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Heavy Single-Unit Truck Original Equipment and Aftermarket Brake Performance Characterization in Field, Test-Track, and Laboratory Environments

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ACRONYMS AND DEFINITIONS

AM – After Market
ABS – Anti-lock Braking System
ATA - American Trucking Association
ATV - All-Terrain Vehicle
Class-7 – A truck or tractor with a GVWR of 26,001-33,000 lbs
Class-8 – A truck or tractor with a GVWR of 33,001 lbs or more
CRSD – Constant Deceleration Rate Stopping Distance
DR – Deceleration Rate
FMCSA – Federal Motor Carrier Safety Administration
FMVSS – Federal Motor Vehicle Safety Standards
GPS – Global Positioning System
GVWR – Gross Vehicle Weight Rating
Heavy Vehicle – GVWR > 26,000 pounds
Hi-PV – High-Speed/High-Load. A set of test conditions on the SSBT in which the product of the load and sliding speed equals the maximum used in this study (approximately 4800 N-m/s or 4.8 kJ/s)
IBT – Initial Brake-Drum Temperature
ID – Internal Diameter
IR – Infra Red
Knox Co. – Knox County Fleet Service Center
LICL – Low-Cost, Imported Aftermarket Truck Brake Lining Material
LLVW – (a.k.a. Curb Wt.) Lightly Loaded Vehicle Weight
LPG – Laurens Proving Grounds
Low-PV – Low-Speed/Low-Load. A set of test conditions on the SSBT in which the product of the load and sliding speed equals the minimum used in this study (approximately 1000 N-m/s or 1.0 kJ/s)
MPH – Miles per Hour
MSD – Maximum Stopping Distance
nDR – Normalized Deceleration Rate
NTRCI – National Transportation Research Center, Inc.
NHTSA – National Highway Traffic Safety Administration
OE – Original Equipment
ORNL – Oak Ridge National Laboratory
PRI – Performance Review Institute
psi – Pounds per Square Inch
RP – Recommended Practice
RR – Ratio of the Sum of the Braking Torques to the Sum of the Gross Axle Weight Ratings
RSD – Recorded Stopping Distance
SAE – Society of Automotive Engineers
SDDI – Stopping Distance Difference Indicator
SiC – Silicon Carbide
SSBT – Sub-Scale Brake Tester
SUT – Single-Unit Truck
TDOS – Tennessee Department of Safety
TMC – Technology and Maintenance Council
TRC – Transportation Research Center, Inc.
VBOX – Velocity Box (from Racelogic)
VDA – Vehicle Dynamics Area
VUT – Vehicle Under Test

Walker (also W) – Walker’s Truck Contractors Inc.
Waste Connections (also WC) – Waste Connections of Tennessee, Inc.

EXECUTIVE SUMMARY

Reducing the disparity between the stopping distances of heavy trucks and the lighter vehicles with which they share the road continues to be one of the National Highway Traffic Safety Administration's high-priority areas. Current truck designs typically take between 1.5 and 2 times as far to stop from highway speeds, as do passenger cars. Truck brake performance has been identified as a major factor contributing to crashes involving large trucks. Analysis of the 2001 Fatality Analysis Reporting System (FARS) data shows that single-unit trucks (SUTs) are involved in 27 percent of all fatal crashes that involve large trucks (GVWR > 10,000 lbs).

The research described in this report was sponsored by NHTSA through a Cooperative Agreement (# DTNH22-04-H-01397 dated September 17, 2004) with the National Transportation Research Center, Inc. (NTRCI). Oak Ridge National Laboratory (ORNL) conducted the research for NTRCI in conjunction with several local fleet partners who voluntarily provided access to their class-7 and class-8 SUTs for test-track and field testing.

The overall objectives of this work were:

1) to provide objective test data from test-track and field testing to further refine NHTSA's experience base on stopping distances for SUTs (Class-7 single-axle dump truck, Class-8 tandem-axle dump truck, Class-8 tri-axle dump truck, and a Class-8 tandem-axle refuse truck) using original equipment (OE) brake linings for the test-track and field testing;
2) to provide objective data from test-track and field testing for stopping distance performance for the same four vehicle configurations using aftermarket (AM) brake linings;
3) to study, via Sub-Scale Brake Testing (SSBT) and chase tests, the behavior of the same OE and AM braking materials addressed in items 1) and 2);
4) to provide real-world driving environment data on the same OE and AM braking materials addressed in items 1) and 2); and
5) to attempt to correlate the results of the bench top, test-track, and field tests.

Information related to friction coefficients for a low-cost imported replacement lining material was also gathered because fleets are now using this material.

The laboratory tests, test-track tests, and real-world field tests were linked tests, i.e., the same brake materials were used in all three testing regimes, and the same trucks were used for the test-track and field tests.

The brake materials tested in this project were selected by contacting the manufacturers/upfitters (the body builder who installed the equipment prior to delivery) of each vehicle and determining the OE brake lining material that was provided with the vehicle when new and was delivered to the end customer complete with body and drop axle as appropriate, and determining if this OE brake material was still available in the market. The AM linings were selected by interviewing the fleet partners to determine the typical replacement lining material used in their operations.

The SSBT tests were conducted under low-speed/low-load ("Low-PV") conditions as well as high-speed/high-load ("High-PV"). For the Low-PV cases, friction coefficient results compared well to those typically reported for brake friction materials in general. The High-PV results, because of thermally induced fade, did not compare as well. SSBT tests were also conducted on a low-cost import replacement lining material, which showed a lower friction coefficient than the other brake linings (both OE and AM) studied in this project (note: no test-track or field testing were conducted on this lining material). Regarding SSBT-based wear tests, a good correlation was found to exist between mass loss (wear) and friction coefficient. For data generated in the SSBT-based friction and wear tests, there was, however, no evident trend that OE brake linings were necessarily any better than AM linings. Similar results were obtained from the Chase tests. [Similar results were obtained from the standard laboratory test method SAE J661, also known as the Chase test. It involves a one-square-inch pad of lining material sliding against the inside of a rotating cast iron drum.] These results clearly indicate that the control of variables inherent in the method of testing is a very important factor in any study of brake material performance. Laboratory tests are a better isolator of the lining-drum material interaction than vehicle tests because the vehicle introduces other variables that can mask or compensate for the characteristics of the materials. Such effects include brake system design, controls like ABS, driver reactions, vehicle condition, tire performance, road surface variations, and more. Therefore, it is not at all surprising that road tests of the same linings did not map one-to-one with results from the more tightly controlled laboratory experiments. From the observation that the laboratory test results showed similar ranges of friction and wear between OE and AM linings, it is evident that there is no a-priori reason to expect that manufacturers will put less engineering effort into developing AM linings than OE linings. In correlating laboratory and field behavior for a large set of linings, a large number of observations would have to be made involving tightly controlled factors. The current study involved a number of factors that were beyond the investigators' direct control.

Test-track testing involved stopping data for the same brake materials addressed in the laboratory-based friction testing. For the stopping data generated from the test-track tests, the OE brake linings were shown to provide higher deceleration rates than the AM brake linings (measurements were taken from the same truck, with the same payload, with the same driver, at the same test track, almost at the same time). While the OE linings outperformed AM linings in this specific case, the performance differences on the test track are likely due to different lining formulations; however, the current study involved too small a sample to draw general conclusions about the vast selection of available commercial linings, and analysis of the lining formulations was beyond the scope of this research.

The field tests involved the least controlled of the test environments. Because the vehicles were engaged in their normal vocational activities, the loads of the vehicles varied. In addition, even though the test vehicle drivers were professional drivers, there was significant variation in the amount and steadiness of the applied braking pressure. Without appropriately "correcting" the data to account for these phenomena, results would be meaningless. ORNL developed a means for correcting collected data due to treadle pressure variations, and variations in the truck weight during testing. For the stopping data generated from the field tests, the OE brake linings were shown to provide higher deceleration rates than the AM brake linings (measurements were taken from sister trucks, with the same driver). Wear analysis for the field test data indicated that the AM brake linings exhibited more wear than the OE brake linings. Interestingly, some of the measurements were possibly confounded due to a "curing" or "swelling" effect as the new brake lining was used.

Comparison of results between testing domains was not straightforward. Selection of the appropriate variables, within appropriate testing environments, etc., can involve significant effort and typically requires significant assumptions. In comparing SSBT friction test results to Chase test results, a fair correlation of relative rankings in friction coefficient between the Chase and SSBT test results was found. Ranking of the AM linings resulted in a widely different order between these tests. Comparison of SSBT, Chase and The Technology and Maintenance Council's Recommended Practice for lining dynamometer testing, RP 628, results showed no evident correlation. It should be noted, however, that the linings used for RP 628 testing were from different batches of lining material than those used for the SSBT and Chase tests that used samples from the same brake shoe for each type of lining. The lack of correlation is therefore not surprising.

Comparison of SSBT/Chase results to the test-track results showed a correlation for special cases of the SSBT (i.e., Low-PV) and Chase tests. Comparison of SSBT/Chase results to the field test results was similar in that moderate correlations existed for certain special cases. Further analysis, correlating both test-track and field observations with SSBT results confirmed these results by showing a significant correlation between Low-PV friction coefficients and observed deceleration rates.

Comparison of the test-track results to the field test results involved separate comparisons between the test-track results from TRC and from LPG. For the TRC data, there was an exceptionally strong correlation between the test-track results and the field test. In contrast, data from LPG produced no correlation with the field data. It should be noted that the TRC tests were done with a strong adherence to FMVSS-121 protocols and in a very controlled environment where every procedure was carefully documented. Similar thoroughness may not have been experienced at LPG.

The research conducted in this project provided good insight into friction performance and stopping performance of heavy SUTs using OE and AM brake linings. The correlation between the laboratory results (friction performance) and more real-world results (stopping performance) was in some cases weak, although significant in others. Such correlation is intuitive and warrants additional attention.

Real-world field testing of brake performance is a good complement to the test-track testing that is typically conducted for brake testing. However, such testing is complex because of the number of intervening variables, and the time required for its conduct. For example, consistency in brake pressure application and vehicle weight were problems in field testing. However, this data is valuable because it brings real-world experience into the research regimen, and if carefully designed and executed, provides an additional dimension to the research. Better and more sophisticated control over the intervening variables while using real-world vehicles is recommended.

Limited lab tests and analysis were performed on one low-cost imported replacement lining material. The preliminary results indicated that this low-cost import reflected a lower friction coefficient than the other brake linings (both OE and AM) studied in this project. The predicted deceleration rate was also found to be at the lower end of those observed during the test-track and field testing experiments. It is therefore recommended that a broad research emphasis be placed on those low-cost imported brake materials. Such products have the potential for poor performance and should be looked at in context of American-made brake materials.

Lastly, a greater emphasis on brake wear is suggested. The effects of ovality and eccentricity can cause undue wear in the braking system and lead to safety problems long before the expected life cycle for a brake is concluded. Such issues should also be studied.

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1.0 Project Overview

1.1 Introduction

Reducing the disparity between the stopping distances of heavy trucks and the lighter vehicles with which they share the road continues to be one of NHTSA's high-priority areas. Current truck designs typically take between 1.5 and 2 times as far to stop from highway speeds, as do passenger cars. Truck brake performance has been identified as a major factor contributing to crashes involving large trucks. Analysis of the 2001 Fatality Analysis Reporting System data shows that SUTs are involved in 27 percent of all fatal crashes that involve large trucks (GVWR > 10,000 lbs.)

