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15. Abstract

A Class 7 school bus and Class 8 straight truck were tested by NHTSA VRTC to evaluate relative braking performance and stability levels of various high-output foundation brake configurations. An abbreviated FMVSS No. 121 test sequence was conducted, with additional tests being performed for research purposes. Each vehicle was tested with three brake configurations: (1) standard S-cam drums (baseline) on all wheel positions; (2) hybrid – Air-disc brakes on the steer axle and S-cam drums on the drive axles; and 3) air disc brakes on all wheel positions. The vehicles were tested at two load conditions, a Lightly Loaded Vehicle Weight (LLVW) and Gross Vehicle Weight Rating (GVWR).

Each vehicle-brake-load combination met the current FMVSS No. 121 standard service brake stops on a dry surface from 60 mph. At LLVW, both vehicles exhibited reductions in stopping distance when the S-cam brakes were replaced with either hybrid or all disc configuration brakes, but the difference between the two change types was negligible at this load. However at GVWR, the benefits of disc brakes at all wheel positions were clearly seen. The disc brake configuration showed shorter stopping distances of 20 and 22 percent for the straight truck and the bus, respectively, where the hybrid brake configurations only produced stopping distances that were 10 percent shorter than S-cam brakes for both trucks.

For brake-in-a-curve tests, adding higher output brakes made little change in stability on the low-µ surface. After meeting the *target* speeds, each configuration was subjected to additional *limit* handling tests (for research) to identify the boundary of stability. Each brake performed well above 82 percent lateral acceleration performance quotient (LAPQ). These results are similar to those found in previous VRTC studies for tractors.

Stability stops were performed on a laterally split friction coefficient surface (split-µ) from 30 mph. Higher output brakes improved stopping performance without any change in stability. Analyses of variance (ANOVA) revealed that, regardless of the vehicle-load-test direction combination, *brake* caused the primary differences in stopping distance.

With same-size chambers, the discs produced higher output force for parking brake drawbar tests. The SAE J1729, "Parking Brake Drawbar Pull Test Procedure - Commercial Vehicle" produced higher margins of compliance than the NHTSA FMVSS No. 121 procedure.

Failed systems tests confirmed stability was maintained in unbalanced brake tests.

Experimental stops from increased entry speeds of 60, 70, and 75 mph showed no degradation in handling or stability. At GVWR, the S-cam configuration showed greater loss in stopping ability, as speed increased, than the hybrid or disc.

16. Key Words	17. Distribution Statement
ABS Braking, Disc Brakes, Hybrid Brakes, S-Cam Brakes, Stopping Distance, FMVSS No. 121, Peterbilt Model 357 day-cab Straight Truck, International CE Model IC-35530 conventional School Bus, BIC, drawbar	Document is available to the public from the National Technical Information Service www.ntis.gov

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EXECUTIVE SUMMARY

This research was performed to assess the braking performance of single unit trucks and buses (SUTs). National Highway Traffic Safety Administration has completed rulemaking to modify Federal Motor Vehicle Safety Standard (FMVSS) No. 121 to reduce the maximum permitted stopping distance of most truck tractors by 30 percent. At the time this research was conducted, NHTSA also contemplated application of the reduced stopping distance to SUT [1]. The research discussed in this report was one of multiple studies performed by VRTC to address this. Testing was conducted on the Transportation Research Center track in East Liberty, Ohio, by the NHTSA Vehicle Research and Test Center (VRTC). The premise of this study was to retrofit commercial vehicles with higher-torque (output) foundation brakes without modifying (or tuning) the suspension or anti-lock braking system (ABS), to determine their effects on stopping distance and vehicle stability. This report presents the results from a 6x4 Class 8 Peterbilt Model 357 day-cab straight truck and a 4x2 Class 7 International CE Model No. IC 35530 (77-passenger) school bus brake tests. An abbreviated FMVSS No. 121 test sequence was conducted for each vehicle, along with additional research tests. Each vehicle was tested with three brake configurations:

1. <u>"S-cam"</u> - standard drum brakes (baseline) on all wheel positions;
2. <u>"Hybrid"</u> - air-disc brakes on the steer axle and traditional S-cam drums on the drive axles; and
3. <u>"Disc"</u> - air disc brakes on all wheel positions.

The vehicles were tested in two load conditions: lightly loaded vehicle weight (LLVW) and gross vehicle weight rating (GVWR).

<u>Dry Braking Tests</u> - Each vehicle-brake-load combination met the current FMVSS No. 121 standard full-treadle application, service-brake stops on a dry surface from 60 mph. At GVWR, the benefits of adding disc brakes in place of S-cams were clearly seen, with the most reduced stopping distances obtained with all disc brakes. On the school bus, all discs showed 22 percent improvement over the S-cams, for a margin of compliance (MOC) of 38 percent. The hybrid (disc/S-cam) improved 10 percent, with a 29 percent MOC. The standard all S-cams produced a 21 percent MOC. On the straight truck, the discs showed 20 percent improvement for 28 percent MOC, the hybrid showed 10 percent gain with 19 percent MOC, and the S-cam produced a 10 percent MOC. ANOVA analyses showed that *vehicle*, *brake*, and *load* individually contributed significantly to stopping distance.

At LLVW, both vehicles exhibited a reduction in stopping distance when disc brakes were placed on the steer axle (hybrid configuration). However, when disc brakes were also added to the drive axles (disc configuration), no further reduction in stopping distance was exhibited, due to the braking ability of the vehicles being traction-limited in the empty mode.

Reservoir pressure, in general, revealed that stops at LLVW consumed more air than the stops at GVWR. When loaded to GVWR, the disc brakes consumed the most air of the three brake configurations tested. This correlated with the disc configuration having the shortest stopping distance of the three configurations. The current FMVSS No. 121 reservoir volume specification appears to satisfy the air demand of disc brakes.

Wheel slip histograms revealed that at LLVW, the S-cam illustrated noticeable differences from the other two brake configurations. The higher slip levels from the higher torque disc and hybrid brake configurations correlated with the reductions in stopping distance. That is, the more aggressive brake configurations that use discs on the steer axle, whether disc or hybrid, operated in more optimal regions of slip, but with little difference between the hybrid and disc configurations. Wheel slip data should be incorporated into modeling of brake systems to reduce the amount of track time required in developing more effective brake systems which reduce stopping distance. Brake effectiveness measures were referenced in two previous reports, "Comparison of Heavy Truck Foundation Brake Performance Measured With an Inertia Brake Dynamometer and Analyses of Brake Output Responses to Dynamic Pressure Inputs" (Hoover & Zagorski, 2005) and "S-Cam Brake Effectiveness Comparison Using Two Fixtures and Two Lining Types on a Single Inertia Dynamometer," (Hoover, Howe, Flick, & Dashner, 2000).

At GVWR, it was also demonstrated that as the brakes became more effective in terms of maximum torque capability, the vehicles' tires operated in more optimal regions of slip. This correlated with the consistent reduction in stopping distance.

Brake-in-a-Curve Tests - Adding high-output disc or hybrid brakes made little change in stability on the low-μ surface compared to the standard S-cam brakes. Each vehicle-brake-load configuration met the current *target* speed test requirements for FMVSS No. 121 stability and control. Additional *limit* speed handling tests were performed to identify the boundary of stability. For the school bus at LLVW, the hybrid brake configuration achieved the lowest performance quotient (LAPQ), 82 percent; whereas at GVWR, it achieved the highest, 100 percent. Neither the S-cam nor the disc configuration exhibited a significant effect due to load.

Of the three brake configurations tested on the straight truck, the hybrid consistently achieved the lowest performance quotient. These results correlate with those found in Dunn, Hoover, and Zagorski (2005).

Split--μ Stopping and Handling Performance – The high output disc brake configuration improved the stopping distance on the split--μ without any change in stability compared to the other two brake configurations tested. Full-treadle service-brake application stops were performed on a laterally split friction coefficient surface (split-μ) from 30 mph. Analyses of variance (ANOVA) revealed that, regardless of the vehicle-load-test direction combination, *brake* caused the primary differences in stopping distance. The disc configuration consistently produced stopping distances 5 to 20 percent shorter than either the hybrid or S-cam configurations. Disc also exhibited, in general, the lowest dispersion. These results are corroborated by those found in Dunn, Hoover, and Zagorski (2005). The differences exhibited between the hybrid and S-cam configurations, if any, depended on the *vehicle*, *load*, and test *direction*.

The slightly superior stopping performance of the disc configuration in this test series appeared to be due to the mechanical design of the brakes. The smaller chamber size of air-disc brakes gave them the ability to recover faster in an ABS modulated stop.

Parking Brake Tests - With same size chambers, disc brakes provided the stronger holding capability for the parking brakes. Each vehicle-brake-load configuration “passed” the grade-holding tests. Drawbar force tests were performed at GVWR, for the S-cam and disc configurations only, as the hybrid configuration used the same type of S-Cam brakes on the drive axle as the S-Cam configuration. For the heavier 6x4 straight truck, the Disc configuration consistently generated higher drawbar forces than the S-Cam configuration (both using 30 in^2 chambers recommended by the original equipment manufacturer). The results for the lighter school bus revealed that the S-cam configuration consistently had somewhat higher margins of compliance than the disc, although both margins were acceptable (greater than 53% MOC). The bus had larger parking chambers with the S-cams, than with the discs (30 in^2 compared to 24 in^2) as specified by the OEM.

In a research mode, the NHTSA FMVSS No. 121, “Drawbar Test Procedure,” and the SAE J1729, "Parking Brake Drawbar Pull Test Procedure - Commercial Vehicle” drawbar test procedures were directly compared for single unit trucks with high-output brakes. Overall, the results revealed that the SAE tests produced greater margins of compliance, than the NHTSA tests. The question then arose that for a marginal- output parking brake system, if a vehicle passed the SAE test, but failed the NHTSA test: Would this parking brake be acceptable?

In actual service, drivers typically apply the service brake – at least somewhat, just before applying the parking brake; but not always. The NHTSA procedure assumes that the service brake be allowed to have one failure (or leak) in that system such that no pressure may be applied to the brake chambers at the moment the parking brake is applied (essentially no service brake application before setting the parking brake). The SAE procedure differs in that it tests the full integrity of the brake system, as it requires a full service brake application be applied at maximum compressor cut-out pressure, and then the parking brake (spring brake) be superimposed over it. This potential compounding was the effort that caused the SAE outputs to be frequently higher than the NHTSA outputs for this test series. A limitation found of the SAE procedure was that no technique was prescribed to confirm that no permanent deformation of the brake components occurred.

Failed Systems Tests - All configurations tested met the standard of 613-foot stopping distance with no stability issues. With the higher output brakes installed, the spring brake inversion valves continued to provide necessary braking assistance to the drive axle brakes in the failed primary reservoir tests. The disc provided the largest margins of compliance for each of the 12 vehicle/failed system/load tests, except one.

Experimental Higher Speed Stopping Performance - Additional full-treadle stops were performed from entry speeds of 60, 70, and 75 mph. As expected, increasing the initial braking speed of the vehicle resulted in increased stopping distance.

It was found that the stopping performance of the vehicles was more adversely affected at GVWR (due to increases in entry speed) than at LLVW. Of the three brake configurations, the all S-cam consistently saw reduced deceleration, due to increased entry speeds. The other two brake configurations did not necessarily exhibit similar performance degradation (in terms of deceleration level) with respect to higher entry speed. At LLVW, the hybrid and disc configurations saw similar results for both vehicles; whereas at GVWR, there were consistent improvements in stopping performance as the brake configurations became more effective.

1 Background and Objectives

This research was performed to assess the braking performance of single unit trucks and buses . National Highway Traffic Safety Administration has completed rulemaking to modify FMVSS No. 121 to reduce the maximum permitted stopping distance of most truck tractors by 30 percent. At the time this research was conducted, NHTSA also contemplated application of the reduced stopping distance to SUTs (NHTSA, n/a. The research discussed in this report was one of multiple studies performed by VRTC to address this.

Testing was conducted on the Transportation Research Center Inc., test track in East Liberty, Ohio, by the NHTSA Vehicle Research and Test Center. 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. Results for some of the recently completed tests are described in References (Dunn & Hoover, 2004; Dunn, Hoover, and Zagorski, 2005; Hoover, Van Buskirk, & Zagorski, 2005).

The premise for this study was to retrofit two commercial single-unit trucks with higher-torque (output) foundation brakes, without modifying (or tuning) the suspensions or anti-lock braking systems; and to determine the effects on braking performance and vehicle stability. This report presents the results of tests on a 2004, conventional-hood, day-cab, Class 8 Peterbilt (6x4) chassis-cab straight truck, Model No. 357 (VIN – 1NPAL00X94N829594) and a 2004, conventional-hood, 77-passenger, Class 7 International CE (4x2) School Bus, Model No. IC 35530 (VIN – 4DRBRAAN14B969164) that were conducted at VRTC. Testing included standard high-speed stops, brake-in-a-curve test, failed systems test, and parking brake performance, along with a few new tests that experimentally sought to find additional limits in braking performance.

2 Test Vehicles

2.1 Description and Overview of the Vehicles

This section provides details of the specific load and equipment components as tested on each of the two vehicles.

2.1.1 International School Bus

The 2004 school bus was equipped with pneumatically controlled and actuated service brakes that were independently ABS-modulated (4S4M). Additional parameters for this vehicle can be found in Tables 2.1 and 2.2.

Table 2.1. Vehicle Weights, Wheelbases, Track Widths, and CG Locations

	International - 4 x 2 School Bus	Peterbilt - 6 x 4 Straight Truck
Lightly Loaded Vehicle Weight, LLVW [lb]*	19,500	20,700
Axle Weights at LLVW, Front / Rear [lb]*	8,180 / 11,390	10,090 / 10,610
Gross Vehicle Weight Rating, GVWR [lb]	30,000	62,000
Gross Vehicle Weight as Tested [lb]	29,620	62,000
Axle Weights at GVW, Front / Rear [lb]	9,860 / 19,760	18,090 / 43,910
Wheelbase [in]	276	275
Track Width - Front/Rear [in]	79.0 / 73.0	79.5 / 74.0
CG Longitudinal Distance from Steer Axle C.L. [in] - LLVW/GVWR**	161 / 184	141 / 195
CG Vertical Distance Above Ground [in] – LLVW/GVWR**	40 / 48	34 / 66

* - This is the nominal empty test weight

** - This is the system (total vehicle) calculated CG

Table 2.2. Suspension, ABS System, and Tires

	International - 4 x 2 School Bus	Peterbilt - 6 x 4 Straight Truck
Front Suspension	10,000 lb leaf spring with shocks	18,000 lb leaf springs with shocks
Rear Suspension	20,000 lb pneumatic with trailing arm leaf spring with shock	44,000 walking beam suspension – No shock
ABS Configuration	Bendix 4s/4m	Meritor Wabco 6s/6m
Steer Axle Tire	11R/22.5 LR H Goodyear G159A Unisteel	315/80R22.5 LR L Bridgestone M843 V-steel MIX
Drive Axle Tire	11R/22.5 LR H Goodyear G159A Unisteel	11R/22.5 14PR LR G Firestone FD663 radial

The bus was tested in both LLVW and GVWR load conditions. LLVW included the unladen vehicle with fuel, instrumentation, data acquisition system, and a driver. In order to achieve GVWR, the bus was loaded with 51 water dummies and three steel armor plates. One plate, weighing 400 lb, was located laterally centered on the floor to the right of the driver's seat and 132 inches in front of the GVW CG. The single plate CG was 3 inches above the floor. Two 500-lb plates were located on the floor of the bus in the aisle. The CG's of these plates were located 26 inches behind the vehicle CG and 5 inches to either side of the vehicle longitudinal centerline. Their vertical CG's were 4-5/8-inches above the floor. To simulate the mass of either three small children or two large children, two water dummies were strapped to each bench seat. The CG height of each nominal 175-lb water dummy was approximately 11 inches above the seat or 25-3/4 inches above the floor. For the GVWR loading condition, the locations of the water dummies, steel plates, data acquisition system, and an inertial measurement device are shown in Figure 2.1. For the LLVW tests, the inertial measurement device was retained at the same CG-location as for the GVW tests.

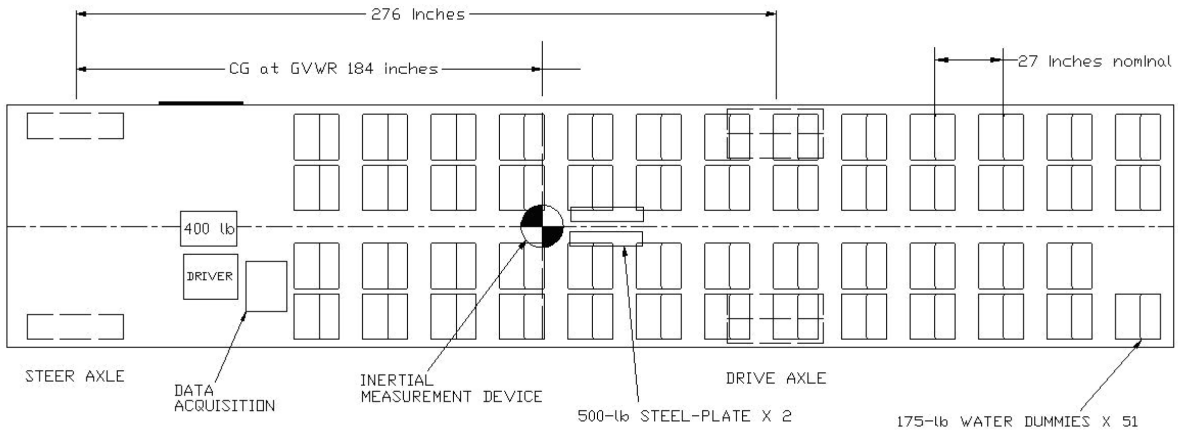


Figure 2.1. Plan View of School Bus at GVWR – Location of Center of Gravity

Notes: (1) 400-lb steel plate was located on the floor to the right of the driver's seat.
(2) Inertial measurement device was mounted on the floor over the GVW CG.

2.1.2 Peterbilt Straight Truck

The 2004Peterbilt straight truck was equipped with pneumatically controlled and applied service brakes, which were independently ABS-modulated (6S6M). Parameters for this straight truck can be found in Tables 2.1 and 2.2.

This truck was also tested in both LLVW and GVWR load conditions. LLVW included the empty vehicle with fuel, instrumentation, data acquisition system, load frame, and a driver. (Note: The inertial measurement device was left in the GVWR location for both load conditions.) To achieve GVWR, the vehicle was loaded with 10 concrete blocks and 4 steel pedestals, where the pedestals were used to achieve the desired CG height. Locations of the load frame, pedestals, and concrete blocks (for the GVWR loading condition) are shown in Figure 2.2. Approximate weights for each concrete block and pedestal are listed, as well.

