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Light and Medium Truck Hydraulic ABS Brake Performance Test:

Straight Line Stopping Performance On a High-Coefficient-of-Friction Surface

DISCLAIMER

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16. Abstract
This report summarizes findings of a small population study of light and medium trucks that are hydraulically braked and are required to meet FMVSS No. 105. The primary goal of these tests was to perform full service brake stops to determine how the stopping performance relates to the current FMVSS No. 105 requirements. Additional stops were added for each truck, from increased speeds, for research purposes. Two medium trucks (a 2001 Chevrolet K-3500 with "as-received" and new OEM brakes and tires and a 2004 Ford F-450) were tested under the 2nd and 3rd effectiveness procedures of FMVSS No. 105. One light truck (a Ford 2003 E-350 van) was tested under the 1st, 2nd, and 3rd effectiveness procedures of FMVSS No. 105.

For two loading conditions, each vehicle was tested in a straight-line stop (with full brake pedal application) on a dry, high-coefficient-of-friction surface. The initial vehicle speeds were 30, 60, and 70 mph. The standard 30- and 60-mph tests were each repeated six times, as required by FMVSS No. 105. The experimental 70-mph tests were repeated just twice, to identify baseline braking ability at increased initial braking speeds. Time history data was not logged. Stopping distance was measured using a Labeco fifth wheel. Individual brake temperatures and brake pedal force were monitored.

Each stop performed with the Chevrolet K-3500 (with both "as-received" and new OEM replacement brakes), the Ford F-450, and the Ford E-350, met the current stopping distance requirements of FMVSS No. 105. The 2nd and 3rd effectiveness procedures for the Chevrolet K-3500 and the Ford F-450 (GVWR and LLVW, respectively) showed similar patterns. Each 2nd effectiveness run of these vehicles produced a consistently smaller margin of compliance than each corresponding 3rd effectiveness run. The Ford F-450 at 60 mph had a consistently smaller margin of compliance than either configuration of the Chevrolet K-3500 at 60 mph. The Chevrolet K-3500, in the "as-received" configuration, had a slightly greater margin of compliance than it did with new OEM brakes and tires. For the "experimental" initial vehicle speed of 70 mph, at GVWR, the Ford E-350 - with the lightest test weight, had the longest average stopping distances, and the largest 95-percent confidence interval. Based on the constant deceleration method, the Ford E-350 exhibited an indication of fade when braked from an initial vehicle speed of 70 mph. The other vehicle brake configurations, from 70 mph, did not. Comparison showed that the mean stopping distances were generally within 4 percent of the minimum stopping distance for each test and initial speed.

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ABS Braking, Hydraulic Disc Brakes, Stopping Distance, FMVSS No. 105, Super Duty Ford F-450 Truck, Super Duty Ford E-350 Van, Heavy Duty Chevrolet K-3500 Truck

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

Approximate Conversions to English Measures

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

NOTE REGARDING COMPLIANCE WITH AMERICANS WITH DISABILITIES ACT SECTION 508

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

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EXECUTIVE SUMMARY

This report summarizes findings of a small population study of light and medium trucks that are hydraulically braked, and are required to meet FMVSS No. 105. The primary goal of these tests was to perform full service brake stops to determine how the stopping performance relates to the current FMVSS No. 105 requirements. The second goal was to explore the braking capabilities of existing vehicles at speeds greater than those of the current stopping distance requirements. Two medium trucks (a 2001 Chevrolet K-3500 with "as-received" and new OEM brakes and tires and a 2004 Ford F-450) were tested using the 2nd and 3rd effectiveness procedures of FMVSS No. 105. One light truck (a 2003 Ford E-350 van) was tested using the 1st, 2nd, and 3rd effectiveness procedure of FMVSS No. 105.

For two load conditions, each vehicle was tested with a straight-line stop (full brake pedal application) on a dry, high-coefficient-of-friction surface. The initial braking speeds tested were 30, 60, and 70 mph. The FMVSS No. 105 standard 30- and 60-mph tests were repeated six times each, but the experimental 70-mph tests were repeated just twice - to limit possible overheating of the brakes. Time history data was not taken. Initial braking speed and stopping distance were measured using a ground-contact fifth wheel. All measured stopping distances were corrected to the desired initial braking speeds, using the standard method as prescribed in SAE J299.[1] Individual brake temperatures and brake pedal forces were monitored. The driver was instructed to perform a full brake application stop without modulation of the pedal, within reasonable safety limits.

Data tables include measurements for both minimum stopping distance and calculated means. Graphical results are shown with histobars illustrating average stopping distance with 95-percent confidence intervals. Also shown are the current stopping distance requirements of FMVSS No. 105. The margins of compliance are shown for the minimum and average stopping distance with the current FMVSS No. 105 requirements in tabular format. A margin of compliance of 50 percent, for example, would correspond with the stopping distance being half of the requirement.

