NHTSA RESEARCH EFFORTS TO SIGNIFICANTLY IMPROVE BRAKING PERFORMANCE OF MEDIUM AND HEAVY TRUCKS

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ABSTRACT

In 1999, National Highway Traffic Safety Administration (NHTSA) researchers theorized that substantial improvements could be made in the braking performance of medium and heavy trucks. Therefore, NHTSA initiated a multi-year research program to learn what improvements in stopping performance could be achieved using advanced, but currently available, brake technology for medium and heavy trucks.

Truck tractors were the first type of heavy truck studied. Tractor testing results, including dry stopping distance, wet brake-in-curve stability evaluations, and wet split coefficient of friction stopping distances are presented. Testing results showed that a 30 percent reduction in maximum permissible dry stopping distances is possible for U.S. truck tractors, with no degradation in other performance areas. Objective measurements of brake torque, measured on NHTSA's inertial brake dynamometer at speeds up to 112.7 kph, are presented. Vehicle dynamics simulation results were used to understand effects that higher-torque brakes might have on jackknife stability during braking of tractor-semitrailer rigs.

Changing tractors to have all air disc brakes make braking performance improvements attainable with incremental costs that are outweighed by the expected benefits. Unforeseen improvements include a nominal 5 to 8 percent improvement in stopping distance during ABS-controlled stops on wet pavement, a result of significantly lower brake hysteresis with air disc brakes. Hybrid brake configurations, utilizing larger, more powerful S-cam drum brakes or air disc brakes on the steer axle only, are also shown to provide significant performance improvements over current foundation brakes. Based on this research, NHTSA has proposed revising FMVSS 121; shortening the maximum permitted stopping distance for truck tractors by 20 to 30 percent.

The paper concludes by briefly discussing NHTSA's research to improve the stopping performance of medium and heavy straight trucks.

INTRODUCTION

In the United States, Federal Motor Vehicle Safety Standards (FMVSS) 105 and 121 currently require medium and heavy trucks (vehicles with Gross Vehicle Weight Ratings (GVWR) of 4,537 kg to 11,794 kg are medium trucks, ones with a GVWR of more than 11,794 kg are heavy trucks) to stop from 96.6 kph, on a high coefficient of friction pavement and with properly working brakes, in the distances shown in Table 1. In comparison, FMVSS 135 requires light vehicles (vehicles with a GVWR of 4,536 kg or less except for motorcycles) to stop, in similar conditions, in 70.0 meters from 100.0 kph. These standards also set required failed system/emergency brake stopping distances (not shown). Required failed system/ emergency brake stopping distances are substantially longer for medium and heavy trucks than for light vehicles.

Table 1: Current Stopping Distance Requirements for Medium and Heavy Trucks

Type of Vehicle	Empty Stopping Distance	Loaded Stopping Distance
Bus	85.3 m	85.3 m
Single Unit Truck	102.1 m	94.5 m
Truck Tractor	102.1 m	N/A
Truck Tractor with Unbraked Control Trailer	N/A	108.2 m

In 1999, NHTSA researchers theorized that substantial improvements (approximately 30 percent reductions in stopping distance) could be achieved in the braking performance of medium and heavy trucks through the use of modern air disc or improved S-cam drum brakes. Based on this thinking, NHTSA Research and Development started performing research to improve medium and heavy trucks' stopping performance.

THE SAFETY PROBLEM

On March 10, 1995, NHTSA published three final rules that reestablished stopping distance requirements for medium and heavy trucks (a 1978 court decision had invalidated these requirements due to concerns about the reliability of medium and heavy truck antilock braking systems (ABS)). These rules also improved the directional stability and control of heavy vehicles during braking by mandating ABS on these vehicles. The phase-in period for the requirements of these rules ended on March 1, 1999.

Crash statistics indicate that the number of fatal and injury crashes for medium and heavy trucks built subsequent to this rulemaking has slightly declined even while the number of vehicle miles traveled (VMT) by these vehicles has increased. However, due to the large number of medium and heavy trucks in the United States, the total number of crashes for these vehicles remains high. Based on data contained in [1], during 2002:

- 434,000 medium and heavy trucks were involved in crashes in the United States.
- 4,542 medium and heavy trucks were involved in fatal crashes killing 4,897 people.
- 130,000 people were injured in medium and heavy truck crashes.

According to [2], in 2001 the medium and heavy truck fatality rate (fatalities per 100 million VMT) was 60 percent higher than the comparable rate for light vehicles (those vehicles with a GVWR of 4,536 kg or less).

NHTSA'S STRATEGY

NHTSA decided to initially focus its research (and subsequent rulemaking) efforts on truck tractors (referred to simply as "tractors" throughout the remainder of this paper). The reasons for selecting this type of vehicle to be our focus were:

1. According to [2], in 2001 while the medium and heavy truck fatality rate was 60 percent higher than the comparable rate for light vehicles, the fatality rate for combination vehicles (tractors pulling one or more trailers) was nearly double that of light vehicles. In comparison, the fatality rate for single-unit trucks was 15 to 20 percent higher than the fatality rate for light vehicles.

2. From [3], although medium trucks (GVWR) of 4,537 kg to 11,794 kg) comprised almost 45 percent of truck sales during the years 2000 – 2001, they were involved in just 11 percent of fatal crashes. Heavy trucks, over half of which are tractors, were involved in the other 89 percent of fatal crashes. Combination vehicles were involved in 2,686 fatalities (63 percent of medium and heavy truck fatalities).

3. There are a relatively limited number of kinds of tractors. The most common tractor is the standard-weight three-axle 6x4 with a front gross axle weight rating (GAWR) of 6,623 kg or less and a rear tandem drive axle with a GAWR of 20,412 kg or less. According to the Truck Manufacturers Association (TMA) and Freightliner, this type of tractor comprises 82 percent of United States production. Freightliner stated that two-axle 4x2 tractors comprise ten percent of tractor production, and severe service tractors comprise seven percent (due to rounding, Freightliner's numbers add to 99 percent). TMA described a severe service tractor as having three axles with either a steer axle GAWR greater than 6,623 kg or tandem drive axles with a total GAWR greater than 20,412 kg. In addition, severe service tractors include those tractors with twin steer axles, auxiliary axles (e.g., lift axles), and/or tridem drive axles. Chassis configurations include 6x4, 8x4, 8x6, 10x6 and 14x4 layouts. However, the specialty chassis configurations (anything other than 6x4) comprise only about one percent of all United States tractor production. For research purposes, NHTSA decided to focus on the standard-weight 6x4 tractor and the 4x2 tractor. NHTSA is currently in the process of performing testing using a simulated 6x4 severe-service tractor.