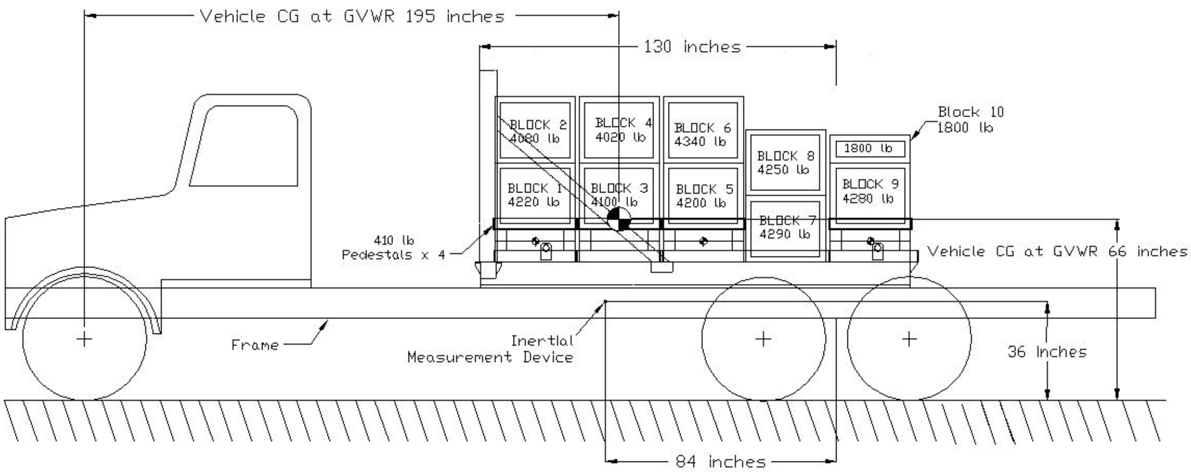


Figure 2.2. Side View of Straight Truck at GVWR – Locations of Concrete Blocks, Metal Pedestals, and Load Frame

2.2 Test Vehicle Brake Configurations

Each vehicle was tested with the following three foundation brake configurations:

1. Standard S-cam drums (baseline) on all wheel positions, labeled "S-cam" in the tables and figures.

2. Hybrid – Air-disc brakes on the steer axle and traditional S-cam drums on the drive axles, labeled "Hybrid" in the tables and figures.

3. Air-disc brakes on all wheel positions, labeled "Disc" in the tables and figures.

Brake specifications are listed in Tables 2.3 to 2.5 for each brake configuration. Dana Corporation performed the brake retrofits on the Peterbilt and ArvinMeritor performed the retrofits on the school bus. Each configured both the hybrid and disc brake assemblies.

Table 2.3. S-Cam Brake Specifications for Standard S-Cam Drum Brakes on Steer and Drive Axles

S-Cam Brake Components	4 x 2 School Bus		6 x 4 Straight Truck	
	Steer Axle	Drive Axle	Steer Axle	Drive Axles
Air Chamber	MGM Type 20L	MGM 30/30L	MGM Type 24	MGM 30/30
Slack Adjuster	5.5-inch auto	5.5-inch auto	Haldex 5.5-inch auto	Haldex 5.5-inch auto
Brake Shoe	MA212	R301	Spicer 819617	Spicer 819707
Brake Lining - Lead	MA212 FF 4702D ANC 6421	R301 FF 4707D ANC 5366	EES 1200-GF 818295-L3	811546 EES 600-FF 4709 3051-1
rake Lining - Trailing	MA212 FF 4702D CAM 6422	R301 FF 4707D CAM 5367	EES 410-FF 818211-L3	811546 EES 600-FF 4709 3051-1
Brake Drum	Gunite 3721	Gunite 3647	Gunite 3687X	Gunite 3600
Brake Type	Meritor Q-plus 15" x 4"	Meritor Q-plus 16.5" x 7"	Dana Spicer 16.5" x 6"	Dana Spicer 16.5" x 7"

Table 2.4. Hybrid Brake Specifications for Air Disc Brakes on Steer Axle and Standard S-Cam Drum Brakes on Drive Axles

Hybrid Brake Components	4 x 2 School Bus		6 x 4 Straight Truck	
	Steer Axle	Drive Axle	Steer Axle	Drive Axles
Air Chamber	DiscPlus #16	MGM 30/30L	Grau Type 24	MGM 30/30
Slack Adjuster	EX-Internal	5.5-inch auto	Internal Control Arm	Haldex 5.5-inch auto
Brake Shoe	DiscPlus	R301	ESD 1550	Spicer 819707
Brake Lining – Lead/Inner	MA 761	R301 FF 4707D ANC 5366	AD1550	811546 EES 600-FF 4709 3051-1
Brake Lining – Trailing/Outer	MA 761	R301 FF 4707D ANC 5367	AD1550	811546 EES 600-FF 4709 3051-1
Brake Drum/Rotor	DiscPlus 17.09" O.D. x 1.77"	Gunite 3647	Webb 16.93" O.D. x 1.77"	Gunite 3600
Brake Type	Meritor EX225L	Meritor Q-plus 16.5" x 7"	Dana ESD 225	Dana Spicer 16.5" x 7"

Table 2.5. Disc Brake Specifications for Air Disc Brakes on Steer and Drive Axless

Disc Brake Components	4 x 2 School Bus		6 x 4 Straight Truck	
	Steer Axle	Drive Axle	Steer Axle	Drive Axles
Air Chamber	DiscPlus #16	DiscPlus # 20/24	Grau Type 24	Grau Type 24/30
Slack Adjuster	EX-Internal	EX-Internal	Internal Control Arm	Internal Control Arm
Brake Pad	DiscPlus	DiscPlus	ESD 1550	ESD 1550
Brake Lining	MA 761	MA 761	AD1550	AD1550
Brake Rotor	DiscPlus 17.09" O.D. x 1.77"	DiscPlus 17.09" O.D. x 1.77"	Webb 16.93" O.D. x 1.77"	Webb 16.93" O.D. x 1.77"
Brake Type	Meritor EX225L	Meritor EX225L	Dana ESD 225	Dana ESD 225

2.3 Test Conditions and Methodology

Tests were performed by VRTC at the TRC test track. Tests were conducted as prescribed in the FMVSS No. 121 and the associated test procedures (49 CFR, §571 and NHTSA, 1993). Additional, non-FMVSS No. 121 tests were performed for research purposes. Unless otherwise noted, tests were performed for each brake configuration and loading condition.

Between testing of each brake configuration, all friction materials were changed, including drums and rotors, pads and shoes, and tires. Also, the anti-lock brake system, suspension, brake controls, and brake application methods were not modified or “tuned” between brake configurations. Prior to testing, a 500-snub burnish was performed for each brake configuration, as prescribed in Section 6.1.8 of FMVSS No. 121 (49 CFR, 2003). Each snub was made from 40 to 20 mph, while maintaining a constant deceleration rate of 10 ft/sec^2.

2.3.1 Instrumentation

Time history data were 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 test procedure (49 CFR, §571 and NHTSA, 1993). The ambient temperature was also recorded.
- Stopping distances were measured with a fifth-wheel assembly, mounted on the rearmost part of the vehicle. Stopping distances and vehicle speed were recorded from a Labeco Track test Fifth Wheel System Performance Monitor, which displays initial braking speed and integrated stopping distance. All measured stopping distances were normalized to the targeted initial braking speeds using the standard method described in SAE J299 (SAE, 1993).
- Individual wheel speeds were measured and recorded using DC tachometer generators.
- Chamber pressures were measured and recorded for each brake position. Additionally, 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. (The straight truck was equipped with parking brakes on both drive axles.)
- Hand wheel 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 (ECU) voltages, were also recorded with the data acquisition system.

2.3.2 Driver Instructions

Two professional drivers alternately drove during the tests, with the same driver being used for an entire set of tests. The drivers were instructed to warm or cool the brakes (before each brake run) so the respective pad or shoe temperatures were within the specified initial brake temperature (IBT) range of 150 to 200 ºF (66-93 ºC).

The individual tests began by accelerating the vehicle to a few mph over the initial braking speed (IBS) of 60 mph, depressing the clutch, 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 0.5 seconds, as outlined in the FMVSS No. 121 and Test Procedure (49 CFR, §571 and NHTSA, 1993). 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 location of each stop in a given series was kept consistent.

2.3.3 Standard FMVSS No. 121 Tests

The two vehicles tested for this program were purchased from regular dealer stock, and were assumed to have already met full FMVSS No. 121 compliance criteria. On this basis, 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-friction surface;
- Brake-in-a-curve tests of a low friction surface;
- Failed systems tests; and
- Drawbar and 20 percent grade holding tests of the parking brake systems.

2.3.3.1 Dry Stopping Performance Tests

Stopping performance tests were conducted according to the procedures outlined in Section 5.3.1 of FMVSS No. 121 (49 CFR, 2003). Full-treadle brake application straight-line stops were performed from 60 mph on a dry surface with a high-coefficient of friction. Six stops were made on the TRC concrete skid pad which had nominal peak and slide coefficients of friction of 0.90 and 0.75, respectively.

2.3.3.2 Brake-in-a-Curve Stability Testing

Stability tests utilized the brake-in-a-curve procedure outlined in Section 5.3.6 of FMVSS No. 121 (49 CFR, 2003). 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 this drive-through speed, full-treadle stops were made. The stops were initiated once the vehicle was established in the center of the 12-foot lane, while in the 500-foot radius curve for at least 60 feet. A total of four stops were made on the wetted Jennite of the vehicle dynamics area (VDA).

To further test the braking stability of the vehicle, *limit* stability and control maneuvers were performed for research purposes. (Note: While above-target-speed tests were not required in the FMVSS No. 121 standard, they were performed to identify the actual upper handling limit on this surface.) The entry speed of the vehicle was increased in 1 mph increments, until the vehicle could not maintain 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.

2.3.3.3 Emergency Brake System Testing

Emergency brake system tests were performed according to the procedures outlined in Section 5.7 of FMVSS No. 121 (49 CFR, 2003). Three separate failed systems tests were performed. They included a failed primary control line, a failed primary reservoir tank, and a failed secondary reservoir tank. The primary control line failure was simulated by removing the primary pneumatic control signal from the relay valves for the drive axles. This simulated a failure of the control signal to reach the drive axle brakes, while still operating the steer axle brakes. The failed primary and secondary reservoirs were separately simulated by having the driver vent the air pressure in the selected tank, to atmospheric pressure, through remotely operated solenoid valves. A full-treadle brake application was made within five seconds after the low-pressure warning alarm activated (nominally at 60 psi). A total of 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 0.90 and 0.75, respectively.

2.3.3.4 Parking Brake Testing

The foundation brake types were compared for static retardation force and grade-holding ability following the procedures outlined in Section 5.6 of (49 CFR, 2003), and in Sections 10.3-G, H, and I of the FMVSS No. 121 test procedures (NHTSA, 1999), with the following exceptions or additions:

a) Static retardation tests were performed at GVWR only, on a Hunter Plate Brake Tester (Flick, 1995), and the maximum vertical and horizontal (pull) forces from the brake tester were recorded, in addition to the force from the standard drawbar load cell.

b) A series of four static retardation tests were performed, with the parking brake applied with no prior service brake application (*NHTSA test* using FMVSS No. 121 guidelines). This test was then repeated (in a research test mode) with the parking brake being applied while the service brakes were at a full-treadle application, using the SAE J1729 procedure (*SAE test*) (SAE, 2000).

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

d) 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 a data sheet. The maximum of all four pulls was recorded as the maximum parking brake force for that given direction.

e) Grade holding tests were performed at LLVW and GVWR load conditions. This test was performed on a 20-percent grade with the vehicle facing uphill, and then downhill.

Since the hybrid configuration was predicted to reveal the same results as the S-cam configuration, drawbar tests were only performed for the S-cam and disc configurations.

2.3.4 Additional Non-FMVSS No. 121 Research Tests

For research and development purposes, additional tests, which were not required in the FMVSS No. 121 standard, were performed. These research tests included panic stops on a laterally split-friction surface and full service brake stops from higher IBS.

2.3.4.1 Split-μ Stopping Performance Tests

Straight-ahead full-treadle service brake application stops were performed on a laterally split-friction-coefficient 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). A total of six stops were conducted for each set of tests.

2.3.4.2 Additional Dry Stopping Performance Tests From Higher Entry Speed

According to the Governors Highway Safety Administration, as of January 2005, there were 12 States that allowed commercial vehicles to travel at 70 mph, and 9 States that allowed 75 mph (GHSA, 2005). Because of this, NHTSA headquarters requested additional straight-ahead stops on a dry surface, with a high-coefficient of friction, from higher entry speeds (IBS). The goal of this experiment was to determine the effects of higher entry speeds on stopping performance and vehicle stability. Nine additional stops were performed for the straight truck on the TRC high-speed test track (HSTT) from 60, 70, and 75 mph. Three stops were made from each entry speed. Due to gearing, the school bus could only achieve 74 mph; therefore, four additional stops were performed from 70 mph on the skid pad. The HSTT had nominal peak and slide coefficients of friction of 0.90 and 0.60, respectively. The skid pad had nominal peak and slide coefficients of friction of 0.90 and 0.75, respectively.

3 Test Results and Discussions

This section includes tables, graphs, and figures that show the findings from both the standard-type FMVSS No. 121 tests, and the exploratory research tests.

3.1 Dry Stopping Performance Test Results

The following are results for the dry stopping performance tests performed on a high-friction coefficient surface. Tables 3.1 and 3.2 list the minimum stopping distance results (along with their corresponding margins of compliance) for the school bus and straight truck, respectively. Current FMVSS No. 121 requires that a vehicle stop shorter than the maximum allowable stopping distance, at least once, in six stops. To be a more reliable prediction of the performance that can be expected from a particular population, calculated means were included, along with both percent differences of mean (from minimum requirement) and standard deviations. Figures 3.1 to 3.4 graphically illustrate the mean stopping distance results, 95 percent confidence limits, and current FMVSS No. 121 minimum stopping distance limits.

Table 3.1. Stopping Distance Results for the School Bus - Straight-Ahead Braking From 60 mph on a High Coefficient of Friction

School Bus		*Minimum*		*Mean*		
Load Condition	***Brake Type***	***Stopping Distance [ft]***	***Percent Margin of Compliance***	***topping tance [ft]***	***Percent Difference From Minimum Requirement***	***Standard Deviation [ft]***
LLVW	**S-Cam**	198	29.4	200	28.5	1.98
	Hybrid	169	39.5	173	38.3	2.51
	Disc	169	39.7	173	38.3	2.54
GVWR	**S-Cam**	222	20.6	228	18.6	4.69
	Hybrid	200	28.5	206	26.4	4.83
	Disc	175	37.6	180	35.9	4.32

Note: The current FMVSS No. 121 limit is 280 feet for a school bus loaded to LLVW and GVWR

Table 3.2. Stopping Distance Results for the Straight Truck - Straight-Ahead Braking From 60 mph on a High Coefficient of Friction

ht Truck		Minimum		Mean		
	Brake Type	***Stopping Distance [ft]***	***Percent Margin of Compliance***	***Stopping Distance [ft]***	***Percent Difference From Minimum Requirement***	***Standard Deviation [ft]***
	S-Cam	178	46.8	183	45.2	2.88
	Hybrid	172	48.6	178	46.8	5.14
	Disc	172	48.7	178	47.0	3.46
	S-Cam	280	9.7	287	7.5	6.92
	Hybrid	251	19.1	255	17.7	3.26
	Disc	224	27.9	230	26.0	3.97

Note: The current FMVSS No. 121 limit is 335 and 310 feet for a straight truck loaded to LLVW and GVWR, respectively

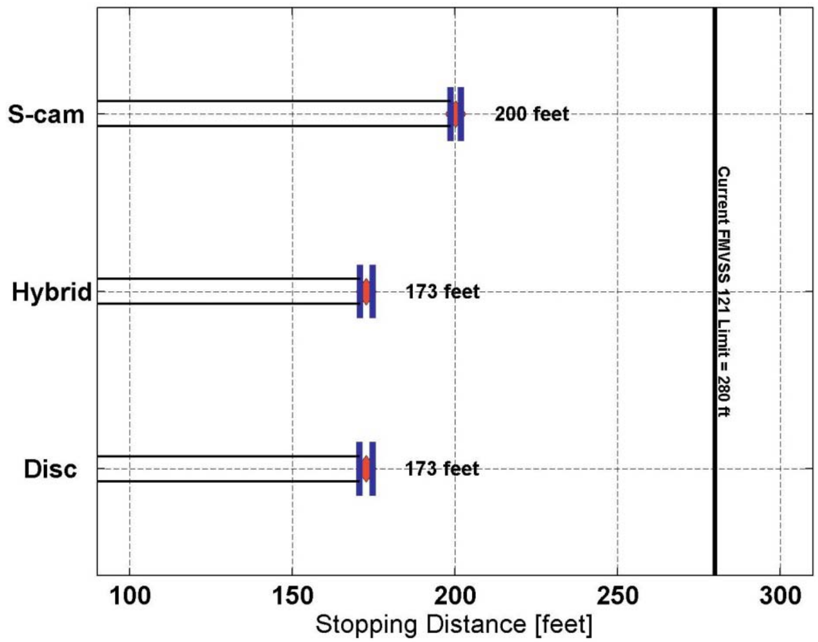


Figure 3.1. School Bus LLVW Mean Stopping Distances for High-µ Stops From 60 mph

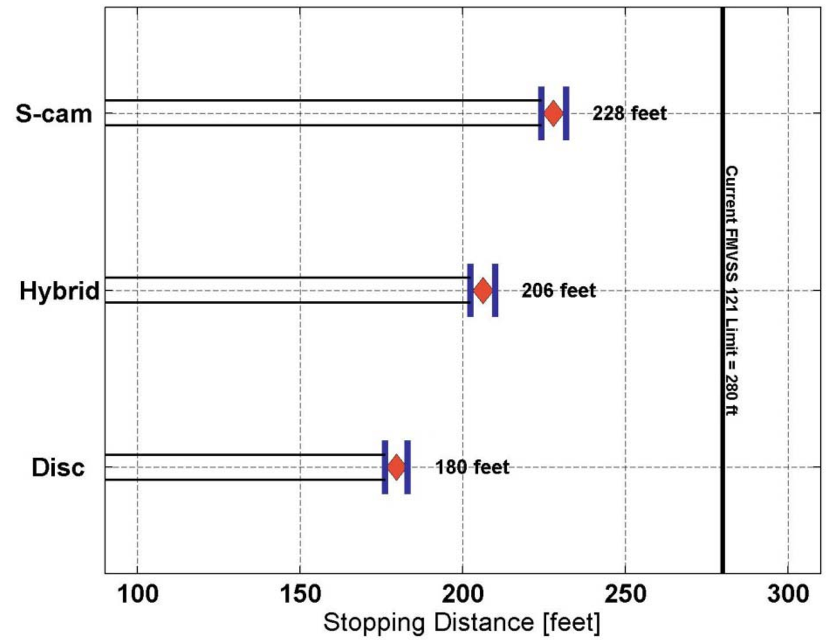


Figure 3.2. School Bus GVWR Mean Stopping Distances for High-µ Stops From 60 mph

Notes for Figures 3.1 to 3.4 – for these horizontal bar charts, Means are indicated numerically and by red diamonds. The 95 percent confidence intervals are shown at the right "upper" end of the histobars as two, parallel blue line segments - to either side of the diamonds. The current FMVSS No. 121 minimum stopping distance Limit is shown as a bold, full-length vertical line near the right side of each graph.