Each stop performed with the Chevrolet K-3500 (with both as-received and new OEM replacement brakes) and Ford F-450 (new vehicle) met the current stopping distance requirements of FMVSS No. 105. The 2nd and 3rd effectiveness procedures for the Chevrolet K-3500 and the Ford F-450 (GVWR and LLVW, respectively) showed similar patterns. Each 2nd effectiveness run of these vehicles had a consistently smaller margin of compliance than the corresponding 3rd effectiveness run. The Ford F-450 at 60 mph had a consistently smaller margin of compliance than either configuration of the Chevrolet K-3500 at 60 mph. The Chevrolet K-3500, in the "as-received" configuration, had a slightly greater margin of compliance than it did with new OEM brakes. The Ford E-350 met the current FMVSS No. 105 requirement for each test phase and initial speed. For an experimental initial braking speed of 70 mph (at GVWR), the Ford E-350 with the lightest test weight, had the longest average stopping distances, and the largest 95-percent confidence interval. Based on the constant deceleration method, the Ford E-350 exhibited an indication of fade from an initial vehicle speed of 70 mph. The other vehicle brake configurations from 70 mph did not. Comparison showed that the mean stopping distances were generally within 4 percent of the minimum stopping distance for each test and initial speed.

1.0 BACKGROUND AND OBJECTIVES

Currently, the FMVSS No's. 105 and 121 braking performance requirements (i.e., those used for medium- and heavy-duty trucks) allow for longer stopping distances than specified in FMVSS No. 135 (i.e., those used for passenger cars). It has been found that this discrepancy in stopping distance is one of the causes for truck-related fatalities in North America.[2] NHTSA believes that brake technology exists for large commercial vehicles that could reduce stopping distances by as much as 30 percent.[2] NHTSA's Vehicle Research and Test Center (VRTC) has performed extensive research on pneumatically-braked commercial vehicles, which fall under FMVSS No. 121.[3 4]

The primary goal of these tests was to perform full service brake stops for a small population of light and medium trucks to determine how the stopping performance relates to the current FMVSS No. 105 requirements. Each vehicle was equipped with ABS hydraulic brakes that fall within FMVSS No. 105. The study measured the stopping distance performance of vehicles configured with all-wheel disc brakes on a dry, high-coefficient-of-friction surface.

A second goal was to experimentally determine the effectiveness of the existing braking systems when pushed to higher initial braking speeds, such as 70 mph.

2.0 TEST VEHICLES

2.1 Description and Overview of the Three Trucks Tested

One light and two medium sized trucks were selected for the tests performed in this study. The light truck was a 2003 Ford E-350 XLT Super Duty Econoline passenger van, purchased by NHTSA for use in another program. The two medium trucks were: (1) a 2001 Chevrolet Silverado K-3500 and (2) a 2004 Ford F-450 XL Super Duty stake body truck. Both medium trucks had dual rear wheels and were leased vehicles. Each truck was configured with ABS modulated hydraulic disc brakes on all wheels. An overview of the test vehicles and descriptions of their respective brakes, tires, and ABS is listed in Tables 1 and 2.

To achieve their Gross Vehicle Weight Ratings (GVWR), the vehicles were loaded as follows:

- The Ford E-350 was loaded with 13 water dummies strapped to the seats and extra ballast strapped onto the floor.
- The Chevrolet K-3500 was loaded with sandbags in the bed to a height level with the top of the sides of the bed.
- The Ford F-450 was loaded with a single concrete ballast block elevated above the load deck on a one-foot pedestal. The concrete block weighed approximately 4,250 lbs.

For both the E350 and the K3500, ballast components were individually small, which enabled fine weight adjustment to nearly the exact GVWR. However, for the F-450, a large concrete block was used as ballast, so the exact GVWR weight was approximated. The FMVSS No. 105 requires a maximum or gross vehicle weight rating, but does not specify a tolerance about the limit. Since identical trucks, but which are equipped with air brakes, are allowed a GVWR tolerance of GVWR +0 percent to -2 percent in TP-121V. Therefore, that GVWR tolerance specification was applied here. Hence the 180-lb variance was -1.2 percent, which was within TP-121V specification for an equivalent weight truck (for the F-450). In each vehicle case, the ballast was positioned in a way that did not cause the front or rear Gross Axle Weight Ratings (GAWR) to be exceeded.

Table 1: Overview of Test Vehicles

Vehicle	2003 Ford E-350 XLT Super Duty Van	2001 Chevrolet Silverado K-3500	2004 Ford F-450 XL Super Duty
Mileage on Odometer When Acquired	895	10,564	89
Lightly Loaded Vehicle Weight-LLVW, lbs	6,580	7,280	10,140
Gross Vehicle Weight Rating-GVWR, lbs*	9,100 (9,100)	11,400 (11,390)**	15,000 (14,820)**
Wheelbase, inches	138	157.5	164.8
Track Width-Front/Rear, inches	69.4/67	68.6/74.7	68.7/74
CG Longitudinal Distance from Steer Axle C.L. (LLVW), inches	72.4	71.8	101.7
CG Longitudinal Distance from Steer Axle C.L. (GVWR), inches	88.5	91.6	106.5

*The actual gross (as tested) vehicle weight is listed in parentheses
**Due to logistics the exact GVWR of the vehicle was not achieved, however weight was within acceptable tolerance of GVWR +0%, -2%.