4. In contrast to tractors, there are many common configurations of straight trucks, including large pickup trucks, flat-bed trucks, trash trucks, dump trucks, and concrete mixers. Much more effort is required to research these many configurations than is the case for tractors.

5. While there are only a limited number of common trailer configurations, NHTSA researchers theorized that most of the improvement in vehicle stopping performance would come from increasing the torque output of the front brakes of a vehicle. Therefore, much more limited safety benefits will be achieved by improving trailer brakes.

While NHTSA is obviously interested in also improving the stopping performance of medium and heavy straight trucks, the research necessary to perform rulemaking for this type of vehicle was delayed until after the tractor research was completed. Straight truck research is currently in progress and will briefly be described at the end of this paper. Research to improve trailer brakes may be performed after the completion of the straight truck research.

Trailer brake stopping distance improvement research has not yet begun and will not be discussed further in this paper.

METHODOLOGY FOR NHTSA DRY TRUCK TRACTOR STOPPING DISTANCE RESEARCH

Research was initiated at NHTSA's Vehicle Research and Test Center (VRTC) in 2001 to evaluate possible improvements in tractor braking performance.

NHTSA researchers, based partially on discussions with air brake suppliers, theorized that most of the improvement in tractor stopping performance would come from increasing the torque output of the front brakes of the tractor. Based on information received and NHTSA's testing experience, NHTSA researchers thought that tractor front axles typically were "underbraked," i.e., their brakes could not produce enough torque to lock up the wheels on the front axle during a full treadle brake application on a high coefficient of friction pavement. There was also thinking that air disc brakes, on all axles, would improve stopping performance due to improved fade resistance and greater torque production consistency.

Based upon this, NHTSA decided to study tractors with four foundation brake configurations: standard S-cam drum brakes plus three "advanced" configurations. The foundation brake configurations examined were:

1. Standard S-cam drum brakes on all axles. These were the brake configurations received with the two 6x4 tractors tested when they were purchased from their manufacturers. This brake configuration will be referred to as "standard drum" throughout the remainder of this paper.

2. Larger S-cam drum brakes on the steer axle and standard S-cam drum brakes on the rear axles. Larger (hence higher torque output), but still commercially available, S-cam drum brakes were fitted onto the steer axle. This was the brake configuration received with the 4x2 tractor tested when it was purchased. This brake configuration was expected to be a relatively inexpensive method of improving tractor braking. However, it was not clear prior to performing this research how much improvement in stopping performance would be gained from this brake configuration versus the improvement that could be gained with the more expensive brake configurations listed below. This brake configuration will be referred to as "hybrid drum" throughout the remainder of this paper.

3. Air disc brakes on the steer axle and standard S-cam drum brakes on the rear axles. Commercially available air disc brakes were fitted onto the steer axle. Air disc brakes typically have substantially greater torque output than do standard steer-axle S-cam drum brakes. This brake configuration was expected to cost more than the hybrid drum configuration but less than the all air disc configuration (described below). This brake configuration will be referred to as "hybrid disc" throughout the remainder of this paper.

4. Air disc brakes on all axles. This brake configuration was expected to be the most expensive bake configuration tested. This brake configuration will be referred to as "all disc" throughout the remainder of this paper

All brake configurations, other than those received when the vehicles were purchased from their manufacturers, were field retrofitted onto the vehicles at VRTC. All of the parts used during these retrofits were commercially available. While the brakes on the retrofitted vehicles worked well, they may not have been as optimized to work with each vehicle's ABS system as were each vehicle's original brakes. Therefore, the braking improvements seen in VRTC's testing are believed to be conservative; manufacturers could do better by optimizing a vehicle's original equipment brakes.

Additional information about the brakes used for each foundation brake configuration is contained in [4] and [5].

Three tractors were tested. All three tractors were fitted with original equipment ABS. Two of these were standard-weight 6x4 tractors: a 1991 Volvo 6x4 tractor and a 1996 Peterbilt 6x4 tractor, both of which had 5,443 kg gross axle weight rating (GAWR) steer axles, 17,237 kg GAWR tandem drive axles, and of 22,680 kg GVWRs. The third tractor was a 2000 Sterling 4x2 tractor with a 5,443 kg GAWR front axle, a 10,297 kg GAWR rear axle, and a 15,740 kg GVWR.

The Sterling 4x2 tractor was originally tested with its as received wheelbase (3.759 m). However, in response to industry concerns that a shorter wheelbase 4x2 tractor might have more stability problems, VRTC has shortened the wheelbase of this tractor to 3.454 m. At the time this paper was written, VRTC was in the process of retesting this tractor. Limited preliminary results are included in this paper.

Tractors were tested at two loadings: LLVW and GVWR. LLVW consisted of a "bobtail" tractor (i.e., one not towing a trailer) that was empty except for a test driver and instrumentation. In the GVWR loading, the tractor was towing an unbraked control trailer of the type used for FMVSS 121 tests. This single axle trailer was loaded so as to achieve the tractor GVWR plus 2,041 kg on the trailer axle.

The following information about the testing methodology is taken from [4]. Additional details may be found in that report.

Full-treadle braking stops were conducted for each tractor at both loadings for each brake configuration. The experienced professional test driver was instructed to fully apply the brakes within 0.2 seconds after the initiation of braking. Full-treadle brake applications were used to obtain the shortest possible stops and to maximize repeatability; each vehicle's ABS modulated the brake line pressure at each wheel so as to prevent wheel lockup from occurring. Stopping distance testing was performed in accordance with the FMVSS 121 test procedure.

Testing was performed on the Transportation Research Center, Inc.'s dry concrete skid pad. This pad has nominal peak and slide coefficients of friction of 98 and 84, respectively.

Brake pad temperatures were monitored as outlined in the FMVSS 121 test procedure. Initial brake pad and/or lining temperatures were in the range of 65.5 to 93.3° C prior to the initiation of each stop.

Stopping distances were measured with a fifth wheel assembly mounted on the tractor frame. Stopping distances were recorded using a Labeco Tracktest Fifth Wheel System Performance Monitor, which displays both the speed at which the brakes were first applied and the vehicle's stopping distance. All measured stopping distances were corrected as per the standard method prescribed in SAE J299 to the intended initial speed of 96.6 kph. Six consecutive repetitions were performed for each tractor-loading-brake configuration tested.

Both average and minimum stopping distances were computed from the six stops. While this paper focuses on the minimum stopping distances (since these are what is used in FMVSS 121 compliance testing), average stopping distance results are contained in [4]. The spread of stopping distances during the six stops was generally small. The difference between the average and the minimum stopping distance was typically three to four percent.

