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Experimental Measurement of The Stopping Performance of A Tractor-Semitrailer From Multiple Speeds

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16. Abstract

On July 27, 2009, the National Highway Traffic Administration (NHTSA) published a final rule reducing the maximum allowable truck tractor stopping distances from 60 mph. FMVSS No. 121 also contains maximum allowable stopping distances for vehicles that cannot attain a speed of 60 mph in two miles. In this case, a vehicle is tested from an initial speed four to eight mph less than the maximum attainable speed.

NHTSA received a petition for reconsideration of the July 27, 2009 final rule requesting that the agency revise the table of stopping distances for those truck tractors that cannot attain an initial test speed of 60 mph. The objective of this research was to obtain data on the stopping performance of one truck tractor-semitrailer combination vehicle from a range of initial speeds. The truck tractor tested was a 1991 Volvo 6x4 tractor towing a 28 foot long, unbraked control trailer. A decision was made to modify the loading from the normal FMVSS No. 121 loaded condition. The loading was changed such that the 60 mph stopping distance specified in FMVSS No. 121 was just achieved (the Modified Gross Vehicle Weight Rating (MGVWR) loading). This vehicle was also tested at its Lightly Loaded Vehicle Weight (LLVW).

For MGVWR loading, as initial speed is decreased from 60 mph, average measured corrected stopping distance drops faster than maximum permitted stopping distance until an initial speed of 35 mph is reached. The MGVWR vehicle had its largest margin of compliance at 35 mph. As initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. The MGVWR vehicle had a negative margin of compliance at an initial speed of 20 mph. The maximum permitted stopping distance for the LLVW vehicle is greater than average measured corrected stopping distance for all initial speeds. The LLVW vehicle had its smallest (though still positive) margin of compliance at an initial speed of 20 mph.

Average MGVWR and LLVW deceleration rise times, 0.43 and 0.30 seconds, respectively, are both less than the 0.45 second rise time that was used to calculate the maximum permitted stopping distances in FMVSS No. 121.

Actual measured steady state deceleration is greater than FMVSS No. 121 assumed deceleration for the MGVWR loading condition for all initial speeds. This is surprising since actual measured corrected stopping distance exceeds maximum permitted stopping distance at an initial speed of 20 mph. This indicates possible discrepancies between the idealized deceleration shape used to calculate the FMVSS No. 121 values and the actual deceleration shape. The actual measured steady state deceleration is substantially greater than the FMVSS No. 121 assumed deceleration for the LLVW loading condition for all initial speeds.

The equation FMVSS No. 121 uses to calculate maximum permitted stopping distances for initial speed below 60 mph was used to calculate steady state vehicle decelerations. The measured steady state decelerations are consistently higher than the steady state decelerations calculated using the FMVSS No. 121 equation. The magnitude of the difference increases with decreasing initial speed. The reasons for the difference between the two steady state decelerations are not known. Also, it is not known which of these methods provides the best estimate for steady state deceleration. In terms of the overall goal of this research, it probably does not matter which estimate of steady state deceleration is best. At an initial speed of 20 mph, measured average corrected stopping distance for the MGVWR loading exceeded the maximum stopping distance permitted by FMVSS No. 121.

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CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
PRESSURE				
psi	pounds per inch^2	0.07	bar	bar
psi	pounds per inch^2	6.89	kilopascals	kPa
VELOCITY				
mph	miles per hour	1.61	kilometers per hour	km/h
ACCELERATION				
ft/s^2	feet per second^2	0.30	meters per second^2	m/s^2
TEMPERATURE (exact)				
°F	Fahrenheit	5/9[(Fahrenheit) - 32°F]	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 THE AMERICANS WITH DISABILITIES ACT, SECTION 508

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

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Executive Summary

On July 27, 2009, the National Highway Traffic Administration (NHTSA) published a final rule amending Federal Motor Vehicle Safety Standard (FMVSS) No. 121, Air Brake Systems, to require improved stopping distance performance for truck tractors. This rule reduced the maximum allowable stopping distance in the loaded to Gross Vehicle Weight Rating (GVWR) condition, for an initial vehicle speed of 60 mph, from 355 feet to 250 feet for "normal duty" truck tractors ("normal duty" truck tractors are two- or three-axle truck tractors with a GVWR of 70,000 pounds or less, and truck tractors with four or more axles and a GVWR of 85,000 pounds or less; these are the type of tractors examined in this report). For all truck tractors, the maximum allowable stopping distance in the unloaded condition, for an initial vehicle speed of 60 mph, was reduced from 335 feet to 235 feet.

FMVSS No. 121 also contains maximum allowable stopping distances for vehicles that cannot attain a speed of 60 mph in two miles of driving on a flat, level roadway. If a vehicle cannot attain a speed of 60 mph, it is tested to ensure that it can meet the maximum permitted stopping distance requirement from an initial speed that is four to eight mph less than the maximum speed that is attainable.

On September 10, 2009, NHTSA received a petition for reconsideration of the July 27, 2009 final rule from the Truck Manufacturers Association (TMA). In this petition, TMA states that NHTSA "did not conduct any testing at reduced speeds... [o]nly tests from an initial speed of 60 mph were conducted."[1] Also, TMA states that "the rulemaking record does not include any data to validate the equation used to derive the reduced speed stopping distance requirements in the final rule."[2]

The objective of this research was to obtain data on the stopping performance of one truck tractor-semitrailer combination vehicle from a range of initial speeds. The truck tractor tested was a 1991 Volvo 6x4 tractor towing a 28 foot long, unbraked control trailer. Vehicle testing was performed in accordance with the Office of Vehicle Safety Compliance Laboratory Test Procedure No. TP-121V-04.

Since only one truck tractor was tested, a decision was made to modify its loading from its normal FMVSS No. 121 Loaded-to-GVWR condition. The loading was changed to a value such that the 60 mph stopping distance specified in FMVSS No. 121 was just achieved (the Modified Gross Vehicle Weight Rating (MGVWR) loading). It is the authors' belief that by loading this vehicle so as to just achieve the 60 mph stopping distance specified in FMVSS No. 121, test results would provide greater insight into the appropriateness of stopping distance values from other vehicle initial speeds that are in FMVSS No. 121. As per FMVSS No. 121, this vehicle was also tested at its Lightly Loaded Vehicle Weight (LLVW).

For the MGVWR loading condition, as initial speed decreased from 60 mph, average measured corrected stopping distance drops faster than maximum permitted stopping distance until an initial speed of 35 mph is reached. The MGVWR vehicle had the largest margin of compliance at an initial speed of 35 mph. As the initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. The MGVWR vehicle had a negative margin of compliance at an initial speed of 20 mph.

[1] US Department of Transportation Docket Document NHTSA-2009-0083-0005, posted 9/17/2009.
[2] Ibid

The maximum permitted stopping distance according to FMVSS No. 121 for the LLVW vehicle is greater than average measured corrected stopping distance for all initial speeds. As initial speed decreased from 60 mph, average measured corrected stopping distance drops at the same rate as maximum permitted stopping distance until an initial speed of 35 mph is reached. The LLVW vehicle had a fairly constant (between 22.0 and 24.8 percent) margin of compliance for initial speeds from 60 to 35 mph. As initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. The LLVW vehicle had its smallest (though still positive) margin of compliance at an initial speed of 20 mph.

The average MGVWR and LLVW deceleration rise times, 0.43 and 0.30 seconds, respectively, are both less than the 0.45 second rise time that was used to calculate the maximum permitted stopping distances in FMVSS No. 121. Assuming a 0.45 second deceleration rise is, therefore, conservative.

Actual measured steady state deceleration is greater than FMVSS No. 121 assumed deceleration for the MGVWR loading condition for all initial speeds. This is surprising since actual measured corrected stopping distance equals maximum permitted stopping distance at an initial speed of 60 mph and exceeds maximum permitted stopping distance at an initial speed of 20 mph. This indicates possible discrepancies between the idealized deceleration shape used to calculate the FMVSS No. 121 values and the actual deceleration shape.

Actual measured steady state deceleration is substantially greater than FMVSS No. 121 assumed deceleration for the LLVW loading condition for all initial speeds. However, in violation of the FMVSS No. 121 assumptions, there is a rapid decrease of steady state deceleration with initial speed for initial speeds below 35 mph.

The equation FMVSS No. 121 uses to calculate maximum permitted stopping distances for initial speed below 60 mph contains four parameters. If values for any three of these parameters are specified, then the corresponding value of the fourth parameter can be calculated. Experimentally measured values of Total Stopping Distance, Vehicle Initial Speed, and Deceleration Rise Time were specified and corresponding Steady State Vehicle Deceleration calculated.

Measured steady state decelerations, as determined by numerically differentiating the speed channel and then averaging the resulting channel from completion of deceleration rise time until end of stop time, are consistently higher than steady state decelerations calculated using the FMVSS No. 121 equation. This difference increases with decreasing initial speed. Reasons for this difference are not known. Also, it is not known which of these methods provides the best estimate for steady state deceleration.

In terms of the overall goal of this research, it probably does not matter which estimate of steady state deceleration is best. At an initial speed of 20 mph, measured average corrected stopping distance for the MGVWR loading exceeded the maximum stopping distance permitted by FMVSS No. 121.

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Brad Bean

1.0 Introduction and Research Objectives

1.1 The Current Version of FMVSS No. 121 Air Brake Systems

On July 27, 2009, the National Highway Traffic Administration (NHTSA) published a final rule in the Federal Register[3] amending Federal Motor Vehicle Safety Standard (FMVSS) No. 121, Air Brake Systems, to require improved stopping distance performance for truck tractors. This rule reduced the maximum allowable stopping distance in the loaded to Gross Vehicle Weight Rating (GVWR) condition, for an initial speed of 60 mph, from 355 feet to 250 feet for the vast majority of truck tractors (two- and three-axle truck tractors with a GVWR of 70,000 pounds or less, and truck tractors with four or more axles and a GVWR of 85,000 pounds or less). For a small minority of truck tractors (three-axle truck tractors with a GVWR greater than 70,000 pounds, and truck tractors with four or more axles and a GVWR greater than 85,000 pounds), the maximum allowable stopping distance in the GVWR loading condition, for an initial speed of 60 mph, was reduced from 355 feet to 310 feet. For all truck tractors, the maximum allowable stopping distance in the unloaded condition, for an initial speed of 60 mph, was reduced from 335 feet to 235 feet.

This report will focus on the braking performance of the vast majority of truck tractors, i.e., two- and three-axle truck tractors with a GVWR of 70,000 pounds or less, and truck tractors with four or more axles and a GVWR of 85,000 pounds or less. These will be referred to in the remainder of this report as “normal duty” truck tractors (as compared to “severe duty” truck tractors, i.e., those three-axle truck tractors with a GVWR greater than 70,000 pounds, and truck tractors with four or more axles and a GVWR greater than 85,000 pounds).

FMVSS No. 121 also contains maximum allowable stopping distances for vehicles that cannot attain a speed of 60 mph in two miles of driving on a flat, level roadway. If a vehicle cannot attain a speed of 60 mph, it is tested to ensure that it can meet the maximum permitted stopping distance requirement from an initial speed that is four to eight mph less than the maximum speed that is attainable. The rightmost column of Table 1 lists maximum permissible stopping distances for normal duty truck tractors in the GVWR loading condition. Similarly, the rightmost column of Table 2 lists maximum permissible stopping distances for both normal duty and severe duty truck tractors in the unloaded condition.