Table 2: Components: Brakes, Tires, and ABS

Vehicle	2003 Ford E-350 XLT Super Duty Van	2001 Chevrolet Silverado K-3500	2004 Ford F-450 XL Super Duty
ABS System	OEM; 4 wheel standard	OEM	OEM; 3S/3M with steer individual control
Steer Axle Tire	LT245/75R16E Goodyear Wrangler HT	LT215/85R16 M + S Goodyear Wrangler AT/S	225/70R19.5 General LMT
Drive Axle Tire	LT245/75R16E Goodyear Wrangler HT	LT215/85R16 M + S Goodyear Wrangler AT/S	225/70R19.5 General LMT
Steer Axle Brake Rotor	Motorcraft; Cast; Vented; YC2J-2C501-CA	AC Delco Vented; 12.795 in x 1.490 in	OEM; Vented Center; 14.5 in x 1.5 in; F81Z-1125-AB
Drive Axle Brake Rotor	Motorcraft; Cast; Vented; YC2Z-1V125-BA	AC Delco Vented 12.795 in x 1.184 in	OEM; Vented Center; 14.5 in x 1.5 in; F81Z-2CO26-AA
Steer Axle Brake Pads	Motorcraft; Lining code: MPV-2000-EE	AC Delco; Block 1: AKNS161H; Block 2: EF12243	OEM; BR-1269
Drive Axle Brake Pads	Motorcraft; Lining code: MPV-2000-EE	AC Delco - Block 1: AKNS161H; Block 2: EF27181, EF26211, EF2Y064, EF2Y071	OEM; BRS-24

2.2 Test Conditions and Procedures

The primary goal of the tests presented in this paper was to perform straight-line brake stops and compare their resulting stopping distances to the current FMVSS No. 105 requirements. The test procedure according to FMVSS No. 105 calls for the vehicle to undergo 1st, 2nd, 3rd, and 4th effectiveness tests. For research purposes, an experimental test was added to the matrix to determine the braking capabilities of the existing vehicles at increased initial braking speeds.

According to FMVSS No. 105, the 1st effectiveness test, which is performed at GVWR, calls for pre-burnish straight-ahead stops on a high-coefficient-of-friction (dry) surface. The 2nd effectiveness test is a repeat after the brakes have been burnished and with the vehicle loaded to GVWR. The 3rd effectiveness test is another repeat of the 2nd effectiveness test, only with the vehicle unloaded to LLVW. The 4th effectiveness, which is a set of brake stops with a partial failure in the system, was not performed on these vehicles.

The leased Chevrolet K-3500 was considered to have "as-received" brakes and tires, which were burnished through previous testing at VRTC; therefore, it did not go through the 1st effectiveness procedure. But, to comply with the testing procedure of using "new OEM" type components (as was used on the other vehicles in this program), a second test was run using new components. The new OEM brakes and tires for this vehicle were burnished before these tests. Both the "as-received" brakes and the new OEM brakes underwent the 2nd and 3rd effectiveness tests.

Since the Ford F-450 was a new vehicle, its brakes were subjected to the burnish procedure before the 2nd and 3rd effectiveness tests were run. For brevity, no pre-burnish tests were performed for the F-450 (i.e., 1st effectiveness).

As stated previously, the Ford E-350 was also an established NHTSA test vehicle. Since there was significant wear on the tires and brakes, and the conditioning was unknown, they were replaced with new OEM parts before testing. Following the 1st effectiveness procedure, the brakes were burnished. Then, the 2nd and 3rd effectiveness tests were performed.

After completing the compulsory panic stops from 30 and 60 mph, two experimental stops from 70 mph were run, to explore the braking capabilities of existing brakes beyond the current requirements of FMVSS No. 105. A list of the loading conditions and initial braking speeds for each vehicle configuration is shown in Table 3.

Table 3: Test Conditions

Vehicle	FMVSS No. 105 Test Phase	Initial Braking Speed, mph
Ford E-350	1st Effect (GVWR)	30
		60
	2nd Effect (GVWR)	30
		60
		70*
	3rd Effect (LLVW)	60
Chevrolet K-3500 (as received)	2nd Effect (GVWR)	60
	3rd Effect (LLVW)	60
Chevrolet K-3500 (new brakes & tires)	2nd Effect (GVWR)	60
		70*
	3rd Effect (LLVW)	60
		70*
F-450	2nd Effect (GVWR)	30
		60
		70*
	3rd Effect (LLVW)	60
		30

* The experimental stops from 70 mph are not required under FMVSS No. 105. They are for research purposes only.

Table 4 lists the minimum stopping distances required by FMVSS No. 105. Under FMVSS No. 105, the stopping distance requirement is dependent upon vehicle GVWR, initial speed and the testing phase (i.e., 1st, 2nd, 3rd, or 4th effectiveness). Stopping distance requirements for the Chevrolet K-3500 and Ford F-450, which have a GVWR greater than 10,000 lbs, are in a different category than the Ford E-350, which has a GVWR between 8,000 and 10,000 lbs, inclusively.

Table 4: FMVSS No. 105 Current Requirements

Vehicle	FMVSS No. 105 Test Phase	Initial Braking Speed, mph	Current Minimum Stopping Distance Requirements, feet
GVWR ≥ 8,000 lbs and ≤ 10,000 lbs	1st Effect (GVWR)	30	72
		60	267
	2nd Effect (GVWR)	30	57
		60	216
	3rd Effect (LLVW)	60	242
GVWR > 10,000 lbs	2nd Effect (GVWR)	30	78
		60	310
	3rd Effect (LLVW)	30	84
		60	335

Under each condition, the vehicle was tested with a straight-line stop performed on a dry, high-coefficient-of-friction surface. Since all vehicles had ABS-controlled brakes, the driver was instructed to perform a full brake application stop without modulation of the pedal, unless excessive brake lockup occurred.