For 2004, NHTSA has reported[1] that 416,000 large trucks were involved in traffic crashes in the United States, that a total of 5,190 people died (12% of all the traffic fatalities reported in 2004), and an additional 116,000 were injured in those crashes. One out of eight traffic fatalities in 2004 resulted from a collision involving a large truck, with SUTs involved in 28 percent of those truck related fatalities. In a widely cited study by Jones and Stein [1], it was reported that brake defects were quite common and were found in 56 percent of the tractor-trailers involved in crashes. In the more recent Large-Truck Crash Causation Study [2], it was concluded that 29.4 percent of all large truck crashes involved brake failure, brakes out of adjustment, or other brake related issues."

Compounding the brake defects issue even more so is the fact that although original equipment (OE) brakes must comply with federal motor vehicle safety standards (FMVSS) which specify maximum stopping distances according to vehicle weight, loading, pedal effort (with and without power assistance) and brake condition (green and burnished linings), there are no federal performance standards for aftermarket (AM) brake linings. It is typically assumed that replacement AM brake linings perform the same as or better than the OE brake linings on a vehicle. Unfortunately, there is currently no methodology or rating system available that can assure OE-equivalent brake performance from AM brake linings.

The research described in this report was sponsored by NHTSA through a Cooperative Agreement (DTNH22-04-H-01397 dated September 17, 2004) to NTRCI. One of the primary goals of the NTRCI in its Heavy Vehicle Safety Program is to conduct research that will contribute significantly to the improvement of the safety associated with heavy truck operations on our highways.

A major factor in heavy vehicle safety is braking system performance. NTRCI has previously conducted research on integrated brake systems, the compatibility of braking between tractors and trailers, and the enhancement of TRUCKSIM to account for fade, humidity and braking torque. The current research extends NTRCI's braking research base and has initiated research outside of the laboratory to include test-track and field testing.

1.2 Objective/Scope

This project had multiple objectives related to heavy truck brake performance and its scope was focused on SUTs per the request of NHTSA. The overall objectives of this work were:

1) to provide objective test data from test-track and field testing to further refine the NHTSA's experience base on stopping distances for SUTs (Class-7 single-axle dump truck, Class-8 tan-

[1] See: http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSF2004/809907.pdf

dem-axle dump truck, Class-8 tri-axle dump truck, and a Class-8 tandem-axle refuse truck) using OE brake linings for the test-track and field testing;
2) to provide objective data from test-track and field testing for stopping distance performance for the same four vehicle configurations using AM brake linings;
3) to study, via Sub-Scale Brake Testing (SSBT) and Chase tests, the behavior of the same OE and AM braking materials addressed in items 1) and 2);
4) to provide real-world driving environment data on the same OE and AM braking materials addressed in items 1) and 2); and
5) to attempt to correlate the results of the bench top, test-track and field tests.

Objectives 1) and 2) focused on stopping distance data collection for the same trucks mounted with OE and AM brakes. A comparison of performance between these classes of brake materials was felt to be of significant interest to NHTSA and the industry. Such stopping tests have typically been performed at a test track where they could be conducted with relative safety and efficiency. However, since ORNL possessed a SSBT capability, it was felt that testing of the same OE and AM brake linings in a laboratory setting, and comparing performance of the materials in the laboratory with that at the test track could add considerable insight into the behavior of these materials, especially if a correlation of performance could be identified between the laboratory testing and test-track testing (Objectives 3 and 5).

After additional discussions with NHTSA, it was suggested that in addition to test-track testing and laboratory testing, that a field test involving the same truck configurations, and the same brake linings would add significant breadth to the brake performance data collected (Objective 4). As a result, three OE brake linings and six AM brake linings were tested in the laboratory, on a test-track, and in a field test. A primary goal was to seek a correlation between the various test domains as specified in Objective 5) of this project. Evidence of such correlations was not found in the literature, and if correlations could be found in this study, extrapolation of performance in the other domains could be achieved. Additionally, the laboratory testing was enlarged to include Chase testing, and if possible data from RP 628 testing.

The test-track, laboratory tests and real-world field tests are linked tasks that could provide valuable information independently, but also provide a regimen of testing that would allow comparison of the performance of similar braking materials, on similar SUTs, in three distinctively different testing environments. Such a comparison could provide insights about variation in expected performance across testing domains, as well as possibly providing a database of performance allowing generalization about the performance of aftermarket braking materials not addressed within this work (Objective 5).

1.3 Project Team

The research described in this report was sponsored by NHTSA through a Cooperative Agreement (# DTNH22-04-H-01397 dated September 17, 2004) with NTRCI, a 501-C3 nonprofit organization located in Knoxville, Tennessee. NTRCI selected ORNL for this research because of its significant prior research in the heavy truck safety area within its Heavy Truck Safety Research Program and because of its prior brake-based research conducted for NHTSA. ORNL provided technical leadership in the conduct of this research and together with the NTRCI engaged fleet partners to support the test-track and field test portions of this research.

1.4 Partners

In order to leverage the resources of this project, NTRCI and ORNL sought the voluntary participation of local fleet partners willing to take part in the test-track and field testing portions of this study. Participation in the study provided benefits to both NTRCI/ORNL as well as the fleet partners. For NTRCI/ORNL, the benefits included access to test vehicles at limited or no cost. For the partner fleets, benefits included new brakes, drums and tires (which were initial conditions for the test-track and field testing), access to the data related to their vehicles that was collected during testing, and publicity related to their involvement in this study.

The fleet partners provided the test vehicles for the field test and the test-track testing on a cost-sharing basis. A partnership agreement was drafted stating that a fleet partner would provide the resources described below.

For the field test, fleet partners would provide –

- Two test vehicles of the same class, 2001-year model or later, with working ABS,
- Shop labor to install new brakes and drums on the test vehicles,
- Driver, fuel, and ballast for the testing, and
- Access to the test vehicle at the beginning and end-of-life of the brakes in order to conduct six repetitions of a straight-line-stopping test.

NTRCI provided the cost of the brakes, drums, and tires for the field test.

For the test-track testing fleet partners would provide –

- One test vehicle, 2001-year model or later with working ABS (preferably one of the field test vehicles).

The fleet partners were compensated for the lease of their vehicles (if required) during test-track activities and for the transport of the test vehicle to and from the test track. NTRCI provided the cost to lease the vehicles, transport them to and from the track, and the brakes, drums, and tires for the test-track testing.

Three partnership agreements were developed and negotiated by NTRCI: the Knox County Fleet Service Center agreed to provide two Class-7, single-axle dump trucks; Waste Connections of Tennessee, Inc. agreed to provide two Class-8, tandem-axle refuse haulers; and Walker's Truck Contractors, Inc. agreed to provide two Class-8, tandem-axle dump trucks and two Class-8, tri-axle dump trucks. Table 1.1 shows pertinent information for each of the fleet test vehicles and photographs of each type of test vehicle are shown in Figures 1.1 though 1.4.

In addition to the fleet partner agreements, NTRCI negotiated contracts with the Transportation Research Center, Inc. (TRC), and Laurens Proving Grounds (LPG) to conduct the test track testing as called out in Section 2.3 and with Link, Inc. to perform the Chase testing called out in Section 2.2. NTRCI contracted with Fleet Tire in Knoxville, Tennessee, to supply all the tires for the field and track tests.

Table 1.1 Fleet Test Vehicles

Vehicle Type	Owner	Identifying Number	Vehicle Mfg.	Vehicle Mfg. Date	Field Test	Test Track Test
Class-7 Dump	Knox Co.	#2879	GMC	2002	Yes	No
Class-7 Dump	Knox Co.	#3212	Chevrolet	2004	Yes	Yes
Class-8 Tandem Dump	Walker	#102	Mack	2004	Yes	Yes
Class-8 Tandem Dump	Walker	#105	Kenworth	2004	Yes	No
Class-8 Tri-Axle Dump	Walker	#107	Mack	2003	Yes	Yes
Class-8 Tri-Axle Dump	Walker	#108	Sterling	2001	Yes	No
Class-8 Tandem Refuse	Waste Connections	#960	Mack	2002	Yes	Yes
Class-8 Tandem Refuse	Waste Connections	#961	Mack	2002	Yes	No

Figure 1.1 Knox County Single-Axle Class-7 Dump Truck.

Table 1.2 Test Vehicle Specifications

Vehicle Number	Veh. Mfg	Final Builder	Wheel Base	GVWR/ GAWR	Drum Size	Chamber Size	Slack Adjuster Size	ABS Control	ABS Layout
#2879	GMC	Rogers Co.	157	30,000 lbs/ F 11K lbs R 19K lbs	F 15.0 R 16.5X7	UNK	UNK	Bendix	4S/4M
#3212	Chevrolet	Ox Bodies, Inc	152	33,000 lbs/ F 12 K lbs R 21 K lbs	F 16.5X5 R 16.5X7	30/30	5.5 in.	Bendix	4S/4M
#102	Mack	Mack	214	68,000 lbs/ F 20K lbs R 48K lbs	F 16.5X6 R 16.5X7	30/30	UNK	Eaton/ Bosch	4S/4M
#105	Kenworth	Kenworth	UNK	68,000 lbs/ F 20K lbs R 48K lbs	F 15X4 R 16.5X7	UNK	UNK	Wabco	4S/4M
#107	Mack	Mack	214	74,000 lbs/ F 20K lbs R 54K lbs	F 16.5X6 R 16.5X7	30/30	UNK	Wabco	UNK
#108	Sterling	Freightliner	240	74.000lbs/ F 20K lbs R 54K lbs	16.5 X7	30/30	6 in	Wabco	UNK
#960	Mack	Heil	210	64,000lbs/ F 20K lbs R 44K lbs	16.5X7	30/30	6 in	Bendix	4S/4M
#961	Mack	Heil	210	64,000 lbs/ F 20K lbs R 44K lbs	16.5X7	30/30	6 in	Bendix	4S/4M

Figure 1.2 Walker Class-8 Tandem-Axle Dump Truck.

Figure 1.3 Walker Class-8 Tri-Axle Dump Truck.

Figure 1.4 Waste Connections Class-8 Refuse Hauler.

1.5 Approach

This project involved the testing of the selected brake materials shown in Table 1.3 on the eight vehicles listed in Table 1.1 (test-track and field testing) as well as bench top testing (Chase tests and ORNL's SSBT – to be described later in this report). The brake materials in Table 1.3 were selected by contacting the manufacturers/upfitters (i.e., the body builder who installed the equipment prior to delivery) of each vehicle and determining the OE brake lining material that was provided with the vehicle when new and was delivered to the end customer complete with body and drop axle as appropriate, and determining if this OE brake material was still available in the market. For all test vehicles, the OE lining materials were still available in the industry, and were manufactured by Arvin Meritor. It should be noted that the Arvin Meritor brake materials were not readily available from the local (Knoxville, Tennessee) Mack and GMC dealers, and had to be special-ordered. Additionally, ORNL was told by Arvin Meritor that the 301 brake material was being phased out and that the 402 brake material was not available as a standard material.

The AM linings used for the testing were selected by interviewing the fleet partners to determine the typical replacement lining material used in their operations. For all of the test vehicles, no fleet partner used OE brake materials as a replacement lining; rather, all AM materials. For this project, the team leadership made a decision to use the same AM materials for each test vehicle that were typically used by the fleet owner. Use of these brake materials was felt to allow the vehicles to operate with brake linings with which the fleets and drivers had experience. These materials were readily available from local suppliers. In the early stages of this project, it was proposed that if funding allowed, a third category of brakes (i.e., "economy" brakes) would also be tested. Unfortunately, funding was not available to test "economy" brake linings. (Note: All AM and OE materials used in the project in the field test or at the test track were from established manufacturers and U.S. suppliers.)