RESULTS FROM NHTSA DRY TRUCK TRACTOR STOPPING DISTANCE RESEARCH

Some of the stopping distances presented in the tables below are taken from [4]. The remainder are new data collected by VRTC.

Tables 2 through 5 summarize the bobtail stopping distances for each of the tractors tested for each foundation brake configuration. Each of these tables includes a column titled Margin of Compliance which contains the percentage by which the measured stopping distance is less than the mandated maximum of 102.1 m.

Table 2: Measured LLVW Stopping Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	61.9	39.4
Hybrid Drum	61.0	40.3
Hybrid Disc	53.9	47.2
All Disc	55.2	46.0

Table 3: Measured LLVW Stopping Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	67.7	33.7
Hybrid Drum	58.2	43.0
Hybrid Disc	53.9	47.2
All Disc	53.6	47.5

Table 4: Measured LLVW Stopping Performance for 2000 Sterling 4x2 Tractor (3.759 wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	58.2	43.0
Hybrid Disc	54.6	46.6
All Disc	55.8	45.4

Tables 6 through 9 summarize the stopping distances for each of the tractors tested loaded to GVWR (by towing an unbraked control trailer) for each foundation brake configuration. Again, each of these tables includes a margin of compliance column. This shows the percent margin of compliance versus the 108.2 m maximum permitted by FMVSS 121.

Table 5: Measured LLVW Stopping Performance for 2000 Sterling 4x2 Tractor (3.454 m wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	57.9	43.3
Hybrid Disc	52.7	48.4
All Disc	Not Yet Tested	N/A

Table 6: Measured GVWR Stopping Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	79.2	26.8
Hybrid Drum	80.4	25.6
Hybrid Disc	75.9	29.9
All Disc	71.6	33.8

Table 7: Measured GVWR Stopping Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	93.6	13.5
Hybrid Drum	76.2	27.0
Hybrid Disc	71.3	34.1
All Disc	66.4	38.6

Table 8: Measured GVWR Stopping Performance for 2000 Sterling 4x2 Tractor (3.759 wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	73.5[1]	32.1
Hybrid Disc	68.0	37.2
All Disc	61.0	43.7

[1] The stopping distance achieved with original equipment brake linings was not repeatable with replacement linings. With replacement brake linings, a minimum stopping distance of 101.2 m was achieved for the hybrid drum configuration. This was the only condition for which different stopping performance was found with replacement linings.

Table 9: Measured GVWR Stopping Performance for 2000 Sterling 4x2 Tractor (3.454 m wheelbase)

Foundation Brake Configuration	**Minimum Stopping Distance** (m)	**Margin of Compliance** (percent)
Standard Drum	Not Tested	N/A
Hybrid Drum	87.8	18.9
Hybrid Disc	71.0	34.4
All Disc	Not Yet Tested	N/A

For tractors tested loaded to GVWR (by towing a loaded, unbraked control trailer), the situation is not as good as it was for the LLVW tractors. While all vehicles easily met the FMVSS 121 requirement, compliance margins exceeding 30 percent were generally achieved only for foundation brake configurations that included air disc brakes on at least the tractor's steer axle.

Data from NHTSA's dry pavement testing confirmed NHTSA researchers' theory that improvements in tractor stopping performance could be achieved by increasing the torque output of the front brakes of the tractor. This trend is clearly present in the data presented in Tables 2 through 9.

All foundation brake configurations tested have some margin of compliance versus the current FMVSS 121 standards. To determine whether a 30 percent reduction in maximum permitted stopping distances is feasible with the advanced brake configurations, the test results in Tables 2 through 9 are compared to the reduced stopping distance (i.e., a 30 percent reduction from either 102.1 m (71.5 m) or 108.2 m. (75.7 m)). For example, the hybrid disc configuration in Table 7 would show a 5.8 percent margin of compliance for the reduced stopping distance. Likewise, the all disc configuration would have a 12.3 percent margin of compliance. Although the margins of compliance are lower with the reduced stopping distances, both tractors and loadings tested had at least one advanced brake configuration that stopped shorter than the reduced stopping distance. The test results show that a 30 percent reduction in the maximum permitted stopping distances in FMVSS 121 is feasible.

Additionally, at GVWR for all tractors for which data are currently available, an improvement in stopping performance was seen from the hybrid disc case to the all disc case. For these two brake configurations, the front brake torque is being generated by the same brake hardware. Even though the front brake torques for these two cases are the same, the margin of compliance for the all disc configuration averaged 5.0

percent higher than for the hybrid disc case. This effect is believed to be due to the improved fade resistance of the all disc configuration since no improvement was seen for the LLVW case. (Brake fade should be less of a problem at lighter loadings.)

METHODOLOGY FOR NHTSA WET TRUCK TRACTOR BRAKE RESEARCH

Brake in a wet, slippery curve stability testing and straight-line stopping on a wet, split-coefficient of friction surface testing (split-mu testing for short) were performed for both the 1996 Peterbilt and the 1991 Volvo 6x4 tractors. Additional information about this testing can be found in [6].

Brake-in-curve stability testing was performed to check for any possible degradation in vehicle lateral stability during braking due to one of the advanced foundation brake configurations. This testing was performed on a wetted Jennite surface on the Transportation Research Center, Inc.'s Vehicle Dynamics Area. The test surface was wetted within one minute of the commencement of each braking run. A single 3.7 m wide lane was marked with pylons on a 152.4 m radius curve. The measured peak coefficient of friction of this curve varied between 0.30 and 0.46 during this testing. (The slide coefficient of friction was not monitored.) This varying peak coefficient of friction caused the FMVSS 121 brake-in-curve passing speed to change from vehicle to vehicle and from brake configuration to brake configuration.

The brake-in-curve stability test protocol began by performing the procedures contained in S5.3.6 of FMVSS 121 and in Section 10.3-D of the FMVSS 121 Laboratory Test Procedure [7]. Following completion of the FMVSS 121 brake-in-curve stability procedure, testing was continued to find the maximum initial (i.e., curve entry) speed at which the professional test driver (with more than 10 years experience) could keep the vehicle within the 3.7 m lane while braking in the curve. To determine the maximum initial speed, the initial speed was increased by 1.6 kph increments above the terminal speed that was determined during the FMVSS 121 brake-in-curve stability testing, up to the speed at which the vehicle consistently slid out of the lane.