Using a skid trailer, peak friction coefficients were measured between 0.99 and 1.02, and slide coefficients, between 0.80 and 0.87.

Time-history data were not taken. Vehicle speed and stopping distance were measured using a ground-contact fifth wheel. All measured stopping distances were corrected to the intended initial braking speed, using the standard method as prescribed by SAE J299.[1] Individual brake temperatures and brake pedal force were monitored by the driver during both burnish snubs and effectiveness stops.

3.0 TEST RESULTS

Results are presented two-fold. First, the minimum stopping distance of six stops initiated from a speed of 30 and 60 mph (and the two stops from 70 mph) are presented in tabular format. Second, results are displayed graphically and in tabular format, including the calculated means of the six (or two) stop data sets. Note that the experimental 70-mph stops were performed for research purposes and are not requirements of FMVSS No. 105.

3.1 Minimum Stopping Distance Results

Currently, FMVSS No. 105 requires that a vehicle stop shorter than the maximum allowable stopping distance at least once in six stops. Table 5 lists the minimum stopping distances measured (of the compulsory six stops) and their respective margins of compliance with the current FMVSS No. 105 standard. The percent margin of compliance (%MC) is calculated using the following equation:

$$\%MC = \frac{SD_{105} - SD}{SD_{105}} \times 100 \qquad (1)$$

where SD_{105} is the current FMVSS No. 105 stopping distance requirement and SD is the minimum of the six test stops.

Additionally, data for the experimental 70-mph tests are included in Table 5, for comparison to the standard minimum stopping distances at 30 and 60 mph. Since no standard exists for these 70-mph stops, no margins were calculated (the table cells are listed as “does not apply” or ”DNA”).

Table 5: Minimum Vehicle Stopping Distances for All Tests and Margins of Compliance With Current FMVSS No. 105 for Required Stops From 30 and 60 mph

Vehicle	FMVSS No. 105 Test Phase	Initial Braking Speed, mph	Minimum Stopping Distance, feet	%Margin of Compliance
Ford E-350	1st Effect (GVWR)	30	50.5	29.9
		60	198.0	25.8
	2nd Effect (GVWR)	30	48.3	15.3
		60	193.9	10.2
		70*	286.4	DNA
	3rd Effect (LLVW)	60	153.8	36.4
Chevrolet K-3500 (as received)	2nd Effect (GVWR)	60	160.5	48.2
	3rd Effect (LLVW)	60	153.3	54.2
Chevrolet K-3500 (new brakes & tires)	2nd Effect (GVWR)	60	172.1	44.5
		70*	241.0	DNA
	3rd Effect (LLVW)	60	154.3	53.9
		70*	214.0	DNA
F-450	2nd Effect (GVWR)	30	45.7	41.4
		60	183.5	40.8
		70*	254.3	DNA
	3rd Effect (LLVW)	60	153.8	54.1
		30	43.4	48.3

*The experimental stops from 70 mph are not required under FMVSS No. 105. They are for research purposes only.
DNA = does not apply, here.

3.2 Mean Stopping Distance Results

To establish a more reliable prediction of the performance that can be expected from a particular population, the mean is considered in the following results. Average stopping distances are listed in Table 6, along with the respective margins of compliance with the current FMVSS No. 105 standard for the 30- and 60-mph stops. As with the minimum stopping distance results, the percent margin of compliance (%MC) is calculated using Equation 1 (however the mean stopping distance is now used instead of the minimum stopping distance for SD in Equation 1).

Table 6: Mean Vehicle Stopping Distances and Margins of Compliance With Current FMVSS No. 105

Vehicle	Test Phase	Initial Speed, mph	Mean Stopping Distance, feet	%Margin of Compliance
Ford E-350	1st Effect (GVWR)	30	51.6	28.3
		60	203.4	23.8
	2nd Effect (GVWR)	30	49.3	13.5
		60	196.4	9.1
		70*	294.1	DNA
	3rd Effect (LLVW)	60	157.5	34.9
Chevrolet K-3500 (as received)	2nd Effect (GVWR)	60	165.8	46.5
	3rd Effect (LLVW)	60	154.9	53.8
Chevrolet K-3500 (new brakes & tires)	2nd Effect (GVWR)	60	177.9	42.6
		70*	241.1	DNA
	3rd Effect (LLVW)	60	159.6	52.4
		70*	216.4	DNA
F-450	2nd Effect (GVWR)	30	47.5	39.1
		60	192.9	37.8
		70*	255.0	DNA
	3rd Effect (LLVW)	60	160.4	52.1
		30	45.2	46.2

*The experimental stops from 70 mph are not required under FMVSS No. 105. They are for research purposes only.
DNA = does not apply, here.

Mean stopping distance results are displayed in Figures 1-5. Results are grouped by vehicle and initial braking speed. Histobars illustrate average stopping distances and are shown with error bars representing 95-percent confidence intervals. Current FMVSS No. 105 requirements are shown. For brevity, test categories are combined in Figures 1-5. As previously mentioned, the Chevrolet K-3500 and Ford F-450 were only tested with the 2nd and 3rd effectiveness procedures. Therefore, the 2nd effectiveness results are provided in the GVWR graphs (Figures 2 and 4) and the 3rd effectiveness are provided in the LLVW graphs (Figures 1 and 3). Table 7 in the appendix has a detailed data list of the mean, minimum, maximum, standard deviation, 95-percent confidence intervals and the current, FMVSS No. 105 requirements for each set of tests.