Table 1.3 Selected Brake Materials

	Knox Co., Class-7 Single-Axle	
#2879 with AM Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	ABEX 6008-1 (4702)	WEBB 65546B
Rear	ABEX 6008-1 (4707)	WEBB 66874B
#3212 with OE Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	Arvin Meritor 212 (4720)	WEBB 65710B
Rear	Arvin Meritor 212 (4707)	WEBB 66874B
	Waste Connections, Class-8 Tandem-Axle	
#960 with OE Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	Arvin Meritor 402 (4720)	Gunite 3595A
Rear	Arvin Meritor 301 (4707)	Gunite 3401X
#961 with AM Brakes		
	Brake Lining Mfg. and PNs	
Front	BrakePro CM24 (4720)	WEBB 68846B
Rear	BrakePro CM24 (4707)	WEBB 66807B
	Walker, Class-8 Tandem-Axle	
# 102 with OE Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	Arvin Meritor 301 (4715)	WEBB 65152B
Rear	Arvin Meritor 301 (4707)	WEBB 66884B
#105 with AM Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	Armada AR3 (4725)	WEBB 65152B
Rear	Armada AR2 (4709)	WEBB 66884B
	Walker, Class-8 Tri-Axle	
#107 with OE Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	Arvin Meritor 301 (4715)	WEBB 65152B
Drop	Carlisle Altec MB21EF (4515)	WEBB 66884B
Rear	Arvin Meritor 301 (4707)	WEBB 66884B
#108 with AM Brakes		
	Brake Lining Mfg. and PNs	**Drum Mfg. and PNs**
Front	FleetPride OTR II (4715)	WEBB 65152B
Drop	Carlisle Altec MB21EF (4515)	WEBB 66884B
Rear	Carlisle Altec MB21EF (4515)	WEBB 66884B

Note: Since it was not possible to determine what was the original equipment installed on the drop axle of Truck # 107, it was decided to use the typical AM linings that the fleet partner used for these brakes.

The testing was divided into the following five domains:

- SSBT – Brake material performance and wear were compared over several scales of friction.
- Chase tests (SAE J 661) – Brake material performance and wear were compared over several scales of friction.
- Test-Track Testing – The test vehicles were monitored for stopping performance under controlled conditions per FMVSS121.
- Performance Field Testing – The test vehicles were monitored for straight-line stopping performance.
- Wear Field Testing – The brake materials on the test vehicles were monitored for total wear during the period of the test.

For the SSBT and Chase tests, one complete shoe of each type of OE and AM material in Table 1.3 were purchased from local suppliers. The linings were removed from the shoe tables, labeled and sent to Link Engineering for the Chase testing. Link Engineering subsequently cut out a section of the lining for their tests. These same linings were then sent back to ORNL for an additional section to be removed for the SSBT testing.

For the test-track testing and field testing, linings were purchased from local suppliers and were marked to identify their usage in either the test-track or field testing. The test-track linings were paired with new drums for the test vehicles and shipped to the test tracks (the Transportation Research Center in East Liberty, Ohio, for testing of the Class-7 single-axle dump, and Laurens Proving Ground, in Mountville, South Carolina, for testing of the remaining vehicles). The field test linings and drums were measured for baseline lining thickness and baseline drum diameter (see Section 2.5 for details) and installed on the field-test vehicles shown in Table 1.1. The internal diameter of the field-test drums was recorded as well

1.6 Schedule

The project schedule is shown in Table 1.4. The project began with a kick-off meeting at NHTSA Headquarters in Washington, DC, in December 2004. This was followed by the procurement of project materials, the establishment of partnerships with local trucking companies, and efforts to establish contract relations with the Link Engineering and the test tracks. The first measurements associated with brake wear were made in March 2005 and the field test portion of the project began immediately thereafter. The first series of brake testing in the field were completed on all of the dump trucks by the end of October 2005 and all of the test-track testing was completed by early February 2006. All project testing was completed on February 28, 2006, and correlation and data analysis was completed in June 2006.

Table 1.4 Project Schedule

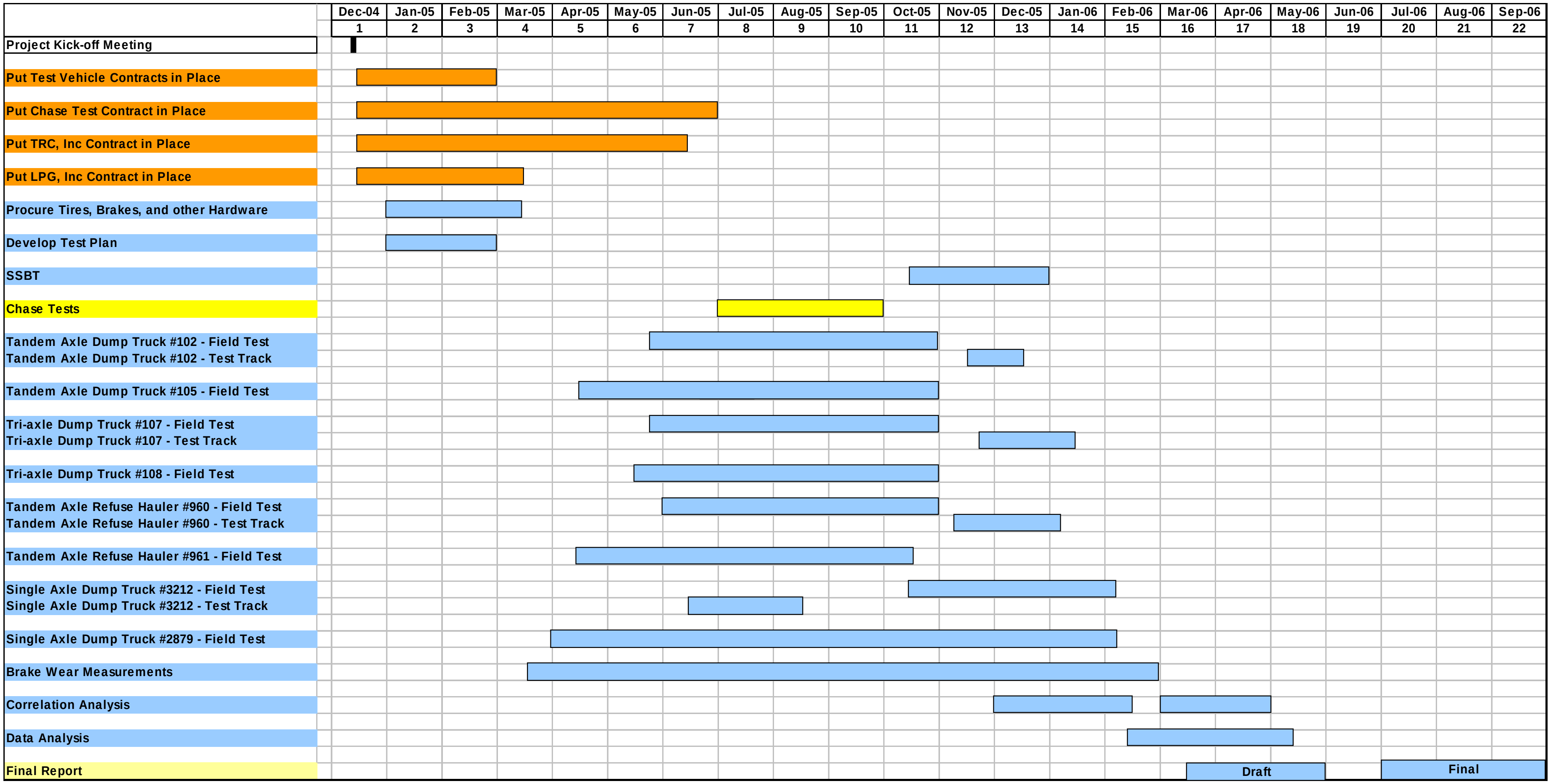

Table 1.5 shows the specific dates and mileages for the testing of each vehicle. The date and mileage upon entering the field test; the date and mileage of the initial and final stopping tests; and the date and mileage as each vehicle ended the field test. Table 1.5 also shows the arrival and departure date at the test-track and mileage for the test vehicles that went to the test track. Accumulated day and miles are listed for each vehicle for the different stages of the field test.

Table 1.5 Timing and Mileage of Vehicle Testing

			Entered Field Test		Initial Stopping Test				Final Stopping Test				End of Test			
Test Series	**Truck #**	**Brake Type**	**Date**	**Mileage**	**Date**	**Mileage**	**Days**	**Miles**	**Date**	**Mileage**	**Days**	**Miles**	**Date**	**Mileage**	**Days**	**Miles**
F1	102	OE	23-May-05	43,908	31-May-05	44,396	8	488	1-Nov-05	60,336	162	16,428	21-Nov-05	62,178	182	18,270
F1	105	AM	18-Apr-05	44,854	3-May-05	47,105	15	2,251	1-Nov-05	67,711	197	22,857	21-Jan-06	74,348	278	29,494
F1	107	OE	23-May-05	99,146	31-May-05	100,087	8	941	1-Nov-05	125,031	162	25,885	26-Nov-05	128,125	187	28,979
F1	108	AM	16-May-05	224,879	31-May-05	227,159	15	2,280	1-Nov-05	250,125	169	25,246	21-Jan-06	260,708	250	35,829
F1	960	OE	7-Apr-05	83,023	Discontinued - Wrong Brakes											
F1	961	AM	13-Apr-05	92,202	19-Apr-05	92,475	6	273	18-Oct-05	106,043	188	13,841	20-Oct-05	106,285	190	14,083
F1	2879	AM	31-Mar-05	48,007	19-Apr-05	48,914	19	907	7-Feb-06	59,885	313	11,878	28-Feb-06	60,567	334	12,560
F1	3212	OE	12-Oct-05	13,849	1-Nov-05	14,536	20	687	8-Feb-06	18,983	119	5,134	28-Feb-06	20,050	139	6,201
F2	960	OE	30-May-05	86,141	31-May-05	86,235	1	94	1-Nov-05	96,309	155	10,168	10-Nov-05	96,798	164	10,657
F2	961	OE	20-Oct-05	106,285	1-Nov-05	107,114	12	829	Discontiued Due to Project Ending							

			Arrived At Test Track		Departed Test Track	
			Date	**Mileage**	**Date**	**Mileage**
Test Track	102	OE/AM	21-Nov-05	62,178	20-Dec-05	63,706
Test Track	107	OE/AM	26-Nov-05	128,025	13-Jan-06	129,553
Test Track	960	OE/AM	10-Nov-05	96,798	6-Jan-06	98,436
Test Track	3212	OE/AM	15-Jun-05	10,718	19-Aug-05	12,032

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2.0 Test Description

2.1 The Sub-Scale Brake Materials Testing System - SSBT

The Sub-Scale Brake Materials Testing System (SSBT) was constructed at ORNL with support from the U.S. Department of Energy. [3] Results from other studies using the machine have been published. [4-6]

2.1.1 Overview

The testing geometry is schematically shown in Figure 2.1. Gray cast iron disks, 127 mm (5.0 in) in diameter serve as the counterface. Sliding specimens are blocks cut from linings. The block face used for sliding is a square with 12.7 mm (1/2 in) on a side. Thus, its contact area is one-quarter that of the standard specimens used for Chase tests, described subsequently.