Note that FMVSS No. 121 does not apply to “any truck or bus that has a speed attainable in 2 miles of not more than 33 mph.”[4] Therefore, although Tables 1 and 2 include both 25 and 20 mph Vehicle Initial Speed rows, these rows cannot be used by any vehicles currently covered by FMVSS No. 121. (Since compliance testing is performed from an initial speed that is four to eight mph less than the maximum speed that is attainable in two miles of driving, the 30 mph Vehicle Initial Speed row could conceivably be used.)

The maximum permissible stopping distances in Tables 1 and 2 were calculated using the equation:

$$S = \frac{1}{2} V_0 t_r + \frac{1}{2}\frac{V_0^2}{d_{ss}} - \frac{1}{24} d_{ss} t_r^2 \qquad \text{(Equation 1)}$$

Where

S = Total Stopping Distance in feet,

V_0 = Vehicle Initial Speed in feet per second,

[3] 74 FR 37122

[4] Federal Motor Vehicle Safety Standard No. 121; Air Brake Systems, S3 (c)

t_r = Deceleration Rise Time in seconds, and
d_{ss} = Steady State Vehicle Deceleration in feet per second squared.

Table 1: Maximum Permissible Stopping Distances at Various Speeds for Two- and Three-Axle Truck Tractors with a GVWR of 70,000 Pounds or Less, and Truck Tractors with Four or More Axles and a GVWR of 85,000 Pounds of Less, in the GVWR Loading Condition. Deceleration rise time is 0.45 seconds.

Vehicle Initial Speed		**Assumed Steady State Vehicle Deceleration**		**Maximum Permitted Stopping Distance from FMVSS No. 121**
(mph)	(ft/sec)	(ft/sec^2)	(g's)	(ft)
20	29.3	18.00	0.56	30.0
25	36.7	18.00	0.56	45.0
30	44.0	17.50	0.54	65.0
35	51.3	17.00	0.53	89.0
40	58.7	17.00	0.53	114.0
45	66.0	16.80	0.52	144.0
50	73.3	16.80	0.52	176.0
55	80.7	16.80	0.52	212.0
60	88.0	16.80	0.52	250.0

Table 2: Maximum Permissible Stopping Distances for Truck Tractors in the Unloaded Condition. Deceleration rise time is 0.45 seconds.

Vehicle Initial Speed		**Steady State Deceleration (Assumed Value)**		**Maximum Permitted Stopping Distance from FMVSS No. 121**
(mph)	(ft/sec)	(ft/sec^2)	(g's)	(ft)
20	29.3	19.80	0.61	28.0
25	36.7	19.40	0.60	43.0
30	44.0	18.80	0.58	61.0
35	51.3	18.10	0.56	84.0
40	58.7	18.10	0.56	108.0
45	66.0	17.95	0.56	136.0
50	73.3	17.95	0.56	166.0
55	80.7	17.95	0.56	199.0
60	88.0	17.95	0.56	235.0

When Equation 1 was used to calculate the maximum permitted stopping distances in Tables 1 and 2, the Acceleration Rise Time, t_r, is assumed to be equal to the maximum permitted air pressure rise time to 60 psi in the brake chambers (for a 100 psi brake application). As per S5.3.3.1 (a) of FMVSS No. 121, t_r is assumed to be equal to 0.45 seconds.

Also note that when Equation 1 was used to calculate maximum permitted stopping distances in Tables 1 and 2, all stopping distances were rounded to the nearest integer foot.

Equation 1 was developed from simple kinematics using the idealized deceleration versus time profile shown in Figure 1. As mentioned above, the Acceleration Rise Time, t_r, used to generate Tables 1 and 2 is always assumed to be 0.45 seconds. The Steady State Vehicle Deceleration , d_{ss}, varies according to both the Vehicle Initial Speed and the vehicle's loading condition. The third and fourth columns from the left hand side of Tables 1 and 2 contain the Steady State Vehicle Deceleration values that were assumed to generate the maximum permissible stopping distances for Loaded-to-GVWR and Unloaded truck tractors, respectively.

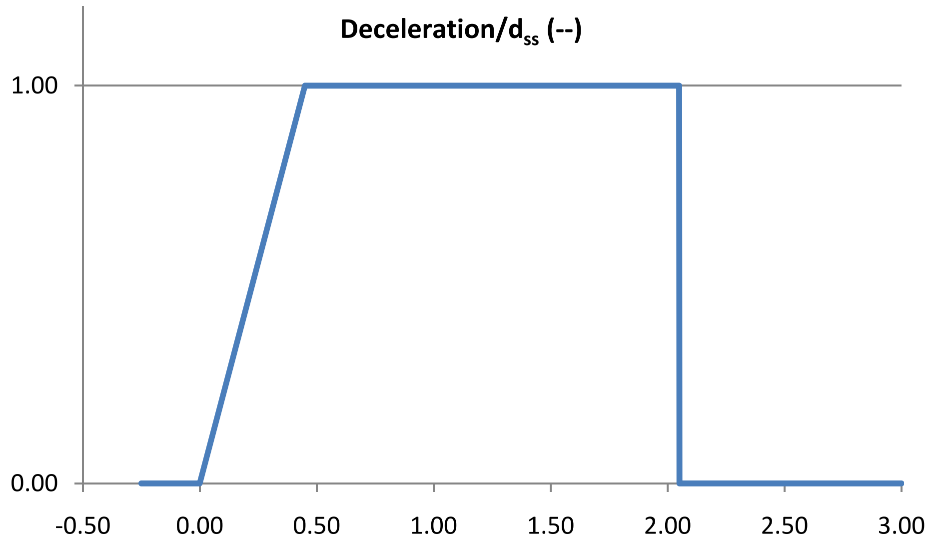

Figure 1: Assumed Vehicle Deceleration versus Time Profile for a Stop Taking 2.05 Seconds

1.2 Research Objective

On September 10, 2009, NHTSA received a petition for reconsideration of the July 27, 2009 final rule from the Truck Manufacturers Association (TMA)[5]. Section 3 of this petition for reconsideration reads as follows:

> "**3. The reduced speed stopping distance requirements are not supported by the rulemaking record.**
> The entire focus of this rulemaking, and of all the known testing to support it, involves stopping distances from 60 mph. In fact, there is no empirical data to support the practicability of, or the justification for, the new stopping distance requirements at initial test speeds 20 through 55 mph. The only analysis on the record is derived from an unproven, unverified mathematical equation that uses data from 60 mph stops to estimate stopping distances for the reduced speeds.
>
> In the preamble, NHTSA states that "we did not conduct any testing at reduced speeds... [o]nly tests from an initial speed of 60 mph were conducted at [NHTSA's Vehicle Research and Test Center]." Id. at 37149. Accordingly, the rulemaking record does not include any data to validate the equation used to derive the reduced speed stopping distance requirements in the final rule. This lack of data is due to the appropriate concentration, by both NHTSA and industry, on the 60 mph stopping distance requirements that would address the large majority of tractors produced.

[5] US Department of Transportation Docket Document NHTSA-2009-0083-0005, posted 9/17/2009

> TMA supports appropriate shortening of the reduced speed stopping distance requirements. However, we object to the requirements included in the final rule. Those reduced speed stopping distances may require the development of complicated and unique braking systems on tractors that, but for their speed being limited, are identical to vehicles for which the 60 mph stopping distances apply. NHTSA must withdraw the reduced speed stopping distance requirements until it has obtained appropriate test data supporting the new requirements for tractors with speeds less than 60 mph. TMA members are currently conducting such testing, and we are willing to provide that data to supplement the agency's testing."

The objective of this research was to obtain information that the agency could use to address TMA's concerns and either defend or revise the table of stopping distances for those truck tractors that cannot attain an initial test speed of 60 mph. `Specifically, this research tested one truck tractor for a range of initial speeds in both loaded and unloaded loading conditions.

Since only one truck tractor was tested, a decision was made to modify its loading from that used for normal FMVSS No. 121 testing in the Loaded-to-GVWR condition. The vehicle loading was changed from that specified in normal FMVSS No. 121 testing for Loaded-to-GVWR testing to a different loading (referred to as the MGVWR condition) such that the 60 mph stopping distance specified in Table 1 was just achieved. It is the authors' belief that by loading this vehicle so as to just achieve the specified 60 mph stopping distance, test results would give greater insight into the appropriateness of stopping distance values from other initial speeds that are in Table 1. Furthermore, direct comparisons of corrected stopping distances and steady state decelerations could be made.

Data collected during this testing were then analyzed; both to see how closely the experimentally measured stopping distance matched Equation 1 as a function of initial vehicle speed and to see how closely experimentally measured data matched the values contained in Tables 1 and 2.

2.0 Experimental Test Program

2.1 Test Plan

The test plan for this research consisted of the following steps:

1. Instrument test vehicle.
2. Burnish test vehicle's brakes.
3. Measure test vehicle brake timing.
4. Load test truck tractor with control trailer to GVWR as per FMVSS No. 121.
5. Perform six stops from as close to 60 mph initial speed as feasible. Calculate corrected stopping distance for each stop and average over all six stops.
6. Adjust test vehicle loading to bring average corrected stopping distance from all six stops closer to the target stopping distance of 250 feet.
7. Iterate Steps 5 and 6 as many times as needed to achieve an average corrected stopping distance of 250±1 feet. This established the Modified Gross Vehicle Weight Rating (MGVWR) loading condition used during this testing.
8. With the test vehicle loaded to the MGVWR condition, perform six stops from as close to each desired initial speed as feasible. Testing was performed at desired initial speeds of 55, 50, 45, 40, 35, 30, 25, 20, and 60 mph, in that order.
9. With the test vehicle in the unloaded (LLVW) condition, perform six stops from as close to each desired initial speed as feasible. Testing was performed at desired vehicle initial speeds of 60, 55, 50, 45, 40, 35, 30, 25, 20, and 60 mph, in that order.
10. With the completion of Step 9, testing for this research was complete. All instrumentation was removed from the test vehicle.

Vehicle testing was performed in accordance with the Office of Vehicle Safety Compliance Laboratory Test Procedure No. TP-121V-04. This Laboratory Test Procedure is based on FMVSS No. 121, Air Brake Systems (Code of Federal Regulations 49 CFR 571.121, 10-1-02 Edition). The sections of this procedure that were used included:

- Section 6. Test Track Requirements
- Section 7. Calibration of Test Instruments
- Section 8. Photographic Documentation
- Section 10.1 Verification of Required Equipment
- Section 10.3. Road Tests
- General Test Condition
- Test Sequence (49 CFR 571.121; S5.3.1)
  C. Burnish (49 CFR 571.121; S6.1.8)
  E. Service Brake Stopping Distance Test (49 CFR 571.121; S5.3.1.1)

2.2 Test Vehicle

The truck tractor tested was a 1991 Volvo 6x4 tractor. For the MGVWR testing, this truck tractor was towing the Transportation Research Center's (TRC's) 28 foot long, unbraked control trailer (loaded with the appropriate weights). Figure 2 shows an overall picture of this truck tractor-semitrailer rig.

Additional information about the 1991 Volvo 6x4 tractor is contained in Appendix A.

Figure 2: 1991 Volvo 6x4 Tractor with TRC's 28 foot long, unbraked control trailer

Please note that since this vehicle was manufactured during 1991, it does not have to meet the stopping distance requirements that are shown in Tables 1 and 2. It has to meet the requirements of the version of FMVSS No. 121 that were in effect in 1991. Past NHTSA testing has demonstrated that this vehicle meets all of the 1991 FMVSS No. 121 requirements. This tractor was equipped with an antilock brake system (ABS) that meets all of the FMVSS No. 121 requirements that became effective on March 1, 1997.