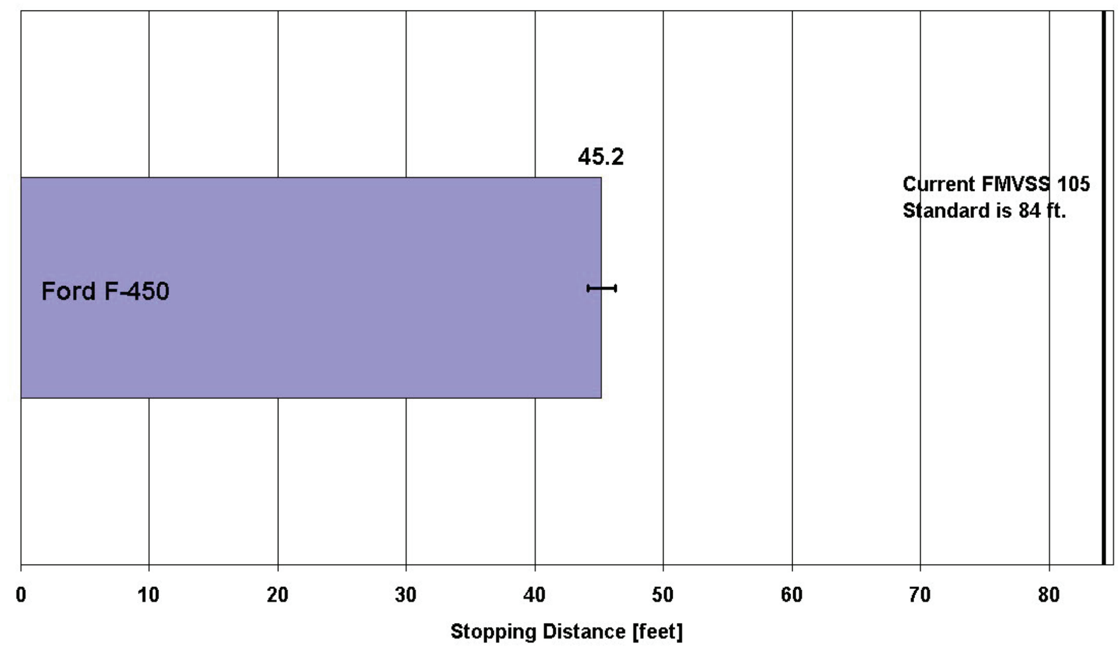

Figure 1: Average stopping distance comparison for the Ford F-450 at LLVW (3rd Effectiveness) condition from an initial speed of 30 mph. 95-percent confidence intervals are plotted at the end of the histobar. Current FMVSS No. 105 requirement is shown. The numeric label is the mean of six stops.

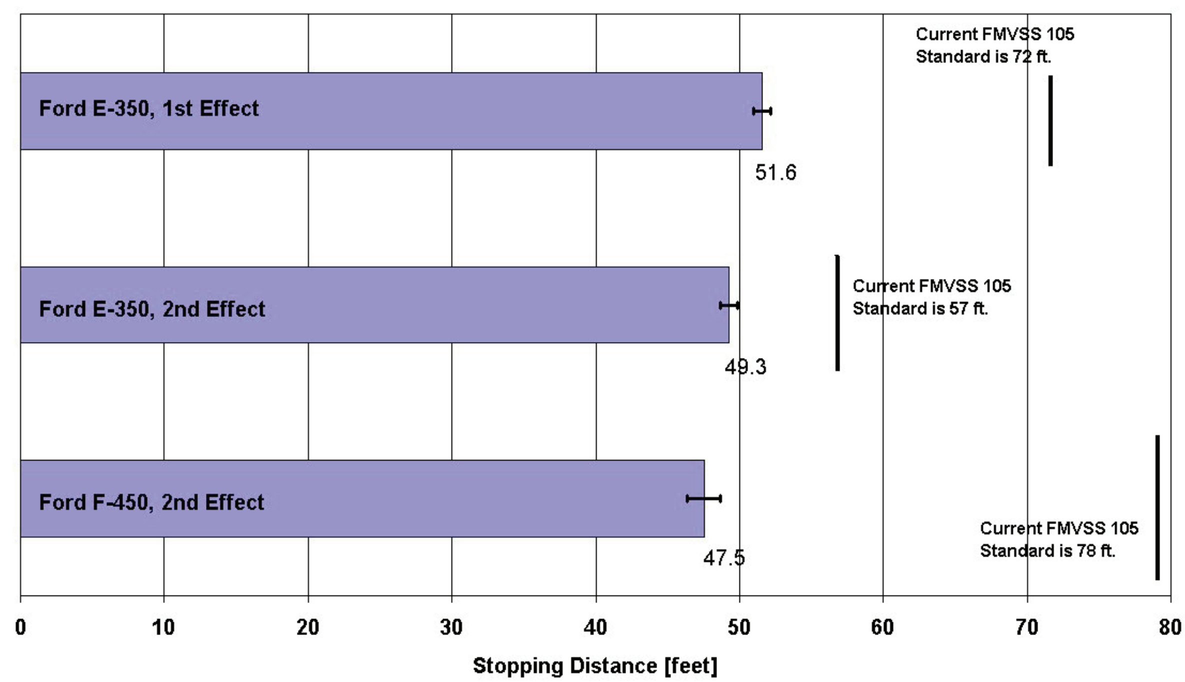

Figure 2: Average stopping distance comparison for vehicles at GVWR condition from an initial speed of 30 mph. 95-percent confidence intervals for all observations are plotted at the end of the histobars. Current FMVSS No. 105 requirements are shown. Numeric labels are the means of six stops.