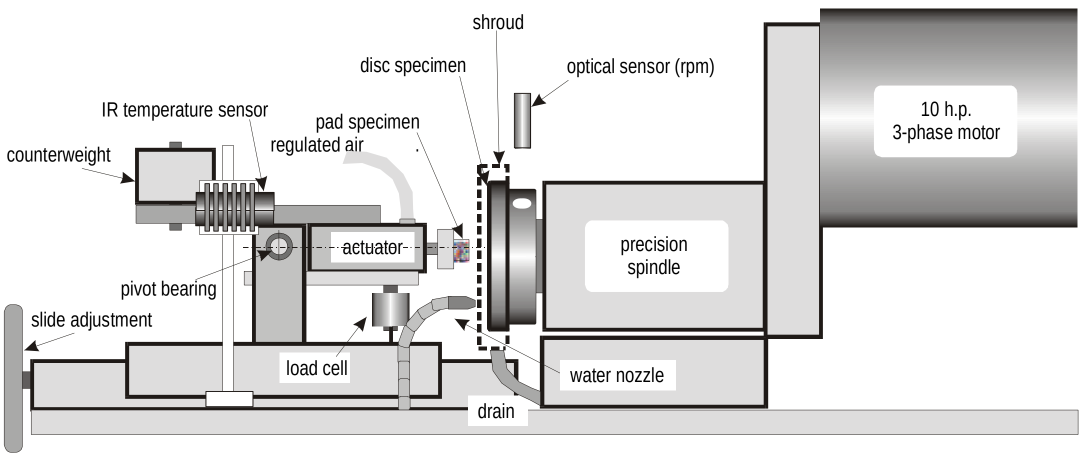

Figure 2.1 Schematic of the SSBT Showing its Main Components.

Wear of the lining material was determined by the weight change between the post-burnished condition and the conclusion of the test series on each block (repeated drags at two combinations of load and contact pressures). There was too little wear to obtain an accurate measure on the cast iron discs and none was reported.

Careful consideration was given to the possible combinations of speed, load, and duration. Chase tests are run at 417 rpm on a drum of 277.4 mm diameter at 667 N on a 1 in x 1 in (25.4 mm x 25.4 mm) pad. In order to compare SSBT results to those from companion Chase tests, two conditions were selected. The first condition involved low-pressure and low-speed and the second involved high-pressure and-high speed.

<u>Sliding Speeds</u>

(a) Comparability to Chase test speed: (417 rev/min) x (3.14159 x 0.2774 m/rev) x (1 min/60 s) = 6.057 m/s (equivalent to 1,072 rpm on the SSBT). This sliding speed corresponds to 33.3 mph on a truck using the standard 16.5 in. diameter brake drums.

(b) Enhanced sliding speed was used to study frictional heating effects: 15.0 m/s (equivalent to 2,656 rpm on the SSBT). This sliding speed corresponds to a vehicle speed of 82.6 mph.

Contact Pressures

(a) The Chase test conditions: (667 N/in.^{2}) x (1 kg/9.81 N) = 67.992 N/in.^{2} or (667 N) x (1kg/9.81 N) x (1 lb/0.454 kg) = 150 lb; thus, 150 psi contact pressure is obtained on a 1 square-inch pad. SSBT test specimens are 0.5 in. x 0.5 in. = 0.25 in.^{2}, so to get 150 psi requires: (150 / 4) = 37.5 lbs force = (37.5 x 0.454 x 9.81) = 167 N for normal force (low). Based on calibration, the air supply pressure needed to obtain 167 N was found to be 32.5 psi.

(b) High pressure was applied using the maximum SSBT load ~ 320 N (59.5 psi). This equates to a contact pressure of about 287 psi, a factor of 1.92 higher than the Chase test pressure.

Temperature Measurement

Temperature of the wear track on the disc was measured with an infrared (IR) pyrometer with a spot size of 3 mm and stand-off distance of approximately 150 mm. The IR spot was positioned at approximately the "1 o'clock" position on the disc face, relative to the "9 o'clock" position of the contact pad. With this method of temperature measurement, the emissivity of the disc surface can affect the accuracy of the temperature measurements, and care was taken to measure emissivity on disk specimens with transfer films on their surfaces. Additional tests with a surface thermocouple probe helped to make further emissivity adjustments. The typical value used for the disc emissivity was 0.22.

Test Procedure

Gray cast iron (~ 3.5 wt % carbon) was used as the standard disc material. Each disc was dressed by hand using 120-grit SiC abrasive paper, with the disk spinning at 400 – 500 rpm. The dressing process took about one minute after which the disk was thoroughly cleaned with a moist paper towel and dried. A new pad specimen was used for each repeat test and was beveled, then run in, before each test.

Burnishing (run-in) was performed by making several drags until at least half of the pad was in contact with the disk. During the run-in, the pad was not only flattened, but the disk was burnished as well. A new cast iron disc was used for each lining material, but was not refinished between repetitive runs with fresh block specimens. The decision not to refinish the disc when replacing the block specimen with one of the same lining material was designed to determine whether the disc continued to be conditioned with repetitive runs. However, there was no trend in the friction or wear data to suggest that repetitive use of the same disc without resurfacing between runs on the same lining material had any effect on results.

In summary, the step-by-step test procedure was as follows:

1) Condition the cast iron disc surface with 120-grit SiC paper (dry).
2) Mount and align the lining block specimen.
3) Burnish (run-in). Run at 6 m/s and 167 N for 5 drags 20 s on, 10 s off (no data recorded).
4) Remove the test block and inspect for contact flatness.
5) Weigh the block to the nearest 0.1 mg and replace in the same position.

6) Run the first set of drags: Run 10 drags 20 s on, 10 s off at 6 m/s and 167 N (record friction and temperature).
7) Wait 5 minutes.
8) Run the second set of drags: Run 10 drags 20 s on, 10 s off at 15 m/s and 320 N (record friction and temperature).
9) Allow the lining to cool.
10) Weigh the block again to the nearest 0.1 mg and subtract from the initial weight to obtain wear loss.

Five tests, each using a separate block, were conducted on each lining material.

2.1.2 Data Collected

The commercial names of the tested friction materials, also identified by the letters ***A*** through ***I***, are presented in Table 2.1. As noted earlier in this report, there were three OE linings and six AM linings.

Table 2.1 Linings Used in This Project, Categories, and Codes Used for Their Tracking

Category*	Product Name	Material Code
OE	ARVIN 212	B
OE	ARVIN 301	C
OE	ARVIN 402	D
AM	ABEX 6008-1	A
AM	Armada AR2	G
AM	Armada AR3	F
AM	BrakePro CM24	E
AM	Carlisle MB21	I
AM	Fleet Pride OTR II	H

* OE = original equipment, AM = aftermarket product

Using a data acquisition rate of 64 readings/s, and using four channels of data (friction force, normal force, temperature, and disk rpm), 153,000 individual data points were obtained for each lining test series. A subset of these data was used to draw conclusions and to conduct correlations with other forms of lining tests.

The first two spreadsheets on the following pages list selected data for friction coefficients for each designated drag along with the corresponding average temperatures of the wear path on the test disks. Table 2.2 lists SSBT data for low-speed/low-load tests and Table 2.3 is SSBT data for the more severe tests. Temperatures were all corrected to reflect an emissivity of 0.22, as determined by a contact thermocouple applied to the test disk following the last drag, and adjusted to match the IR reading.

The third spreadsheet (Table 2.4) lists the wear losses of the pad specimens for each of five tests of each lining material. Wear was measured at the conclusion of the full series of tests on each pad. There was insufficient mass loss for measurement after the low-speed/low-load tests alone; so the final value was measured after twenty total drags, under both mild and more severe drag conditions.

The analysis in Section 2.1.3 treats the data on the basis of OE versus AM behavior, and analyzes general trends in friction and wear, and the relationships between those quantities.

Table 2.2 Friction and Disk Track Temperature Data for Low-Load/Low-Speed Tests

		Low pressure, low speed: P = 167 N (32.5 psi), v = 6.0 m/s					
		Next to Last Drag			Last Drag		
Lining	Spec	Friction Coefficient		Ave Temp	Friction Coefficient		Ave Temp
		Average	Std Dev	(C)	Average	Std Dev	(C)
A	1	0.318	0.014	66.2	0.358	0.032	69.4
	2	0.603	0.090	89.5	0.598	0.090	94.8
	3	0.575	0.076	88.0	0.591	0.083	95.6
	4	0.459	0.057	71.7	0.484	0.074	74.9
	5	0.485	0.069	80.8	0.496	0.065	85.0
Column ave		0.488	0.061	79.2	0.505	0.069	83.9
B	1	0.440	0.057	67.3	0.460	0.065	72.5
	2	0.550	0.080	78.8	0.561	0.086	81.9
	3	0.560	0.092	81.1	0.569	0.098	84.8
	4	0.535	0.077	74.9	0.561	0.082	80.7
	5	0.506	0.081	64.2	0.522	0.085	69.3
Column ave		0.518	0.077	73.3	0.535	0.083	77.8
C	1	0.545	0.062	79.0	0.569	0.069	83.8
	2	0.525	0.040	70.1	0.558	0.057	74.6
	3	0.393	0.062	85.0	0.392	0.063	90.5
	4	0.502	0.059	70.5	0.538	0.069	74.3
	5	0.595	0.113	81.0	0.615	0.117	85.5
Column ave		0.512	0.067	77.1	0.534	0.075	81.7
D	1	0.677	0.149	95.6	0.680	0.152	102.1
	2	0.646	0.108	92.5	0.668	0.111	99.2
	3	0.697	0.264	85.1	0.686	0.259	90.6
	4	0.616	0.146	85.1	0.591	0.138	92.3
	5	0.626	0.128	89.9	0.618	0.123	95.5
Column ave		0.652	0.159	89.6	0.649	0.157	95.9
E (1)	1	0.386	0.019	50.0	0.375	0.019	77.6
	2	0.391	0.013	52.1	0.383	0.012	81.1
	3	0.406	0.018	57.3	0.409	0.018	89.2
	4	0.399	0.022	58.5	0.396	0.023	91.5
	5	0.425	0.021	63.1	0.434	0.020	98.4
Column ave		0.401	0.019	56.2	0.399	0.018	87.6
F	1	0.508	0.044	74.4	0.517	0.043	78.1
	2	0.601	0.126	84.9	0.598	0.117	86.4
	3	0.533	0.090	77.2	0.531	0.092	80.8
	4	0.582	0.068	79.9	0.599	0.082	82.3
	5	0.631	0.098	83.2	0.635	0.096	86.2
Column ave		0.571	0.085	79.9	0.576	0.086	82.8
G	1	0.529	0.018	51.1	0.542	0.023	53.6
	2	0.506	0.024	52.1	0.532	0.024	55.6
	3	0.491	0.030	52.1	0.528	0.030	54.7
	4	0.555	0.032	56.8	0.548	0.032	58.0
	5	0.572	0.041	88.8	0.605	0.037	92.6
Column ave		0.531	0.029	60.2	0.551	0.029	62.9
H	1	0.437	0.034	57.3	0.458	0.027	89.8
	2	0.468	0.022	52.0	0.471	0.018	82.6
	3	0.416	0.016	48.8	0.425	0.016	75.7
	4	0.428	0.016	53.2	0.424	0.017	82.8
	5	0.426	0.038	48.9	0.443	0.063	78.1
Column ave		0.435	0.025	52.0	0.444	0.028	81.8
I	1	0.467	0.026	57.8	0.470	0.025	89.5
	2	0.433	0.036	51.2	0.433	0.033	81.3
	3	0.557	0.041	56.2	0.599	0.066	88.7
	4	0.501	0.020	48.1	0.512	0.023	74.9
	5	0.456	0.049	51.2	0.443	0.050	80.6
Column ave		0.483	0.034	52.9	0.491	0.039	83.0