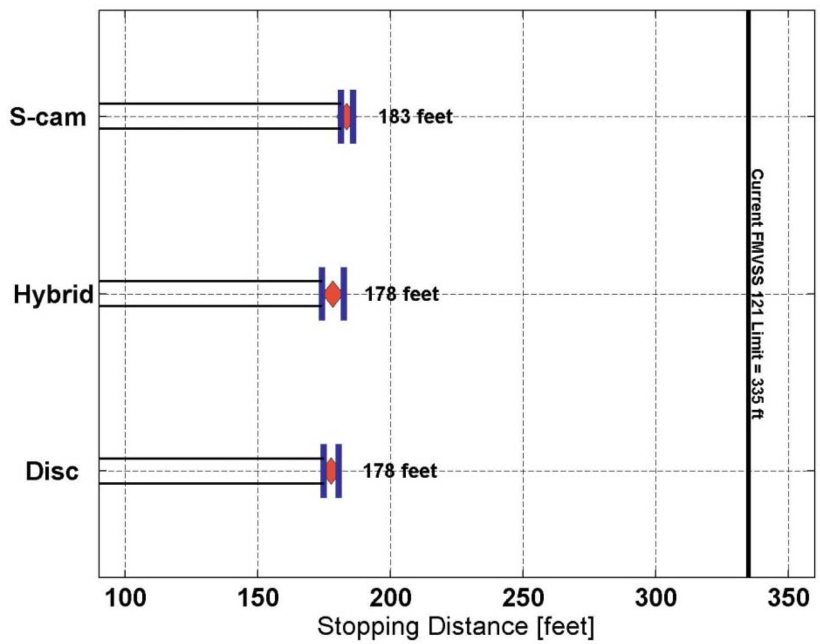


Figure 3.3. Straight Truck LLVW Mean Stopping Distances for High-μ Stops From 60 mph

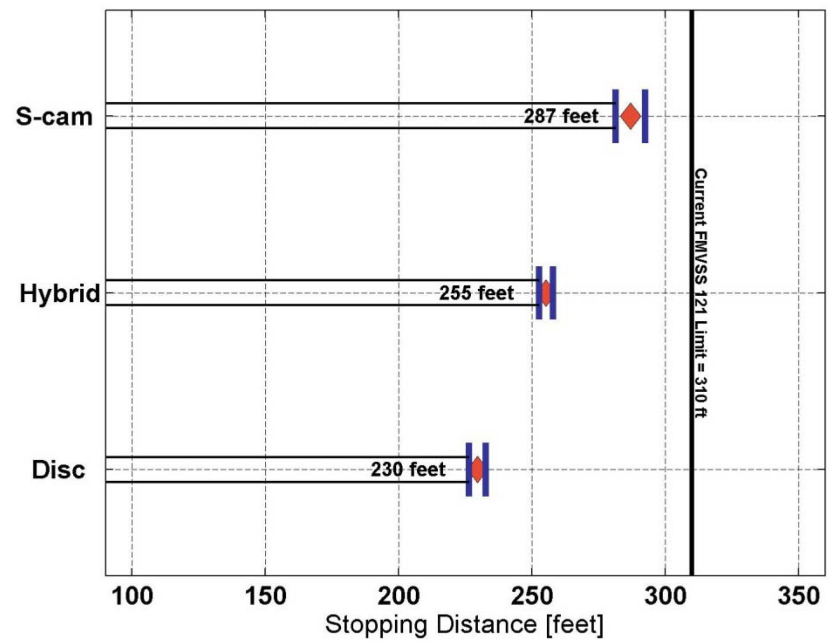


Figure 3.4. Straight Truck GVWR Mean Stopping Distances for High-μ Stops From 60 mph

Based on Tables 3.1 and 3.2, and Figures 3.1 to 3.4, the following results were demonstrated:

- Each brake-load configuration for the school bus met the current FMVSS No. 121 limit with the smallest margin of compliance being 20.6 percent for the S-cam configuration loaded to GVWR. The largest margin of compliance was 39.7 percent for the disc configuration loaded to LLVW.
- Each brake-load configuration for the straight truck met the current FMVSS No. 121 limit with the smallest margin of compliance being 9.7 percent for the S-cam configuration loaded to GVWR. The largest margin of compliance was 48.7 percent for the disc configuration loaded to LLVW.
- For both vehicles, corresponding margins of compliance were consistently greater at the LLVW load condition, than GVWR. Currently, FMVSS No. 121 requirements allow trucks (e.g., a straight truck), under a LLVW condition, to have a longer stopping distance than under a GVWR load condition (310 feet compared to 335 feet). For a school bus, both load conditions must meet a limit of 280 feet.
- At LLVW, both vehicles exhibited an improvement (or reduction) in stopping distance when disc brakes were placed on the steer axle (i.e., the hybrid configuration). When disc brakes were placed on the drive axles, in addition to the steer axle, there was no further reduction in stopping distance. That is, a point of diminishing return occurred with stopping performance becoming traction-limited in this load condition.
- At GVWR, for both vehicles, as the brake configurations became more aggressive (in terms of increased brake torque capacity) there were consistent decreases in stopping distance. That is, the hybrid configuration had a shorter stopping distance than the S-cam configuration and the disc configuration had a shorter stopping distance than the hybrid.
- In general, the difference between the margins of compliance and the mean percentages of difference from the standard minimum stopping distance, were not greater than 2 percent.

3.1.1 Dry Stopping Performance ANOVA Results

ANOVAs were performed using the SAS package, with corrected stopping distance as the dependent variable. Six repetitions for each tractor-brake-load configuration were analyzed. ANOVA results were used to gauge main and interaction effects of independent treatments, in this case, *brake* type, *vehicle*, *load*, or *replication*. The effect of *brake* on the results was the primary interest. For these analyses, a "Pr > F" (probability greater than F) value of 0.05 was used as a criterion for statistical significance for a specific treatment or effect on the outcome of stopping distance, meaning a 95 percent significance level was desired to conclude statistical difference.

Initially, an analysis was performed with both vehicles combined. The results are listed in Table 3.3. The main and interaction effects are listed with the corresponding degrees of freedom (DOF), F values, and Pr > F values. Based on this analysis, the effects of *vehicle*, *brake*, and *load* were statistically significant. The effect of *replication* was not significant; the order in which the stops were performed did not have an effect on the stopping distance results.

The interactions between *vehicle* and *load*, and between *brake* and *load*, were statistically significant. That is, the effects of *vehicle* and *brake* were not consistent between loads. The interaction between *vehicle* and *brake* were not statistically significant. This revealed that the effect of *brake* was consistent between both vehicles.

Table 3.3. ANOVA Dry Stopping Performance Results – Results Are Combined for School Bus and Straight Truck

Effect	*DOF*	*F Value*	*Pr > F*	*Significant*
Vehicle	1	302.97	< 0.0001	Yes
Brake	2	194.24	< 0.0001	Yes
Load	1	1189.38	< 0.0001	Yes
Vehicle x Brake	2	2.19	0.1259	No
Vehicle x Load	1	354.19	< 0.0001	Yes
Brake x Load	2	54.39	< 0.0001	Yes
Replication	5	0.72	0.6151	No

Individual ANOVAs were performed for each vehicle. For these analyses, the main effects of *brake* and *load*, individually, and the interaction between *brake* and *load*, were of interest. Tables 3.4 and 3.5 list the results for the school bus and straight truck, respectively. For each effect, the corresponding DOF, F values, and Pr > F values, were listed. Also listed were the magnitudes of treatment effect or ω^2 terms. These estimate the percentage of total model variance attributed to that effect. A larger number signified a greater importance of that treatment. The equation used to compute the ω^2 term was derived in (Keppel, 1991). The sum of the ω^2 terms alluded to the total amount of variance in the data that could be described by that statistical model (see bottom rows in each table). The complement to that number was the amount of variance unexplained in the model. The sum of the ω^2 terms usually agreed to within a few percent of the model overall R^2 value; the closer to 1.0, the better.

Based on the analysis for the school bus, the individual effects of *brake* and *load* were significant (Table 3.4). The interaction between *brake* and *load* were also statistically significant. This revealed that the effect of *brake* was not consistent for each *load*. The magnitudes of treatment effects displayed that the effect of *brake* accounted for the greatest variance in the model, 59 percent.

Table 3.4. Separate ANOVA Dry Stopping Performance Results for School Bus

Effect	*DOF*	*F Value*	*Pr > F*	*Magnitude of Treatment Effect, ω^2*
Brake	2	333.16	< 0.0001	0.586
Load	1	348.18	< 0.0001	0.306
Brake x Load	2	43.78	< 0.0001	0.076
Total Percent of Variance Accounted for in Model				0.968

Table 3.5 displays the results for the separate ANOVA of the straight truck. As with the school bus, the effects of *brake* and *load* were significant. The interaction between *brake* and *load* were statistically significant, revealing that the effect of *brake* was not consistent for each *load*. The

magnitudes of treatment effects displayed that the effect of *load* accounted for the greatest variance in the model, 84 percent.

Table 3.5. Separate ANOVA Dry Stopping Performance Results for Straight Truck

Effect	*DOF*	*F Value*	*Pr > F*	*Magnitude of Treatment Effect, ω^2*
Brake	2	149.47	< 0.0001	0.092
Load	1	2688.62	< 0.0001	0.836
Brake x Load	2	98.31	< 0.0001	0.061
Total Percent of Variance Accounted for in Model				0.989

In-depth analysis tests were conducted and the results are displayed in Table 3.6. For both vehicles at LLVW, the hybrid and disc configurations were statistically different than the S-cam configuration, while the hybrid and disc were statistically similar. Once disc brakes were placed on the steer axle, adding higher torque brakes on the drive axle provided no additional braking benefit. This indicates that the benefit of placing disc brakes at all brake positions was not realized in the LLVW condition.

All three brake configurations were statistically different from one another at GVWR, and the results were consistent for each vehicle. In terms of reduced stopping distance, the hybrid configuration outperformed the S-cam configuration, and the disc outperformed the hybrid. A substantial benefit was achieved by adding the disc brakes to the steer axle. An even larger benefit was realized when adding disc brakes at all wheel positions in the GVWR load condition. The results for LLVW and GVWR agree with Figures 3.1 to 3.4.

Table 3.6. In-Depth Analysis Test Results – Brake Rankings and Mean Stopping Distances for School Bus and Straight Truck

Load	***School Bus***			***Straight Truck***		
LLVW	S-Cam > (Hybrid = Disc)*			S-Cam > (Hybrid = Disc)*		
	200	173	173	183	178	178
GVWR	S-Cam > Hybrid > Disc			S-Cam > Hybrid > Disc		
	228	206	180	287	255	230

* - An equal sign indicates the two brake configurations were found to be statistically similar

3.1.2 Reservoir Pressure

Tables 3.7 and 3.8 display percent of decrease in reservoir air pressure for both the school bus and straight truck, respectively. These rates were calculated by finding the difference of the reservoir pressure measurements made at the beginning and end of the stops, and dividing by the initial reservoir pressures. The averages of six stops are shown for each brake configuration, for the individual primary and secondary reservoirs, and by load condition. The primary reservoir tank provided air for the drive axles and the secondary reservoir tank provided air for the steer axle.

Table 3.7. School Bus Reservoir Air Pressure – Average Percentage Decrease in Pressure

Load Condition	S-Cam		Hybrid		Disc	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
LLVW	25.9	23.4	24.2	29.8	24.5	30.5
GVWR	9.3	18.4	11.7	21.9	10.2	22.2

Table 3.8. Straight Truck Reservoir Air Pressure – Average Percentage Decrease in Pressure

Load Condition	S-Cam		Hybrid		Disc	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
LLVW	19.8	18.8	19.4	18.9	19.3	18.6
GVWR	16.8	16.5	16.2	16.5	19.7	18.3

These results illustrate that both vehicles, in general, consumed more air when at LLVW than when loaded to GVWR (i.e., both reservoirs for each configuration had a greater decrease in pressure at LLVW, than at GVWR). This is expected since at LLVW there is less normal force on the tires. This allows more longitudinal tire slip, thus necessitating more ABS modulation, and more air consumption.

The school bus at LLVW (Table 3.7) had approximately the same decrease in pressure for the primary reservoir for each brake configuration (~24 to 26%). When comparing the hybrid and disc brake configurations to the S-cam configuration, the secondary reservoir had a higher decrease in pressure (~30% compared to 23%). In correlation with the average stopping distance results in Figure 3.1, the hybrid and disc brake configurations revealed the same decrease in average stopping distance and consumed approximately the same amount of air. At GVWR, the hybrid and disc brake configurations consumed more air than the S-cam configuration for the secondary reservoir (~22% compared to ~18%). For the primary reservoir, the differences between the three brake configurations were small, not more than 2 percent. Comparing with Figure 3.2, the increase in air consumption for the hybrid and disc configurations correlate with the decrease in stopping distance from the S-cam configuration, but they do not correlate with the disc exhibiting a shorter stopping distance than the hybrid.

The straight truck, when loaded to LLVW (Table 3.8), had approximately the same decrease in pressure for each configuration (~19 to 20% and ~19% for the primary and secondary reservoirs, respectively). These results correlate with the small spread in average stopping distance between the three brake configurations (0-5 ft, see Figure 3.3). At GVWR, the disc brake configuration consumed more air for each reservoir, but resulted in the shortest average stopping distance of the three brake configurations (compare Table 3.8 to Figure 3.3).

3.1.3 Wheel Slip Histogram Plots

In terms of wheel slip, histograms reveal where each wheel spends time throughout the stop. The trucking industry widely accepts that there is a direct correlation between wheel slip and longitudinal (brake) force. Stopping distance can be greatly affected by tire slip and distribution as reflected in a wheel slip histogram. Longitudinal wheel slip values were computed for each brake position. Figure 3.5 depicts the arrangement used to label each brake position for the school bus and straight truck.

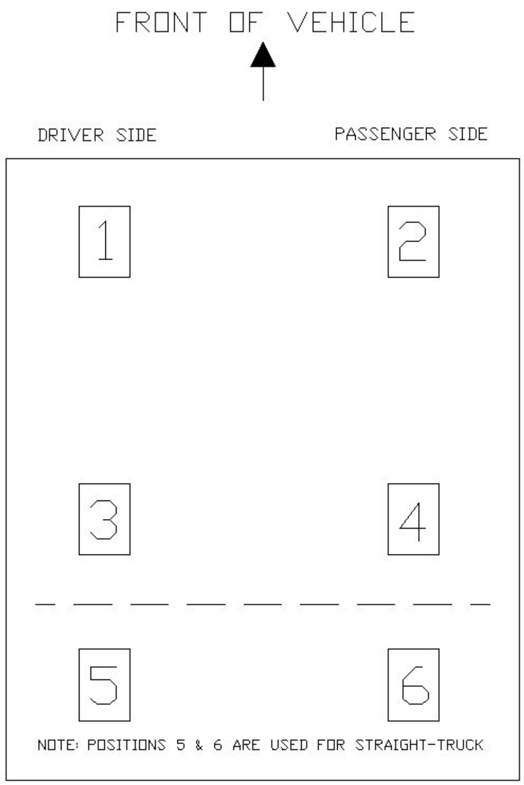


Figure 3.5. Brake Positions for School Bus and Straight Truck

Figures 3.6 to 3.13 display average wheel slip histogram plots. For each brake position monitored during each stop, longitudinal wheel slip was computed for the duration of the entire braking maneuver. This brake position slip data was tallied into equally spaced (2%) histogram bins from 0-100 percent slip. Then, the individual bin results for all six stops in each test series were averaged to provide a condensed view of the overall slip characteristics.

The figures display the S-cam configuration results as the baseline (in light green), and are co-plotted with the hybrid or disc configuration results (in blue). The areas where the two configurations (i.e., S-cam and hybrid, or S-cam and disc) overlay one another are shown in dark green. For black and white prints, the S-cam is light gray; the hybrid or disc is black; and the overlapping portions of the histobars are medium gray.

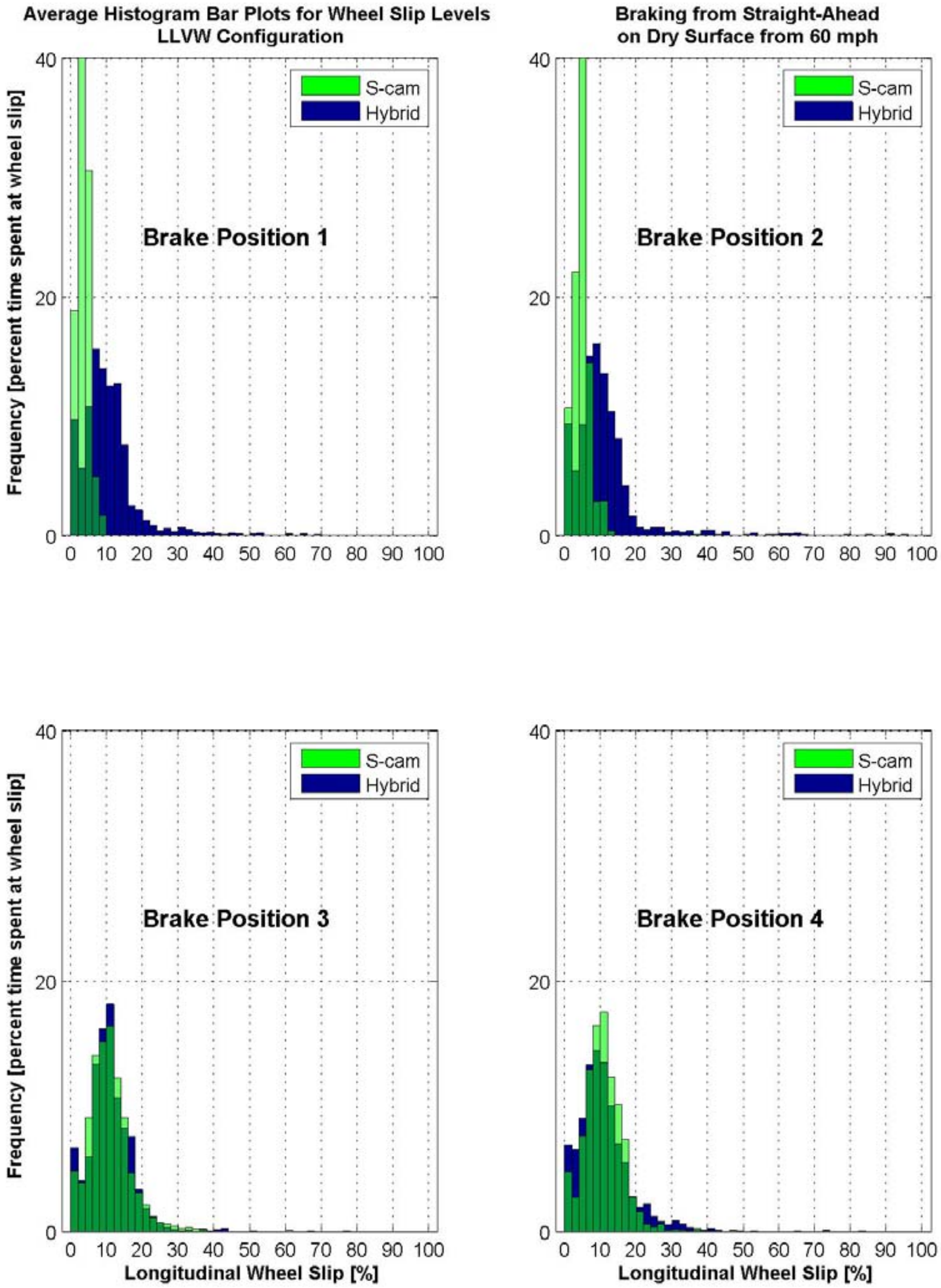


Figure 3.6. Average Wheel Slip Histograms - LLVW School Bus Dry Stops From 60 mph