NHTSA researchers hypothesized that vehicles with air disc brakes will stop in a shorter distance in a split-mu situation. Split-mu testing was performed to test this hypothesis. This testing was also performed on the Transportation Research Center, Inc.'s Vehicle Dynamics Area. The test course consists of one half lane of wetted asphalt and one half lane of wetted Jennite. The measured peak/slide coefficients of friction of the wetted asphalt averaged 0.86/0.60 while for the wetted Jennite they averaged 0.35/0.10 during this testing.

For test efficiency, a stop from an initial speed of 48.2 kph was made in one direction (east-to-west), then a stop in the opposite direction (west-to-east). Six stops were performed at each test condition, three in each direction. Again, both average and minimum stopping distances were computed from the six stops. While this paper focuses on the minimum stopping distances (since these are what is used in FMVSS 121 compliance testing), average stopping distance results are contained in [6].

The test driver was instructed to establish 48.2 kph while approaching the wetted test course in a straight-ahead approach. Upon reaching a traffic pylon (positioned such that the entire vehicle would be on the wetted surface at the instant braking began), the driver would apply full treadle braking within 0.2 seconds. The professional test driver would apply corrective steering during the stop to keep the vehicle inside the 3.7 m lane.

Stopping distance data collection and correction were performed in the same manner as was discussed for the dry stopping distance research.

RESULTS FROM NHTSA WET TRUCK TRACTOR BRAKE RESEARCH

Tables 10 through 13, which contain data from [6], summarize the results of the FMVSS 121 portion of the brake-in-curve testing. As the tables show, both tractors passed the FMVSS 121 brake-in-curve requirement for all foundation brake configurations. However, the hybrid drum and hybrid disc configurations seem to be performing slightly worse, only passing three out of four tests (the FMVSS 121 required minimum number of passes) in the LLVW Peterbilt test.

Table 10: LLVW Brake-in-Curve FMVSS 121 Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	37.0	4
Hybrid Drum	38.7	4
Hybrid Disc	40.3	3
All Disc	41.9	4

Table 11: LLVW Brake-in-Curve FMVSS 121 Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	40.3	4
Hybrid Drum	45.1	3
Hybrid Disc	43.5	3
All Disc	40.3	4

Table 12: GVWR Brake-in-Curve FMVSS 121 Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	37.0	4
Hybrid Drum	37.0	4
Hybrid Disc	40.3	3
All Disc	41.9	4

Table 13: GVWR Brake-in-Curve FMVSS 121 Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**FMVSS 121 Passing Speed** (kph)	**Number of Stops Passed**
Standard Drum	40.3	4
Hybrid Drum	41.9	4
Hybrid Disc	46.7	3
All Disc	40.3	4

As was mentioned above, following completion of the FMVSS 121 brake-in-curve stability procedure, testing was continued to find the maximum initial speed at which the test driver could maintain the vehicle within the 3.7 m lane while braking in the curve. The limit vehicle initial speed was used to calculate its "Lateral Acceleration Performance Quotient" (LAPQ). LAPQ is defined as the ratio of the maximum attainable lateral acceleration (calculated from curve radius and initial speed) during the brake-in-curve test divided by the maximum drive-through lateral acceleration (with no braking) expressed as a percentage. Rationalizing vehicle/brake configuration performances in this way normalizes the limit brake-in-curve speed as a function of the limit drive-through speed. Since both tests were performed on the same day, the variability of the pavement's coefficient of friction is largely mitigated.

Tables 14 through 17, which contain data from [6], summarize the results of the LAPQ portion of the brake-in-curve testing.

Table 14: LLVW Brake-in-Curve LAPQ Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	49.9	40.3	65
Hybrid Drum	51.5	41.9	66
Hybrid Disc	53.1	49.9	57
All Disc	54.7	40.3	83

Table 15: LLVW Brake-in-Curve LAPQ Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	53.1	54.7	103
Hybrid Drum	59.6	54.7	92
Hybrid Disc	58.0	49.9	74
All Disc	53.1	53.1	100

Table 16: GVWR Brake-in-Curve LAPQ Performance for 1991 Volvo 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	48.3	45.1	87
Hybrid Drum	49.9	38.6	60
Hybrid Disc	53.1	45.1	72
All Disc	54.7	54.7	100

Table 17: GVWR Brake-in-Curve LAPQ Performance for 1996 Peterbilt 6x4 Tractor

Foundation Brake Configuration	**Max Drive-Through Speed** (kph)	**Limit BIC Speed** (kph)	**LAPQ** (%)
Standard Drum	53.1	54.7	106
Hybrid Drum	56.4	56.4	100
Hybrid Disc	62.8	51.6	67
All Disc	53.1	46.7	77

Just as with the number of passes of FMVSS 121 brake-in-curve requirement, for LAPQ the hybrid drum and hybrid disc configurations seem to be performing slightly worse than the standard drum and all disc configurations. NHTSA researchers speculate that this may be because the hybrid brake configurations are not as optimally tuned as the standard drum or all disc configurations. Additional research would be required to prove or disprove this conjecture.

Stopping distance results from the split-mu testing were analyzed combining results from both tractors. This was done so as to give a more representative comparison of foundation brake effects for the real world in which there is a large and varied fleet of 6x4 tractors having different layouts in terms of suspension design, wheelbase, ABS controls, etc.

Tables 18 and 19, which contain data from [6], summarize the results of the split-mu testing with data from the two tractors combined together.

Table 18: LLVW Split-Mu Performance with Data From the Two Tractors Combined

Foundation Brake Configuration	**Mean Stopping Distance** (m)	**Standard Deviation** (m)
Standard Drum	32.1	1.5
Hybrid Drum	32.5	3.9
Hybrid Disc	31.6	1.1
All Disc	29.3	1.1

Table 19: GVWR Split-Mu Performance with Data From the Two Tractors Combined

Foundation Brake Configuration	**Mean Stopping Distance** (m)	**Standard Deviation** (m)
Standard Drum	30.1	2.0
Hybrid Drum	30.8	1.7
Hybrid Disc	30.8	0.6
All Disc	28.3	0.8

Examination of Tables 18 and 19 leads to two interesting points. First, the mean stopping distance at both the LLVW and GVWR loadings is shortest for the all disc foundation brake configuration. All brake configurations, for any load condition up to and including GVWR, were capable of locking the wheels on any axle while on the split-mu course (this is not the case for the dry pavement testing). Therefore, the apparent advantage in stopping ability on the split-mu course for the all disc foundation brake configuration is attributed to efficiencies in their operation beyond their ultimate capacity to generate brake torque.