Although this vehicle is fairly old, the age of the tractor is expected to ***not*** affect the results of this research. While the ABS may not be the most modern design, it was sufficient to prevent the tractors wheels from locking up. The effects of age on braking system performance were compensated for by use of the Modified Gross Vehicle Weight Rating loading (see discussion in Section 2.5, below) for the most important portion of this testing. The age of the vehicle could have slightly affected stopping performance during the LLVW testing; however, for this loading the vehicle had such a large margin of compliance that the slight effects of vehicle age were not important. All in all, the use of a current model year tractor is expected to have resulted in the same research results.

During testing performed with the tractor in both the Gross Vehicle Weight Rating loading and the Modified Gross Vehicle Weight Rating loading (see discussion in Section 2.5, below), the Volvo tractor was towing an unbraked control trailer. This control trailer conforms to all of the requirements specified for an unbraked control in FMVSS No. 121[6].

The control trailer used was a 1977 Ravens 28-foot long, flatbed semitrailer. Additional information about this semitrailer is contained in Appendix B.

2.3 Test Vehicle Instrumentation

Prior to testing, the 1991 Volvo 6x4 truck tractor was instrumented to measure and record the following data channels:

- Vehicle Speed,
- Wheel Rotational Speeds,
- Brake Pedal Trigger Switch,
- Stopping Distance,
- Longitudinal Deceleration,
- Treadle Valve Pressure,
- Primary and Secondary Reservoir Pressures,
- Brake Chamber Pressures, and
- Brake Lining Temperatures.

Office of Vehicle Safety Compliance Laboratory Test Procedure TP-121V-04 instrumentation typically used by the Transportation Research Center was installed for this testing.

Upon the completion of instrumentation installation, a brake burnish, per the requirements of Office of Vehicle Safety Compliance Laboratory Test Procedure No. TP-121V-04 was performed.

2.4 Test Vehicle Brake Timing

Brake timing testing (performed as per Step 3 of the Test Plan) was conducted using the FMVSS No. 121 test conditions and procedures. Apply tests measure the time for the air pressure to rise to 60 psi following a 100 psi application of air at the treadle valve. Release tests measure the time for the air pressure to fall from 95 to 5 psi when, after a 95 psi brake application has been made and air pressure has reached steady state, the driver releases the treadle valve.

Initially, the brake apply timing of both tractor drive axles did not comply with the requirements of FMVSS No. 121 (a maximum apply time of 0.45 seconds). This is believed to be due to the fact that it had been several years since this vehicle's brakes had last had significant maintenance. Therefore, as a first corrective action, the rear relay valve was replaced. This helped but was insufficient to have both tractor drive axles comply with the requirements of FMVSS No. 121. Therefore, as a second corrective action, lubrication was performed of the s-cam brake shaft bearings (note that s-cam brakes were only present on this truck tractor's drive axle brakes; the front axle was fitted with air disc brakes during this testing) via the lubrication fittings and the service brakes exercised in a number of stops. This second corrective action was sufficient to have both tractor drive axles comply with the requirements of FMVSS No. 121.

Table 3 summarizes results of brake timing tests that were performed for this truck tractor. As can be seen, all brakes meet the timing requirements of FMVSS No. 121 (apply times of less than 0.45 seconds for each of the brakes and 0.35 seconds for the 50 cubic inch gladhand reservoir and release times of less than 0.55 seconds for each of the brakes and 0.75 seconds for the 50 cubic inch gladhand reservoir).

[6] Federal Motor Vehicle Safety Standard No. 121; Air Brake Systems, S6.1.10

Table 3: Brake Actuation and Release Times

Run No.	Front Axle		Intermediate Drive Axle		Rear Drive Axle		50 cubic inch Gladhand Reservoir	
	Apply Time (sec)	Release Time (sec)	Apply Time (sec)	Release Time (sec)	Apply Time (sec)	Release Time (sec)	Apply Time (sec)	Release Time (sec)
1	0.30	0.50	0.41	0.49	0.40	0.46	0.35	0.68
2	0.31	0.47	0.42	0.47	0.41	0.45	0.33	0.68
3	0.31	0.51	0.42	0.51	0.41	0.48	0.33	0.68
Average	**0.31**	**0.49**	**0.42**	**0.49**	**0.41**	**0.46**	**0.34**	**0.68**

2.5 Establishing Modified Gross Vehicle Weight Rating Vehicle Loading

As stated above, since only one truck tractor was tested, a decision was made to modify its loading for normal FMVSS No. 121 testing in the Loaded-to-GVWR condition. The vehicle loading was changed from that specified for normal FMVSS No. 121 testing in the Loaded-to-GVWR testing to a different loading (referred to as the MGVWR condition) such that the 60 mph stopping distance specified in Table 1 was just achieved. It is the authors' belief that by loading this vehicle so as to just achieve the 60 mph stopping distance specified in Table 1, test results would give greater insight into the appropriateness of stopping distance values from other initial speeds that are in Table 1. Furthermore, direct comparisons of corrected stopping distances and steady state decelerations could be made.

To determine the MGVWR vehicle loading, the following procedure (Steps 4 through 7 of the Test Plan) was used:

1. Load test truck tractor with control trailer to GVWR as per FMVSS No 121.
2. Perform six stops from as close to 60 mph initial speed as feasible. Calculate corrected stopping distance for each stop and average resulting data over all six stops.
3. Adjust test vehicle loading to bring the average corrected stopping distance from all six stops closer to the target of 250 feet.
4. Iterate Steps 5 and 6 as many times as needed to achieve an average corrected stopping distance of 250±1 feet. This established the Modified Gross Vehicle Weight Rating (MGVWR) loading condition used during this testing.

Initially, the Volvo 6x4 tractor and control trailer were loaded, as specified by FMVSS No. 121 for the Loaded to GVWR condition, so as to have the following loads on each axle:

Front Axle: 11,120 pounds
Drive Axles: 33,680 pounds
Trailer Axles: 4,510 pounds
Total Weight: 49,310 pounds

The Loaded to GVWR Volvo 6x4 tractor and control trailer were then used to perform six stops from an initial speed of 60 mph. Table 4 summarizes the resulting stopping distances.

Table 4: Stopping Performance for the GVWR Vehicle

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	60.5	277.7	273.1
2	60.1	275.1	274.2
3	59.8	294.6	296.6
4	60.2	315.2	313.1
5	60.4	324.0	319.7
6	60.0	291.1	291.1
		Average Corrected Stopping Distance	**294.6**

Since average corrected stopping distance for the vehicle in the Loaded to GVWR condition exceeded 250 ft, ballast was removed. Since sensitivity of stopping distance to ballast changes was not known, initially 3,000 pounds of ballast was removed. This reduced the weight of the Volvo 6x4 tractor and control trailer to 46,310 pounds (the Iteration 2 Weight). The Iteration 2 Weight Volvo 6x4 tractor and control trailer was then used to perform six stops from an initial speed of 60 mph. Table 5 summarizes the resulting stopping distances.

Table 5: Stopping Performance for the Iteration 2 Weight Vehicle

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.6	289.0	292.9
2	59.7	271.3	274.0
3	60.4	289.0	285.2
4	60.1	290.9	289.9
5	60.2	293.9	292.0
6	60.2	294.2	292.2
		Average Corrected Stopping Distance	**287.7**

Since average corrected stopping distance for the vehicle at the Iteration 2 weight continued to exceed 250 ft, additional ballast was removed. Now, however, enough data was available to estimate, based on linear extrapolation, the amount of ballast that needed to be removed to attain a corrected stopping distance of 250 ft. Based on this calculation, an additional 12,000 pounds of ballast was removed. This reduced the weight of the Volvo 6x4 tractor and control trailer to 34,310 pounds (the Iteration 3 Weight). The Iteration 3 Weight Volvo 6x4 tractor and control trailer was then used to perform six stops from an initial speed of 60 mph. Table 6 summarizes the resulting stopping distances.

Table 6: Stopping Performance for the Iteration 3 Weight Vehicle

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.9	221.0	221.7
2	59.6	232.3	235.4
3	60.4	226.1	223.1
4	60.4	226.4	223.4
5	59.4	223.7	228.2
6	60.1	230.8	230.0
		Average Corrected Stopping Distance	**227.0**

Since average corrected stopping distance for the vehicle at the Iteration 3 weight was less than 250 ft, ballast was added. Now, however, enough data was available to estimate, based on quadratic interpolation, the amount of ballast that needed to be added to attain a corrected stopping distance of 250 ft. Based on this calculation, 6,310 pounds of ballast was added. This increased the weight of the Volvo 6x4 tractor and control trailer to 40,620 pounds (the Iteration 4 Weight). The Iteration 4 Weight Volvo 6x4 tractor and control trailer was then used to perform six stops from an initial speed of 60 mph. Table 7 summarizes the resulting stopping distances.

Table 7: Stopping Performance for the Iteration 4 Weight Vehicle

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	60.5	243.9	239.9
2	60.3	251.0	248.5
3	60.3	259.2	256.6
4	60.2	244.3	242.7
5	60.2	252.0	250.3
6	60.2	251.7	250.0
		Average Corrected Stopping Distance	**248.0**

Unfortunately, at this point in this test program, winter weather set in. Due to weather, testing could not be performed from December 19, 2009 through March 7, 2010. When testing resumed in March 2010, the first tests performed checked whether the stopping performance for the Iteration 4 vehicle had changed during the winter. Changes in stopping performance during the winter are likely to occur for such reasons as weather-induced changes to the test pavement's frictional characteristics, aging-induced effects on the tires' frictional characteristics, etc. Not surprisingly, the average corrected stopping distance in March 2010 of the Iteration 4 vehicle was found to differ from its average corrected stopping distance in December 2009. The March 2010 average corrected stopping distance was 240.9 ft.

Since the average corrected stopping distance for the vehicle at the Iteration 4 weight was less than 250 ft, ballast was added. A constant reduction to previous stopping distance data of 7.1 ft was assumed.

Quadratic interpolation could then be used to estimate the amount of ballast that needed to be added to attain a corrected stopping distance of 250 ft. Based on this calculation, 2,220 pounds of ballast was added. This increased the weight of the Volvo 6x4 tractor and control trailer to 42,840 pounds (the Iteration 5 Weight). The Iteration 5 Weight Volvo 6x4 tractor and control trailer was then used to perform six stops from an initial speed of 60 mph. Table 8 summarizes the resulting stopping distances.

Table 8: Stopping Performance for the Iteration 5 Weight Vehicle

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.9	246.0	246.8
2	59.8	240.5	242.1
3	60.1	253.5	252.7
4	60.1	250.5	249.7
5	60.3	252.8	250.3
6	59.7	259.8	262.4
		Average Corrected Stopping Distance	**250.7**

Since average corrected stopping distance for the vehicle at the Iteration 5 weight was within ±1 ft of the desired 250 ft, the Iteration 5 weight was selected as this vehicle's Modified Gross Vehicle Weight Rating (MGVWR) that was used for the MGVWR portion of the subsequent testing. In the MGVWR loading condition, the Volvo 6x4 tractor with the control trailer had the following loads on each axle:

Front Axle: 10,990 pounds
Drive Axles: 27,360 pounds
Trailer Axles: 4,490 pounds
Total Weight: 42,840 pounds

3.0 Test Results

As per Step 8 of the Test Plan, with the test vehicle loaded to MGVWR condition, six stops were performed from each desired initial speed. From testing performed to establish MGVWR condition, data had already been collected for an initial speed of 60 mph. Testing was next performed at initial speeds of 55, 50, 45, 40, 35, 30, 25, and 20 mph, in that order. Stopping distance data from this testing is summarized in Table 9.

