction.

Split-mu tests showed little difference in stopping distances or decelerations between the four brake types tested. The decelerations did indicate a side-to-side bias in total vehicle response to the stops on this surface, which were substantiated by driver comments and handwheel angle data. When loaded to GVWR and LLVW, the big S-cam brakes required the biggest driver handwheel inputs of the four brake types.

5.0 REFERENCES

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6.0 APPENDIX A

As referenced in Table 2.2, the following Table 6.1 shows the longitudinal center of gravity (CG) values computed for each of the test vehicle loads and brake types.

Table 6.1. Longitudinal CG Calculations for Each Brake Configuration

Truck	Foundation Brakes	Load Condition	Steer Axle (lbs)	Tandem Drive Axles (lbs)	Total Weight (lbs)	Longitudinal CG * (in)
Chassis-Cab**	Hybrid Disc	MT	12,190	10,160	22,350	96.03
Refuse Hauler	Hybrid S-Cam	GVWR	19,900	45,580	65,480	146.18
		LLVW***	19,500	19,200	38,700	104.19
Chassis-Cab	Hybrid S-Cam	GVWR	19,850	45,850	65,700	146.55
		LLVW	18,730	19,870	38,600	108.10
		MT	12,300	10,000	22,300	94.17
	Big S-Cams	GVWR	19,760	45,950	65,710	146.85
		LLVW	18,570	19,890	38,460	108.60
		MT	12,210	10,040	22,250	94.76
	Hybrid Disc	GVWR	19,790	45,980	65,770	146.81
		LLVW	18,810	19,860	38,670	107.85
		MT	12,200	9,980	22,180	94.49
	All-Disc	GVWR	19,540	46,220	65,760	147.60
		LLVW	18,700	19,800	38,500	108.00
		MT	12,110	10,040	22,150	95.19

Note * - longitudinal CG is measured from the centerline of the steer axle.
Note ** - This test was performed on a VIPER system at TARDEC in Michigan.
Note *** - The complete vehicle refuse hauler in the LLVW load condition was comparable to the partially loaded Chassis-Cab in the LLVW load condition.
Both trucks had 210-inch wheelbases.

As referenced in section 2.3, the following Figures 6.1 through 6.4 show plots of the temperatures logged for each wheel during the 500-snub burnish. Each figure represents another brake type configured on the chassis-cab mock-up truck.