Second, the GVWR stopping distance variability (as indicated by the standard deviation of stopping distance) was lower for the configurations that include air disc brakes. This indicates that the air disc brakes have a more consistent torque output than do drum brakes. Improved consistency of torque output (versus drum brakes) is seen for hydraulic disc brakes; it appears that this characteristic also carries over to air disc brakes.

These two topics are further discussed at the end of the section of this paper that presents brake dynamometer testing and results.

The split-mu data were analyzed on a tractor-by-tractor basis. However, due to space limitations, a summary of this analysis is not included in this paper. The interested reader is referred to [6].

BRAKE DYNAMOMETER TESTING AND RESULTS

In support of NHTSA's studies of heavy truck brake types and their effects on vehicle stopping performance and stability, NHTSA VRTC evaluated four brakes on its Greening Brake Dynamometer. Results from this study are more fully documented in [8]; only a summary is given here.

Two S-cam drum brakes and two air disc brakes were tested. The two S-cam drum brakes were the two S-cam drum brakes that were on the rear axles of the 1991 Volvo and 1996 Peterbilt when they were tested in their standard drum configuration. Similarly, the two air disc brakes tested were the two rear axle air disc brakes from these vehicles when tested in their all disc configuration. One disc and one drum brake were from Manufacturer A; the other disc and drum brake were from Manufacturer B. To allow data to be treated statistically, five copies of each brake were tested.

The brakes were tested on VRTC's Greening Brake Dynamometer. The dynamometer was set up to simulate the conditions seen by the rear axles of the Volvo and Peterbilt during the testing described earlier in this paper. Testing consisted of five parts: brake burnish, retardation testing, fade and recovery testing, additional retardation testing, and dynamic input testing. The brake burnish, retardation testing, and fade and recovery testing were performed in accordance with the FMVSS 121 dynamometer test procedures described in [9].

Following completion of the FMVSS 121 testing, additional retardation testing was performed. Additional retardation tests with 620 and 690 kPa brake applications at 80.5 kph were performed. The brake retardation procedure was then repeated for speeds of 48.3, 96.6, and 112.7 kph, at treadle application pressures from 138 to 690 kPa.

After completion of additional brake retardation testing, some brake assemblies were subjected to low frequency dynamic pressure inputs designed to evaluate the brake assembly's transient response characteristics. The input pressure dynamics were intended to compare how different brakes might perform under the control of ABS or Electronic Stability Control systems. The dynamic input stops were performed from speeds of 48.3, 80.5, and 96.6 kph. The following five dynamic inputs were used:

1. Sinusoidal input,
2. Triangular wave input,
3. Swept sinusoidal input,
4. Step input, and
5. Series of step inputs.

A complete description of these inputs is in [9].

Sample results from the brake dynamometer testing are shown below. Again, more complete results are contained in [9]. Figure 1 summarizes the brake retardation test results for Manufacturer A's S-cam drum brake. Each data point represents the mean of data from five brakes tested at speeds of 48.3, 80.5, 96.6, and 112.7 kph for a range of brake application pressures. Third order polynomial fit lines indicating the 95 percent confidence intervals about the mean torque outputs bound the data series for each speed. As can be seen from Figure 1, there is a 50 percent reduction in the S-cam drum brake's output torque for an application pressure of 690 kPa as the speed in increased from 48.3 to 112.7 kph.

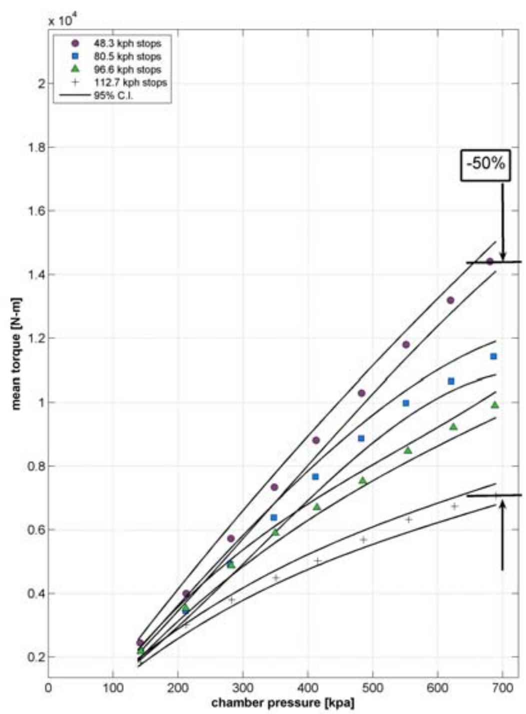

Figure 1: S-cam drum brake torque spreads – Manufacturer A.

Figure 2 summarizes the brake retardation test results for Manufacturer A's air disc brake. The format of this figure is exactly the same as Figure 1's; only the brake tested has changed. As can be seen from Figure 2, there is a 21 percent reduction in the air disc brake's output torque for an application pressure of 690 kPa as the speed is increased from 48.3 to 112.7 kph.

Similar figures are available for Manufacturer B's brakes. Due to space limitations, these figures are not included in this paper. However, they show the same trends as Figures 1 and 2. Table 20 summarizes the reduction in torque output for all four brakes tested torque for an application pressure of 690 kPa as the speed is increased from 48.3 to 112.7 kph.

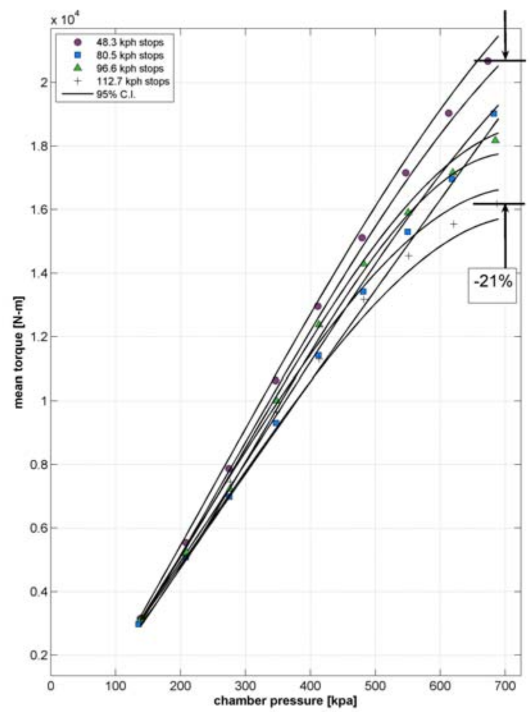

Figure 2: Air disc brake torque spreads – Manufacturer A.

Table 20: Nominal Percent Loss in Maximum Brake Torque as Speed is Increased from 48.3 to 112.7 kph.