Table 9: Summary of MGVWR Stopping Distance Data

	Target Speed = 60 mph			**Target Speed = 55 mph**			**Target Speed = 50 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.9	246.0	246.8	54.9	197.1	197.8	50.3	166.5	164.5
2	59.8	240.5	242.1	55.2	207.2	205.7	50.7	165.0	160.5
3	60.1	253.5	252.7	55.2	201.0	199.5	49.9	170.2	170.9
4	60.1	250.5	249.7	55.3	211.8	209.5	50.1	171.0	170.3
5	60.3	252.8	250.3	55.0	190.9	190.9	50.4	172.1	169.4
6	59.7	259.8	262.4	55.2	201.2	199.7	50.2	170.8	169.4
		Average Value	**250.7**		**Average Value**	**200.5**		**Average Value**	**167.5**
		Standard Deviation	**6.8**		**Standard Dev.**	**5.9**		**Standard Dev.**	**4.1**

	Target Speed = 45 mph			**Target Speed = 40 mph**			**Target Speed = 35 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	44.9	136.6	137.2	40.3	106.3	104.7	35.3	80.2	78.8
2	45.1	139.0	138.4	40.4	106.1	104.0	35.8	81.0	77.4
3	45.5	137.0	134.0	39.6	103.9	106.0	35.4	81.7	79.9
4	44.9	133.3	133.9	40.3	108.2	106.6	35.2	79.6	78.7
5	45.1	136.8	136.2	40.1	100.2	99.7	35.3	81.0	79.6
6	45.6	139.1	135.5	40.1	105.7	105.2	35.2	79.2	78.3
		Average Value	**135.9**		**Average Value**	**104.4**		**Average Value**	**78.8**
		Standard Deviation	**1.8**		**Standard Dev.**	**2.5**		**Standard Dev.**	**0.9**

	Target Speed = 30 mph			**Target Speed = 25 mph**			**Target Speed = 20 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	30.2	61.7	60.9	24.8	43.0	43.7	20.2	32.7	32.1
2	30.1	62.3	61.9	25.6	45.3	43.2	20.2	31.2	30.6
3	30.8	63.4	60.1	24.7	42.8	43.8	20.3	32.4	31.4
4	30.5	63.6	61.5	24.6	45.3	46.8	20.0	30.4	30.4
5	30.2	62.3	61.5	25.2	44.7	44.0	20.3	31.9	31.0
6	30.2	63.6	62.8	25.4	44.9	43.5	20.2	32.5	31.9
		Average Value	**61.4**		**Average Value**	**44.2**		**Average Value**	**31.2**
		Standard Deviation	**0.9**		**Standard Dev.**	**1.3**		**Standard Dev.**	**0.7**

As a check that nothing about the vehicle's braking performance had changed during the lower initial speed MGVWR testing, at the completion of this lower initial speed testing a final MGVWR tests series was performed with an initial speed of 60 mph. Table 10 summarizes the results of this testing.

Table 10: Stopping Distance Data from MGVWR Check Test Series

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	60.5	252.7	248.5
2	59.8	252.7	254.4
3	60.5	249.8	245.7
4	59.7	244.1	246.6
5	59.6	250.2	253.6
6	60.2	235.6	234.0
		Average Corrected Stopping Distance	**247.1**
		Standard Deviation	**7.3**

The difference between averaged corrected stopping distance from the initial 60 mph MGVWR testing and the final 60 mph MGVWR Check Test Series, 3.6 ft, is less than the standard deviation for either test series. The Student t-Test, assuming equal variances, was run for these two populations. The resulting t-Statistic was 0.86, which is considerably less than the critical t-Statistic value (the value for which there is a 95 percent probability that two populations are different) for these population sizes of 2.23. Therefore, nothing about this vehicle's braking performance changed during lower initial speed MGVWR testing.

Deceleration data collected during MGVWR testing from all of the initial speeds tested was analyzed. For this analysis, it was assumed that vehicle deceleration during each stop had the idealized shape shown in Figure 1, i.e., a ramp rise followed by holding constant at its steady state value until the end of the stop. Note that unlike Figure 1 in which the ramp rise time was fixed at 0.45 seconds, for this analysis the ramp rise time was allowed to vary and was determined by the analyst. Figure 3 shows both the measured and idealized deceleration for a typical stop from an initial speed of 60 mph.

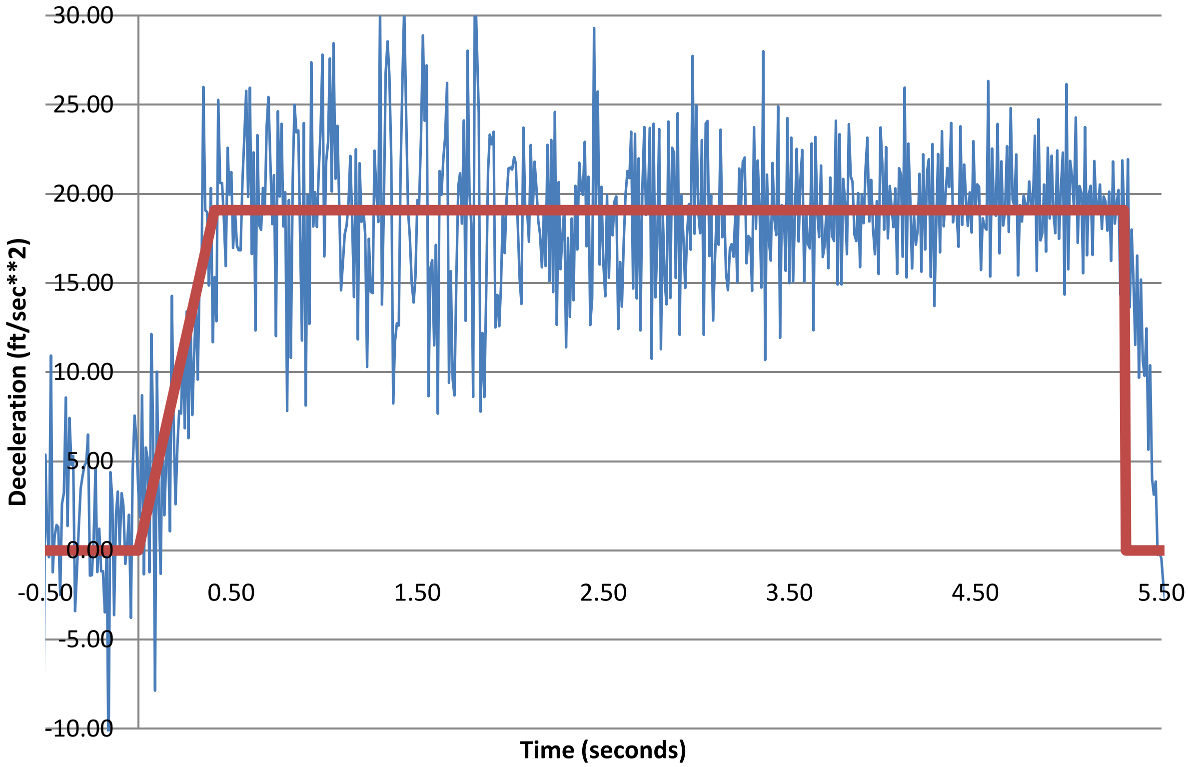

Figure 3: Measured and Idealized Deceleration for a Typical 60 mph Stop

For each stop, the analyst determined, somewhat subjectively, $t_{r,}$ the Deceleration Rise Time in seconds, from a time history trace of deceleration versus time. The analyst also determined the time at which deceleration began to drop rapidly to zero.

After Deceleration Rise Time had been determined, $d_{ss,}$ the Steady State Vehicle Deceleration was determined. This was initially done by determining the average value of deceleration, as measured by the longitudinal accelerometer that was mounted on the vehicle during testing, from the end of the Deceleration Rise Time to the time at which deceleration began to drop rapidly to zero. Unfortunately, values for Steady State Vehicle Deceleration obtained via this method seemed unreasonably high, indicating calibration problems with the longitudinal accelerometer. Therefore, a new deceleration channel was calculated for each stop by dividing the change in measured vehicle speed between each two successive data collection points by the time interval between these two data points (0.01 seconds). Steady State Vehicle Deceleration values were then re-calculated by determining the average value of this channel from the end of the Deceleration Rise Time to the time at which the deceleration began to drop rapidly to zero. This method gave more reasonable values for Steady State Vehicle Decelerations (although, as discussed later, still somewhat too high values).

Table 11 summarizes the Deceleration Rise Times and the Steady State Vehicle Decelerations that were determined from the MGVWR testing from all initial speeds.

Table 11: Summary of MGVWR Deceleration Data

Stop Number	Target Speed = 60 mph		Target Speed = 55 mph		Target Speed = 50 mph	
	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)
1	0.50	17.7	0.36	18.9	0.40	18.9
2	0.37	18.0	0.34	17.9	0.48	19.6
3	0.39	17.1	0.42	18.6	0.40	18.4
4	0.35	17.3	0.46	17.6	0.37	18.2
5	0.41	17.1	0.43	19.5	0.43	18.6
6	0.37	16.4	0.35	18.4	0.40	18.6
Average	**0.40**	**17.3**	**0.39**	**18.5**	**0.41**	**18.7**
Stand. Dev.	**0.05**	**0.6**	**0.05**	**0.7**	**0.04**	**0.5**

Stop Number	Target Speed = 45 mph		Target Speed = 40 mph		Target Speed = 35 mph	
	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)
1	0.38	19.0	0.37	19.4	0.31	20.8
2	0.53	19.1	0.40	19.5	0.46	20.9
3	0.45	19.3	0.36	19.5	0.38	21.1
4	0.43	19.7	0.41	19.8	0.40	21.3
5	0.44	19.0	0.39	21.4	0.46	20.6
6	0.41	18.6	0.39	19.1	0.39	21.4
Average	**0.44**	**19.1**	**0.39**	**19.8**	**0.40**	**21.0**
Stand. Dev.	**0.05**	**0.3**	**0.02**	**0.8**	**0.06**	**0.3**

Stop Number	Target Speed = 30 mph		Target Speed = 25 mph		Target Speed = 20 mph	
	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)
1	0.37	21.0	0.58	21.9	0.38	18.6
2	0.62	21.0	0.54	20.7	0.38	20.2
3	0.54	20.8	0.55	22.8	0.37	19.4
4	0.60	20.5	0.67	21.3	0.41	21.0
5	0.37	19.9	0.57	20.6	0.36	19.8
6	0.49	21.1	0.45	21.4	0.63	20.7
Average	**0.50**	**20.7**	**0.56**	**21.4**	**0.42**	**20.0**
Stand. Dev.	**0.11**	**0.4**	**0.07**	**0.8**	**0.10**	**0.9**

As per Step 9 of the Test Plan, with the test vehicle in the unloaded condition (LLVW), six stops were performed from each desired initial speed. Testing was performed at initial speeds of 60, 55, 50, 45, 40, 35, 30, 25, and 20 mph, in that order. Stopping distance data from this testing is summarized in Table 12.