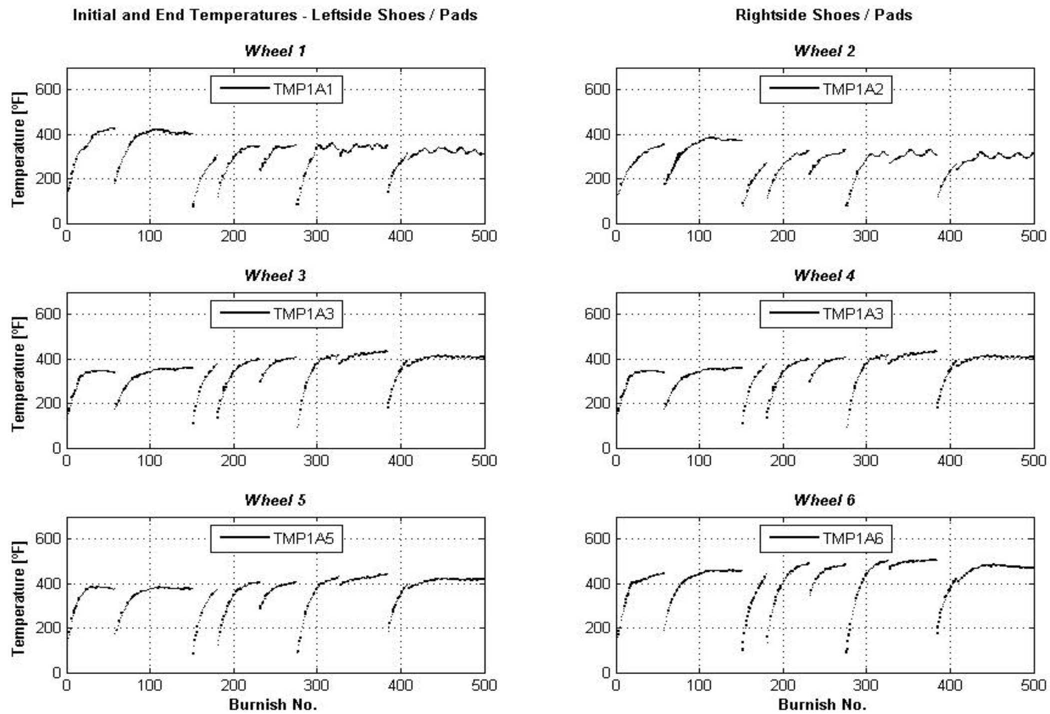

Figure 6.1. Burnish Temperatures for Hybrid S-Cam Brakes

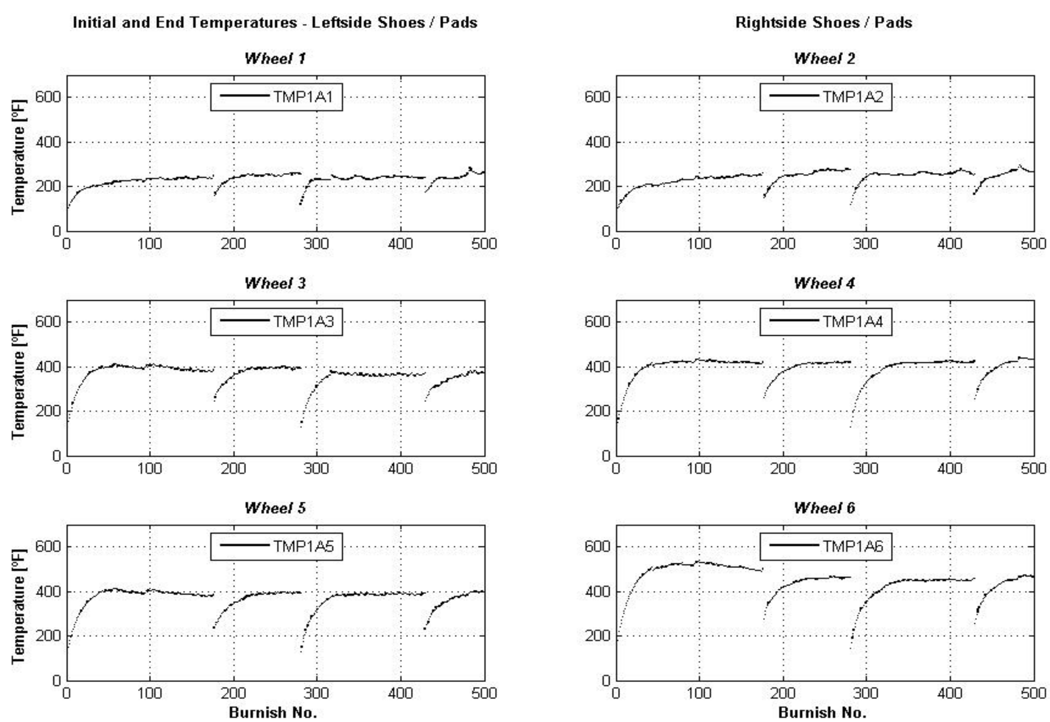

Figure 6.2. Burnish Temperatures for Big S-Cam Brakes

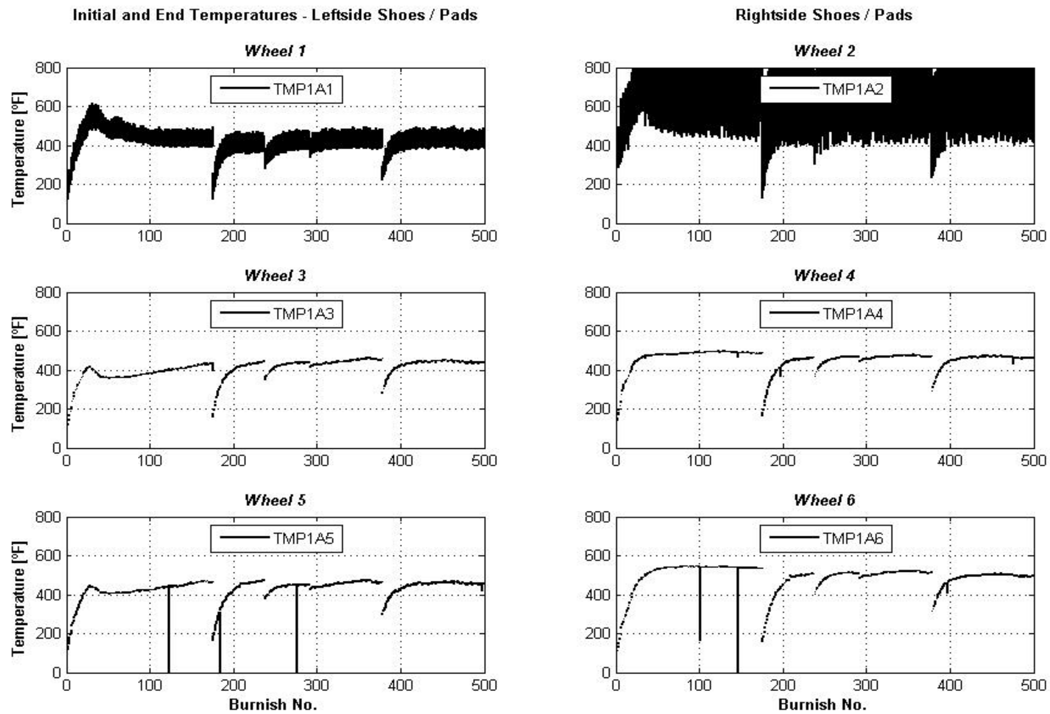

Figure 6.3. Burnish Temperatures for Hybrid Disc Brakes

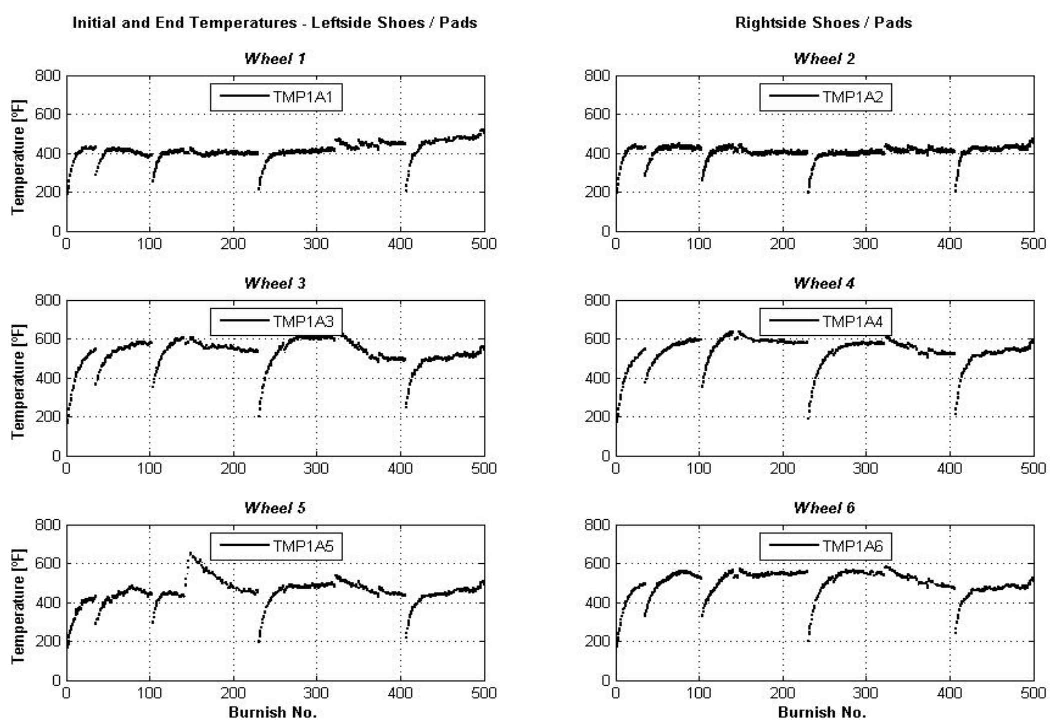

Figure 6.4. Burnish Temperatures for All-Disc Brakes

Section 3.5 refers to this complete set of data for the service brake stops performed from 30 mph on the Split-Mu surface which are listed in Table 6.2. All of the Minimum stopping distance values are compared graphically in Figure 6.5.

Table 6.2. Complete Data Set for Split-Mu Stops from 30 mph

Brake	Load	Direction	Stopping Distance			Minimum	Mean	Max	Std. Dev.	95% Conf. Range