Table 2.3 Friction and Disk Track Temperature Data for High-Load/ High-Speed Tests

		High pressure, high speed: P = 320 N (59 psi), v = 15.0 m/s								
		Second drag			Fifth drag			Tenth Drag		
Lining	Spec	Friction Coefficient		Ave Temp	Friction Coefficient		Ave Temp	Friction Coefficient		Ave Temp
		Average	Std Dev	(C)	Average	Std Dev	(C)	Average	Std Dev	(C)
A	1	0.353	0.018	114.4	0.300	0.017	178.8	0.259	0.024	220.0
	2	0.389	0.025	123.1	0.332	0.021	179.9	0.246	0.022	226.7
	3	0.288	0.016	117.8	0.342	0.022	179.3	0.263	0.022	218.2
	4	0.401	0.023	118.6	0.322	0.019	182.6	0.278	0.024	223.9
	5	0.352	0.017	106.9	0.293	0.017	175.6	0.277	0.024	214.3
Column ave		0.357	0.020	116.2	0.318	0.019	179.2	0.265	0.023	220.6
B	1	0.325	0.013	116.2	0.303	0.009	170.3	0.239	0.015	212.3
	2	0.385	0.012	126.4	0.343	0.013	183.9	0.277	0.012	224.7
	3	0.363	0.012	111.3	0.343	0.011	180.0	0.285	0.018	228.8
	4	0.365	0.014	135.3	0.305	0.011	194.9	0.249	0.016	225.5
	5	0.377	0.015	118.4	0.340	0.013	173.4	0.296	0.014	212.7
Column ave		0.363	0.013	121.5	0.327	0.011	180.5	0.269	0.015	220.8
C	1	0.363	0.017	110.0	0.303	0.015	169.1	0.251	0.014	205.0
	2	0.229	0.012	106.1	0.202	0.009	160.8	0.175	0.009	209.3
	3	0.236	0.013	116.4	0.213	0.010	178.5	0.173	0.012	228.0
	4	0.326	0.029	114.9	0.307	0.019	170.4	0.274	0.018	211.8
	5	0.353	0.020	121.4	0.320	0.021	183.2	0.258	0.016	226.8
Column ave		0.301	0.018	113.8	0.269	0.015	172.4	0.226	0.014	216.2
D	1	0.497	0.036	136.7	0.542	0.060	220.3	0.399	0.013	318.1
	2	0.421	0.042	126.7	0.472	0.084	221.6	0.365	0.084	321.1
	3	0.495	0.068	125.0	0.497	0.087	208.9	0.412	0.079	316.9
	4	0.484	0.063	116.6	0.550	0.064	201.1	0.446	0.082	315.1
	5	0.471	0.035	119.3	0.519	0.068	206.9	0.413	0.068	306.6
Column ave		0.474	0.049	124.9	0.516	0.073	211.8	0.407	0.065	315.6
E (1)	1	0.361	0.015	63.4	0.316	0.034	113.3	0.330	0.013	243.2
	2	0.338	0.045	58.4	0.317	0.045	96.4	0.352	0.047	236.5
	3	0.384	0.048	65.1	0.342	0.049	105.9	0.359	0.051	239.0
	4	0.386	0.047	63.9	0.350	0.046	108.9	0.355	0.050	251.4
	5	0.390	0.026	69.9	0.340	0.020	111.7	0.365	0.037	259.5
Column ave		0.372	0.036	64.1	0.333	0.039	107.2	0.352	0.040	245.9
F	1	0.370	0.018	110.6	0.355	0.019	172.0	0.293	0.016	223.6
	2	0.418	0.030	121.9	0.380	0.027	179.0	0.317	0.026	229.5
	3	0.384	0.030	129.7	0.360	0.020	188.8	0.268	0.022	224.8
	4	0.386	0.023	117.1	0.388	0.019	180.7	0.309	0.021	230.9
	5	0.426	0.031	117.8	0.394	0.023	182.0	0.336	0.024	235.9
Column ave		0.397	0.026	119.4	0.375	0.022	180.5	0.305	0.022	228.9
G	1	0.402	0.031	78.1	0.392	0.033	117.1	0.335	0.045	147.5
	2	0.385	0.031	81.2	0.364	0.034	119.5	0.300	0.047	151.2
	3	0.384	0.031	81.8	0.360	0.042	119.8	0.297	0.050	152.5
	4	0.394	0.033	89.8	0.373	0.028	130.3	0.299	0.055	167.2
	5	0.416	0.057	134.6	0.414	0.053	200.0	0.338	0.085	263.6
Column ave		0.396	0.037	93.1	0.381	0.038	137.3	0.314	0.056	176.4
H	1	0.231	0.027	56.7	0.249	0.018	95.4	0.188	0.008	193.3
	2	0.313	0.030	58.1	0.300	0.025	100.9	0.225	0.012	202.2
	3	0.338	0.023	57.7	0.289	0.021	95.0	0.242	0.018	199.5
	4	0.314	0.041	46.3	0.370	0.067	65.1	0.340	0.033	144.3
	5	0.393	0.047	62.6	0.345	0.019	97.4	0.251	0.014	198.6
Column ave		0.318	0.034	56.3	0.311	0.030	90.8	0.249	0.017	187.6
I	1	0.220	0.039	57.3	0.227	0.049	89.1	0.173	0.018	163.8
	2	0.240	0.032	60.8	0.168	0.015	82.0	0.130	0.014	155.6
	3	0.393	0.048	64.0	0.280	0.014	97.8	0.172	0.013	188.9
	4	0.311	0.022	55.3	0.189	0.014	79.4	0.175	0.017	146.7
	5	0.285	0.017	55.4	0.233	0.017	81.6	0.179	0.010	158.3
Column ave		0.290	0.032	58.6	0.219	0.022	86.0	0.166	0.014	162.7

Table 2.4 Wear Data for SSBT Tests

Lining	Spec	Pad Weight Loss (grams)	Std Dev of weight loss
A	1	0.0283	
	2	0.0324	
	3	0.0267	
	4	0.0283	
	5	0.0252	
	Average	0.0282	0.003
B	1	0.0298	
	2	0.0337	
	3	0.0392	
	4	0.0361	
	5	0.0344	
	Average	0.0346	0.003
C	1	0.0256	
	2	0.0277	
	3	0.0355	
	4	0.0320	
	5	0.0317	
	Average	0.0305	0.004
D	1	0.1535	
	2	0.1620	
	3	0.1337	
	4	0.1205	
	5	0.1095	
	Average	0.1358	0.022
E (1)	1	0.0906	
	2	0.0762	
	3	0.0767	
	4	0.0819	
	5	0.0914	
	Average	0.0834	0.007
F	1	0.0465	
	2	0.0515	
	3	0.0500	
	4	0.0609	
	5	0.0565	
	Average	0.0531	0.006
G	1	0.0595	
	2	0.0589	
	3	0.0524	
	4	0.0595	
	5	0.0545	
	Average	0.0570	0.003
H	1	0.0181	
	2	0.0225	
	3	0.0183	
	4	0.0110	
	5	0.0213	
	Average	0.0182	0.004
I	1	0.0111	
	2		
	3	0.0227	
	4	0.0148	
	5	0.0145	
	Average	0.0158	0.005

2.1.3 Analysis

The average friction coefficients for the last two drags on each lining material at low-pressure/low-speed (Chase test conditions) are listed in Table 2.5. The average friction coefficient for the OE linings is slightly higher than for AM linings. Comparable data for the high-speed and high-load cases are given in Tables 2.6 and 2.7. While the average friction of OE linings is higher than for AM linings, that difference for high-speed, high-load results is not very great.

Figure 2.2 shows the average friction coefficient for the last (10^{th}) drag of each series of tests, and Figure 2.3 shows the percent reduction in friction that resulted from the higher energy drags. Except for lining E with 11 percent, the other linings suffered between 37 percent and 66 percent friction reduction under more severe sliding conditions. The normal term used to describe a temporary loss of braking ability due to frictional heat build-up is called "fade." Whether SSBT data can be used to predict the relative fade performance of linings under actual service conditions has not been established, but results are interesting enough to pursue this line of inquiry.

Table 2.5 Friction Coefficients (μ) for the Last Two Drags on Low-Speed and Low-Load Tests (167 N, 6 m/s, Average of Five Runs)

Lining Code	Product Name	9^{th} Drag Avg. μ	9^{th} Drag Std. Dev.	10^{th} Drag Avg. μ	10^{th} Drag Std. Dev.
B	ARVIN 212	0.518	0.077	0.535	0.083
C	ARVIN 301	0.512	0.067	0.534	0.075
D	ARVIN 402	0.652	0.159	0.649	0.157
	Avg. (OE linings)	0.561	0.101	0.573	0.105
A	ABEX 6008-1	0.488	0.061	0.505	0.069
E	BrakePro CM24	0.401	0.019	0.399	0.018
F	Armada AR3	0.571	0.085	0.576	0.086
G	Armada AR2	0.531	0.029	0.551	0.029
H	Fleet Pride OTR II	0.435	0.025	0.444	0.028
I	Carlisle MB21	0.483	0.034	0.491	0.039
	Avg. (AM linings)	0.485	0.042	0.494	0.045

Table 2.6 Average Friction Coefficients (μ) for High-Speed and High-Load Tests (320 N, 15 m/s, Based on Five Runs)

Lining Code	Product Name	2^{nd} Drag μ Average	5^{th} Drag μ Average	10^{th} Drag μ Average
B	ARVIN 212	0.363	0.327	0.269
C	ARVIN 301	0.301	0.269	0.226
D	ARVIN 402	0.474	0.516	0.407
	Avg. (OE linings)	0.379	0.371	0.301
A	ABEX 6008-1	0.357	0.318	0.265
E	BrakePro CM24	0.372	0.333	0.352
F	Armada AR3	0.397	0.375	0.305
G	Armada AR2	0.396	0.381	0.314
H	Fleet Pride OTR II	0.318	0.311	0.249
I	Carlisle MB21	0.290	0.219	0.166
	Avg. (AM linings)	0.355	0.323	0.275

Table 2.7 Standard Deviation in Friction Coefficients (μ) for High-Speed and High-Load Tests (320 N, 15 m/s, Based on Five Runs)

Lining Code	Product Name	2^{nd} Drag μ Std. Dev	5^{th} Drag μ Std. Dev.	10^{th} Drag μ Std. Dev
B	ARVIN 212	0.013	0.011	0.015
C	ARVIN 301	0.018	0.015	0.014
D	ARVIN 402	0.073	0.049	0.065
	Avg. (OE linings)	0.035	0.025	0.031
A	ABEX 6008-1	0.020	0.019	0.023
E	BrakePro CM24	0.036	0.039	0.040
F	Armada AR3	0.026	0.022	0.022
G	Armada AR2	0.037	0.038	0.056
H	Fleet Pride OTR II	0.034	0.030	0.017
I	Carlisle MB21	0.032	0.022	0.014
	Avg. (AM linings)	0.031	0.028	0.029

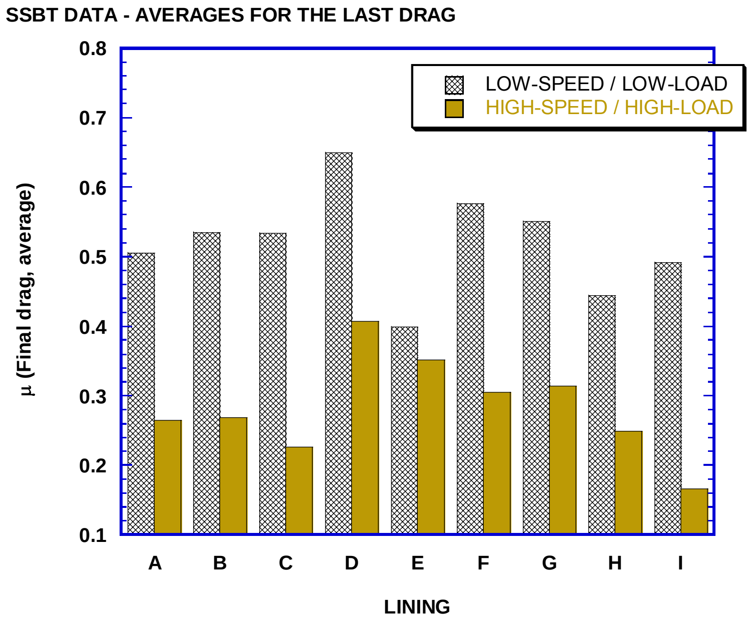

Figure 2.2 Comparison of Average Friction Data for the Last (10th) Drag of Linings Under Low-Speed/Low-Load Conditions and High-Speed/High-Load Conditions.