Table 12: Summary of LLVW Stopping Distance Data

	Target Speed = 60 mph			**Target Speed = 55 mph**			**Target Speed = 50 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.5	182.1	185.2	55.5	159.2	156.3	49.4	121.5	124.5
2	59.8	181.8	183.0	55.7	155.6	151.7	50.8	129.7	125.6
3	61.0	192.8	186.5	54.3	148.8	152.7	50.0	124.8	124.8
4	59.9	184.0	184.6	55.6	160.4	157.0	50.3	120.9	119.5
5	59.9	182.2	182.8	54.7	154.8	156.5	50.0	128.6	128.6
6	59.9	179.7	180.3	54.6	155.4	157.7	50.1	127.1	126.6
		Average Value	**183.7**		**Average Value**	**155.3**		**Average Value**	**124.9**
		Standard Deviation	**2.2**		**Standard Dev.**	**2.5**		**Standard Dev.**	**3.1**

	Target Speed = 45 mph			**Target Speed = 40 mph**			**Target Speed = 35 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	45.5	102.1	99.9	40.5	84.2	82.1	35.3	64.8	63.7
2	45.0	104.9	104.9	41.4	87.7	81.9	34.2	61.8	64.7
3	45.5	105.1	102.8	40.9	84.6	80.9	35.6	63.0	60.9
4	45.6	105.6	102.8	40.3	84.7	83.4	35.6	66.3	64.1
5	45.8	105.1	101.5	40.4	84.4	82.7	36.4	69.4	64.2
6	45.3	106.3	104.9	41.0	84.1	80.0	35.3	64.8	63.7
		Average Value	**102.8**		**Average Value**	**81.9**		**Average Value**	**63.5**
		Standard Deviation	**2.0**		**Standard Dev.**	**1.2**		**Standard Dev.**	**1.4**

	Target Speed = 30 mph			**Target Speed = 25 mph**			**Target Speed = 20 mph**		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	30.7	49.5	47.3	25.1	36.0	35.7	20.5	28.6	27.2
2	30.2	48.9	48.3	25.1	36.7	36.4	20.0	24.6	24.6
3	30.5	48.6	47.0	25.0	37.4	37.4	20.0	25.7	25.7
4	29.5	48.5	50.2	24.8	36.5	37.1	20.3	25.5	24.8
5	30.2	48.0	47.4	25.2	36.1	35.5	19.2	24.0	26.0
6	30.0	48.8	48.8	25.3	34.7	33.9	19.9	25.6	25.9
		Average Value	**48.1**		**Average Value**	**36.0**		**Average Value**	**25.7**
		Standard Deviation	**1.2**		**Standard Dev.**	**1.3**		**Standard Dev.**	**1.0**

Finally, as a check that nothing about the vehicle's braking performance had changed during lower initial speed LLVW testing, at the completion of this lower initial speed testing a final LLVW tests series was performed with an initial speed of 60 mph. Table 13 summarizes the results of this testing.

Table 13: Stopping Distance Data from LLVW Check Test Series

	Target Speed = 60 mph		
Stop Number	**Actual Initial Speed (mph)**	**Measured Stopping Distance (ft)**	**Corrected Stopping Distance (ft)**
1	59.2	184.3	189.3
2	59.8	188.1	189.4
3	60.4	185.4	183.0
4	60.3	187.4	185.5
5	59.3	181.9	185.2
6	60.1	181.7	181.1
		Average Corrected Stopping Distance	**185.6**
		Standard Deviation	**3.3**

The difference between averaged corrected stopping distance from the 60 mph LLVW testing and from the final 60 mph LLVW Check Test Series, 1.9 ft, is less than the standard deviation for either test series. The Student t-Test, assuming equal variances, was run for these two populations. The resulting t-Statistic was 1.14, which is considerably less than the critical t-Statistic value (the value for which there is a 95 percent probability that the two populations are different) for these population sizes of 2.23. Therefore, nothing about the vehicle's braking performance changed during lower initial speed LLVW testing.

Again, for the LLVW test data, for each stop, the analyst determined, somewhat subjectively, $t_{r,}$ Deceleration Rise Time in seconds, from the time history trace of deceleration versus time. The analyst also determined the time at which the deceleration began to drop rapidly to zero.

After the Deceleration Rise Time had been determined, Steady State Vehicle Deceleration (in feet per second squared) was determined. This was initially done by determining the average value of deceleration, as measured by the longitudinal accelerometer, from the end of the Deceleration Rise Time to the time at which the deceleration began to drop rapidly to zero. As was the case for the MGVWR data, the values for Steady State Vehicle Deceleration obtained found calibration problems with the longitudinal accelerometer. Therefore, a new deceleration channel was again calculated for each stop by dividing the change in measured vehicle speed between each two successive data collection points by the time interval between these two data points (0.01 seconds). The LLVW Steady State Vehicle Deceleration values were then re-calculated by determining the average value of this channel from the end of the Deceleration Rise Time to the time at which the deceleration began to drop rapidly to zero. This method gave more reasonable LLVW Steady State Vehicle Deceleration values (although, as discussed later, the resulting values were still seemed somewhat too high).

Table 14 summarizes the Deceleration Rise Times and the Steady State Vehicle Decelerations that were determined from LLVW testing from all initial speeds.

Table 14: Summary of LLVW Deceleration Data

Stop Number	Target Speed = 60 mph		Target Speed = 55 mph		Target Speed = 50 mph	
	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)	Deceleration Rise Time (sec)	Steady State Deceleration (ft/sec^2)
1	0.25	22.8	0.32	23.4	0.31	24.6
2	0.27	23.7	0.28	23.4	0.35	24.3
3	0.29	22.7	0.32	24.5	0.31	24.3
4	0.26	22.3	0.27	22.7	0.28	25.4
5	0.28	22.9	0.27	23.2	0.33	24.3
6	0.24	23.3	0.28	22.6	0.32	24.5
Average	**0.27**	**23.0**	**0.29**	**23.3**	**0.32**	**24.6**
Stand. Dev.	**0.02**	**0.5**	**0.02**	**0.7**	**0.02**	**0.4**
Stop Number	**Target Speed = 45 mph**		**Target Speed = 40 mph**		**Target Speed = 35 mph**	
	Deceleration Rise Time (sec)	**Steady State Deceleration (ft/sec^2)**	**Deceleration Rise Time (sec)**	**Steady State Deceleration (ft/sec^2)**	**Deceleration Rise Time (sec)**	**Steady State Deceleration (ft/sec^2)**
1	0.28	24.6	0.28	23.7	0.29	24.3
2	0.28	23.8	0.31	24.8	0.33	26.0
3	0.27	24.2	0.31	24.9	0.31	25.9
4	0.28	23.8	0.33	24.8	0.31	23.9
5	0.31	24.6	0.33	24.5	0.32	24.5
6	0.31	23.7	0.28	24.2	0.30	23.7
Average	**0.29**	**24.1**	**0.31**	**24.5**	**0.31**	**24.7**
Stand. Dev.	**0.02**	**0.4**	**0.02**	**0.4**	**0.01**	**1.0**
Stop Number	**Target Speed = 30 mph**		**Target Speed = 25 mph**		**Target Speed = 20 mph**	
	Deceleration Rise Time (sec)	**Steady State Deceleration (ft/sec^2)**	**Deceleration Rise Time (sec)**	**Steady State Deceleration (ft/sec^2)**	**Deceleration Rise Time (sec)**	**Steady State Deceleration (ft/sec^2)**
1	0.32	24.2	0.29	23.0	0.32	22.6
2	0.29	24.3	0.29	23.5	0.30	22.5
3	0.34	25.0	0.25	21.2	0.27	21.4
4	0.33	23.8	0.31	21.6	0.30	20.5
5	0.33	25.4	0.32	23.8	0.27	21.0
6	0.31	23.5	0.29	23.5	0.25	21.9
Average	**0.32**	**24.4**	**0.29**	**22.8**	**0.29**	**21.7**
Stand. Dev.	**0.02**	**0.7**	**0.02**	**1.1**	**0.03**	**0.8**

4.0 Analysis of Test Results

4.1 Analysis of Stopping Distance

Table 15 compares maximum permitted stopping distance according to FMVSS No. 121 (as shown in Table 1) with average measured corrected stopping distance for a variety of speeds (as shown in Table 9) with the test vehicle at MGVWR loading. The margin of compliance, calculated as a percentage of maximum permitted stopping distance according to FMVSS No. 121, is also shown. Speeds for which the margin of compliance is negative are highlighted. Please note that since this vehicle was manufactured during 1991, it does not have to meet the stopping distance requirements that are shown in Tables 1 and 2. It has to meet the requirements of the version of FMVSS No. 121 that were in effect in 1991. Past NHTSA testing has demonstrated that this vehicle meets all of the 1991 FMVSS No. 121 requirements. Furthermore, the MGVWR tests are not part of the FMVSS No. 121 standard; they were done solely for research purposes.

Table 15: Stopping Distance Analysis of the MGVWR Test Data

Initial Speed (mph)	Maximum Permitted Stopping Distance (ft)	Average Measured Corrected Stopping Distance (ft)	Margin of Compliance (%)
60	250.0	**250.7**	**-0.3 %**
55	212.0	200.5	5.4 %
50	176.0	167.5	4.8 %
45	144.0	135.9	5.6 %
40	114.0	104.4	8.4 %
35	89.0	78.8	11.5 %
30	65.0	61.4	5.5 %
25	45.0	44.2	1.8 %
20	30.0	**31.2**	**-4.0 %**

Figure 4 shows maximum permitted stopping distance according to FMVSS No. 121 and average measured corrected stopping distance graphed against initial speed for the MGVWR loading condition.

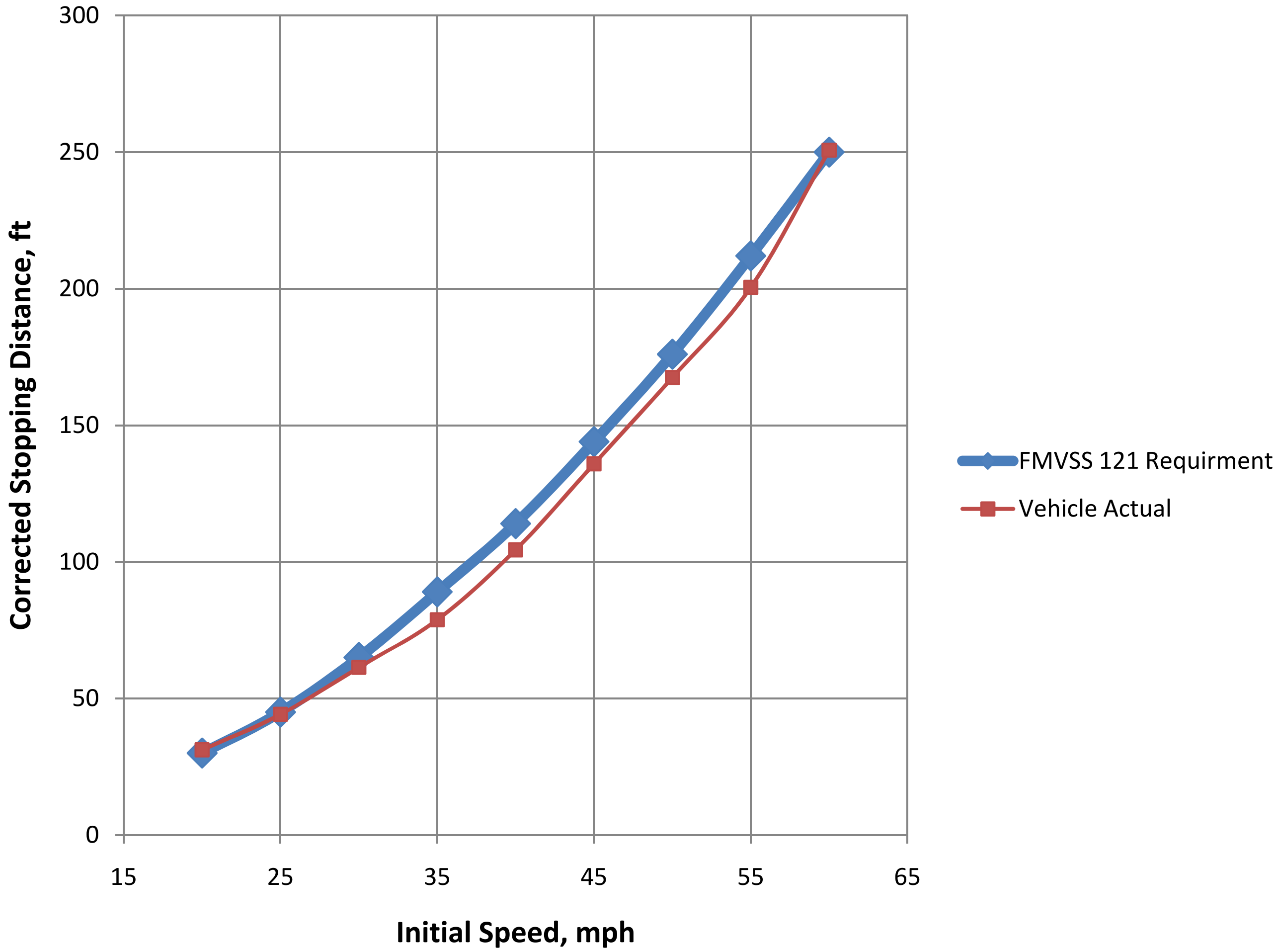

Figure 4: Maximum Permitted Stopping Distance and Average Measured Corrected Stopping Distance graphed against Initial Speed at MGVWR Loading

As Figure 4 and Table 15 show, maximum permitted stopping distance according to FMVSS No. 121 for the MGVWR loading condition matches average measured corrected stopping distance for an initial speed of 60 mph. As explained above, this is by design and is the criteria used to determine the MGVWR loading condition.