Brake Type	Manufacturer A	Manufacturer B
S-cam Drum	-50 %	-42 %
Air Disc	-21 %	-24 %

The air disc brakes retained much more of their low-speed performance potential at high speeds than did their S-cam brake counterparts. However, the low-to-medium speed performance of the S-cam brakes could be on par with the air disc assemblies, given the appropriate combination of brake chamber size, slack adjuster length, and lining and drum materials. The performance differences at higher vehicle braking speeds are directly attributable to thermal and mechanical disadvantages that affect S-cam drum brakes' performance at high speed and energy levels.

One set of results from the dynamic pressure input testing is shown in Figure 3. This figure is for Manufacturer A's S-cam drum and air disc brakes. The particular dynamic pressure input used to generate Figure 3 is a sinusoidal input with a period of 2.5 seconds. Normalized (current brake torque divided by maximum brake torque expressed as a percentage) hysteresis plots are shown. The upper panel shows data from Manufacturer A's S-cam drum brake while the lower panel shows data from Manufacturer A's air disc brake.

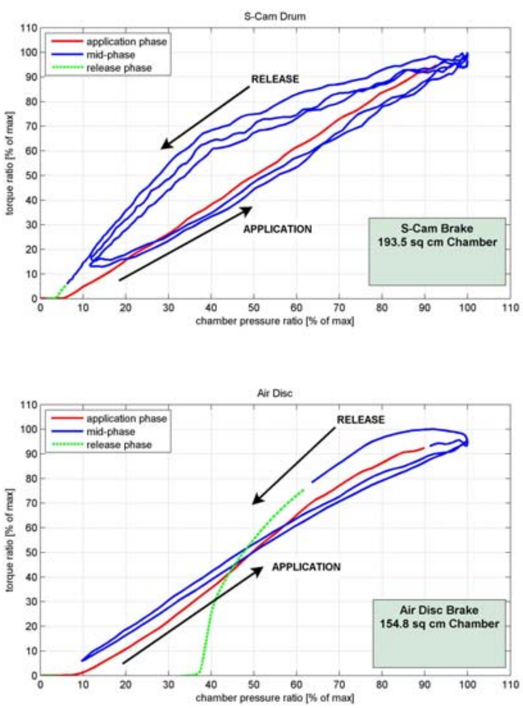

Figure 3: Sinusoidal wave input (2.5-second period) from 96.6 kph on S-cam drum (type 30 chamber) and air disc (type 24 chamber) brakes by Manufacturer "A" – normalized torque versus pressure.

Figure 3 shows that the air disc brake had less hysteresis than the corresponding A's S-cam drum brake. Similar results were seen for the other brake for the other smoothly varying dynamic pressure inputs.

Another set of results from the dynamic pressure input testing is shown in Figure 4. This figure shows hysteresis for an abruptly changing pressure input (a step with a very fast rise time). As Figure 4 shows, there was a substantial increase in air disc brake hysteresis, to approximately the levels seen for S-cam drum brakes, for the suddenly changing step inputs.

The reduction in hysteresis for smoothly varying dynamic pressure inputs is believed to be, at least partially, responsible for the advantage in stopping ability on the split-mu course for the all disc foundation brake configuration that was pointed out earlier in this paper. It is also thought to contribute to the reduction in stopping distance variability on a split-mu surface that is seen for configurations that include air disc brakes.

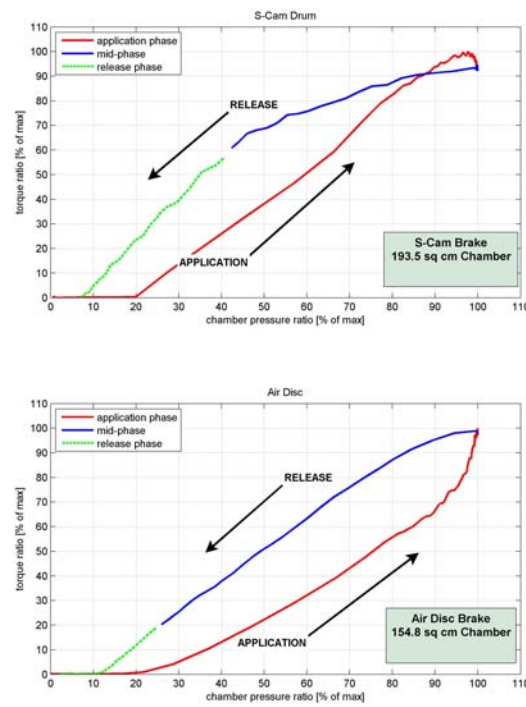

Figure 4: Step input and release from 96.6 kph on S-cam (type 30 chamber) and air disc (type 24 chamber) of Manufacturer "A" – normalized torque versus pressure.

On the split-mu course, the coefficient of friction between the vehicles' tires and the pavement limited stopping distance, not the magnitude of the torques generated by the vehicles' brakes. In other words, the vehicles' brakes had sufficient capacity to lock up the vehicles' tires; the brakes could do no more to stop the vehicle. To prevent wheels from locking up, the vehicles' ABS was cycling during the stop. The cycling of the ABS generates smoothly varying dynamic pressure inputs of the type for which S-cam drum brakes exhibit higher hysteresis than do air disc brakes. This higher hysteresis increases the percent of time for which the torque output of S-cam drum brakes is reduced due to the cycling of the ABS. This in turn, increases the vehicles' stopping distances. It also increases the variability in vehicles' stopping distances by making the torque produced by a brake for a given application pressure depend more upon the time history of the air pressure at the brake chamber.

SIMULATION STUDY OF EFFECTS OF SHORTER TRUCK TRACTOR STOPPING DISTANCES ON JACKKNIFE STABILITY

One concern with improving the braking performance of tractors is that this requires more force to be transmitted from the tractor to the semitrailer during braking. This increased force is transmitted through the articulation point formed by placing the fifth wheel/kingpin into compression. If the vehicle is not traveling straight ahead, a component of the force acting through the wheel/kingpin articulation point acts to push the rear tandem axle (assuming a 6x4 tractor; nothing really changes for a 4x2 tractor except that "rear tandem axle" would be replaced by "rear axle") sideways. If the rear axle(s) is pushed too hard sideways, its limit of adhesion might be exceeded. When this occurs, the rear axle(s) move rapidly sideways and a "jackknife" occurs. (A jackknife is defined as an event in which the tractor rotates rapidly in yaw until it strikes the semitrailer.)

Due to the relatively small changes in the forces involved, this is a difficult topic to study by means of test track testing. Therefore, NHTSA researchers decided to perform a simulation study to examine whether the theoretical mechanism just described will, in fact, occur for actual tractors. Additional details about this research, beyond those that will fit into this paper, are contained in [10].