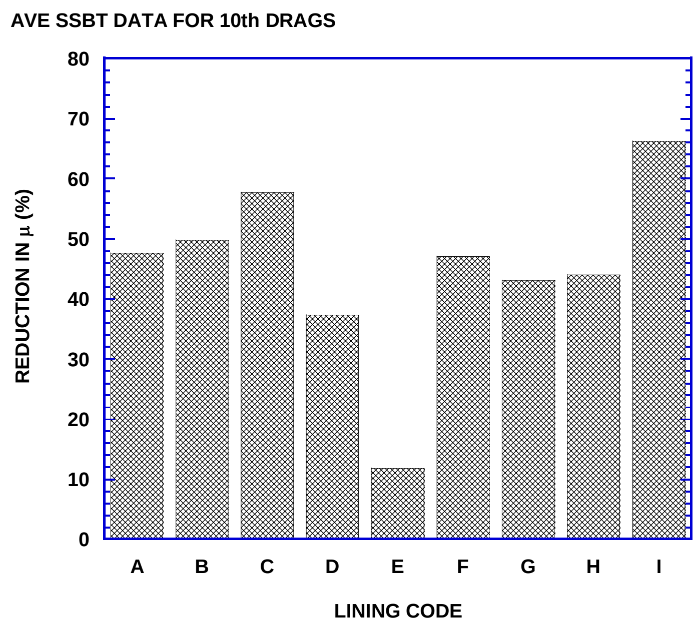

Figure 2.3 Percent Reduction in Friction Coefficient on the Last Drag of the High-Speed and High-Load Condition Compared to the Last Drag for the Low-Speed and Low-Load Condition For Each Lining Material (an Average of Five Tests per Value).

Frictional heating effects varied with the lining material. Based on previous work by many investigators, higher sliding friction forces are expected to generate more heat under similar test conditions. Table 2.8 compares the average disc temperatures of the last drag for the low-speed/low-load runs and the high-speed/ high-load runs. It could not be generalized that OE linings run either hotter or cooler than AM linings.

Table 2.8 Disc Wear Track Temperature for the Last Drag of Each Series

Lining Code	Low-Speed / Low-Load Average (Std. Dev.) Temperature, ^{o}C	High Speed / High Load Average (Std. Dev.) Temperature, ^{o}C
B (OE)	77.8 (6.6)	220.8 (7.7)
C (OE)	81.7 (7.1)	216.2 (10.5)
D (OE)	95.9 (4.8)	315.6 (5.5)
A (AM)	83.9 (11.7)	220.6 (4.8)
E (AM)	87.6 (8.3)	245.9 (9.5)
F (AM)	82.8 (3.6)	228.9 (5.0)
G (AM)	92.6 (16.7)	176.4 (49.3)
H (AM)	81.8 (5.4)	187.6 (24.4)
I (AM)	83.0 (6.1)	162.7 (15.9)

The disc track temperatures generated under two test conditions are shown in Figure 2.4. Figure 2.5 indicates that the increase in disc temperature when running under low- and high-severity test conditions (ΔT) is roughly related to the magnitude of the friction coefficient under the high-severity test conditions.

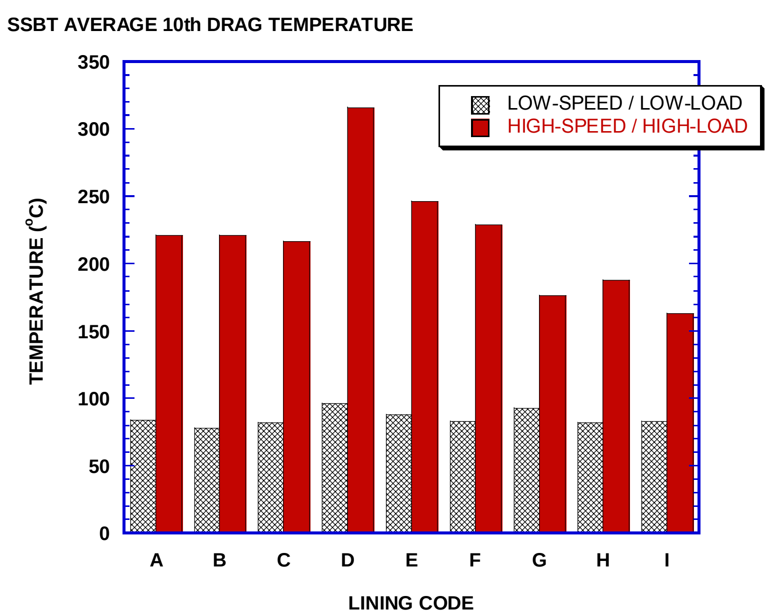

Figure 2.4 Effects of Test Conditions on Disc Specimen Wear Track Temperature.

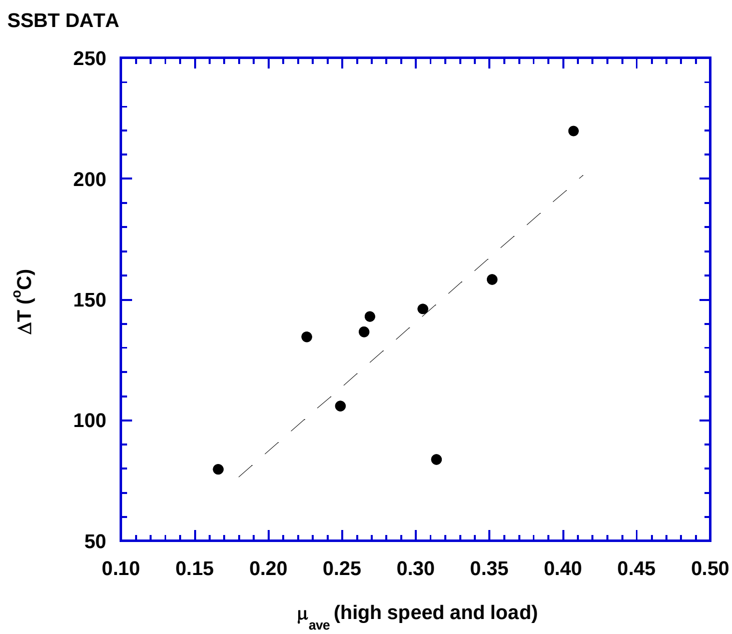

Figure 2.5 Approximate Relationship Between Temperature Difference for the Last Drag of the High- and Low-Severity Tests and the Magnitude of the Friction Coefficient for the High-Severity Test.

Table 2.9 shows both the lining wear data and their relative wear rankings. Three of the AM linings had less wear than the OE linings. Lining D (OE) had the largest wear loss by far, but it also had the highest friction coefficients as well [see Tables 2.5 and 2.6].

Table 2.9 Wear and Relative Rankings of Linings Tested on the SSBT

Lining Code	Average Mass Loss (mg)	Std. Dev. of Mass Loss (mg)	Relative Ranking*
B	34.6	3.0	5
C	30.5	4.0	4
D	135.8	22.0	9
Avg. OE	67	9.7	
A	28.2	3.0	3
E	83.4	7.3	8
F	53.1	5.6	6
G	57.0	3.3	7
H	18.2	4.5	2
I	15.8	4.9	1
Avg. AM	42.6	4.8	

* 1 = least wear, 9 = most wear

As shown in Figure 2.6, there was a good second-degree polynomial correlation between lining wear and friction coefficient for the last drag in the high-speed/high-load series. Excepting the anomalous result for lining "E," a similarly good fit resulted for the low-speed/low-load data in Figure 2.7.

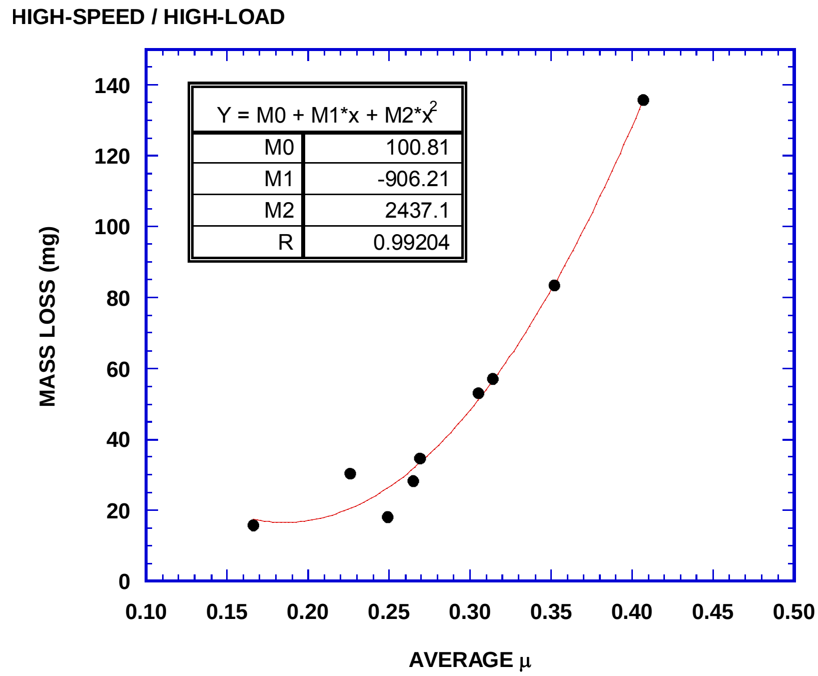

Figure 2.6 Correlation Between Lining Specimen Wear and the Friction Coefficient for the Final Drag of the Test Series at High-Speed and High-Load.

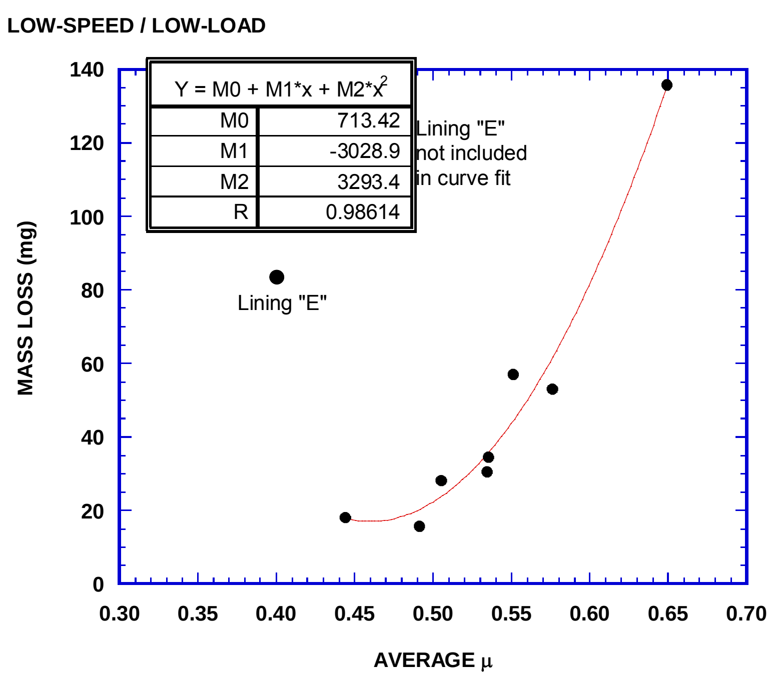

Figure 2.7 Correlation Between Lining Specimen Wear and the Friction Coefficient for the Final Drag of the Test Series at Low-Speed and Low-Load.