Hybrid S-Cam	GVWR	E-W	91	94	95	91	93	95	2.08	91, 96
Big S-Cam	GVWR	E-W	90	90	92	90	91	92	1.15	89, 92
Hybrid Disc	GVWR	E-W	88	90	93	88	90	93	2.52	87, 93
All-Disc	GVWR	E-W	89	94	97	89	93	97	4.04	89, 98
Hybrid S-Cam	GVWR	W-E	95	98	98	95	97	98	1.73	95, 99
Big S-Cam	GVWR	W-E	100	103	104	100	102	104	2.08	100, 105
Hybrid Disc	GVWR	W-E	93	92	96	92	94	96	2.08	91, 96
All-Disc	GVWR	W-E	95	102	107	95	101	107	6.03	95, 108
Hybrid S-Cam	LLVW	E-W	91	93	96	91	93	96	2.52	90, 96
Big S-Cam	LLVW	E-W	94	95	94	94	94	95	0.58	94, 95
Hybrid Disc	LLVW	E-W	94	97	99	94	97	99	2.52	94, 100
All-Disc	LLVW	E-W	95	96	101	95	97	101	3.21	94, 101
Hybrid S-Cam	LLVW	W-E	98	95	102	95	98	102	3.51	94, 102
Big S-Cam	LLVW	W-E	104	109	107	104	107	109	2.52	104, 110
Hybrid Disc	LLVW	W-E	89	96	100	89	95	100	5.57	89, 101
All-Disc	LLVW	W-E	111	111	108	108	110	111	1.73	108, 112
Hybrid S-Cam	MT	E-W	81	87	86	81	85	87	3.21	81, 88
Big S-Cam	MT	E-W	87	94	87	87	89	94	4.04	85, 94
Hybrid Disc	MT	E-W	94	86	85	85	88	94	4.93	83, 94
All-Disc	MT	E-W	97	93	95	93	95	97	2.00	93, 97
Hybrid S-Cam	MT	W-E	90	94	93	90	92	94	2.08	90, 95
Big S-Cam	MT	W-E	97	106	107	97	103	107	5.51	97, 110
Hybrid Disc	MT	W-E	90	92	93	90	92	93	1.53	90, 93
All-Disc	MT	W-E	110	109	107	107	109	110	2.08	107, 110

Figure 6.5 depicts the variation in the 24 relative minimum stopping distance values from Table 6.2. The horizontal bars are grouped in six bands by load and direction. Each band contains four bars that correspond to the brake configurations (top to bottom) which are: hybrid S-cam, big S-cam, hybrid disc, and all-disc.