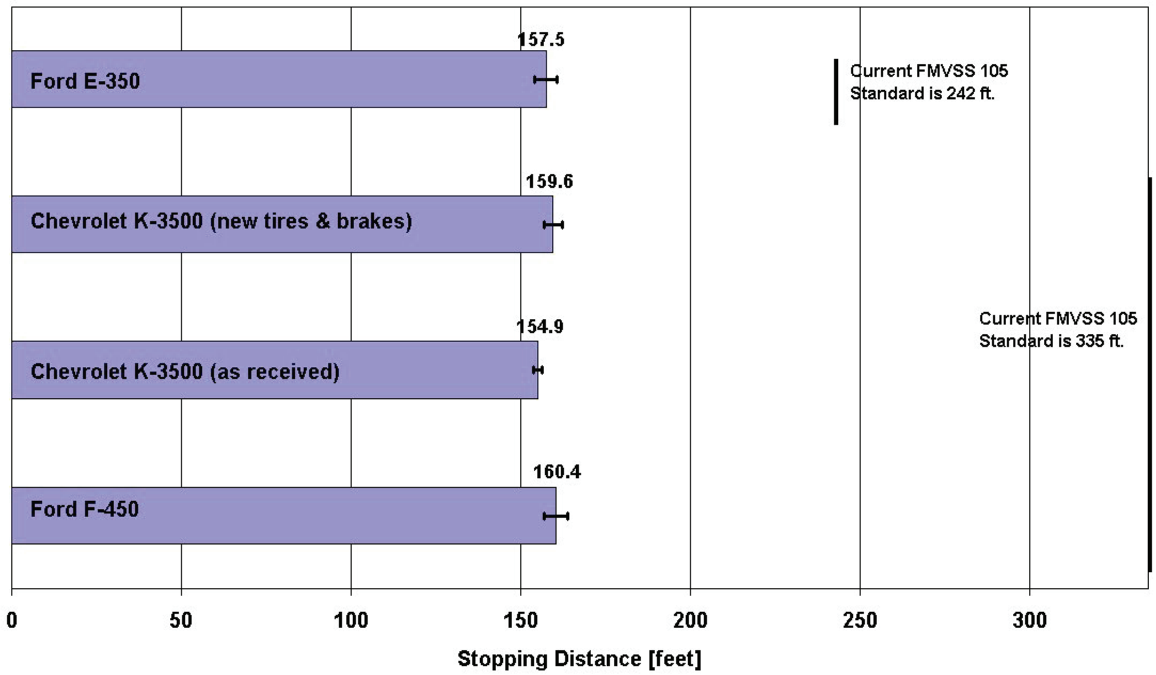

Figure 3: Average stopping distance comparison for vehicles at LLVW (3rd Effectiveness) condition from an initial speed of 60 mph. 95-percent confidence intervals for all observations are plotted at the end of the histobars. Current FMVSS No. 105 requirements are shown. Numeric labels are the means of six stops.