As initial speed decreased from 60 mph, average measured corrected stopping distance drops faster than maximum permitted stopping distance until an initial vehicle speed of 35 mph is reached. As per Table 15, for the MGVWR loading condition, the vehicle had the largest positive margin of compliance at an initial speed of 35 mph.

As initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. As per Table 15, for the MGVWR loading condition, the vehicle had a negative margin of compliance at an initial speed of 20 mph.

Table 16 compares maximum permitted stopping distance according to FMVSS No. 121 (as shown in Table 2) with average measured corrected stopping distance for a variety of speeds (as shown in Table 9) with the unloaded (LLVW) test vehicle. The margin of compliance, calculated as a percentage of maximum permitted stopping distance according to FMVSS No. 121, is also shown.

Table 16: Stopping Distance Analysis of the LLVW Test Data

Initial Speed (mph)	Maximum Permitted Stopping Distance (ft)	Average Measured Corrected Stopping Distance (ft)	Margin of Compliance (%)
60	235.0	183.7	22.7 %
55	199.0	155.3	22.0 %
50	166.0	124.9	24.8 %
45	136.0	102.8	24.4 %
40	108.0	81.9	24.2 %
35	84.0	63.5	24.4 %
30	61.0	48.1	21.1 %
25	43.0	36.0	16.3 %
20	28.0	25.7	8.2 %

Figure 5 shows maximum permitted stopping distance according to FMVSS No. 121 and average measured corrected stopping distance graphed against initial speed for the LLVW vehicle.

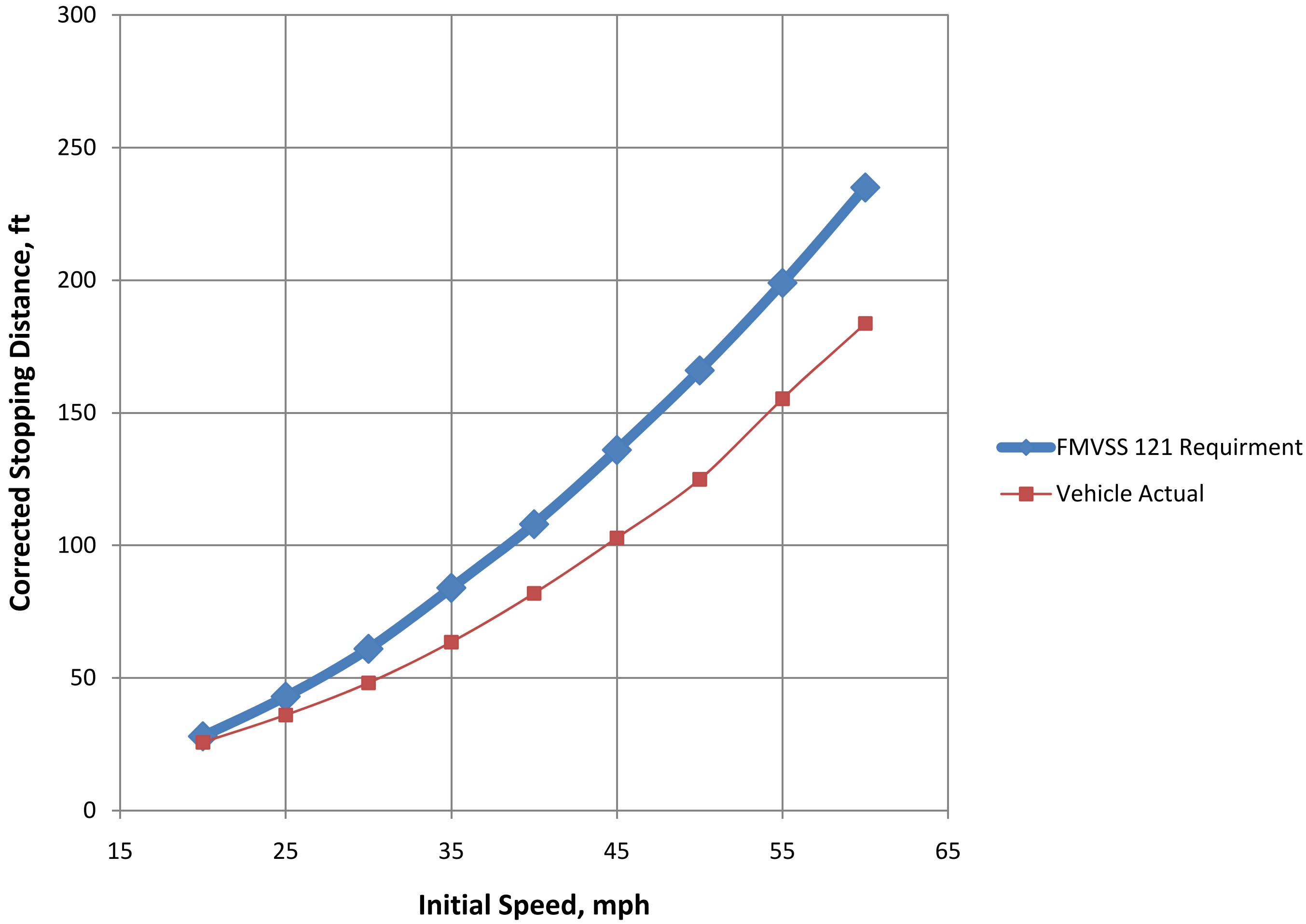

Figure 5: Maximum Permitted Stopping Distance and Average Measured Corrected Stopping Distance graphed against Initial Speed at LLVW Loading

As Figure 5 and Table 16 show, maximum permitted stopping distance according to FMVSS No. 121 for the LLVW vehicle is less than average measured corrected stopping distance for all initial speeds. As initial speed decreased from 60 mph, average measured corrected stopping distance drops at the same rate as maximum permitted stopping distance until an initial vehicle speed of 35 mph is reached. As per Table 16, the LLVW vehicle had a fairly constant (between 22.0 and 24.8 percent) margin of compliance for initial speeds from 60 to 35 mph.

As initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. As per Table 16, the LLVW vehicle had its smallest (though still positive) margin of compliance at an initial speed of 20 mph.

4.2 Analysis of Deceleration Rise Time

Table 17 summarizes average deceleration rise time and standard deviations of the deceleration rise time for the MGVWR and LLVW vehicle.

Table 17: Deceleration Rise Times from MGVWR and LLVW Testing

Initial Speed (mph)	MGVWR Vehicle Loading		LLVW Vehicle Loading	
	Deceleration Rise Time (seconds)	Standard Deviation of Rise Time (seconds)	Deceleration Rise Time (seconds)	Standard Deviation of Rise Time (seconds)
60	0.40	0.05	0.27	0.02
55	0.39	0.05	0.29	0.02
50	0.41	0.04	0.32	0.02
45	0.44	0.05	0.29	0.02
40	0.39	0.02	0.31	0.02
35	0.40	0.06	0.31	0.01
30	0.50	0.11	0.32	0.02
25	0.56	0.07	0.29	0.02
20	0.42	0.10	0.29	0.03
Average	**0.43**	**0.6**	**0.30**	**0.02**

A first observation is that the deceleration rise time is longer for MGVWR loading than it is for the LLVW vehicle. This is confirmed by performing a Student t-Test (assuming equal variances) on the two populations. The resulting t-Statistic was 11.64, which is considerably more than the critical t-Statistic value (the value for which there is a 95 percent probability that the two populations are different) for these population sizes of 1.98. It was expected that deceleration rise time would be longer for the MGVWR loading than for the LLVW vehicle since less air pressure is required to achieve maximum deceleration for the LLVW vehicle.

Linear regression analysis was used to perform a least squares fit of the MGVWR experimental data using initial speed as the independent variable and deceleration rise time as the dependent variable. This analysis resulted in an intercept of 0.5311 and a slope of -0.0024 along with a R^2 value of 0.14. The 95 percent confidence limits on this slope are -0.0041 to -0.0008. Therefore, the deceleration rise time for the MGVWR loading decreases slightly, on the average, with increasing initial speed.

Linear regression analysis was used to perform a least squares fit of the LLVW experimental data using initial speed as the independent variable and deceleration rise time as the dependent variable. This analysis resulted in an intercept of 0.3121 and a slope of -0.0004 along with a R^2 value of 0.04. The 95 percent confidence limits on this slope include zero. Therefore, the deceleration rise time for the LLVW loading does not vary systematically with initial speed.

The average MGVWR and LLVW deceleration rise times, 0.43 and 0.30 seconds, respectively, are both less than the 0.45 second rise time that was used in Equation 1 to calculate maximum permitted stopping distances in Tables 1 and 2. Assuming a 0.45 second deceleration rise is, therefore, conservative. This will tend to make it easier for vehicles to meet the FMVSS No. 121 requirements.

4.3 Analysis of Steady-State Deceleration

Table 18 summarizes average steady-state decelerations and standard deviations of steady-state deceleration for the MGVWR and LLVW vehicle loadings.

Table 18: Steady-State Decelerations from MGVWR and LLVW Testing

Initial Speed (mph)	MGVWR Vehicle Loading		LLVW Vehicle Loading	
	Steady-State Deceleration (ft/sec^2)	Standard Deviation of Steady-State Deceleration (ft/sec^2)	Steady-State Deceleration (ft/sec^2)	Standard Deviation of Steady-State Deceleration (ft/sec^2)
60	17.3	0.6	23.0	0.5
55	18.5	0.7	23.3	0.7
50	18.7	0.5	24.6	0.4
45	19.1	0.3	24.1	0.4
40	19.8	0.8	24.5	0.4
35	21.0	0.3	24.7	1.0
30	20.7	0.4	24.4	0.7
25	21.4	0.8	22.8	1.1
20	20.0	0.9	21.7	0.8
Average	**19.6**	**0.6**	**23.7**	**0.7**

Tables 19 and 20, for MGVWR and LLVW loading, respectively, compare the assumed steady-state deceleration values used to calculate maximum permitted stopping distances from various initial speeds (as shown in Tables 1 and 2) with average measured steady-state decelerations (as shown in Table 18). The margin of compliance, calculated as a percentage of assumed steady-state deceleration values, is also shown.