The heavy truck dynamics simulation package used for this research was TruckSim™ version 5.0 [11]. The TruckSim software is a commercially available, multi-body dynamics simulation package intended for use in simulating medium and heavy trucks. It treats the vehicle chassis, suspension, and drivetrain masses as a collection of rigid bodies. Linear and nonlinear forces and moments both act on the vehicle and are applied internally to hold the vehicle together. The TruckSim software simulates the dynamics of the vehicle, including highly nonlinear aspects such as tire force models, suspension deflection models, leaf spring models, and the hitch model.

The tractor simulated during this research was the same 1991 Volvo 6x4 that has been used for much of the testing described in this paper. For this simulation research, the Volvo tractor was towing a 16.0 m long 1992 Fruehauf van trailer. The geometric, inertial, steering, suspension and tire properties of this tractor-semitrailer are documented in [12] and [13]. The validation of this model is documented in [14].

One attractive feature of TruckSim is that advanced vehicle component models, written using Simulink, can be used to model portions of the vehicle that are of particular interest for a research program in far greater detail than they are normally modeled by TruckSim. For this research, an advanced brake system model was developed. A nonlinear Simulink model was written that provided a detailed model of the Volvo tractor/Fruehauf trailer's brake system dynamics, brake torque outputs, and brake hysteresis. This model is described in greater detail in [10] and [15].

The detailed brake system model developed for this research includes the following significant features:

- First-order differential equations model system dynamics for the control (treadle) circuit and main brake actuation circuits.
- Time delays for control (treadle) signals are based on the physical location of the associated modulator valve.
- Four-sensor/four-modulator (4s/4m) integrated ABS control system for the tractor.
- Two-sensor/two-modulator (2s/2m) integrated ABS control system for the semitrailer.
- Simulated ABS controller calculations lag.
- ABS control strategy based on longitudinal wheel slip level and tangential acceleration, tuned to match actual vehicle performance on wet and dry surfaces.
- Quadratic model of brake torque output as a function of application speed and chamber pressure.
- Brake system hysteresis as seen in modern S-cam drum brakes.
- The ability to simulate air disc brakes with various sizes of pneumatic brake chambers using data generated by VRTC's Greening Brake Dynamometer.

The simulation study examined the performance of the Volvo tractor towing the Fruehauf semitrailer.

The Volvo tractor was equipped with either S-cam drum brakes or air disc brakes. The Fruehauf semi-trailer was always equipped with S-cam drum brakes.

Two vehicle loadings were simulated: no payload, and with the semitrailer loaded with five concrete blocks (two in the front of the semitrailer, three in the rear), each with a mass of 1,928 kg. This loaded the combination vehicle to one-half of GVWR. GVWR loading was not simulated because preliminary analyses indicated that, for the situations being studied, jackknifing was more likely to occur with a less loaded vehicle.

These preliminary analyses also indicated that, for the situations being studied, jackknifing was more likely to occur on a low coefficient of friction roadway. Therefore, the two road surfaces simulated both had lower coefficients of friction than would a dry road. One had a peak coefficient of friction (mu-peak) of 0.55 (corresponding to wet Jennite) and the second had a mu-peak of 0.30 (corresponding to snow with some ice covered pavement). Realistic traction surfaces were simulated by having the levels of adhesion vary slightly around their above listed means. Variance of the surface coefficient of friction about its mean was deemed necessary to simulate "real-world" surfaces, which do not have constant coefficients of friction.

The maneuver simulated was brake-in-curve, similar to the previously described experimental wet testing. The same 152.4 m curve radius was used. The curve entry speed (initial speed) was dependent upon the vehicle loading and the pavement coefficient of friction. The initial speed was set so as to attain 90 percent of the lateral acceleration seen during the highest lateral acceleration, successful, simulated drive-through of the 152.4 m radius curve.

Two brake applications were simulated: Full Treadle and Half Treadle. For a Full Treadle brake application, air pressure at the treadle valve was ramped from 0 to 690 kPa in 0.3 seconds. For a Half Treadle brake application, air pressure was ramped from 0 to 345 kPa in 0.5 seconds. Two ABS configurations were examined: fully operational and non-operational.

Tables 21 and 22 summarize the results from the simulated jackknife stability study. The number in each cell of these tables is the maximum tractor yaw rates, in degrees per second. Each cell's background color indicates the jackknife stability for that particular condition with white indicating that there was no stability problem, light gray indicating a near jackknife (high hitch articulation angle and/or high hitch forces), and dark gray indicating that a jackknife occurred.

Examination of Tables 21 and 22 shows the following:

- The peak tractor yaw rate was generally less for the cases with air disc brakes on the Volvo tractor than for cases with S-cam drum brakes.
- No simulated jackknifes or near jackknifes were seen for the ABS On case.

Table 21: Simulated Jackknife Stability Results - Vehicle with no load

		0.55 Mu-Peak		0.30 Mu-Peak	
		Drum	**Disc**	**Drum**	**Disc**
Half Treadle Brake Apply	**ABS On**	6.9	6.2	5.8	5.6
	ABS Off	49.7	19.3	4.7	2.2
Full Treadle Brake Apply	**ABS on**	6.4	6.6	6.0	6.2
	ABS Off	8.8	3.5	2.0	1.2

Table 22: Simulated Jackknife Stability Results - Vehicle loaded to one-half GVWR

		0.55 Mu-Peak		0.30 Mu-Peak	
		Drum	**Disc**	**Drum**	**Disc**
Half Treadle Brake Apply	**ABS On**	7.2	6.7	7.5	6.7
	ABS Off	50.9	34.9	7.8	2.6
Full Treadle Brake Apply	**ABS on**	6.9	6.4	7.5	7.6
	ABS Off	12.5	6.0	2.3	1.3

- Multiple simulated jackknifes and near jackknifes were seen for the ABS Off case. However, either jackknifes/near jackknifes were seen for both the S-cam drum brakes and the air disc brakes or they were seen for just the S-cam drum brakes. No cases were found for which there was a jackknife/near jackknife for air disc brakes for which S-cam drum brakes did not also have a problem.

In summary, NHTSA's simulation study of jackknife stability for combination vehicles found that, whether ABS was functional or not, the higher torque output brakes on the tractor displayed no negative effects on jackknife stability for the brake-in-curve maneuvers simulated.

COSTS AND BENEFITS OF SHORTER TRUCK TRACTOR STOPPING DISTANCES

NHTSA has estimated the costs and benefits of improving tractor-stopping distances. Only a brief summary is given here; additional information about these topics can be found in [3] and [16].