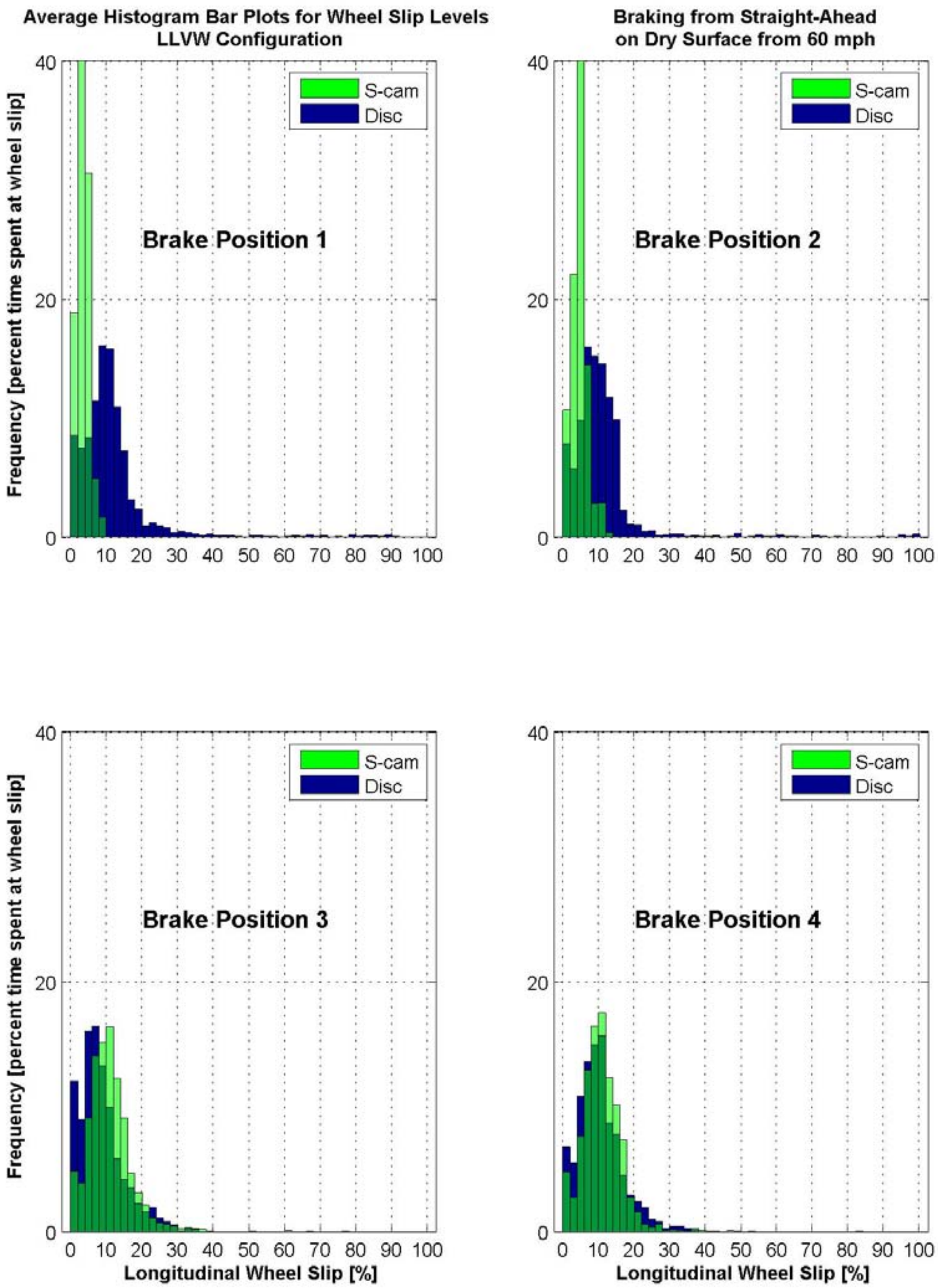


Figure 3.7. Average Wheel Slip Histograms - LLVW School Bus Dry Stops From 60 mph

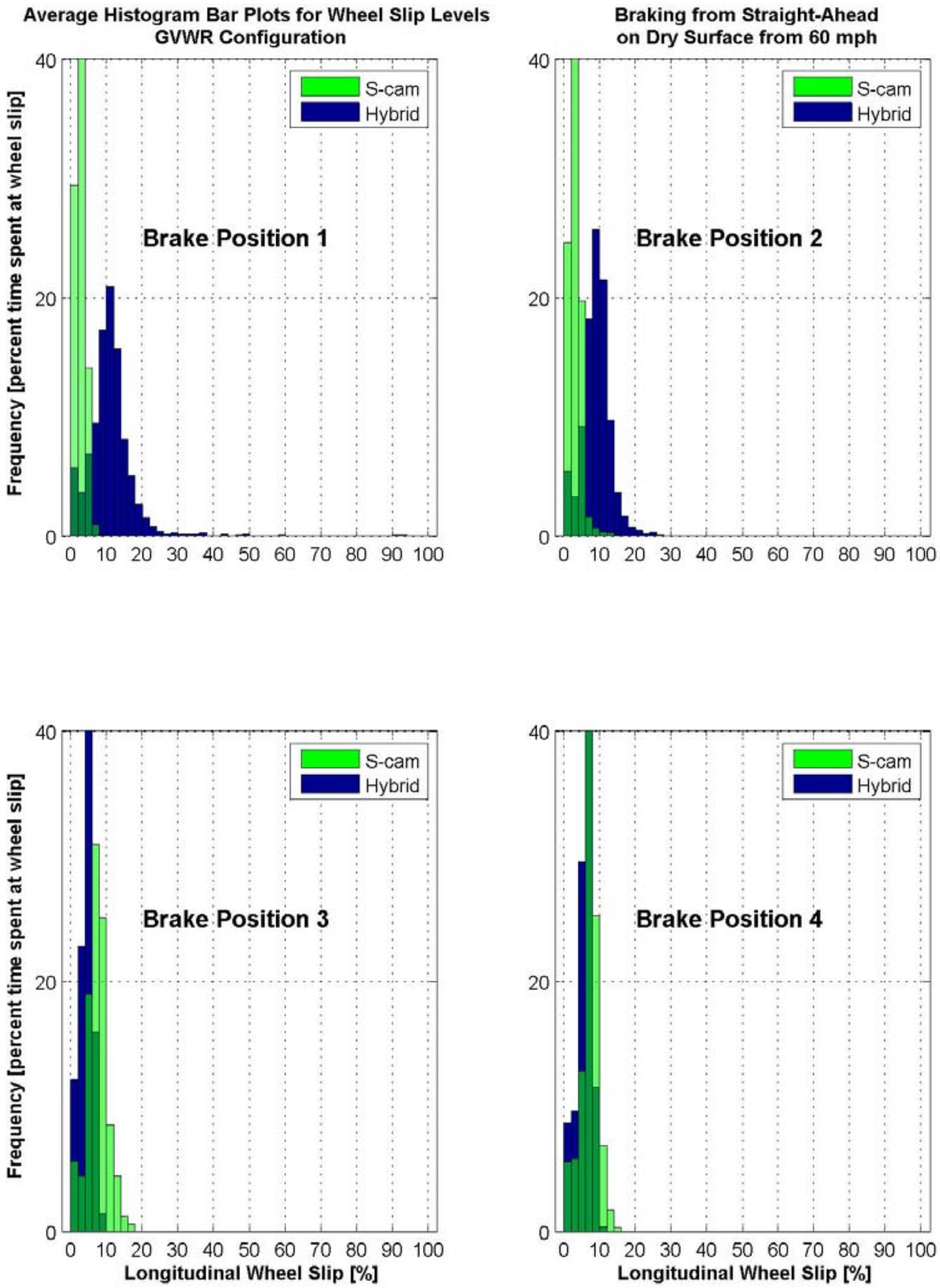


Figure 3.8. Average Wheel Slip Histograms - GVWR School Bus Dry Stops From 60 mph

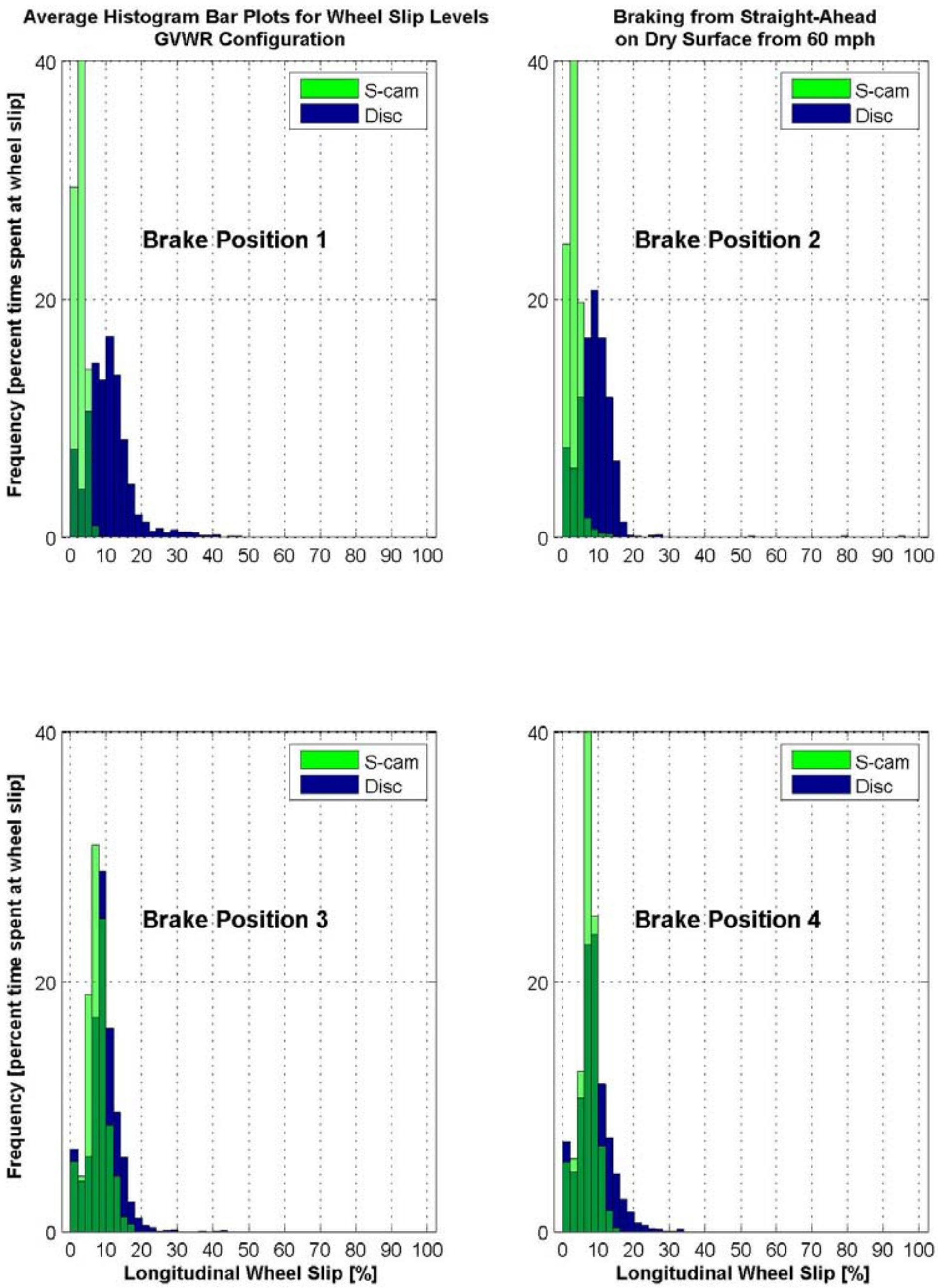


Figure 3.9. Average Wheel Slip Histograms - GVWR School Bus Dry Stops From 60 mph

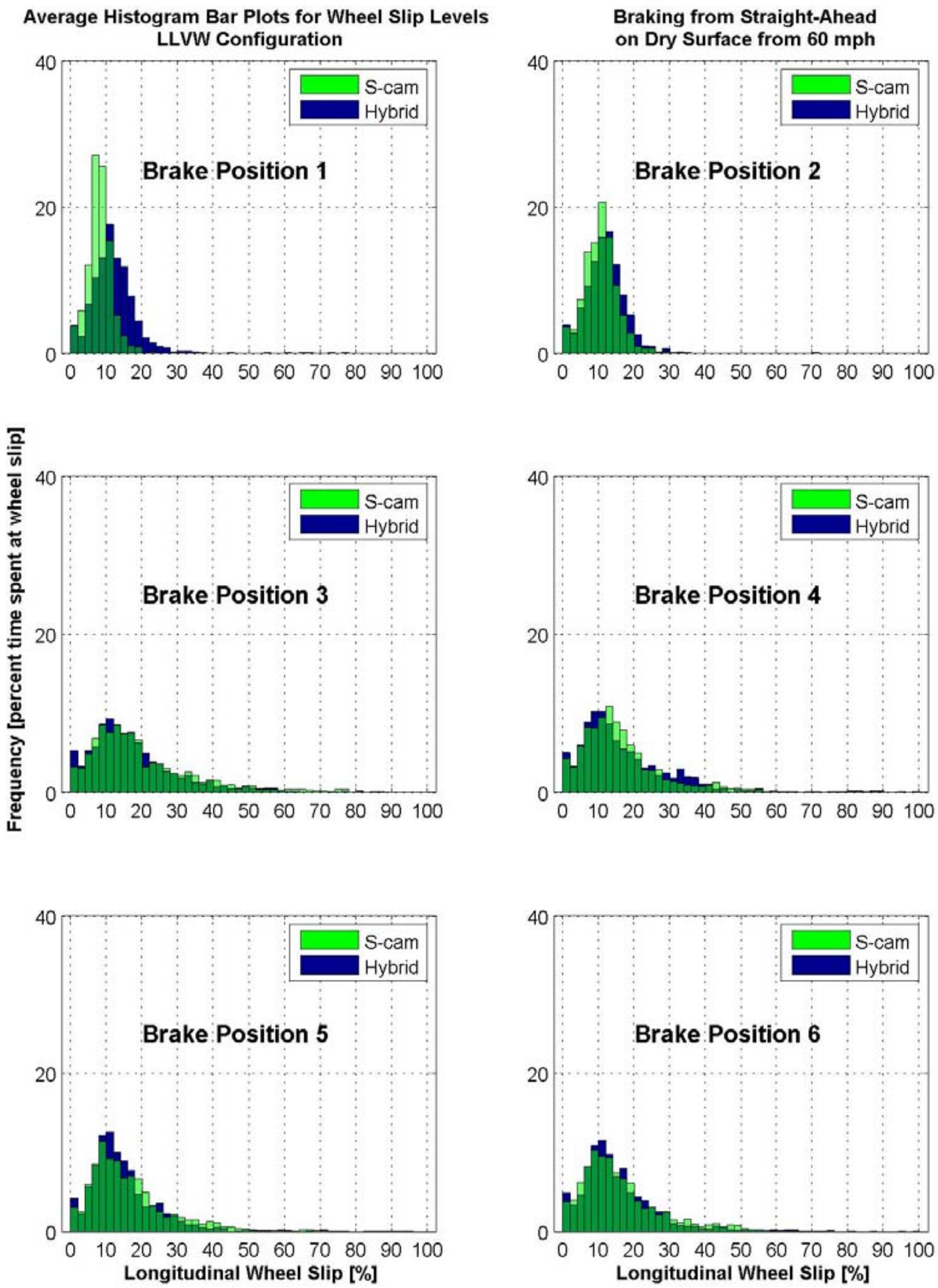


Figure 3.10. Average Wheel Slip Histograms - LLVW Straight Truck Dry Stops From 60 mph

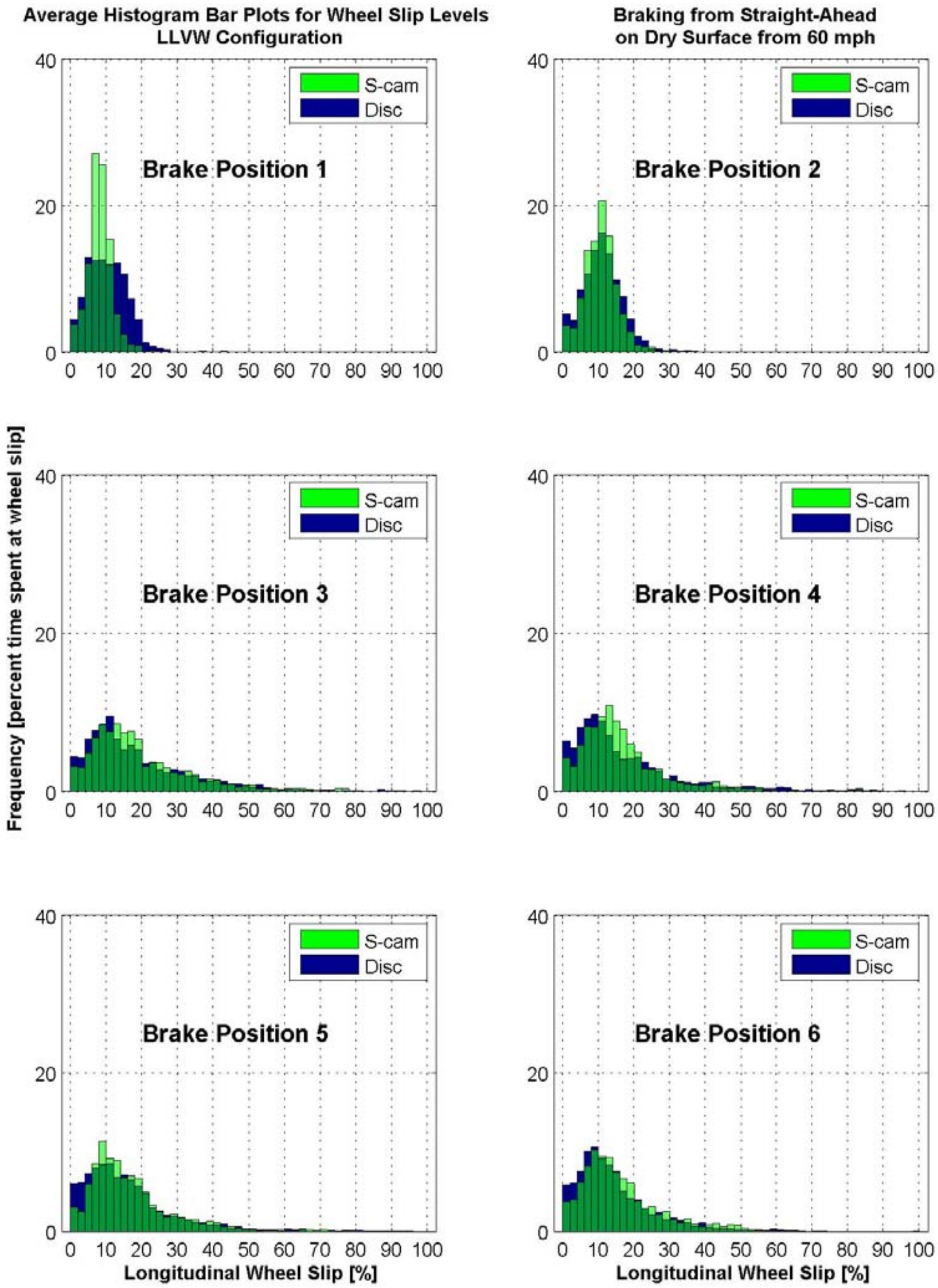


Figure 3.11. Average Wheel Slip Histograms - LLVW Straight Truck Dry Stops From 60 mph