Table 19: Steady-State Analysis of MGVWR Test Data

Initial Speed (mph)	Assumed Steady State Vehicle Deceleration (ft/sec^2)	Measured Steady-State Deceleration (ft/sec^2)	Margin of Compliance (%)
60	16.80	17.30	3.0 %
55	16.80	18.50	10.1 %
50	16.80	18.70	11.3 %
45	16.80	19.10	13.7 %
40	17.00	19.80	16.5 %
35	17.00	21.00	23.5 %
30	17.50	20.70	18.3 %
25	18.00	21.40	18.9 %
20	18.00	20.00	11.1 %

Table 20: Steady-State Analysis of LLVW Test Data

Initial Speed (mph)	Assumed Steady State Vehicle Deceleration (ft/sec^2)	Measured Steady-State Deceleration (ft/sec^2)	Margin of Compliance (%)
60	17.95	23.00	28.1 %
55	17.95	23.30	29.8 %
50	17.95	24.60	37.0 %
45	17.95	24.10	34.3 %
40	18.10	24.50	35.4 %
35	18.10	24.70	36.5 %
30	18.80	24.40	29.8 %
25	19.40	22.80	22.7 %
20	19.80	21.70	14.6 %

Figure 6 shows assumed steady state vehicle decelerations used to calculate maximum permitted stopping distances at various speeds in FMVSS No. 121 and average measured steady state decelerations graphed against initial speed for the MGVWR loading condition.

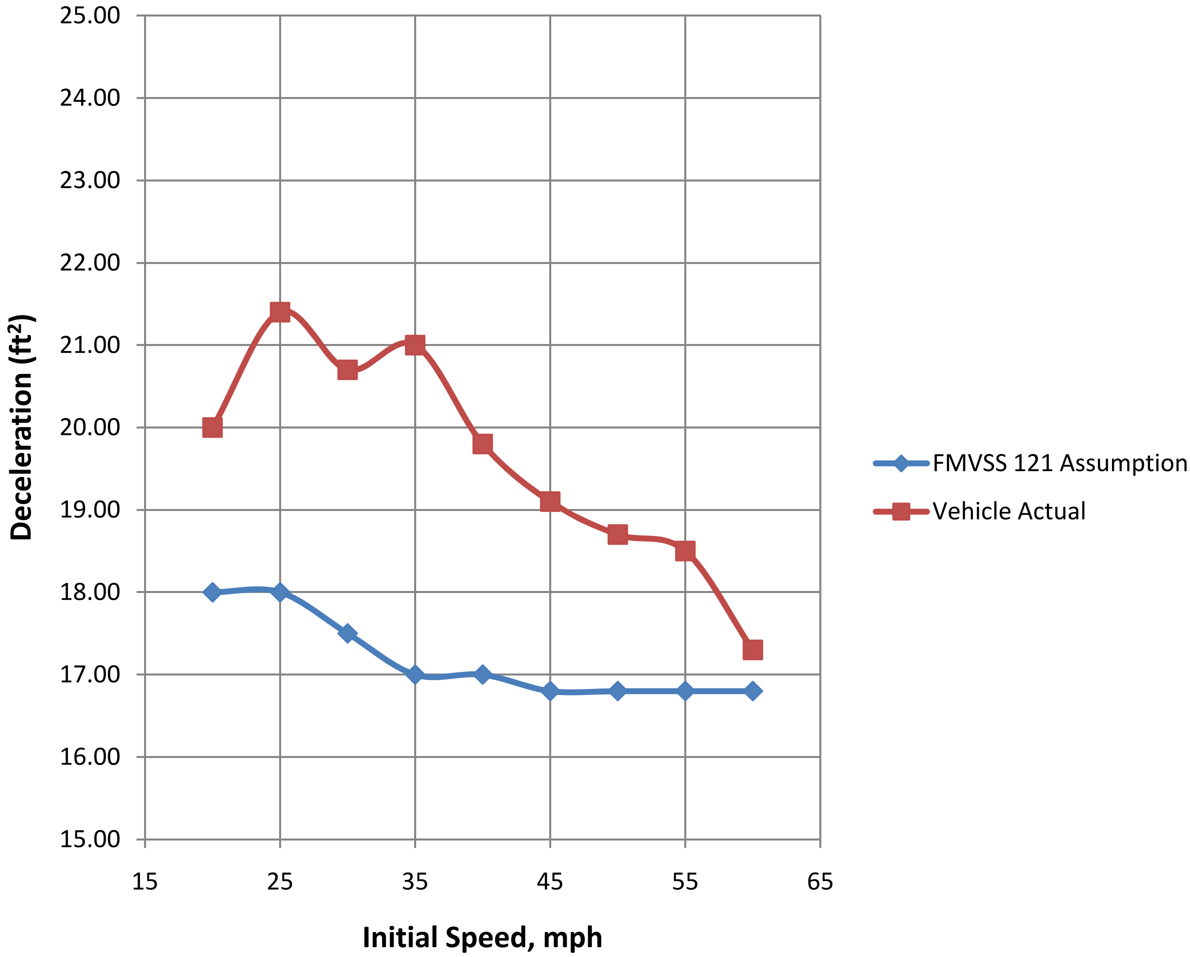

Figure 6: FMVSS No. 121 Assumed and Average Measured Deceleration graphed against Initial Speed at MGVWR Loading

As Figure 6 and Table 19 show, actual measured steady state deceleration is greater than FMVSS No. 121 assumed deceleration for the MGVWR loading condition for all initial speeds. This is surprising since, as shown in Figure 4 and Table 15, actual measured corrected stopping distance equals maximum permitted stopping distance at an initial speed of 60 mph and exceeds maximum permitted stopping distance at an initial speed of 20 mph. This indicates possible discrepancies between the idealized deceleration shape used to calculate Equation 1 and the actual deceleration shape.

Figure 7 shows assumed steady state vehicle decelerations used to calculate maximum permitted stopping distances at various speeds in FMVSS No. 121 and average measured steady state decelerations graphed against initial speed for the LLVW loading condition.

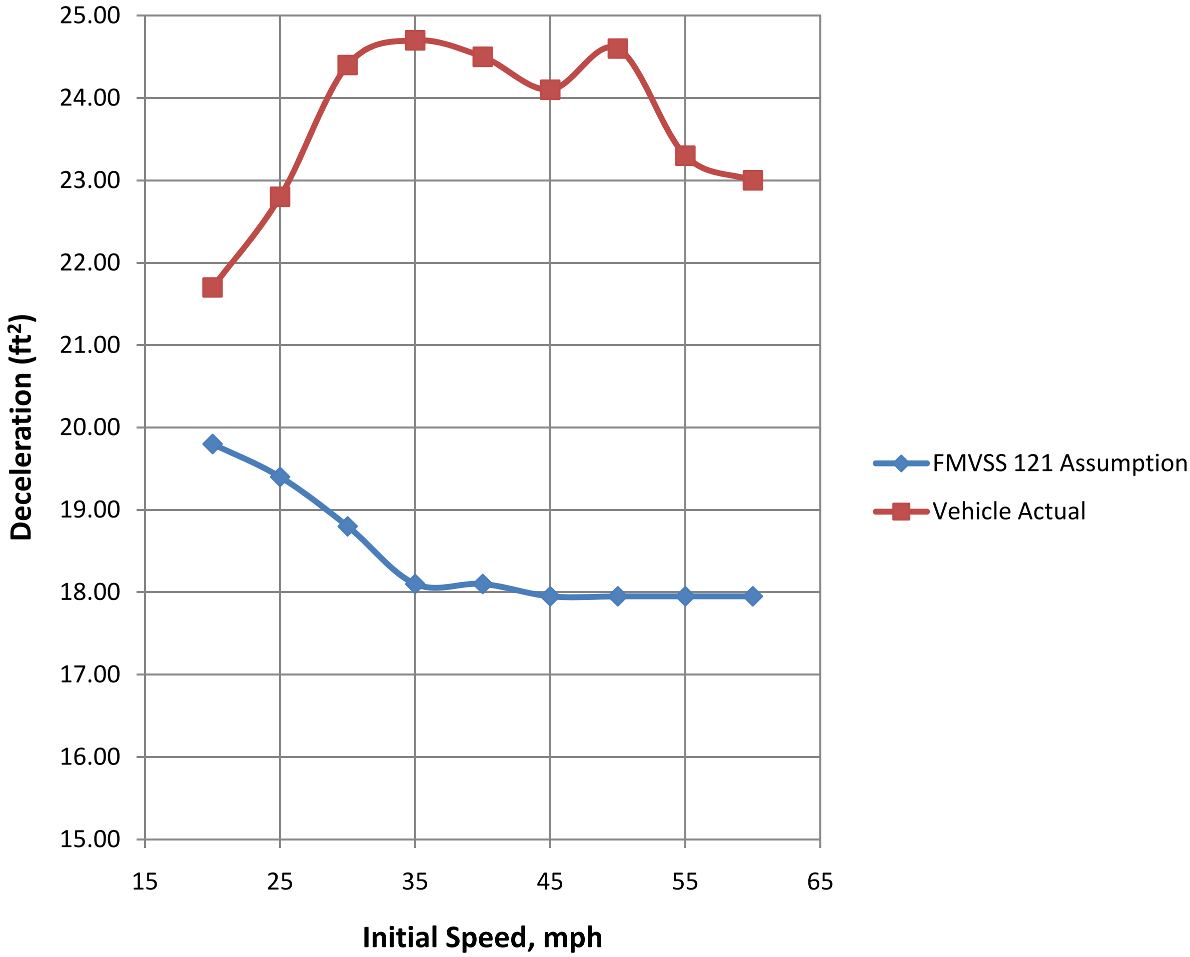

Figure 7: FMVSS No. 121 Assumed and Average Measured Deceleration graphed against Initial Speed at LLVW Loading

As Figure 7 and Table 20 show, actual measured steady state deceleration is substantially greater than FMVSS No. 121 assumed deceleration for the LLVW loading condition for all initial speeds. This is as expected since, as shown in Figure 5 and Table 16, actual measured corrected stopping distance is always less than maximum permitted stopping distance for all initial speeds for the LLVW loading. However, in violation of FMVSS No. 121 assumptions, there is a rapid decrease of steady state deceleration with initial speed for initial speeds below 35 mph.

Based in the issues above, the authors decided to further examine steady state deceleration. Equation 1 contains four parameters:

- S = Total Stopping Distance,
- V_0 = Vehicle Initial Speed,
- t_r = Deceleration Rise Time, and
- d_{ss} = Steady State Vehicle Deceleration.

If values for any three of these parameters are specified, then the corresponding value of the fourth parameter can be calculated. Therefore, the authors decided to specify the experimentally measured values of Total Stopping Distance, Vehicle Initial Speed, and Deceleration Rise Time and calculate the corresponding Steady State Vehicle Deceleration. Table 21 summarizes the results of this calculation for the MGVWR stops while Table 22 summarizes the results for the LLVW stops.