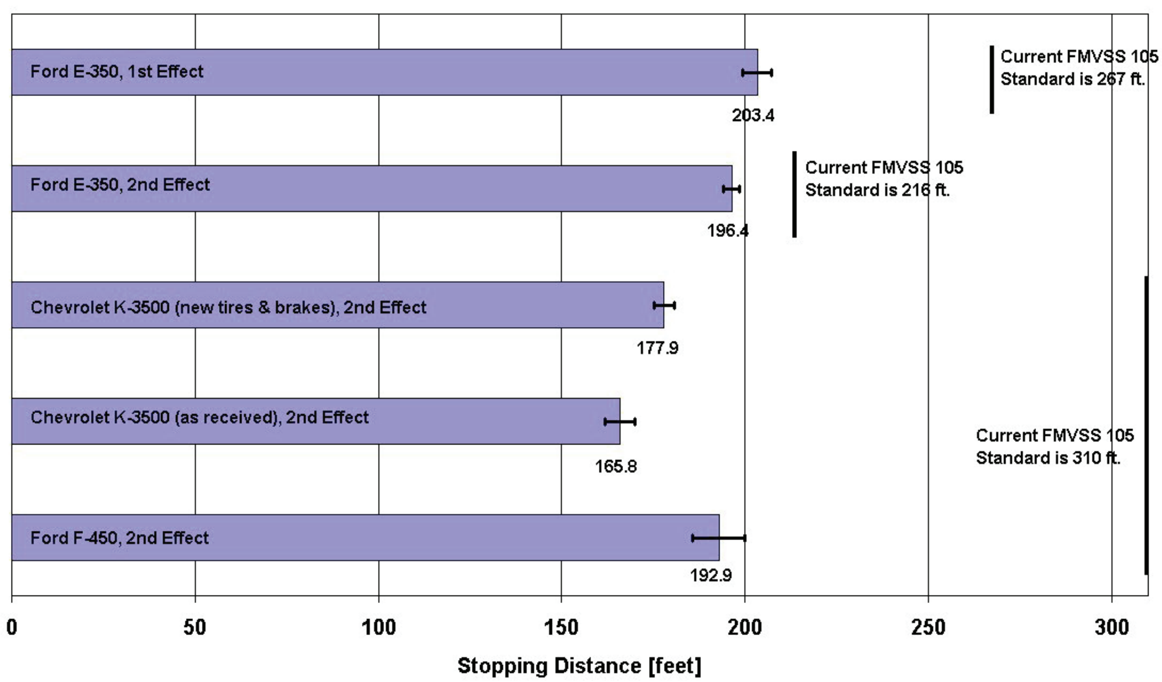

Figure 4: Average stopping distance comparison for vehicles at GVWR condition from an initial speed of 60 mph. 95-percent confidence intervals for all observations are plotted at the end of the histobars. Current FMVSS No. 105 requirements are shown. Numeric labels are the means of six stops.

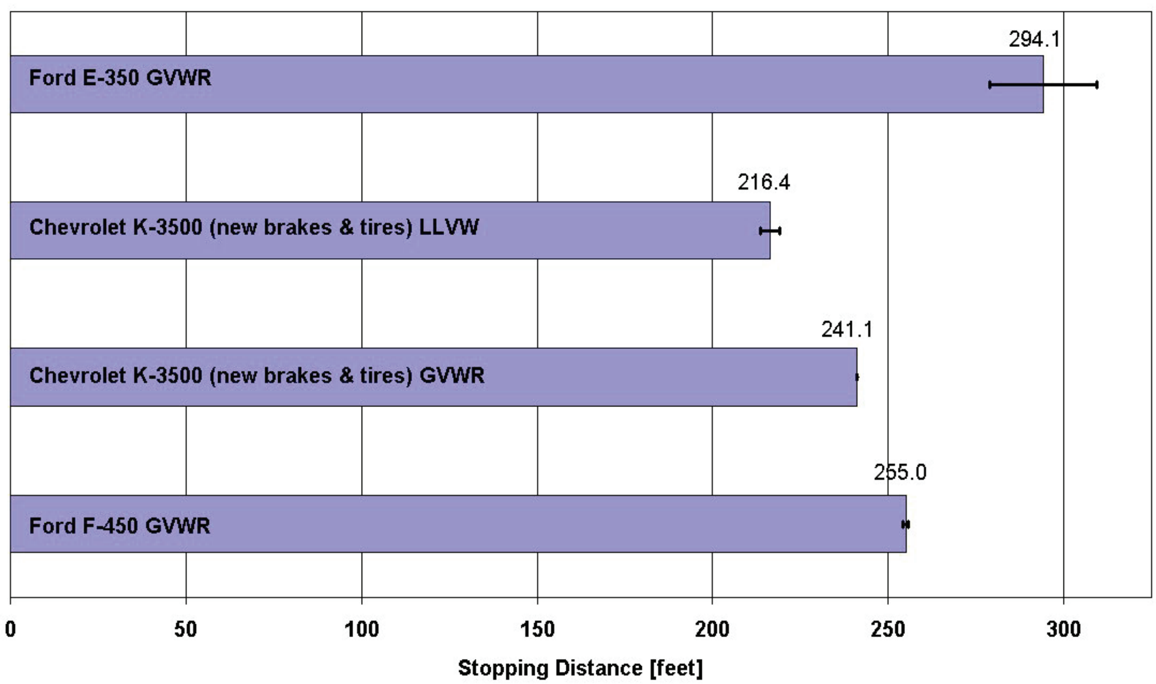

Figure 5: Average stopping distance comparison for vehicles from an "experimental" initial braking speed of 70 mph. 95-percent confidence intervals for all observations are plotted at the end of the histobars. Numeric labels on the bars are the means of two stops. Note: there are no current stopping distance requirements for stops from initial braking speeds of 70 mph. These 70-mph stops were performed for research purposes only.

4.0 DISCUSSION AND CONCLUSIONS

This chapter discusses where the vehicles used in this study rank with respect to the current FMVSS No. 105 requirements. First, conclusions are made based on the shortest stop observed during six stops. Currently, FMVSS No. 105 requires a vehicle to stop shorter than the maximum allowable distance at least once within six stops. Second, conclusions are made based on a mean of six standard stops initiated at 30 and 60 mph (and two experimental stops from 70 mph). As previously stated, the mean is considered to be a more reliable prediction of the performance that can be expected from a particular population if the brakes are fully burnished prior to the first stop.

4.1 Minimum Stopping Distance Requirements

Based on Table 5, the Ford E-350, the Chevrolet K-3500 (as-received and with new OEM brakes and tires), and the Ford F-450, met the current FMVSS No. 105 requirements for each test phase and initial speed.

Comparison of Tables 5 and 6 shows that the mean stopping distance is generally within 4 percent of the minimum stopping distance for standard tests. Because of this relatively small difference, using the mean stopping distance does not change the results or rankings. The close groupings are largely the result of these trucks being equipped with ABS and the brakes being in a fully burnished condition at the start of the testing. It should be noted that FMVSS No. 105 is written to accommodate vehicles with or without ABS.[5] For vehicles without ABS there may be larger differences between mean and minimum stopping distances due to dispersion in the data collected.