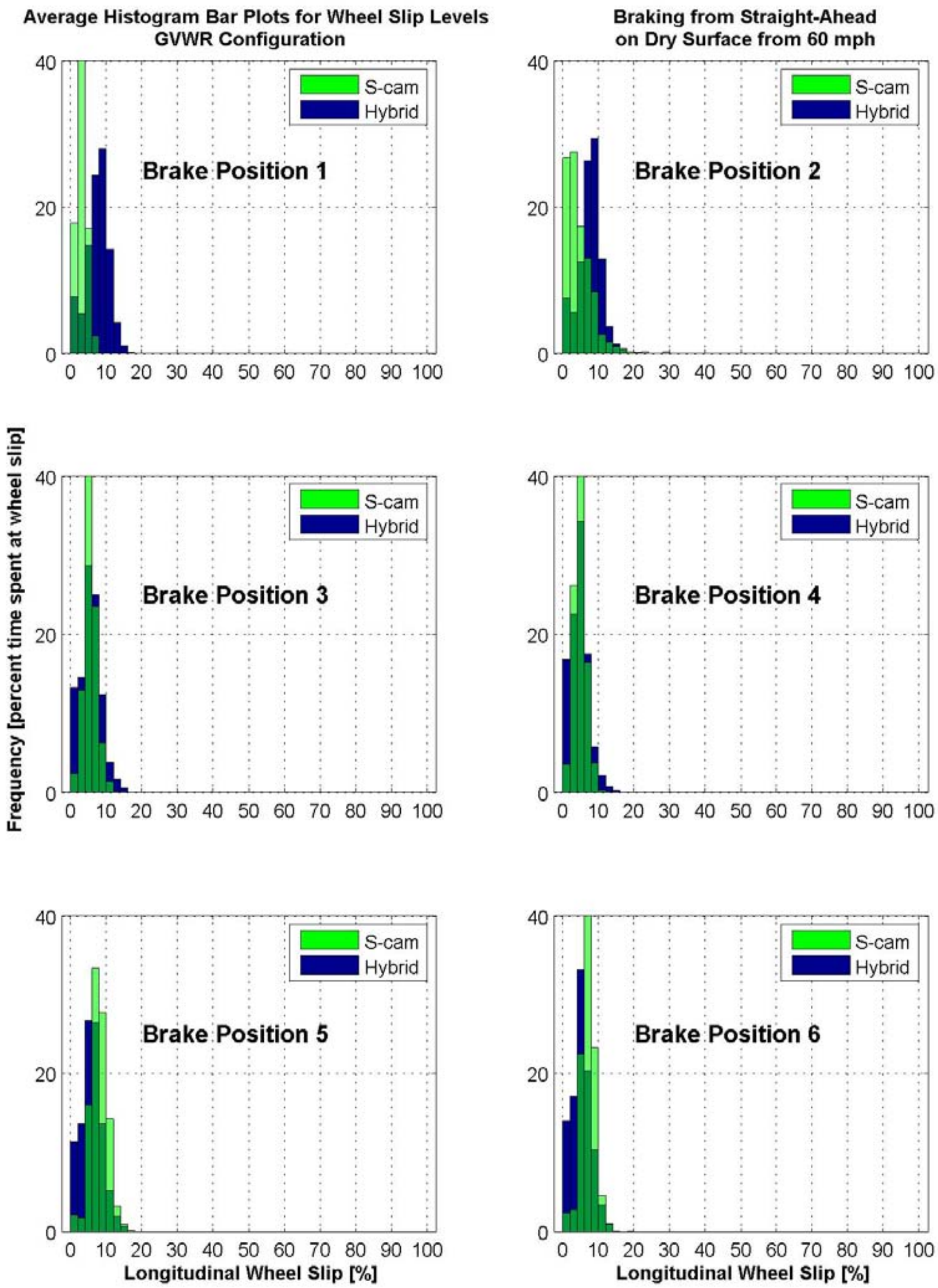


Figure 3.12. Average Wheel Slip Histograms - GVWR Straight Truck Dry Stops From 60 mph

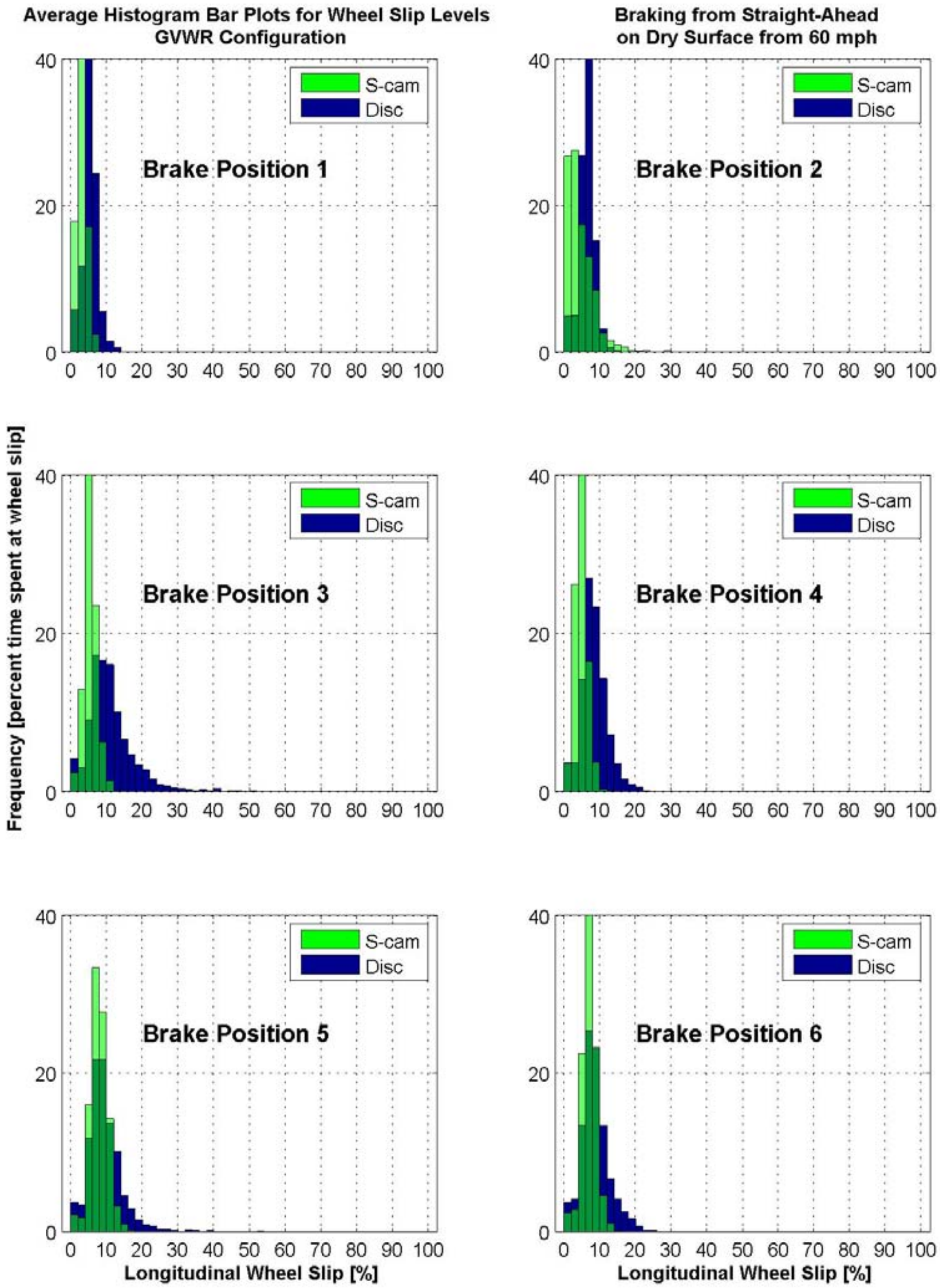


Figure 3.13. Average Wheel Slip Histograms - GVWR Straight Truck Dry Stops From 60 mph

The following results were found:

- For the school bus at LLVW, placement of disc brakes on the steer axle (hybrid configuration) caused brake positions 1 and 2 to spend time at more optimal levels of slip (Figure 3.6). Placement of disc brakes on the drive axle did not cause brake positions 3 and 4 to spend more time at higher levels of slip (Figure 3.7). Figure 3.1 and Table 3.7 demonstrate that a point of diminishing returns was reached, as the braking capability of the vehicle was traction-limited by the tires.

- At GVWR, placement of disc brakes on the steer axle (hybrid) for the school bus caused brake positions 1 and 2 to spend more time at higher levels of slip and reduce stopping distance (compare Figure 3.8 with Figure 3.2). In contrast to the LLVW condition, further placement of disc brakes on the drive axles caused brake positions 3 and 4 to spend more time at higher levels of slip (Figure 3.9) resulting in a further reduction of stopping distance (compare with Figure 3.2). While a correlation could be made on why the hybrid and disc configurations had a shorter stopping distance when compared to the S-cam configuration, no discernible conclusion could be made on why the disc had a shorter stopping distance than the hybrid, when looking at the percentage decrease in pressure (compare Figures 3.7 and 3.8 to Table 3.7).

- For the straight truck at LLVW, there were no discernible differences between the baseline (S-cam) and either of the hybrid or disc (Figures 3.10 and 3.11). Small differences were exhibited with the average stopping distance and air consumption results showing strong correlation with the average stopping distance results (Figure 3.3) and air consumption in Table 3.8. .

- There were noticeable differences between the S-cam and both the hybrid and disc configurations, for the straight truck at GVWR (Figures 3.12 and 3.13). The hybrid configuration, with disc brakes on the steer axle, caused the wheels (brake positions 1 and 2) to spend more time at higher regions of slip. This resulted in a shorter stopping distance (compare Figure 3.12 to Figure 3.4). Placement of disc brakes on the drive axles, in general, resulted in the drive axles (brake positions 3 – 6) spending more time at higher levels of slip which further reduced stopping distance (compare Figure 3.13 to Figure 3.4). Table 3.8 indicates that the disc brake configuration consumed the most air and, based on Figure 3.13, spent the most time at optimal levels of slip.

3.2 Brake-in-a-Curve Stability Testing Results

The following are results for the brake-in-a-curve stability tests conducted, including four standard *target* speed stops and the experimental *limit* speed stops.

3.2.1 Stability and Control - 75 Percent of Drive-Through Speed

Tables 3.9 and 3.10 illustrate stability control test results for the school bus and straight truck, respectively. The tables list the drive-through speed, 75 percent of drive-through speed (*target* test speed), and the number of stops "passed" for each configuration. The last column lists the corresponding peak friction coefficients, which were measured on or near the test date. To prevent damage to the surface, slide friction coefficients were not measured. FMVSS No. 121

required trucks and buses to perform low-coefficient stability and control tests *only* in the LLVW load condition. For research and development purposes, the tests were performed at GVWR, as well.

FMVSS No. 121 required the vehicle to complete three of four stops without leaving the 12-ft wide lane, while performing a full-treadle brake application from an entry speed at 75 percent of the drive-through speed. For these tests, both vehicles completed all four stops while maintaining the lane, for each brake-load configuration, indicating that each exceeded the minimum requirement of the current standard.

Table 3.9. School Bus Results for Brake-in-a-Curve Tests on Water-Sprayed Jennite Surface at 75 Percent of Drive-Through Speed

Load Condition	*Brake Type*	*Drive-Through Speed [mph]*	*75 Percent of Drive-Through Speed [mph]*	*Number of Stops Passed at 75 Percent of Drive-Through Speed*	*Measured Peak Surface Coefficient*
LLVW	**S-Cam**	29	22	4	0.30
	Hybrid	31	23	4	0.32
	Disc	35	26	4	0.39
GVWR	**S-Cam**	29	22	4	0.29
	Hybrid	29	22	4	0.32
	Disc	35	26	4	0.40

Table 3.10. Straight Truck Results for Brake-in-a-Curve Tests on Water-Sprayed Jennite Surface at 75 Percent of Drive-Through Speed

Load Condition	*Brake Type*	*Drive-Through Speed [mph]*	*75 Percent of Drive-Through Speed [mph]*	*Number of Stops Passed at 75 Percent of Drive-Through Speed*	*Measured Peak Surface Coefficient*
LLVW	**S-Cam**	25	19	4	0.25
	Hybrid	30	23	4	0.37
	Disc	32	24	4	0.41
GVWR	**S-Cam**	25	19	4	0.25
	Hybrid	30	23	4	0.37
	Disc	31	23	4	0.28

3.2.2 Stability and Control – Limit Handling Speed

Tables 3.11 and 3.12 display limit handling stability and control test results for the school bus and straight truck, respectively. For each brake-load configuration, the speed ratio of the brake-in-a-curve *limit* speed to drive-through speed is listed in the fifth column of the tables. The sixth column lists the lateral acceleration performance quotient (LAPQ), which was developed and implemented in (Dunn, Hoover, & Zagorski, 2005) for tractors. LAPQ normalizes the SUT's limit 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. This rationalization normalizes the brake-in-a-curve *limit* speed as a function of the maximum drive-through speed. Both evaluations were performed on the same test day, largely mitigating the effect of the surface traction coefficient. The performance quotients for the straight truck and the bus were calculated 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 12ft lane; and*

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

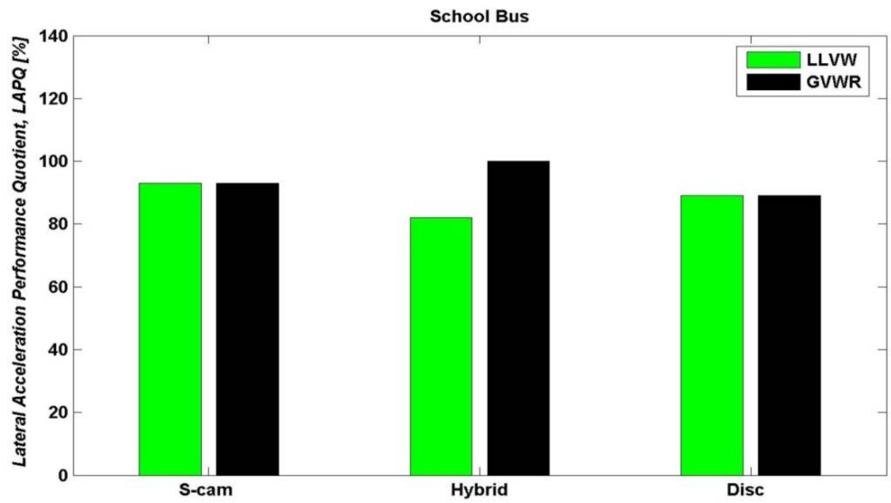
Table 3.11. School Bus Results for Brake-in-a-Curve Tests on Water-Sprayed Jennite Surface at Limit Handling Speed

Load Condition	Brake Type	Drive-Through Speed [mph]	Limit Speed [mph]	Speed Ratio [%]	LAPQ [%]	Measured Peak Surface Coefficient
LLVW	S-Cam	29	28	97	93	0.30
	Hybrid	31	28	90	82	0.32
	Disc	35	33	94	89	0.39
GVWR	S-Cam	29	28	97	93	0.29
	Hybrid	29	29	100	100	0.32
	Disc	35	33	94	89	0.40

Table 3.12. Straight Truck Results for Brake-in-a-Curve Tests on Water-Sprayed Jennite Surface at Limit Handling Speed

Load Condition	Brake Type	Drive-Through Speed [mph]	Limit Speed [mph]	Speed Ratio [%]	LAPQ [%]	Measured Peak Surface Coefficient
LLVW	S-Cam	25	28	112	125	0.25
	Hybrid	30	29	97	93	0.37
	Disc	32	32	100	100	0.41
GVWR	S-Cam	25	28	112	125	0.25
	Hybrid	30	30	100	100	0.37
	Disc	31	32	103	107	0.28

Figure 3.14 graphically illustrates the results which reveal that for the school bus at LLVW, the hybrid achieved the lowest LAPQ - with a value of 82 percent; whereas at GVWR, it achieved the highest LAPQ - with a value of 100 percent. When examining the S-cam and disc configurations, there appeared to be no significant change in brake-in-a-curve stability of the vehicle due to load.



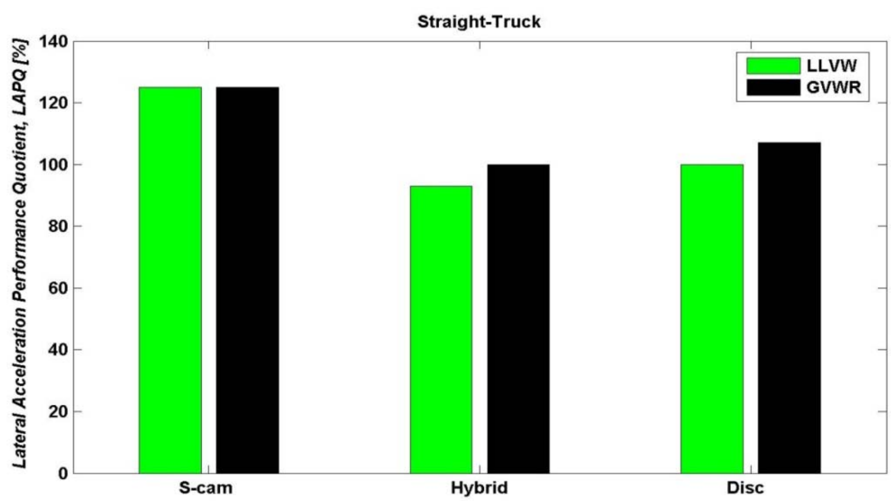


Figure 3.14. Limit Handling LAPQ for School Bus and Straight Truck

For the straight truck, the S-cam configuration consistently achieved the highest performance quotient. The hybrid configuration attained a maximum BIC lateral acceleration at or near the maximum drive-through acceleration, but its performance was the lowest of the three foundation brake configurations.

Each vehicle-brake-load configuration completed four stops at 75 percent of the drive-through speed, while maintaining the lane (see Tables 3.09 and 3.10), and achieved relatively high LAPQ levels (greater than 80%, see Tables 3.11 and 3.12, and Figure 3.14). This could be due to both vehicles being equipped with independently modulated ABS brakes, which maximized the stability of the vehicles. If the vehicles were equipped with systems that did not independently modulate each brake, for example, a 4s/3m for the school bus or a 4s/4m for the straight truck, the vehicles' stability might be compromised.

3.3 Wetted Split-μ Stopping Performance Results

Stopping performance results on a lateral split coefficient of friction surface are displayed in Tables 3.13 and 3.14 for the school bus and straight truck, respectively. Tables 3.13 and 3.14 show the results with both directions combined. The last columns list the corresponding peak and slide surface coefficients for both surfaces, measured on or near the test date. Figures 3.15 to 3.18 graphically illustrate the results.