Table 21: Calculated Steady-State Deceleration from MGVWR Test Data

Initial Speed (mph)	Assumed Steady-State Deceleration (ft/sec^2)	Measured Steady-State Deceleration (ft/sec^2)	Calculated Steady-State Deceleration from Eq. 1 (ft/sec^2)	Measured minus Calculated Declaration (ft/sec^2)
60	16.80	17.30	16.60	0.70
55	16.80	18.50	17.60	0.90
50	16.80	18.70	17.60	1.10
45	16.80	19.10	17.90	1.20
40	17.00	19.80	18.50	1.30
35	17.00	21.00	19.20	1.80
30	17.50	20.70	19.10	1.70
25	18.00	21.40	19.70	1.70
20	18.00	20.00	17.10	2.90

Table 22: Calculated Steady-State Deceleration from LLVW Test Data

Initial Speed (mph)	Assumed Steady-State Deceleration (ft/sec^2)	Measured Steady-State Deceleration (ft/sec^2)	Calculated Steady-State Deceleration from Eq. 1 (ft/sec^2)	Measured minus Calculated Declaration (ft/sec^2)
60	17.95	23.00	22.50	0.50
55	17.95	23.30	22.60	0.70
50	17.95	24.60	23.70	0.90
45	17.95	24.10	23.30	0.80
40	18.10	24.50	23.50	0.90
35	18.10	24.70	23.60	1.10
30	18.80	24.40	23.50	0.90
25	19.40	22.80	21.90	0.90
20	19.80	21.70	20.00	1.70

Tables 21 and 22 demonstrate that measured steady state decelerations, as determined by numerically differentiating the speed channel and then averaging the resulting deceleration channel from the completion of the deceleration rise time until the end of stop time, are consistently higher than steady state decelerations calculated using Equation 1. The magnitude of this difference increases with decreasing initial speed. Reasons for this difference are not known. Also, it is not known which of these methods provides the best estimate for steady state deceleration.

In terms of the overall goal of this research, it probably does not matter which estimate of steady state deceleration is best. At an initial speed of 20 mph, measured average corrected stopping distance for the MGVWR loading exceeded maximum stopping distance permitted by FMVSS No. 121.

5.0 Summary and Conclusions

On July 27, 2009, the National Highway Traffic Administration (NHTSA) published a final rule amending Federal Motor Vehicle Safety Standard (FMVSS) No. 121, Air Brake Systems, to require improved stopping distance performance for truck tractors. This rule reduced maximum allowable stopping distance in the loaded to Gross Vehicle Weight Rating (GVWR) condition, for an initial speed of 60 mph, from 355 feet to 250 feet for "normal duty" truck tractors ("normal duty" truck tractors are two- or three-axle truck tractors with a GVWR of 70,000 pounds or less, and truck tractors with four or more axles and a GVWR of 85,000 pounds or less; these are the type of tractors examined in this report). For all truck tractors, maximum allowable stopping distance in the unloaded condition, for an initial speed of 60 mph, was reduced from 335 feet to 235 feet.

FMVSS No. 121 also contains maximum allowable stopping distances for vehicles that cannot attain a speed of 60 mph in two miles of driving on a flat, level roadway. If a vehicle cannot attain a speed of 60 mph, it is tested to ensure that it can meet maximum permitted stopping distance requirement from an initial speed that is four to eight mph less than the maximum speed that is attainable.

On September 10, 2009, NHTSA received a petition for reconsideration of the July 27, 2009 final rule from the Truck Manufacturers Association (TMA). In this petition, TMA states that NHTSA "did not conduct any testing at reduced speeds... [o]nly tests from an initial speed of 60 mph were conducted."[7] Also, TMA states that "the rulemaking record does not include any data to validate the equation used to derive the reduced speed stopping distance requirements in the final rule."[8]

The objective of this research was to obtain data on the stopping performance of one truck tractor-semitrailer combination vehicle from a range of initial speeds. The truck tractor tested was a 1991 Volvo 6x4 tractor. For the loaded condition testing, this truck tractor was towing the Transportation Research Center's (TRC's) 28 foot long, unbraked control trailer (loaded with the appropriate weights). Vehicle testing was performed in accordance with the Office of Vehicle Safety Compliance Laboratory Test Procedure No. TP-121V-04.

Since only one truck tractor was tested, a decision was made to modify its loading from the normal FMVSS No. 121 Loaded-to-GVWR condition. The loading was changed to a value such that the 60 mph stopping distance specified in FMVSS No. 121 was just achieved (the Modified Gross Vehicle Weight Rating (MGVWR) loading). It is the authors' belief that by loading this vehicle so as to just achieve the 60 mph stopping distance specified, the test results would provide greater insight into the appropriateness of stopping distance values from other initial speeds that are in FMVSS No. 121. As per FMVSS No. 121, this vehicle was also tested at its Lightly Loaded Vehicle Weight (LLVW).

Maximum permitted stopping distance according to FMVSS No. 121 for the GVWR loading condition matches average measured corrected stopping distance for the MGVWR loading condition for an initial speed of 60 mph. This is by design and is the criteria used to determine the MGVWR loading condition.

For the MGVWR loading condition, as initial speed decreased from 60 mph, average measured corrected stopping distance drops faster than maximum permitted stopping distance until an initial speed of 35 mph is reached. The MGVWR vehicle had the largest margin of compliance at an initial speed of 35 mph. As

[7] US Department of Transportation Docket Document NHTSA-2009-0083-0005, posted 9/17/2009
[8] Ibid

initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. The MGVWR vehicle had a negative margin of compliance at an initial speed of 20 mph.

Maximum permitted stopping distance according to FMVSS No. 121 for the LLVW vehicle is greater than average measured corrected stopping distance for all initial speeds. As initial speed decreased from 60 mph, average measured corrected stopping distance drops at the same rate as maximum permitted stopping distance until an initial speed of 35 mph is reached. The LLVW vehicle had a fairly constant (between 22.0 and 24.8 percent) margin of compliance for initial speeds from 60 to 35 mph. As initial speed decreased from 35 mph, maximum permitted stopping distance drops faster than average measured corrected stopping distance. The LLVW vehicle had its smallest (though still positive) margin of compliance at an initial speed of 20 mph.

Deceleration rise time is longer for the MGVWR loading condition than it is for the LLVW vehicle. It was expected that deceleration rise time would be longer for the MGVWR loading than for the LLVW vehicle since less air pressure is required to achieve maximum deceleration for the LLVW vehicle. The deceleration rise time for the MGVWR loading decreased with increasing initial speed. For the LLVW loading, deceleration rise time did not vary systematically with initial speed.

Average MGVWR and LLVW deceleration rise times, 0.43 and 0.30 seconds, respectively, are both less than the 0.45 second rise time that was used to calculate maximum permitted stopping distances in FMVSS No. 121. Assuming a 0.45 second deceleration rise is, therefore, conservative. This will tend to make it easier for vehicles to meet the FMVSS No. 121 requirements.

Actual measured steady state deceleration is greater than FMVSS No. 121 assumed deceleration for the MGVWR loading condition for all initial speeds. This is surprising since actual measured corrected stopping distance equals the maximum permitted stopping distance at an initial speed of 60 mph and exceeds maximum permitted stopping distance at an initial speed of 20 mph. This indicates possible discrepancies between the idealized deceleration shape used to calculate the FMVSS No. 121 values and the actual deceleration shape.

Actual measured steady state deceleration is substantially greater than FMVSS No. 121 assumed deceleration for the LLVW loading condition for all initial speeds. This is as expected since actual measured corrected stopping distance is always less than the maximum permitted stopping distance for all initial speeds for the LLVW loading. However, in violation of the FMVSS No. 121 assumptions, there is a rapid decrease of steady state deceleration with initial speed for initial speeds below 35 mph.

Based in the issues above, the authors decided to further examine steady state deceleration. The equation FMVSS No. 121 uses to calculate maximum permitted stopping distances for initial speeds below 60 mph contains four parameters. If values for any three of these parameters are specified, then the corresponding value of the fourth parameter can be calculated. Therefore, the authors decided to specify the experimentally measured values of Total Stopping Distance, Vehicle Initial Speed, and Deceleration Rise Time and calculate the corresponding Steady State Vehicle Deceleration.

Measured steady state decelerations, as determined by numerically differentiating the speed channel and then averaging the resulting deceleration channel from the completion of the deceleration rise time until the end of stop time, are consistently higher than the steady state decelerations calculated using the FMVSS No. 121 equation. The magnitude of the differences increases with decreasing initial speed. The reasons for the differences between the two steady state decelerations, one determined by numerically differentiating the speed channel and then averaging the resulting deceleration channel and the other determined by calculation from the FMVSS No. 121 equation, are not known. Also, it is not known which of these methods provides the best estimate for steady state deceleration.

In terms of the overall goal of this research, it probably does not matter which estimate of steady state deceleration is best. At an initial speed of 20 mph, measured average corrected stopping distance for the MGVWR loading exceeded the maximum stopping distance permitted by FMVSS No. 121.

Appendix A: 1991 Volvo 6x4 Truck Tractor Data

TEST VEHICLE INFORMATION: Note: Many characteristics are only available from Manufacturer provided information.

Year/Make/Model/Body Type 1991 White GMC (Made by Volvo)

VIN: 4VIWDBJH5NN645138

TRC/NHTSA NO.: TRC 162   Build Date: June 1991

ENGINE DATA: Type: Cummins, model # CUM91 N14-460E 460

TRANSMISSION: 18 speed x manual ____ automatic ____ overdrive

AXLE/DRIVE CONFIGURATION: 6 x 4

INITIAL ODOMETER READING: 65,471 miles.

OPTIONS:____

WHEELBASE (in.): 189.5

AERODYNAMIC TREATMENTS: Yes x   No ______

BRAKES:

Axles	Type[1]	Size	Make	Lining (Edge Code)
1	disc	16.54 x 1.77	Meritor	N/A
2	s-cam drum	16.5 x 7	Meritor	NA212FF47030
3	s-cam drum	16.5 x 7	Meritor	NA212FF47030

[1] Cam, disc, wedge, etc.

BRAKE DRUM/ROTOR:

Axles	Type[2]	Make	Dust Shields Installed?
1	rotor	Meritor	No
2	drum	Rockwell	No
3	drum	Rockwell	No

[2] Cast or composite drum, vented or non-vented rotor, etc.

ACTUATION DETAILS:

AIR CHAMBERS / SLACK ADJUSTERS

Axles	Make	Type[3]	Length or Wedge angle	Cam Rotation[4]
1	Meritor	20	5.5”	N/A
2	Meritor	30	5.5”	opposite
3	Meritor	30	5.5”	opposite

[3] Size and diaphragm or piston

[4] Same or opposite to forward wheel rotation

TIRES

Axles	Pressure (psi)	Size	Make	Model	Static Loaded Radius: Measured	Static Loaded Radius: Databook
1	105	275/80R24.5	Michelin	X2A-1	N/A	N/A
2	100	275/80R24.5	Michelin	XDA-3	N/A	N/A
3	100	275/80R24.5	Michelin	XDA-3	N/A	N/A

REMARKS:

ABS: Rear axle disabled

Mfr: Wabco Model: unknown Configuration: 4S/4M

FRONT SUSPENSION:

Type: leaf spring Make: Rockwell Model: 2FF961HX2-FF961

REAR SUSPENSION:

Type: leaf spring Make: Rockwell Model: RT40-145

Rear Axle Spread, (in): 96”

FIFTH WHEEL:

Fifth Wheel Height Relative to Ground, mm (in): 45”

Fifth Wheel Position, mm (in)[5]: 24.5”

[5] Relative to rear axle(s) centerline

Appendix B: 1977 Ravens Flatbed Semitrailer Data

TEST VEHICLE INFORMATION:

MANUFACTURE DATE: August 1977
MAKE AND MODEL: Ravens, modified flatbed trailer

VIN: 771207

TRC IDENTIFICATION: FMVSS 121 Control Trailer

AXLE CONFIGURATION AND SUSPENSION: Single Axle, air suspension

WHEELBASE (in.): 259 (center of axle to kingpin)

BED STYLE AND LENGTH: Flatbed, 28'

BRAKES: Not Equipped

TIRES

		Pressure (psi)	Size	Make
Axles:	1	100	11R22.5	Ameri-Harvest

REMARKS:

Originally manufactured as a 48' tandem spread axle aluminum trailer. Modified in-house to reduce deck length to FMVSS requirements, one axle retained with brakes removed, and adjustable ballast retention cage installed.

DOT HS 811 488
June 2011

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