4.2 Further Technical Discussion with Mean Stopping Distance

Observation of Figures 1-4 and the margins of compliance in Table 6, reveal that each stop, made with the Ford E-350, the Chevrolet K-3500 (as-received and with new OEM brakes and tires) and the Ford F-450, met the current FMVSS No. 105 requirements.

In general, vehicles with a heavier load condition have longer stopping distances.[3 6] Currently, in FMVSS No. 105, light and medium trucks with a GVWR of 8,000 lbs or greater, under a LLVW (3rd effectiveness) condition, are permitted to have longer stopping distances than under a GVWR (2nd effectiveness) load condition. Because of this, the means of the GVWR runs (for the Chevrolet K-3500 and Ford F-450) had consistently smaller margins of compliance than did each of the respective LLVW runs (see Table 6).

When the vehicles' 60-mph stops are considered, comparison shows that the Ford F-450 had a consistently smaller margin of compliance than either of the Chevrolet K-3500 brake configurations. For example, at GVWR, the Ford F-450 had a 37.8-percent margin of compliance, whereas the Chevrolet K-3500 (as-received and with new OEM brakes) had a 46.5-percent and 42.6-percent margin of compliance, respectively.

Comparing the two configurations for the Chevrolet K-3500, the "as-received" condition had a slightly greater margin of compliance than it did with new OEM brakes (properly burnished per FMVSS No. 105) and new tires. The differences were 1.3 percent and 3.9 percent for LLVW and GVWR configured vehicles, respectively (Table 6). The stopping distance results are statistically similar for both brake configurations in the LLVW condition, whereas the results are statistically different in the GVWR configuration with the "as-received" being shorter (Figures 3 and 4). The reasons for this difference are not known.

Figure 5 displays the experimental results from the stops with an initial maneuver entrance speed of 70 mph. As previously mentioned, FMVSS No. 105 limits are not shown because 70 mph is not an initial speed requirement under the current standard. Of the stops at GVWR, the Ford E-350 had the lightest test weight (9,100 lbs), but the longest average stopping distance. Of the three vehicles, at an initial speed of 70 mph, the Ford E-350 also had the largest 95-percent confidence interval.

An indication of fade can be found by projecting the 70-mph stopping distance from 60 mph (by using constant deceleration theory) by multiplying by the ratio of $(70)^2/(60)^2$. A stopping distance greater than the projected may indicate that the brakes are exhibiting fade during the stop. The Ford E-350 had a greater stopping distance, 294.1 ft (Table 6 and Figure 5), than the projected stopping distance of 267.3 ft. Although brake temperatures were not recorded, the authors believe that brake fade is primarily responsible for this discrepancy. The other vehicle brake configurations exhibited stopping distances shorter than those projected. Their projected 70-mph stopping distances from 60 mph were 242.1 ft, 217.2 ft and 262.6 ft for the Chevrolet K-3500 (2nd effectiveness), the Chevrolet K-3500 (3rd Effectiveness) and the Ford F-450 (3rd Effectiveness), respectively. Therefore, brake fade does not appear to be occurring during a 70-mph stop for these two medium trucks.

The authors recommend that a follow-up study be conducted to identify the population distribution and performance of all-drum, drum/disc combination, and all-disc brakes on current production single unit trucks (SUTs).

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APPENDIX

Table 7: Raw Data for Figures 1-5. All Data Points Used in the Previous Figures.

Vehicle	FMVSS No. 105 Test Phase	Initial Braking Speed, mph	Stopping Distance, feet					Current FMVSS No. 105 Minimum Stopping Distance Requirement, feet
			Min	max	mean	standard deviation	95% C.I.	
Ford E-350	1st Effect (GVWR)	30	50.5	52.7	51.6	0.73	0.59	72
		60	198.0	211.3	203.4	4.88	3.90	267
	2nd Effect (GVWR)	30	48.3	50.3	49.3	0.71	0.57	57
		60	193.9	200.8	196.4	2.69	2.15	216
		70	286.4	301.9	294.1	10.96	15.19	DNA
	3rd Effect (LLVW)	60	153.8	164.9	157.5	4.07	3.26	242
Chevrolet K-3500 (as received)	2nd Effect (GVWR)	60	160.5	174.7	165.8	5.12	4.10	310
	3rd Effect (LLVW)	60	153.3	157.7	154.9	1.55	1.24	335
Chevrolet K-3500 (new brakes & tires)	2nd Effect (GVWR)	60	172.1	181.6	177.9	3.43	2.75	310
		70	241.0	241.1	241.1	0.04	0.04	DNA
	3rd Effect (LLVW)	60	154.3	163.3	159.6	3.26	2.61	335
		70	214.0	218.8	216.4	3.42	2.73	DNA
Ford F-450	2nd Effect (GVWR)	30	45.7	49.7	47.5	1.45	1.16	78
		60	183.5	203.5	192.9	8.85	7.08	310
		70	254.3	255.7	255.0	0.97	0.77	DNA
	3rd Effect (LLVW)	60	153.8	165.0	160.4	4.35	3.48	335
		30	43.4	46.8	45.2	1.33	1.06	84

*The experimental stops from 70 mph are not required under FMVSS No. 105. They are for research purposes only.
DNA = does not apply, here.

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