Table 3.13. Stopping Distance Results for the School Bus - Straight-Ahead Braking from 30 mph on a Wetted Split-μ Surface

		Stopping Distance [ft]				***Wet Asphalt***		***Wet Jennite***	
Load Condition	***Brake Type***	***Min.***	***Mean***	***Max.***	***Std. Dev.***	***Peak Surface Coefficients***	***Slide Surface Coefficients***	***Peak Surface Coefficients***	***Slide Surface Coefficients***
LLVW	**S-Cam**	88	94	98	3.19	0.79	0.50	0.30	0.11
	Hybrid	91	94	100	3.75	0.76	0.48	0.32	0.10
	Disc	80	83	84	1.45	0.89	0.70	0.37	0.13
GVWR	**S-Cam**	91	94	99	3.20	0.79	0.50	0.29	0.11
	Hybrid	97	104	111	5.98	0.76	0.48	0.33	0.10
	Disc	83	85	87	1.79	0.90	0.70	0.39	0.13

Table 3.14. Stopping Distance Results for the Straight Truck - Straight-Ahead Braking From 30 mph on a Wetted Split-μ Surface

		Stopping Distance [ft]				***Wet Asphalt***		***Wet Jennite***	
Load Condition	***Brake Type***	***Min.***	***Mean***	***Max.***	***Std. Dev.***	***Peak Surface Coefficients***	***Slide Surface Coefficients***	***Peak Surface Coefficients***	***Slide Surface Coefficients***
LLVW	**S-Cam**	92	96	100	3.38	0.85	0.56	0.27	0.09
	Hybrid	91	96	99	2.61	0.77	0.52	0.37	0.10
	Disc	84	86	87	1.05	0.90	0.70	0.40	0.13
GVWR	**S-Cam**	95	98	102	2.64	0.85	0.57	0.28	0.09
	Hybrid	92	93	94	0.91	0.77	0.52	0.36	0.10
	Disc	86	89	92	2.43	0.83	0.68	0.27	0.10

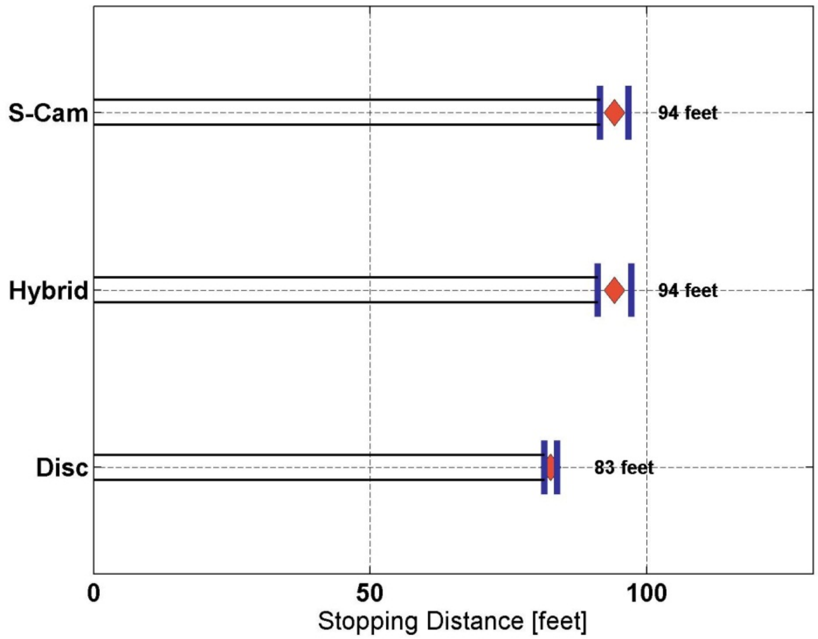


Figure 3.15. School Bus LLVW Mean Stopping Distances for Split-μ Stops From 30 mph

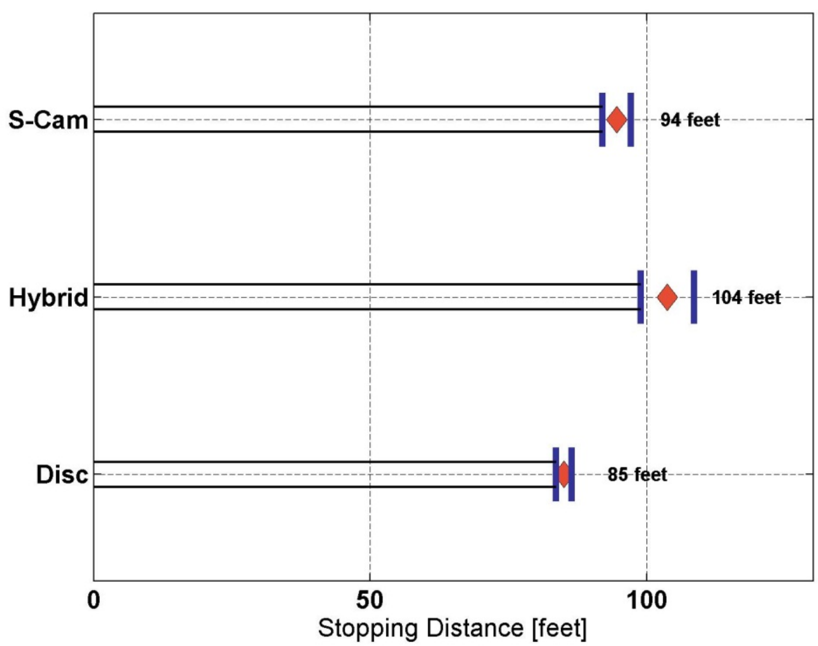


Figure 3.16. School Bus GVWR Mean Stopping Distances for Split-μ Stops From 30 mph

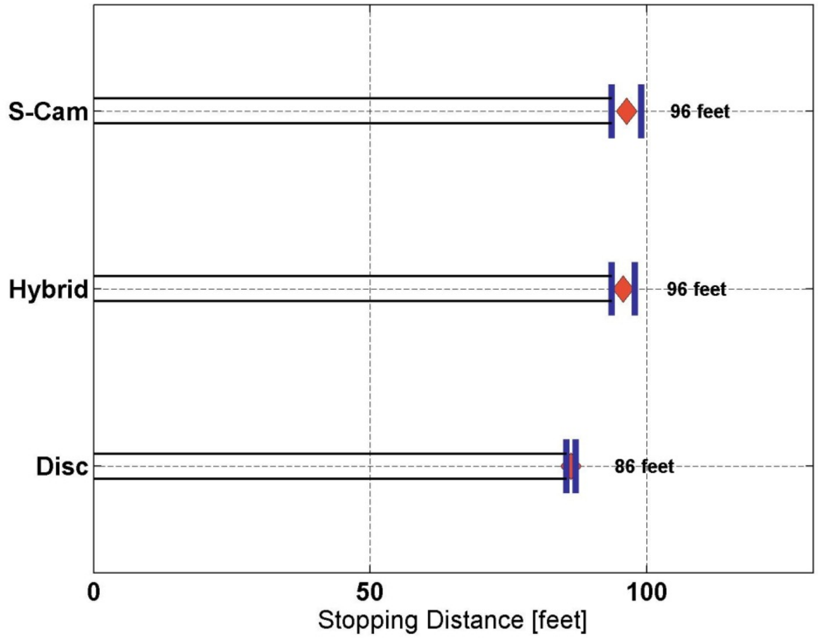


Figure 3.17. Straight Truck LLVW Mean Stopping Distances for Split-μ Stops From 30 mph

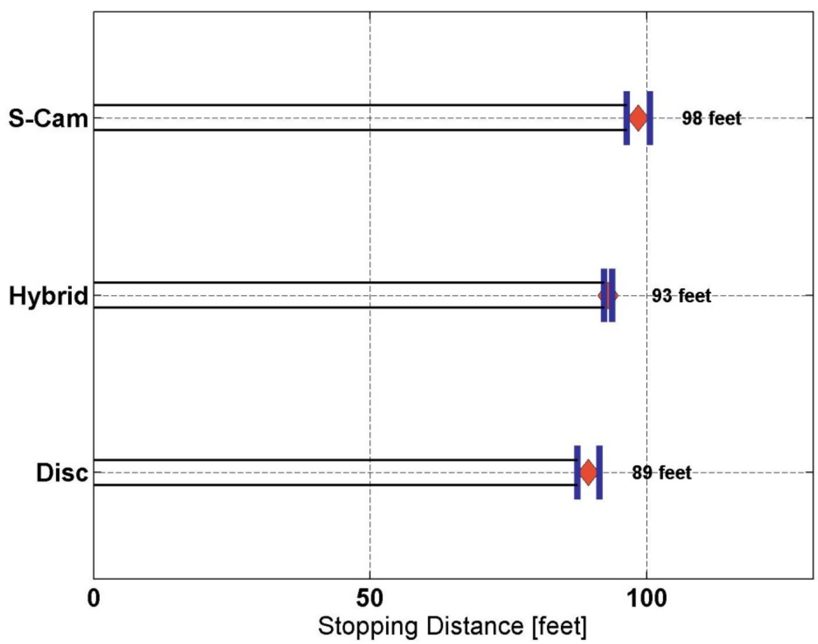


Figure 3.18. Straight Truck GVWR Mean Stopping Distances for Split-μ Stops From 30 mph

3.3.1 Wetted Split-μ Stopping Performance ANOVA Results

ANOVAs were performed with SAS using corrected stopping distance as the dependent variable. The results were used to gauge main and interaction effects of independent treatments of *brake* type, *load*, and *direction*. Similar to the dry stopping performance analyses, the effect of *brake* (on the results) was of primary interest. For these analyses, a "Pr > F" (probability greater than F) value of 0.05 was used as the criterion for statistical significance.

3.3.1.1 ANOVA Wetted Split-μ Stopping Performance Results for School Bus

Table 3.15 lists the ANOVA results for the school bus. For each effect, the DOF, the F, and "Pr > F" values are listed. Also listed are the corresponding magnitudes of treatment of effect (ω^2 terms) (see section 3.1.1 for a further description).

Table 3.15. ANOVA Wetted Split-μ Stopping Performance Results for School Bus

Effect	*DOF*	*F Value*	*Pr > F*	*Magnitude of Treatment of Effect, ω^2*
Brake	2	83.21	< 0.0001	0.680
Load	1	18.34	0.0003	0.072
Direction	1	0.81	0.3763	N.S.
Load x Direction	1	2.15	0.1559	N.S.
Brake x Direction	2	4.58	0.0206	0.030
Brake x Load	2	7.06	0.0039	0.050
Total Percent of Variance Accounted for in Model				0.835

N.S. – Not significant

Based on results in Table 3.15, the individual effects of *brake* and *load* were significant. The effect of *direction* was not significant (a good result). The interaction between *brake* and *load*, and between *brake* and *direction*, were significant. This demonstrates that the effect of *brake* was not consistent for each combination of *brake* and *direction*, and of *brake* and *load*. While the interaction between *brake* and *direction* was significant, the corresponding ω^2 was small. The interaction between *load* and *direction* were not significant indicating that effect of *load* was consistent for all combinations of *load* and *direction*. The effect of *brake* accounted for the greatest variance in the model, 68 percent.

Table 3.16 lists the in-depth analysis results for the school bus. The in-depth analysis test displays brake rankings for different combinations of *load* and *direction*. The corresponding mean stopping distances are listed for each ranking.

In general, the in-depth analysis results demonstrate that regardless of the way the *load* and *direction* are broken up, the disc brake was statistically different than both the S-cam and the hybrid configurations. The results were not only statistically different, but they also exhibited consistently shorter mean stopping distances. With the directions combined, at LLVW, the hybrid and S-cam configurations were statistically similar; but at GVWR, the S-cam brake outperformed the hybrid. These results are consistent with those found in (Dunn, Hoover, and Zagorski, 2005).

Table 3.16. Wetted Split-μ Stopping Performance In-Depth Analysis Results for School Bus

Load	*Direction*	*Brake Rankings**
Combined	**E-W**	S-Cam > Hybrid > Disc 101 93 84
Combined	**W-E**	(S-Cam = Hybrid) > Disc 96 95 84
LLVW	**Combined**	(S-Cam = Hybrid) > Disc 94 94 83
GVWR	**Combined**	Hybrid > S-Cam > Disc 104 94 85
LLVW	**E-W**	(Hybrid = S-Cam) > Disc 94 93 83
LLVW	**W-E**	(S-Cam = Hybrid) > Disc 95 94 82
GVWR	**E-W**	Hybrid > S-Cam > Disc 108 94 84
GVWR	**W-E**	(Hybrid = S-Cam) > Disc 99 95 86

* - An equal sign indicates that the two brake configurations were statistically similar

3.3.1.2 ANOVA Wetted Split-μ Stopping Performance Results for Straight Truck

Table 3.17 displays the results for the straight truck. These results indicate that the effects of *brake* and *direction* were significant, but the effect of *load* was not. However, the ω^2 for *direction* was much less than that associated with *brake*.

Interaction between *load* and *direction* were not significant, revealing that for all combinations of *load* and *direction*, the results were consistent. The interactions between *brake* and *direction*, and between *brake* and *load*, were significant, indicating that the effect of *brake* was not consistent for different combinations of *brake* and *load*, and *brake* and *direction*. The effect of *direction* was small as indicated by the small ω^2 for this term, while the effect of *brake* accounted for the greatest variance in this model, 71 percent.

Table 3.17. ANOVA Wetted Split-μ Stopping Performance Results for Straight Truck

Effect	*DOF*	*F Value*	*Pr > F*	*Magnitude of Treatment of Effect ω^2*
Brake	2	107.06	< 0.0001	0.707
Load	1	2.95	0.0988	N.S.
Direction	1	18.87	0.0002	0.060
Load x Direction	1	1.72	0.2015	N.S.
Brake x Direction	2	7.14	0.0037	0.041
Brake x Load	2	10.08	0.0007	0.061
Total Percent of Variance Accounted for in Model				0.877

N.S. – Not Significant

Table 3.18 lists results for the in-depth analysis which indicate that regardless of the way the *loads* and *directions* are broken down, the disc brake configuration was consistent and statistically different than both the S-cam and hybrid configurations. Further, the disc configuration consistently exhibited shorter average stopping distances.

Table 3.18. Wetted Split-μ Stopping Performance In-Depth Analysis Results for Straight Truck

Load	*Direction*	*Brake Rankings**
Combined	**E-W**	S-Cam > Hybrid > Disc 100 95 88
Combined	**W-E**	(S-Cam = Hybrid) > Disc 95 93 88
LLVW	**Combined**	(S-Cam = Hybrid) > Disc 96 96 86
GVWR	**Combined**	S-Cam > Hybrid > Disc 98 93 89
LLVW	**E-W**	(S-Cam = Hybrid) > Disc 99 97 86
LLVW	**W-E**	(Hybrid = S-Cam) > Disc 94 93 86
GVWR	**E-W**	S-Cam > Hybrid > Disc 101 93 90
GVWR	**W-E**	(S-Cam = Hybrid) > Disc 96 93 89

* - An equal sign indicates that the two brake configurations were statistically similar

The differences between the hybrid and S-cam configurations depended on which way the direction and load were re-grouped. When the directions were combined at LLVW, the S-cam and hybrid configurations were statistically similar. At GVWR, stopping distances for the S-cam configuration were statistically longer than the hybrid.

At LLVW, the S-cam and hybrid configurations exhibited statistically similar results. The disc configuration was statistically shorter than either the S-cam or hybrid. The benefits of disc brakes were further realized when looking at the results at GVWR. As the brake configuration became more aggressive (i.e., the hybrid was more aggressive than the S-cam, and the disc was more aggressive than the hybrid), there was a consistent reduction in average stopping distance.

A prime similarity was identified for both vehicles in Tables 3.16 and 3.18. The disc brake configuration had slightly higher performance than the S-cam and hybrid configurations, in terms of shorter average stopping distance. As expected, on a low-medium friction coefficient surface, significant ABS modulation occurred regardless of the brake type and load condition. In other words, neither brake configuration was torque limited, as might be seen on a higher coefficient surface. Similar average stopping distances would be anticipated but the data contradict this assumption.

This is believed to be due to the mechanical design of the brakes themselves. When compared to an S-cam brake, the air chamber was smaller for a disc brake (service brake chamber sizes are summarized in Table 3.19). When the ABS was modulating the disc brakes through a smaller chamber, in theory, the disc brake should recover and cycle more quickly than the S-cam brake, resulting in a lower stopping distance.

Table 3.19. Summary of Chamber Sizes (in^2) for the School Bus and Straight Truck

	School Bus		***Straight Truck***	
Brake Type	***Steer Axle***	***Drive Axle***	***Steer Axle***	***Drive Axle***
S-Cam	20	30	24	30
Hybrid	16	30	24	30
Disc	16	20	24	24

As the foundation brakes were retrofitted, the chamber sizes changed more significantly for the school bus than for the straight truck (Table 3.19). This correlated with the school bus having more significant changes in stopping distance than the straight truck. When compared to the S-cam configuration, the school bus with disc brakes showed an improvement in stopping distance of 12-18 percent; whereas the straight truck exhibited a smaller improvement of 10 percent. Further mechanical design model effects of brake total hysteresis were discussed in (Dunn, 2003).

3.4 Parking Brake Test Results

The following results detail the parking brake tests performed. Grade holding and drawbar tests were both conducted. Additional reference information on parking brake testing for trucks can be found in (Hoover & Howe, 2002).

Both vehicles passed the 20-percent grade holding tests, for each load condition, direction (uphill and downhill), and brake configuration. While on the grade with the parking brake engaged, no movement was exhibited within the allotted 300-second (5-minute) holding period.

Tables 3.20 and 3.21 list the drawbar-pull test results for the school bus and straight truck, respectively. The FMVSS No. 121 standard required that the maximum force/Gross Axle Weight Rating (GAWR) ratio be greater than or equal to 0.28, for each parking brake equipped axle. The tables include maximum drawbar force, maximum force/GAWR ratio, and corresponding margins of compliance; all for each pull direction, axle, and brake configuration.

3.4.1 Drawbar Test Results for School Bus

The 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 forward. Because of this, the brakes became more effective in the forward direction; and therefore, resulted in higher margins of compliance, in this direction.

With the exception of the NHTSA test in the forward direction, the S-cam configuration consistently achieved higher margins of compliance, than the disc. It was noted that the S-cam configuration had type 30 parking brake chambers; whereas, the disc configuration had smaller type 24 (see Tables 2.3 and 2.5). Because of this difference, no direct conclusion was made on whether the disc brakes were less effective for parking, than the S-cam drum brakes.

When comparing the two sets of tests, the SAE test consistently achieved higher margins of compliance, than the corresponding NHTSA test results. The only exception was the disc brake configuration, in the forward direction.

3.4.2 Drawbar Test Results for Straight Truck

As with the school bus, the corresponding margins of compliance for the forward direction were consistently higher, than for the rearward direction results. As previously stated, this might be due to the forward burnish direction.

Corresponding margins of compliance for disc parking brakes were consistently higher than the S-cam configuration. In contrast to the school bus, both straight truck brake configurations had the same parking chamber size, type 30. This led to the conclusion that disc brakes were the more effective parking brakes for this vehicle.

For the S-cam configuration, the lead axle consistently achieved lower margins of compliance than the trailing axle. In contrast, for the disc configuration, the trailing axle was consistently lower than the lead axle. During the burnish, the trailing axle for the S-cam configuration consistently achieved higher lining temperatures than the lead axle for unknown reasons. The slightly higher burnish temperatures may have caused the trailing drive axle brakes to gain more effectiveness and produce higher margins of compliance. Looking at the disc configuration, no correlation could be made between burnish temperatures and parking brake performance.

When comparing the two tests run on the straight truck, the SAE test consistently produced higher margins of compliance than the corresponding NHTSA test results. With the SAE test, a full-treadle service brake application was administered, and then the parking brake applied. This allowed the brakes to gain more grip; and therefore, be more effective. The SAE test nearly doubled the lower margin of compliance for the S-cam brakes, but added only about half that much extra for the higher margin of compliance disc brakes.

Table 3.20. Parking Brake Test Results for School Bus

School Bus		NHTSA Test - 0 psi Treadle Pressure			SAE Test - Max Cut-Out Treadle Pressure		
Pull Direction	*Brake Type*	*Draw Force [lbf]*	*Force-GAWR Ratio*	*Margin of Compliance [%]*	*Draw Force [lbf]*	*Force-GAWR Ratio*	*Margin of Compliance [%]*
Forward	**S-Cam**	11268	0.563	101.2	13057	0.653	133.2
	Disc	12816	0.641	128.9	12425	0.621	121.9
Rearward	**S-Cam**	10529	0.526	88.0	11134	0.557	98.8
	Disc	8583	0.429	53.3	8908	0.445	59.1

Note: Minimum draw force requirement for school bus was 5,600 lb

Table 3.21. Parking Brake Test Results for Straight Truck

Straight Truck			NHTSA Test - 0 psi Treadle Pressure			SAE Test - Max Cut-Out Treadle Pressure		
Pull Direction	*Axle*	*Brake Type*	*Draw Force [lbf]*	*Force-GAWR Ratio*	*Margin of Compliance [%]*	*Draw Force [lbf]*	*Force-GAWR Ratio*	*Margin of Compliance [%]*
Forward	**Lead**	**S-Cam**	7373	0.335	19.7	8477	0.385	37.6
		Disc	12128	0.551	96.9	13801	0.627	124.0
	Trailing	**S-Cam**	9450	0.430	53.4	11395	0.518	85.0
		Disc	11826	0.538	92.0	12766	0.580	107.2
Rearward	**Lead**	**S-Cam**	6922	0.315	12.4	8216	0.373	33.4
		Disc	10017	0.455	62.6	10714	0.487	73.9
	Trailing	**S-Cam**	7121	0.324	15.6	8277	0.376	34.4
		Disc	8960	0.407	45.5	9851	0.448	59.9

Note: Minimum draw force requirement for straight truck was 6,160 lb

3.5 Emergency Brake System Testing Results

The following are results for the emergency brake system (failed systems) tests performed. Tables 3.22 and 3.23 list the results for the school bus and straight truck, respectively. Current FMVSS No. 121 required that a vehicle stop shorter than the maximum allowable stopping distance, at least once in six stops. The maximum allowable stopping distance for both buses and single-unit trucks with failed systems was 613 ft. The following tables list the minimum and mean stopping distances, and the corresponding margins of compliance, for each brake-load configuration and simulated failure.