2.1.4 Results

Based on the results of SSBT tests on nine lining materials, it could not be stated that OE linings performed better or worse than AM linings. Data were obtained for specific lining materials under specific test conditions, but there were an insufficiently large number of different lining materials involved in this study to draw any general conclusions about these two classes. Lining "D" in particular exhibited extremes in both traction and wear loss, and since there were only three OE lining compositions tested ("B", "C", and "D") the effect of the data for "D" tended to bias the average for the OE linings toward higher values. Considering the other two OE linings, their friction coefficients and wear values fell within the range of the AM linings tested. The friction coefficient and wear loss results for all SSBT tests are summarized in Table 2.10.

Table 2.10 Consolidated Results of SSBT Tests

Lining Code	Product Name	Low-PV 10th Drag Average μ	High-PV 10th Drag Average μ	Average Wear Loss (mg)
B	ARVIN 212	0.535	0.269	34.6
C	ARVIN 301	0.534	0.226	30.5
D	ARVIN 402	0.649	0.407	135.8
	Avg. (OE linings)	0.573	0.301	67.0
A	ABEX 6008-1	0.505	0.265	28.2
E	BrakePro CM24	0.399	0.352	83.4
F	Armada AR3	0.576	0.305	53.1
G	Armada AR2	0.551	0.314	57.0
H	Fleet Pride OTR II	0.444	0.249	18.2
I	Carlisle MB21	0.491	0.166	15.8
	Avg. (AM linings)	0.494	0.275	42.6

2.1.5 Conclusion

The following conclusions were obtained from SSBT tests of lining samples. Low-speed/low-load tests had similar test pressures and speeds to previously reported Chase tests and the high-speed/high-load tests used the maximum capabilities of the SSBT apparatus. Five tests were performed on each lining material. Friction coefficient, wear loss, and disc temperature data were obtained.

- Friction coefficients for the less severe conditions were comparable to those typically reported for friction materials (0.35-0.50), but those for the more severe conditions were lower. Friction coefficients for less severe conditions ranged between about 0.40 to 0.65, and those for the more severe conditions ranged between about 0.17 to 0.41.
- Friction-induced temperature rises varied from less than 100^{o}C for low-speed/low-load tests to as much as 315^{o}C for the more severe testing conditions.

- There was a good second-degree polynomial relationship between the mass loss (wear) and average friction coefficient for the last drag of high-speed/high-load tests. Except for one lining, a similarly good correlation was noted for the low-speed/ low-load tests as well.
- Although the original equipment linings averaged slightly higher friction, due to the influence of one lining in particular, there was no evident trend that OE linings were necessarily any better than AM linings in friction or wear.

2.2 Chase Tests

The Chase test was developed as a laboratory-scale test method for measuring the consistency of lining products in terms of their friction and wear characteristics. It was intended as a quality control measurement for purchasers of lining materials and not intended to simulate on-vehicle performance. Despite this limitation, the test, in the form of an SAE standard, has been used by purchasing agents to specify replacement brake linings for commercial and municipal truck fleets. Nevertheless, the widespread use of Chase tests for lining evaluation made it advisable to include such data in this project. Tests were performed by Link Testing Laboratories, Detroit, Michigan, and the full set of raw data is available in a separate project report. Five duplicate tests were run on each lining type.

2.2.1 Overview

The standard Chase test uses a rotating cast iron drum of prescribed composition and surface finish against which a small square pad of lining material is pressed using a sequence of applications. The full procedure is described in the SAE J661 standard [7], but a summary of the conditions and stages of testing is presented in Table 2.11, and the testing geometry is schematically shown in Figure 2.8. The drum inner diameter is about 10.97 in. (278.7 mm), and based on the standard procedure, 417 rpm corresponds to a sliding speed of 6.084 m/s.

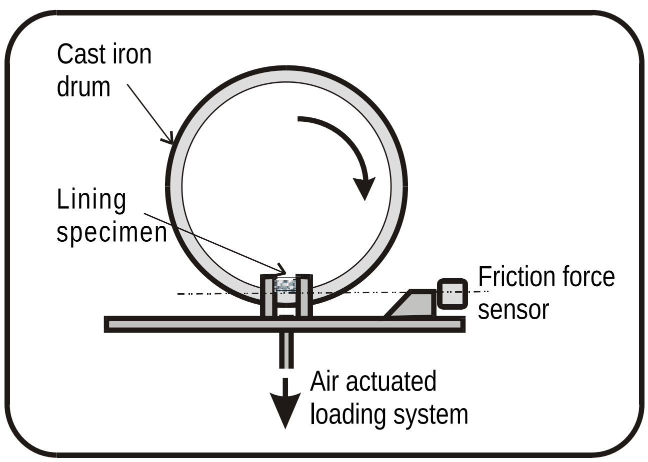

Figure 2.8 General Configuration of the Chase Test. The Lining Slides on the Curved Surface of the Inside of the Drum.

Table 2.11 Summary of SAE J661: "Brake Lining Quality Test Procedure"
(Section numbers refer to the paragraph numbers in the SAE procedure).

Section	Sequence Name	Procedure	Number of Drags	Notes
5.3	Burnish	Run a minimum of 20 min at 312 rpm and 440 N (100 lb-f) at 93 C (200 F).	1	To produce contact over at least 95% of the lining surface.
5.4	Initial thickness and mass measurement	Measure lining thickness in three places and weigh to the nearest 1 mg.	Not applicable	
5.5	Initial wear measurement	Measure height reading on the machine gage with a 667 N load applied, but no motion.	Not applicable	Measure in the drum temperature range of 88-99 C (190-210 F).
6.1	Baseline run	10 s on and 20 s off at 667 N at 417 rpm.	20	Begin at 82-93 C (180-200 F); maintain 82-104 C.
6.2	First fade run	Starting at 82 C, apply 667 N at 417 rpm continuously until temperature reaches 288C (550 F).	1	Record friction at 28 C (50 F) intervals.
6.3	First recovery run	Turn on cooling air and make a 10 s application at 667 N and 417 rpm every 100 F, starting with 500 F.	4	Record friction at 56 C intervals.
6.4	Second wear measurement	(see Section 5.5).	1	
6.5	Wear run	20 s on and 10 s off at 667 N, 417 rpm.	100	Begin at drum temp. of 193-204 C (380-400 F) and using forced air keep final temperatures 193-216 C (480-420 F).
6.6	Third wear measurement	(see 5.5).	Not applicable	
6.7	Second fade run	Cool drum. At 82 C (180 F) apply spec. at 667 N, 417 rpm, and begin heating until 343 C (650 F) is reached, or for 10 min.	1	Record friction every 28 C (50 F) starting at 93 C (200 F). Record time to reach 343 C.
6.8	Second recovery run	Turn on cooling air and make a 10 s application at 667 N and 417 rpm every 100 F, starting with 600 F.	5	Record friction at 56 C intervals.
6.9	Baseline rerun	(see Section 6.1).	20	
6.10	Final wear measurement	(see Section 5.5).	Not applicable	
6.11	Measure and weight specimen	(see Section 5.4).	Not applicable	
		TOTAL APPLICATIONS	152	

Wear of the lining specimens is generally measured in terms of both thickness change and mass change. In the current project, measurements of the drum wear were also attempted, but these dimensional changes are so small relative to the size of the drum specimen that their accuracy cannot be strongly relied upon.

SAE J866 [8] establishes a standard coding scheme for linings based on the friction coefficients (COF) that are measured in accordance with the SAE J661 procedure. It simply partitions friction coefficients into the categories as follows and reports values for "normal" and "hot" testing conditions.

C	COF ≤ 0.15
D	> 0.15 but ≤ 0.25
E	> 0.25 but ≤ 0.35
F	> 0.35 but ≤ 0.45
G	> 0.45 but ≤ 0.55
H	> 0.55
Z	unclassified

The "normal" value comes from an average of four readings on the second fade curve at drum temperatures between 200 and 400^{o}F (93-204^{o}C). Temperature is measured using thermocouples embedded into the drum. The "hot" value represents the average of ten readings; namely, two points at 400 and 300^{o}F on the first recovery, five points between 450 and 630^{o}F on the second fade, and three points between 500 and 300^{o}F on the second recovery.

2.2.2 Data Collected

The friction coefficients, obtained from test method SAE J661 and letter-graded using the provisions of SAE J866, are listed in Table 2.12. The rankings were based on the numerical values of the friction coefficients, from highest (1) to lowest (9). When equal numbers were encountered, the same rankings were assigned. In some cases, the only difference was in the third decimal place, and such precision is not warranted in light of typical testing variability; therefore, a courser ranking was also performed (Table 2.13). This resulted in fewer categories but probably a more realistic assessment of trends. Note that rankings were not equivalent for normal and hot coefficient of friction (COF) data. Under the "normal" COF heading in Table 2.12, lining "D" stood out as substantially higher than the others, the second tier grouped between 0.50 and 0.52, and the third grouping was between about 0.43 and 0.45. Due to the difference in fade behavior of linings there was more of a spread in groupings for the hot COF data than for the normal COF data, but lining "D" was still the highest in the hot category. There are two listings for Lining "E". The first Lining "E" sample [designated E(1)] failed two SAE J661criteria: the Maximum Absolute Variation below Average exceeded 0.050, and the Maximum Percentage Variation exceeded 20 percent. A sample of Lining "E" from a second brake shoe in the set was run and it passed. This result demonstrates that J661 performance can vary between one brake block and another. Lining "E" was also an outlier in the SSBT tests described earlier.

Table 2.12 SAE J661 Friction Coefficients (COF) and SAE J866 Letter Grades

Lining Code	"Normal" COF	Normal Ranking*	"Hot" COF	Hot Ranking*	J866 Grade
A	0.432	8	0.415	8	FF
B	0.438	7	0.462	4	FG
C	0.500	4	0.452	6	GG
D	0.564	1	0.539	1	HG
E1	0.442	6	0.376	9	FF
E2	0.477	5	0.376	9	GF
F	0.508	3	0.484	2	GG
G	0.517	2	0.464	3	GG
H	0.442	5	0.459	5	FG
I	0.386	9	0.424	7	FF

* Ranking from high (1) to low, equal values given equal rankings.

Table 2.13 Ranking of Linings Based on Nominal Variations in Friction Measurements

Lining Code	"Normal" COF Ranking*	"Hot" COF Ranking*
A	3	4
B	3	3
C	2	3
D	1	1
E (1 and 2)	3	5
F	2	2
G	2	3
H	3	3
I	4	4

* Ranking from high (1) to low.

2.2.3 Analysis

The large number of friction readings that are generated by each SAE J661 test offers a large number of possible ways in which to analyze and rank linings, and therefore, the challenge was to find the most significant data on which to base the comparison of test methods and lining performance.