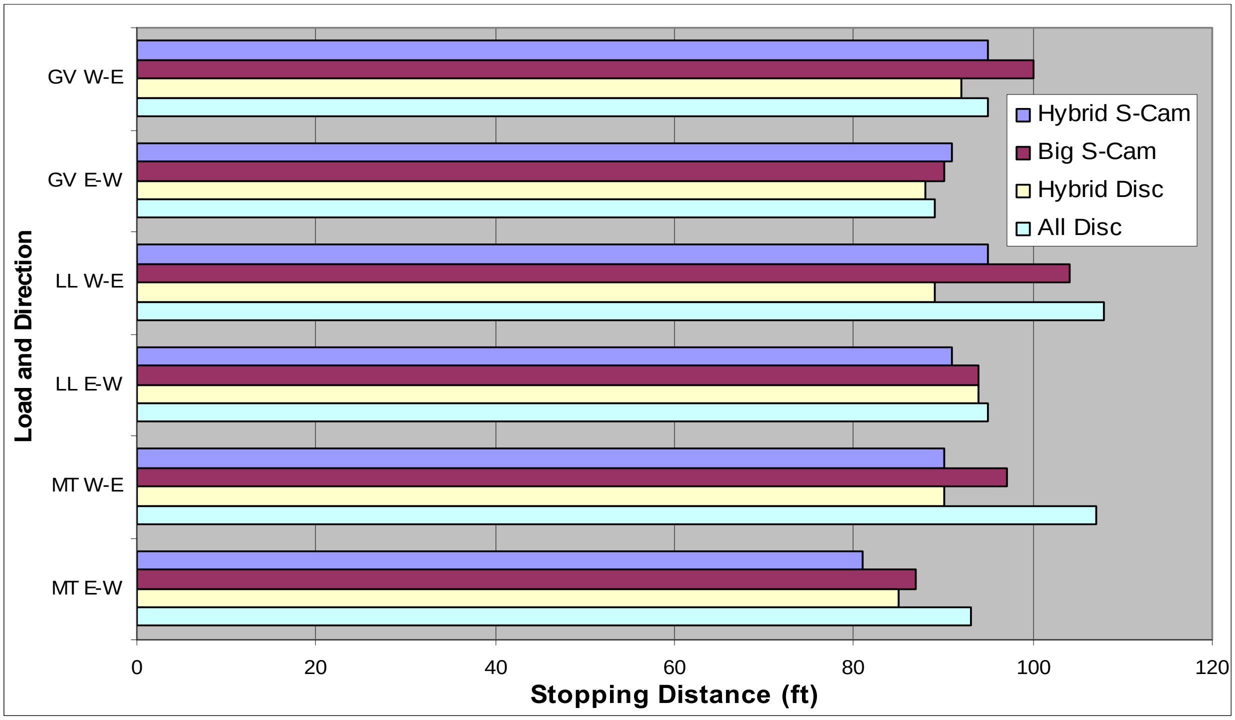

Figure 6.5. Relative Minimum Stopping Distances for Lateral Split-Mu Stability Tests

7.0 APPENDIX B

Global coding of tractor brake configurations was developed by NHTSA in 2000 to optimize data processing of the thousands of files for the shorter stopping distance research program.[4 5] Hybrid brakes originally referred to a mix of high output steer axle brakes and standard output drive axle brakes, without reference to foundation brake type (drum, disc, or wedge). As SUTs were added to the test matrix, more disc brake combination codes were added. These codes have been used universally in over a dozen briefs and research reports.

Established Brake Codes are:

S: Standard or small steer axle S-cam brakes (typically 15"dia x 4" wide) and standard 16.5"x7" drive axle S-cam brakes

X: Hybrid S-Cam refers to high output steer axle S-cam brakes (typically 16.5"dia x 5"or 6" wide) and standard 16.5"x7" drive axle S-cam brakes

B: Big S-Cam (both larger diameter and/or wider shoes) refers to higher output steer axle S-cam brakes (typically 16.5"dia x 7" wide) and higher output 16.5"x8" or 8-5/8"" drive axle S-cam brakes.

H: Hybrid Disc refers to high output steer axle disc brakes (typically 22.5"dia rotors) and standard 16.5"x7" drive axle S-cam brakes

D: all-disc refers to high output disc brakes (typically 22.5"dia rotors) at all wheel positions.

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