Based on the tables, the following results were exhibited:

- Of the three brake configurations, the disc brake configuration generally achieved the highest margins of compliance. These differences were more pronounced when loaded to GVWR, similar to results seen for the full service brake system tests.

- For both vehicles, the failed secondary reservoir tests consistently resulted in longer stopping distances than the failed primary reservoir tests, except for the straight truck - in the S-cam configuration - at GVWR. Secondary reservoir failure resulted in both vehicles losing braking ability at the steer axles and only had the drive axle brakes to slow down. Failure of the primary reservoir resulted in the service brakes of the drive axles discontinuing operation. However, the parking (spring) brakes did apply and engage, allowing the driver to retain the ability to modulate the spring brakes manually, to prevent wheel lock and to maintain lane control.

- For the school bus, venting of the primary control line from the treadle caused the primary control to the drive axle relay valve to fail. Redundancy was built into the bus braking system so the secondary control (treadle) line acted in backup to control the drive axle brakes, along with the usual steer axle brakes. As a result, the stopping distances were comparable to the full service brake stops from 60 mph (see Table 3.1). The straight truck was not equipped with this type of auxiliary control line on its drive axle relay valve, which resulted in longer stops.

Table 3.22. Failed System Stopping Distance Results for School Bus

School Bus		***Failed Primary Reservoir***				***Failed Secondary Reservoir***				***Failed Primary Control Line***			
Load Condition	***Brake Type***	***Minimum***		***Mean***		***Minimum***		***Mean***		***Minimum***		***Mean***	
		S.D. [ft]	***%MC***	***S.D. [ft]***	***%Diff***	***S.D. [ft]***	***%MC***	***S.D. [ft]***	***%Diff***	***S.D. [ft]***	***%MC***	***S.D. [ft]***	***%Diff***
LLVW	**S-Cam**	214	65.0	217	64.7	306	50.0	318	48.1	197	67.9	200	67.4
	Hybrid	205	66.6	210	65.8	319	47.9	329	46.3	174	71.6	178	71.0
	Disc	184	70.0	186	69.7	287	53.1	299	51.2	170	72.2	176	71.3
GVWR	**S-Cam**	338	44.9	341	44.4	395	35.6	401	34.5	233	62.0	237	61.3
	Hybrid	269	56.1	273	55.4	464	24.3	484	21.1	219	64.3	223	63.6
	Disc	225	63.4	228	62.8	298	51.4	316	48.4	177	71.1	180	70.6

S.D. = Stopping Distance
%MC = Percent Margin of Compliance - Current FMVSS No. 121 Limit is 613 feet
%Diff = Percent Difference of Mean From Minimum Limit

Table 3.23. Failed System Stopping Distance Results for Straight Truck

Straight Truck		***Failed Primary Reservoir***				***Failed Secondary Reservoir***				***Failed Primary Control Line***			
Load Condition	***Brake Type***	***Minimum***		***Mean***		***Minimum***		***Mean***		***Minimum***		***Mean***	
		S.D. [ft]	***%MC***	***S.D. [ft]***	***%Diff***	***S.D. [ft]***	***%MC***	***S.D. [ft]***	***%Diff***	***S.D. [ft]***	***%MC***	***S.D. [ft]***	***%Diff***
LLVW	**S-Cam**	267	56.4	293	52.2	351	42.7	371	39.5	234	61.9	262	57.3
	Hybrid	234	61.9	254	58.6	333	45.6	351	42.8	217	64.7	240	60.8
	Disc	232	62.1	254	58.5	349	43.1	359	41.5	229	62.7	263	57.2
GVWR	**S-Cam**	462	24.6	476	22.3	440	28.3	462	24.6	454	25.9	473	22.9
	Hybrid	355	42.1	367	40.1	501	18.2	522	14.8	353	42.4	359	41.4
	Disc	266	56.7	270	55.9	334	45.5	339	44.7	243	60.3	250	59.2

S.D. = Stopping Distance
%MC = Percent Margin of Compliance - Current FMVSS No. 121 Limit is 613 feet
%Diff = Percent Difference of Mean From Minimum Limit

3.6 Experimental Dry Stopping Performance Tests From Higher Entry Speeds

The following are results for the experimental, dry stopping performance service-brake tests conducted from entry speeds over 60 mph. The test objectives and methodologies were discussed in Section 2.3.4.2. For the school bus, results of the six standard service-brake stops from 60 mph (discussed in Section 3.1) were compared to four experimental stops from 70 mph, all of which were performed on the skid pad. For the straight truck, three stops were performed from each entry speed of 60, 70, and 75 mph on the high-speed test track. These stops were run in addition to the standard 60 mph service brake tests discussed in Section 3.1.

3.6.1 Average Stopping Distance

Tables 3.24 and 3.25 display the average stopping distance results for the school bus and straight truck, respectively. The increases in stopping distance from 60 mph are presented for the 70 and 75 mph stops. Using the S-cam brake configuration as the baseline, the percentages of decrease in stopping distances are also listed for the hybrid and disc configurations. Figures 3.19 to 3.22 graphically illustrate the results.

Increasing the initial braking speed of the vehicle increased the stopping distance. When compared to LLVW, the GVWR stops consistently had larger increases in stopping distance from 60 mph, for each vehicle and brake configuration. It was concluded that increased entry speed more adversely affected the stopping distance of the vehicle at GVWR than at LLVW.

The hybrid and disc brake configurations consistently had shorter stopping distances than the S-cam configuration. Furthermore, when increasing the entry speed above 60 mph, both configurations had smaller “increases” in stopping distance, than the S-cam. When comparing the hybrid configuration to the disc, the differences between them depended on the load condition.

Table 3.24. Dry Stopping Performance Test Results From Higher Entry Speeds for the School Bus

School Bus		**S-Cam**		**Hybrid**		**Disc**	
Load Condition	**Speed [mph]**	**Average S.D. [ft]**	**Percent Increase from 60 mph***	**Average S.D. [ft]****	**Percent Increase from 60 mph***	**Average S.D. [ft]****	**Percent Increase from 60 mph***
LLVW	60	200	-	173 (13.7)	-	173 (13.8)	-
	70	287	43	240 (16.4)	39	231 (19.3)	34
GVWR	60	228	-	206 (9.6)	-	180 (21.2)	0
	70	373	64	295 (21.0)	43	241 (35.6)	34

* - This is the percent increase in S.D. from 60 mph

** - The percent decrease in S.D. from the S-cam configuration is listed in parenthesis

Table 3.25. Dry Stopping Performance Test Results From Higher Entry Speeds for the Straight Truck

Straight Truck		**S-Cam**		**Hybrid**		**Disc**	
Load Condition	**Speed [mph]**	**Average S.D. [ft]**	**Percent Increase from 60 mph***	**Average S.D. [ft]****	**Percent Increase from 60 mph***	**Average S.D. [ft]****	**Percent Increase from 60 mph***
LLVW	60	183	-	176 (4.0)	-	180 (1.4)	0
	70	259	42	240 (7.4)	37	246 (5.2)	36
	75	304	66	273 (10.2)	55	277 (8.8)	54
GVWR	60	285	-	246 (13.9)	-	217 (24.0)	0
	70	471	65	379 (19.5)	54	320 (32.1)	47
	75	592	107	462 (21.9)	88	380 (35.7)	75

* - This is the percent increase in S.D. from 60 mph

** - The percent decrease in S.D. from the S-cam configuration is listed in parenthesis

At LLVW, a more aggressive brake configuration did not necessarily result in a decrease in stopping distance. The straight truck had slightly longer stopping distances for the disc than for the hybrid configuration. A point of diminishing return was met, as the vehicle's braking ability was traction-limited at LLVW. When looking at the GVWR test results, the benefits of disc brakes at each wheel position were realized. The disc configuration consistently outperformed the other two by showing less sensitivity to fade at higher speeds.

As expected, higher entry speeds resulted in increased stopping distances. Causes for increased stopping distances were briefly discussed in (Zagorski & Dunn, 2005). In summary, reduced brake torque, reduced friction coefficient, and higher work demand due to higher entry speeds were considered to be the three main contributors to increased stopping distances.

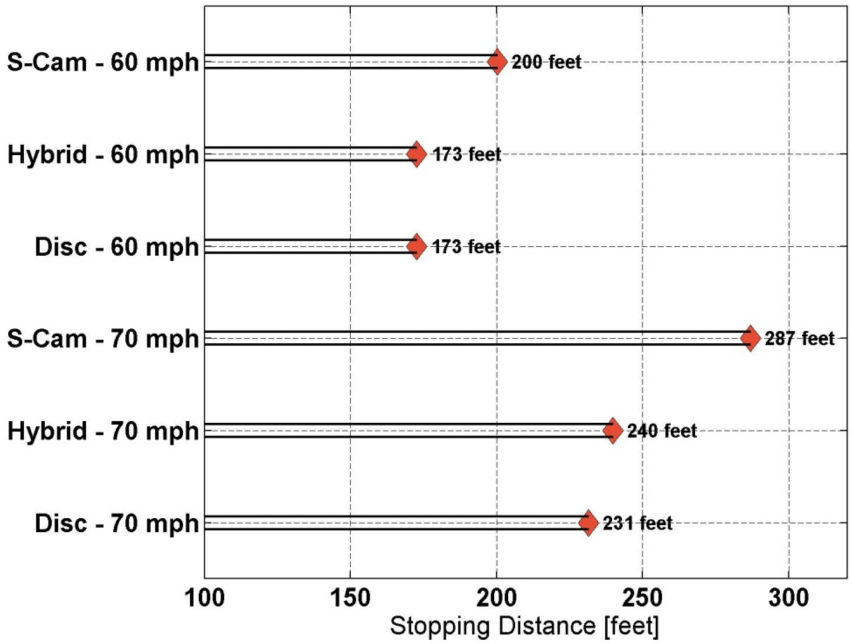


Figure 3.19. School Bus LLVW Mean Stopping Distances for High-μ Stops From 60 and 70 mph

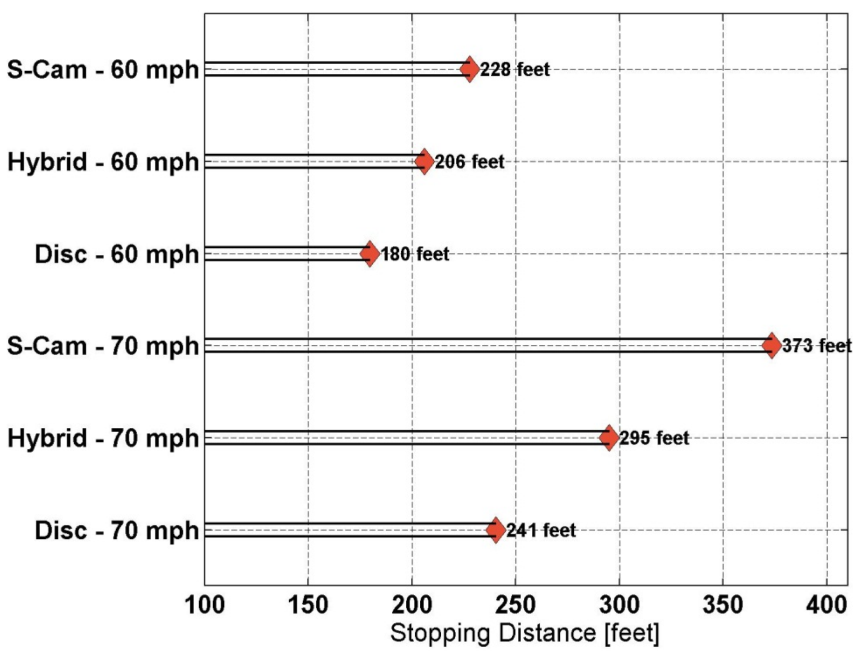


Figure 3.20. School Bus GVWR Mean Stopping Distances for High-μ Stops From 60 and 70 mph

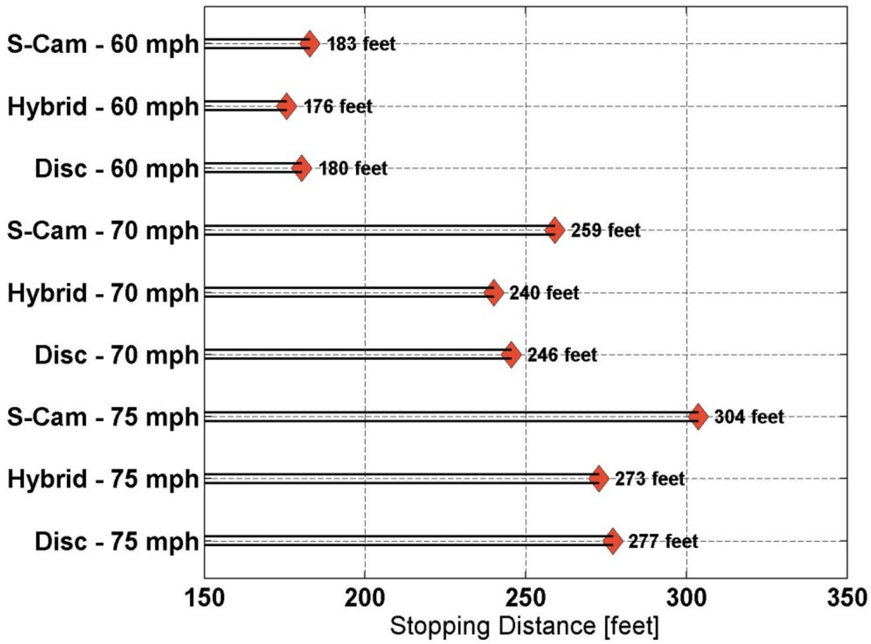


Figure 3.21. Straight Truck LLVW Mean Stopping Distances for High-μ Stops From 60, 70, and 75 mph

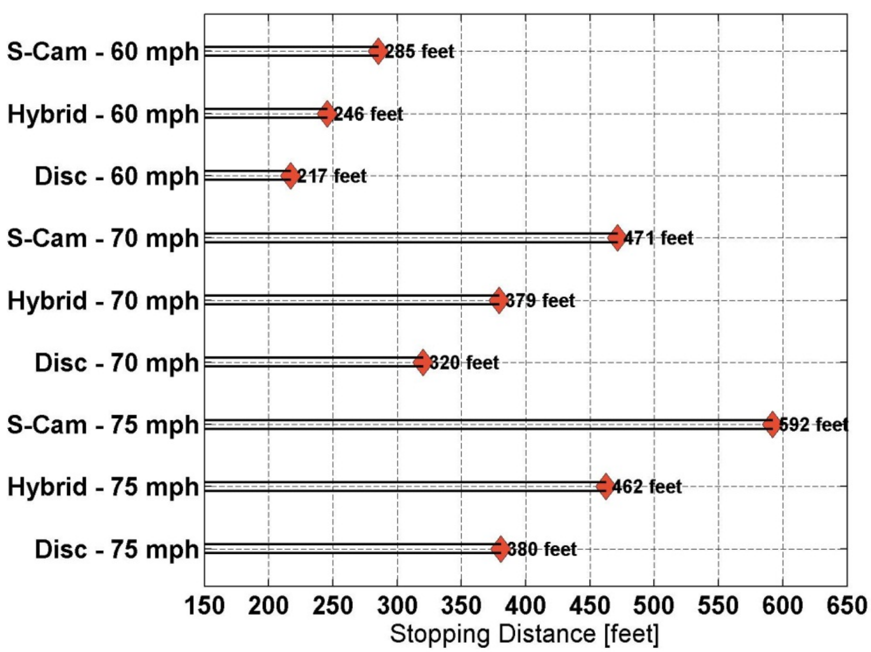


Figure 3.22. Straight Truck GVWR Mean Stopping Distances for High-μ Stops From 60, 70, and 75 mph

3.6.2 Average Deceleration Rate

The average longitudinal deceleration rate for each high-speed stop was computed using Equation 2 (EQ-2).

$$A_x = \frac{V_x^2}{2 \times SD \times g} \qquad \text{(EQ-2)}$$

where,

$A_x = average\ deceleration,\ in\ g;$

$V_x = entry\ speed\ of\ vehicle,\ in\ ft/\mathrm{sec};$

$SD = measured\ stopping\ distance,\ in\ ft;\ and$

$g = gravitational\ constant = 32.174\ ft/\mathrm{sec}/\mathrm{sec}.$

The mean decelerations for the three, four, or six stop averages were calculated next. These mean values were listed in Tables 3.26 and 3.27 for each load, speed, and brake configuration, for both the school bus and the straight truck, respectively. Using 60 mph as the baseline, the corresponding increases in mean deceleration rate were computed and added to these tables. A decrease in mean deceleration indicated a reduction in torque and friction coefficient due to increased speed(see Zagorski & Dunn, 2005). Figure 3.23 graphically illustrates the mean deceleration results.

At LLVW, both vehicles configured with S-cams had a decrease in mean deceleration, as the speed was increased. Conversely, the hybrid and disc configurations did not show similar trends. When increasing the maneuver entrance speed reduced deceleration for the hybrid and disc, the effect was small (not more than 2%). Further, the school bus and straight truck achieved higher average decelerations for some of the higher entry speeds (e.g., the straight truck in the disc configuration from 75 mph).

In comparison, the GVWR load condition consistently exhibited a decrease in deceleration rate, with higher entry speeds, for each vehicle and brake configuration, with the exception of the school bus in the disc configuration. Based on these results, it was concluded that at LLVW, only the S-cam configured vehicles decelerations were adversely affected by higher entry speeds; whereas at GVWR, all three brake configurations were negatively affected.

The hybrid configuration consistently achieved higher deceleration levels than the S-cam configuration, for each vehicle and load condition. This correlated with the hybrid-braked vehicles consistently having lower mean stopping distances, than the vehicles with S-cam brakes. When comparing the hybrid to the disc brake configuration, the disc configuration (at GVWR) consistently achieved higher deceleration levels. In contrast, at LLVW, the disc configuration did not necessarily achieve higher deceleration levels than the hybrid. This correlated with the stopping distance results presented in Tables 3.24 and 3.25.