First, NHTSA estimated the target population for this research. The target population consists of braked heavy truck crashes in which the front of the truck hits another vehicle or object. NHTSA used 2000 through 2002 FARS data to estimate the average annual number of fatalities and 2000 through 2002 GES data to estimate the annual number of property damage only (PDO) vehicle involvements and injuries in the United States. Table 23 summarizes these estimates.

Table 23: Estimated Number of Involvements in Braked Heavy Truck Crashes

Crash Type	Injury Level	Number
PDO	**None**	**39,628**
Injury	**AIS 1**	**11,837**
Injury	**AIS 2**	**1,718**
Injury	**AIS 3**	**668**
Injury	**AIS 4**	**95**
Injury	**AIS 5**	**51**
Fatal	**Fatal**	**978**

As explained in detail in the Preliminary Regulatory Impact Analysis, Notice of Proposed Rulemaking – FMVSS No. 121, Air Brake Systems, Stopping Distance, NHTSA estimated safety benefits for both 20 percent and 30 percent reductions in maximum permitted tractor stopping distance. A 20 percent reduction in maximum permitted tractor stopping distance is estimated to prevent 104 fatalities per year in the United States, reduce 120 serious (AIS 3 through 5) injuries per year, and save between $32 million (3 % discount rate) and $27 million (7 % discount rate) in property damage. A 30 percent reduction in maximum permitted tractor stopping distance is estimated to prevent 257 fatalities per year in the United States, reduce 284 serious (AIS 3 through 5) injuries per year, and save between $166 million (3 percent discount rate) and $136 million (7 percent discount rate) in property damage. (The discount rates account for the fact that these savings will occur at some time in the future. Therefore, their present value must be discounted. NHTSA uses both a 3 percent and a 7 percent discount rate for all present value calculations.)

Potential compliance costs for the 20 percent and 30 percent reductions in maximum permitted tractor stopping distance vary considerably and are dependent upon the type of brake systems chosen by the vehicle manufacturers and purchasers. Although the research suggests that air disc brakes at all wheel positions would be most effective in reducing stopping distance, NHTSA's data also indicates that either larger (higher torque output) S-cam drum brakes on just the steer axle or air disc brakes on just the steer axle could also achieve these stopping distance reductions. NHTSA's cost estimates do not include potential costs for changes to the vehicle frame or suspension, possible increased fuel costs, or maintenance costs. With these caveats, NHTSA estimates that the cost to comply with a 30 percent reduction in maximum permitted tractor stopping distance would vary between $153 per vehicle for larger S-cam drum brakes on just the steer axle to $1,308 per vehicle for air disc brakes on all axles. The cost for air disc brakes on just the steer axle is estimated at $536 per vehicle. The costs of achieving a 20 percent reduction in tractor stopping distance would be approximately one-third lower.

Table 24 summarizes the estimated costs for the entire United States vehicle fleet of these brake improvements.

Table 24: Estimated Annual Costs for Upgrading the Entire United States Tractor Fleet

	Larger Drum Brakes on Steer Axle	**Air Disc Brakes on Steer Axle**	**Air Disc Brakes on All Axles**
20 % Reduction	$14 Million	$50 Million	$119 Million
30 % Reduction	$20 Million	$70 Million	$170 Million

To determine the net costs, the estimated annual property damage savings were subtracted from the estimated annual costs for the entire fleet. To determine the equivalent lives saved, NHTSA used a weighting formula for the AIS 1 through AIS 5 injuries and added this number to the estimated fatalities prevented. Using this information, the net cost per equivalent life saved was calculated as summarized in Tables 25 and 26.

Table 25: Net Cost per Equivalent Life Saved for a 20 Percent Reduction in Tractor Stopping Distance

Brake System	3 Percent Discount	7 Percent Discount
Larger Drum Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on Steer Axle	$156,000	$251,000
Air Disc Brakes on All Axles	$743,000	$968,000

Table 26: Net Cost per Equivalent Life Saved for a 30 Percent Reduction in Tractor Stopping Distance

Brake System	3 Percent Discount	7 Percent Discount
Larger Drum Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on Steer Axle	Property damage savings exceeds costs	Property damage savings exceeds costs
Air Disc Brakes on All Axles	$13,000	$144,000

NHTSA MEDIUM AND HEAVY STRAIGHT TRUCK STOPPING DISTANCE RESEARCH

Although a few wrap-up work items remain to be performed, NHTSA has nearly completed its research aimed at improving the stopping performance of tractors. The next focus will likely be improving the stopping performance of medium and heavy straight trucks. A very brief summary of NHTSA research performed to date for these vehicles will be given.

A considerable amount of NHTSA research has already been performed on the stopping performance of existing medium and heavy straight trucks ([17] and [18], plus another upcoming report). These studies evaluated the braking performance of vehicles with their original equipment brakes.

NHTSA has also completed one heavy straight truck study (documented in [19]) in which two vehicles, a Class 7 school bus and a Class 8 straight truck, were fitted with standard S-cam drum brakes, hybrid disc brakes, and all disc brakes, just as was done for the tractor studies described earlier in this paper. This study performed, among other testing, straight line stopping on a dry, high coefficient of friction pavement. For the Class 7 school bus, relative to the standard drum foundation brake configuration, 9.9 percent and 22.0 percent nominal reductions in stopping distance, respectively, were found for the hybrid disc and all disc configurations. For the class 8 straight truck, the nominal improvements were 10.4 percent and 20.0 percent, respectively.

NHTSA is continuing its research to improve medium and heavy straight truck stopping performance. There are, of course, many medium and heavy straight truck configurations sold which makes this a much more difficult problem than was the case for tractors. One strategy that NHTSA is using is that the braking performance of eight heavy straight trucks (with their original equipment brakes) has been measured. The straight truck with the poorest braking performance of these eight is in the process of being tested in the hybrid disc and all disc foundation brake configurations.

CONCLUSIONS

This research has shown that a substantial improvement in tractor stopping performance is possible through the use of modern air disc or improved S-cam drum brakes. No lateral stability or jackknife stability problems were found due to higher torque output brakes on the tractor. A 20 to 30 percent reduction in maximum permitted tractor stopping distance using either air disc or improved S-cam drum brakes has been found to be cost effective.

Based on this research, NHTSA issued on December 15, 2005 a Notice of Proposed Rulemaking [3] that proposed revising FMVSS 121. NHTSA proposed to shorten the maximum permitted stopping distance for truck tractors by 20 to 30 percent.

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