Table 3.26. Dry Stopping Performance Test Results From Higher Entry Speeds for the School Bus - Mean Deceleration

Load Condition	Speed [mph]	S-Cam		Hybrid		Disc	
		Mean Decel. [g]	Percent Increase from 60 mph*	Mean Decel. [g]	Percent Increase from 60 mph*	Mean Decel. [g]	Percent Increase from 60 mph*
LLVW	60	0.601	-	0.697	-	0.697	-
	70	0.571	-5.0	0.683	-2.0	0.708	1.5
GVWR	60	0.528	-	0.584	-	0.671	0
	70	0.439	-16.9	0.556	-4.9	0.681	1.6

* - A negative value corresponds with a decrease in deceleration level

Table 3.27. Dry Stopping Performance Test Results from Higher Entry Speeds for the Straight Truck - Mean Deceleration

Load Condition	Speed [mph]	S-Cam		Hybrid		Disc	
		Mean Decel. [g]	Percent Increase from 60 mph*	Mean Decel. [g]	Percent Increase from 60 mph*	Mean Decel. [g]	Percent Increase from 60 mph*
LLVW	60	0.658	-	0.686	-	0.668	-
	70	0.632	-3.9	0.683	-0.4	0.668	-0.1
	75	0.619	-5.9	0.690	0.6	0.679	1.6
GVWR	60	0.422	-	0.490	-	0.555	0
	70	0.348	-17.5	0.432	-11.8	0.513	-7.6
	75	0.318	-24.8	0.407	-16.9	0.495	-10.9

* - A negative value corresponds with a decrease in deceleration level

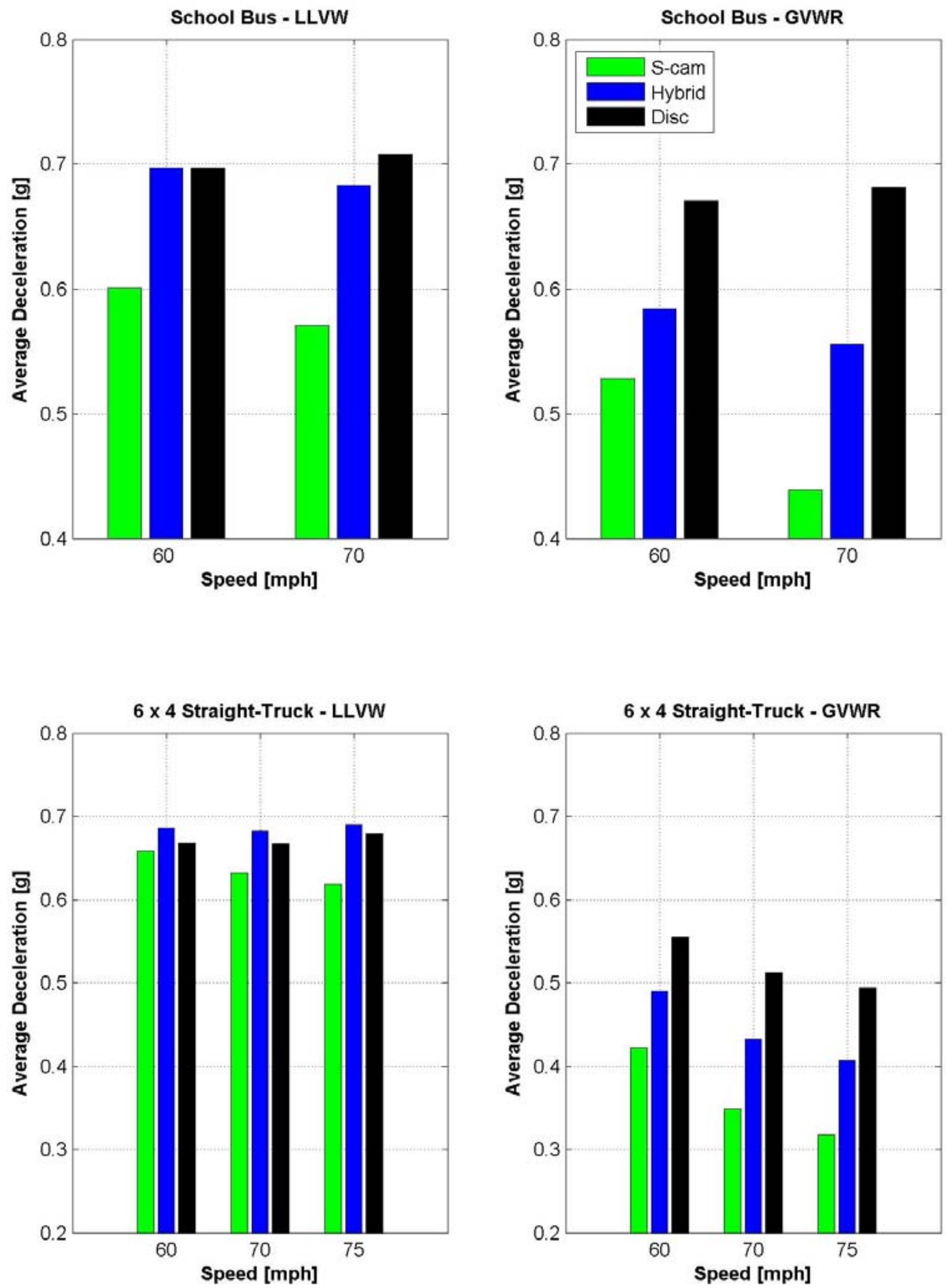


Figure 3.23. Mean (Average) Deceleration Rates for High-µ Stops From 60, 70, and 75 mph for School Bus and Straight Truck

Note - Results are displayed for three brake configurations. For black-and-white prints, the first set of histobars is the S-cam configuration; the second set is the hybrid; and the third is the disc.

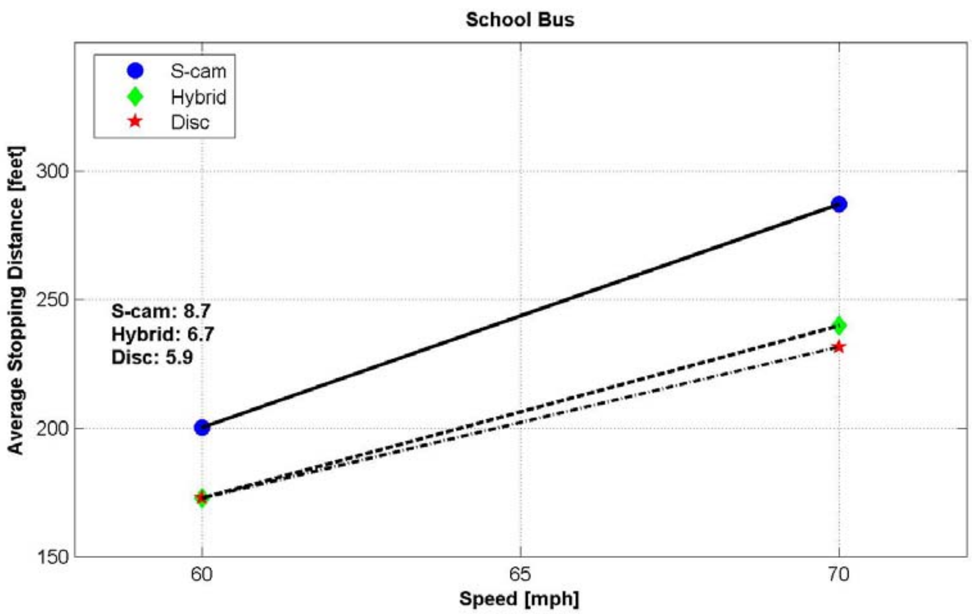
3.6.3 Linear Regression of Stopping Distance

To further quantify the benefits of the air-disc brakes, a linear regression was performed on average stopping distance, as a function of speed. This revealed the effect of higher vehicle entry speed on stopping distance. Figures 3.24 and 3.25 show these results graphically, with the slopes for each "fit" displayed on each plot. The slopes from the linear regression and corresponding correlation coefficients (R^2) are listed in Table 3.28. The correlation coefficients for the school bus were not listed, because linear regression performed between two points automatically result in R^2 values of 1.0.

Based on the graphical results for the straight truck, it would appear that a higher order polynomial (e.g., 2nd order) would give a better curve fit. However, the authors felt that for these few data points, a linear fit gave a good estimate of the expected increased stopping distance, due to the higher initial speeds (see correlation coefficients R^2 listed in Table 3.28).

Table 3.28. Stopping Distance Linear Regression Results for Dry Stops on High Friction Coefficient from High Speeds for the School Bus and Straight Truck.

		S-Cam		Hybrid		Disc	
Load Condition	**Vehicle**	**Slope [ft/mph]**	**R^2**	**Slope [ft/mph]**	**R^2**	**Slope [ft/mph]**	**R^2**
LLVW	**School Bus**	8.7	N/A	6.7	N/A	5.9	N/A
	Straight Truck	8.0	0.998	6.5	1.000	6.5	1.000
GVWR	**School Bus**	14.6	N/A	8.9	N/A	6.1	N/A
	Straight Truck	20.2	0.995	14.3	0.997	10.8	0.998



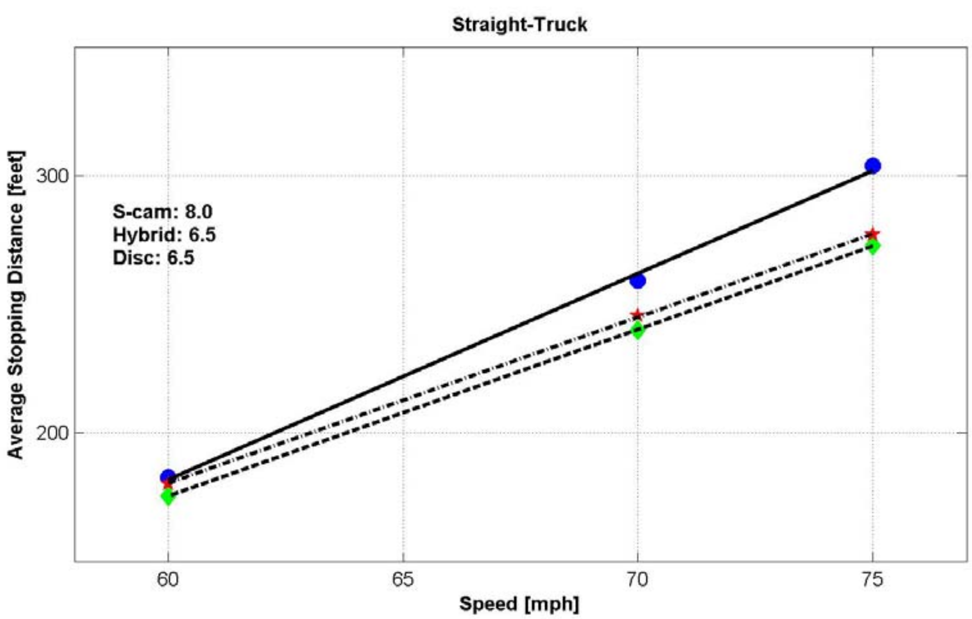
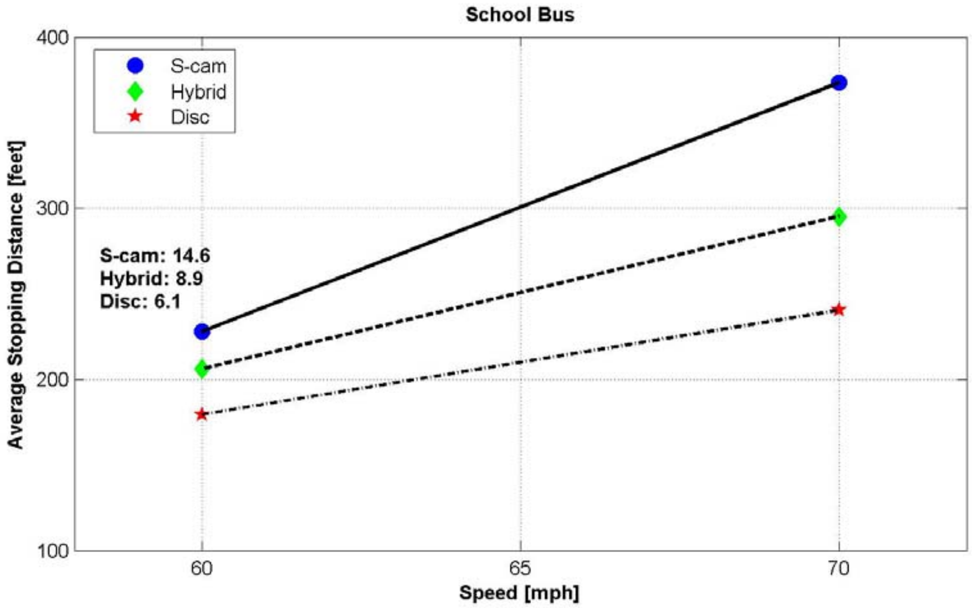


Figure 3.24. LLVW Stopping Distance Linear Regression for High-μ Stops From High Speeds for School Bus and Straight Truck

Note - Results for three brake configurations are shown. The slopes (in ft/mph) for each analysis are shown in the table on the graph.



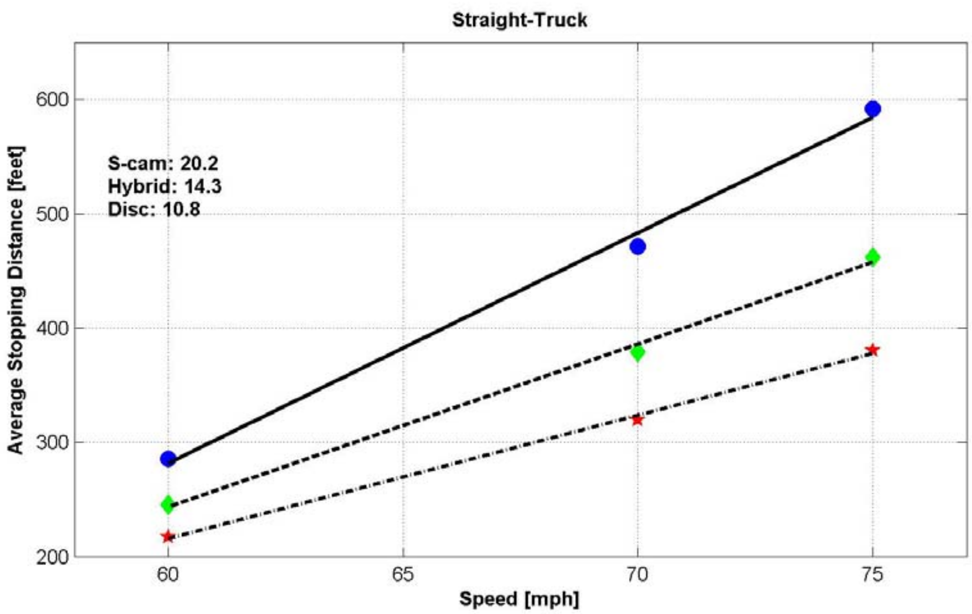


Figure 3.25. GVWR Stopping Distance Linear Regression for High--µ Stops From High Speeds for School Bus and Straight Truck

Comparison showed that the LLVW condition consistently produced lower slope values than the corresponding GVWR conditions.

At LLVW, both vehicles in the hybrid and disc configurations had similar slopes of approximately 6.0 – 6.5 ft/mph. This could be attributed to diminishing returns, where the performance of both vehicles was traction-limited due to lack of normal force (load) on the tires. Because of this, the ABS modulated earlier than if the vehicles were loaded to GVWR, and the output of the brakes was not used to its fullest capability.

The results from the vehicles in the hybrid configuration consistently had a lower slope than the corresponding vehicles equipped with S-Cam brakes – where a high slope indicated loss of effectiveness due to fade. The disc configuration consistently exhibited lower slope levels than the hybrid. These results led to the conclusion that as the braking abilities of the vehicles became more aggressive (i.e., brake torque capacity was increased), the stopping performance showed less adverse effect, due to higher entry speed. This conclusion was consistent with the brake dynamometer data presented in Zagorski and Dunn (2005).

Additional comparable reference information on panic stops from speeds other than 60 mph for truck tractors can be found in Garrott (2001).

4 Conclusions

Overall, two heavy commercial trucks stopped quicker and handled well when the standard S-cam brakes were changed to high-output disc or hybrid configuration brakes. The Class 7 school bus and Class 8 straight truck were both tested with three brake configurations (S-cam, hybrid, and disc), in two load conditions (GVWR and LLVW). Tests included standard service brake stops, brake-in-a-curve stability, parking brake holding, failed systems, and two exploratory research areas – split--µ stopping performance and stops from higher speeds.

Dry Braking Tests - Each vehicle-brake-load combination met the current FMVSS No. 121 stopping distance requirements from 60 mph. At GVWR, the margins of compliance were: disc 38 percent, hybrid 29 percent, and S-cam (baseline) 21 percent. ANOVA showed that *vehicle, brake,* and *load* each individually contributed significantly to stopping distance.

At LLVW, both vehicles exhibited shorter stopping distances with hybrid brakes (disc on steer axle/S-cam on rear axles). However, when disc brakes were also added to all axles (disc configuration); no further reduction in stopping distance was exhibited.

While disc used a little more air in the LLVW, the current FMVSS No. 121 reservoir volume specification appears to satisfy the volume of air demanded.

Wheel slip histograms revealed differences between the brake systems and should be incorporated into brake system modeling.

Brake-in-a-Curve Tests - Adding higher output brakes made little change in stability on the low-µ surface. After meeting the *target* speeds, each vehicle-brake-load configuration was subjected to additional *limit* speed handling tests (for research) to identify the boundary of stability. Each brake performed well above 82 percent LAPQ. These results correlate with those found for Class 8 tractors in Dunn, Hoover, and Zagorski (2005).

Split-µ Stopping Performance Tests - Higher output brakes improved the stopping distance on the split-µ without any change in stability. For stops from 30 mph, ANOVA revealed that, regardless of the vehicle-load-test direction combination, *brake* caused the primary differences in stopping distance. The slightly better stopping performance of the disc configuration appeared to be due to the mechanical design of the brakes. The smaller chamber size of air-disc brakes gave them the ability to recover faster in an ABS modulated stop.

Parking Brake Tests - With same size chambers, disc brakes provided the stronger holding capability of the parking brakes. Each vehicle-brake-load configuration “passed” the grade-hold tests. Drawbar force tests showed the straight truck disc consistently outperformed the S-cam, where the bus reversed this with S-cam somewhat outperforming the disc. However, the bus had smaller chambers on the disc than on the S-cam; where the straight truck used same size chambers for both S-cam and disc brakes.

In the research experiment, the SAE tests generally produced greater margins of compliance than the NHTSA tests. However, the SAE test required compounding the service brakes. In actual service, drivers typically apply the service brake somewhat just before applying the parking brake; but not always. The SAE procedure tests the full integrity of the complete brake system by requiring the parking brake to be applied over a full service brake application. This compounding caused the SAE outputs to be frequently higher than the NHTSA outputs for this test series. One limitation of the SAE procedure was the lack of a prescribed technique to confirm that no permanent deformation of the brake components occurred.

One possible improvement to the SAE test procedure would be to apply an initial service brake application, as long as the service brake pressure was limited to a point where the pin force did not exceed that measured with only the parking brake applied – for example 60 psi. This would allow the service brake to be applied to stop the vehicle where necessary and, with an active anti-compounding system functioning, the pushrod pin force would never exceed that experienced by just the spring brake application. Over-compounding would not be an issue. The outputs measured would track those of the NHTSA test, but would exercise all of the brake components in the more normal-use mode of the SAE test.

Failed Systems Tests - All configurations passed the Failed Primary Control Line and both Failed Reservoir Tests within the standard 613-foot stopping distance, with no stability issues. With the higher output brakes installed, the spring brake inversion valves continued to provide necessary braking assistance to the drive axle brakes, in the failed primary reservoir tests. The disc provided the largest margins of compliance for each of the 12 vehicle/failed system/load tests, except one.

Experimental Higher Speed Stopping Performance Tests - Additional stops performed from entry speeds of 60, 70, and 75 mph handled well, with no additional deviation from road center being caused by the higher speeds. Stopping performance was more adversely affected at GVWR than at LLVW. Of the three brake configurations, the all S-cam consistently saw reduced stopping performance due to increased entry speeds, and stops were quadratically longer due to fade. The hybrid and disc stopping distance increases were more subdued (more linear).

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