One important characteristic of a lining is its constancy in friction over the wide temperature range that may be experienced in service. The SAE J661 method does not address braking during cold temperatures as might be experienced in northern climates or during severe winter weather. Nor does it address stopping in wet environments or after drum exposure to corrosive deicers, but it does provide information on friction coefficients during repeated braking under dry conditions, in which the drum temperature rises as high as 650°F (343°C). This trend is shown in Figure 2.9 based on the average friction coefficient (five individual tests per plotted point) versus temperature in the second fade segment of SAE J661 (see Table 2.11, section 6.7) for all nine lining materials. In general, the maximum friction coefficient occurs above room temperature and precedes the drop-off at higher temperatures, sometimes called "fade."

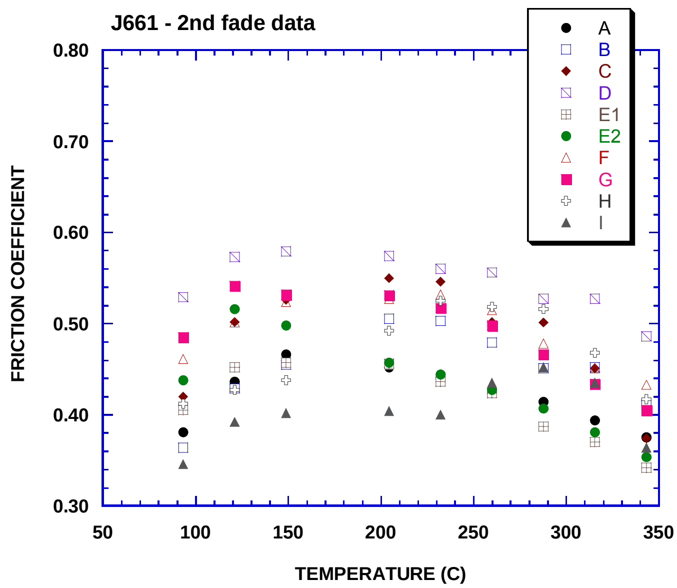

Figure 2.9 Effect of Drum Temperature on Friction Coefficient for All Linings (Five-Test Average/Point).

Curves for the data in Figure 2.9 can be closely represented in this temperature range by a third-degree polynomial equation of the form:

$$y = m_o + m_1 x + m_2 x^2 + m_3 x^3 \qquad (2.1)$$

where y = average friction coefficient, x = temperature in degrees F, and $m_{o,1,2,3}$ are coefficients in units of (1/^{o}F). Table 2.14 gives the coefficients for each lining material and the Pearson's least squares curve fit parameter (R) which is an indication of the closeness of fit between the data and Equation (2.1). An R value of 1.000 indicates a perfect fit. [Note: Sometimes the statistical quantity R^2 is used to describe the degree to which data conform to a mathematical curve fit. Use of R^2 would result in lower values than the R values used throughout this report.] The closeness of fit of the test data to the equation enables an estimate to be made of the temperatures for the maximum friction coefficient of each lining. Setting the first derivative of Equation (2.1) equal to zero, and solving the quadratic formula for its two roots, one can determine the maximum of the curve that falls within the range of 200 to 650^{o}F. These values are also given in Table 2.14 and range from 335 – 507^{o}F (168 – 264^{o}C). Figure 2.10 exemplifies how closely the equations fit the data for two different linings.

Table 2.14 Average Friction Coefficient as a Function of Temperature

Lining	m_o	m_1	m_2	m_3	R	$T_{max\ COF}$ (°F)	$T_{max\ COF}$ (°C)
A	-0.1027	3.926E-03	-8.545E-06	5.612E-09	0.980	351.3	177.4
B	-0.1232	3.581E-03	-6.393E-06	3.314E-09	0.982	412.2	211.2
C	-0.0230	3.218E-03	-5.154E-06	1.792E-09	0.980	392.6	200.3
D	0.2618	2.149E-03	-4.418E-06	2.554E-09	0.964	348.6	175.8
E (1)	0.0392	2.956E-03	-6.306E-06	3.815E-09	0.993	338.0	170.0
E (2)	0.0316	3.588E-03	-8.523E-06	5.826E-09	0.957	307.3	152.9
F	0.1071	2.679E-03	-5.086E-06	2.656E-09	0.987	371.4	188.6
G	0.1542	2.677E-03	-5.575E-06	3.155E-09	0.988	335.9	168.8
H	0.5996	-2.229E-03	8.020E-06	-7.742E-09	0.991	497.8	258.8
I	0.4458	-1.073E-03	4.110E-06	-4.015E-09	0.809	506.7	263.7

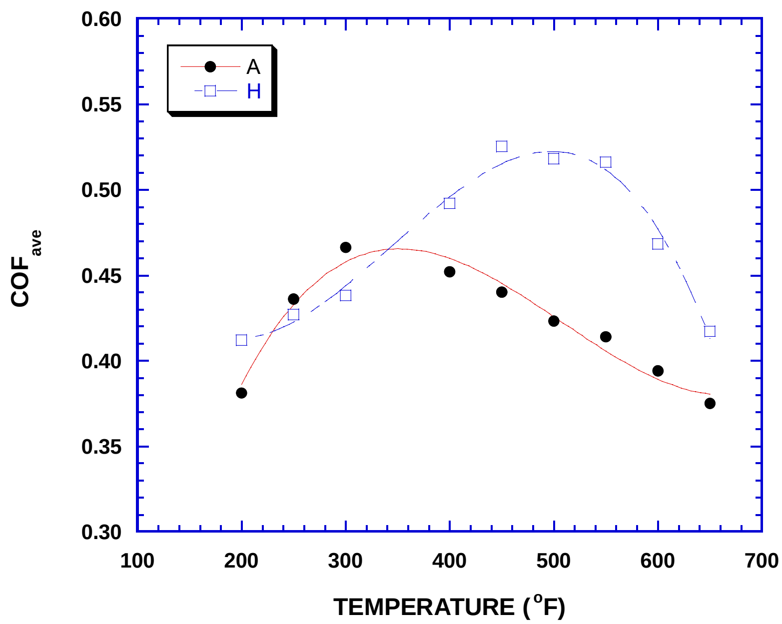

Figure 2.10 Example of Fitting Equation (2.1) to Second Fade Segment Data for Linings A and H.

There was no apparent correlation between the temperature of the maximum friction coefficient (Table 2.12) with either the "hot" (Figure 2.11) or the "normal" (Figure 2.12) friction ratings. Differences in the formulations of the linings eliminates the possibility of drawing general conclusions about the relationship between braking effectiveness, as indicated by the friction coefficient, and the temperature at which traction is highest.

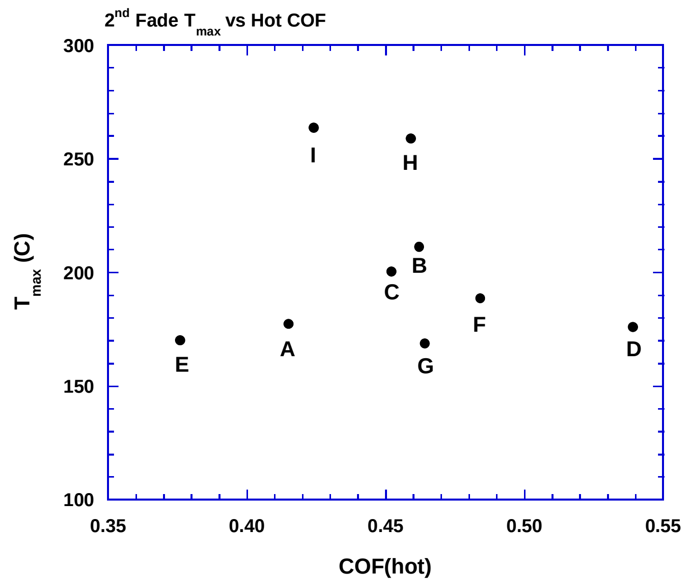

Figure 2.11 No Correlation Existed Between the "Hot" Friction Rating and the Temperature at Which the Friction Reached a Maximum ["E" refers to E(1)].

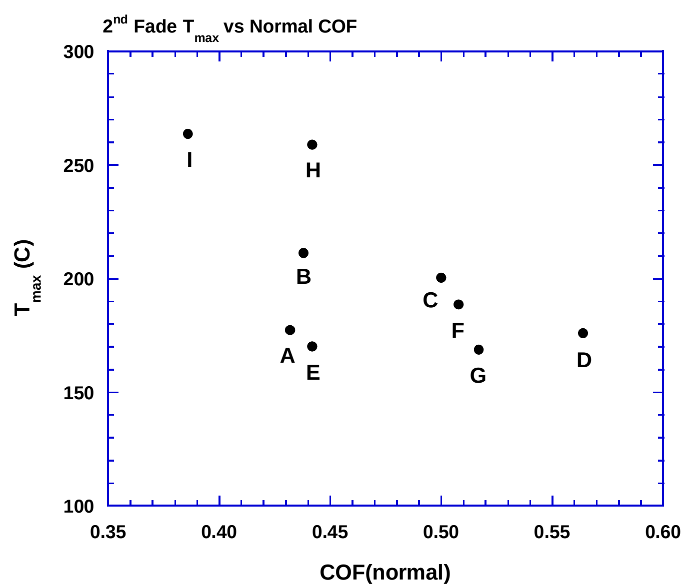

Figure 2.12 No Correlation Existed Between the "Normal" Friction Rating and the Temperature at Which the Friction Reached a Maximum ["E" refers to E(1)].

Lining wear was measured in two ways, by loss in thickness and by loss in weight. Drum wear was measured with a micrometer at three positions around the drum circumference. Lining wear data is summarized in Table 2.15 in terms of percent change and drum wear in μm. The averages are also plotted in order of increasing thickness loss in Figure 2.13. Some of the differences in ranking by mass or thickness involve the fact that linings differed in density, so the same weight change could produce different thickness changes in linings with different densities, but having the same pad area.

Table 2.15 Summary of Lining and Drum Wear Measurements (Based on Five Tests)

Lining Code	Lining Average Mass Loss (%)	Standard Deviation (%)	Lining Average Thickness loss (%)	Standard Deviation (%)	Drum Average Thickness Loss (μm)	Standard Deviation (μm)
A	4.1	0.3	3.9	0.7	7.8	3.2
B	4.9	0.5	3.3	0.7	13.7	8.5
C	5.4	0.3	4.7	1.3	19.3	8.5
D	8.4	0.4	6.2	0.7	3.9	3.2
E (1)	2.5	1.2	1.9	1.1	5.9	2.3
E (2)	3.1	0.9	3.5	1.2	30.5	11.1
F	7.4	0.6	5.5	1.9	21.1	10.2
G	6.6	0.4	4.3	1.9	9.9	5.3
H	4.1	0.5	2.8	0.5	6.2	2.5
I	4.1	0.4	2.3	0.3	6.0	5.1

As shown in Figure 2.13 and Table 2.15, lining samples "E(1)" and "E(2)" presented much different wear results. Recalling that sample "E" first failed the variability criteria of the J661 test, and when retested, the second result "E(2)," which was given a "pass" rating on the test, not only had somewhat higher normal temperature friction (Table 2.3) but had considerably higher lining and drum wear than sample "E(1)." The shoe-to-shoe lining variation demonstrates that at least some linings can produce significant lot-to-lot variations in wear resistance. The average friction was similar for the "E(1)" shoe and the "E(2)" shoe even though the 0.035 increase in normal friction for "E(2)" bumped it into the next higher J886 rating category.

Generally, the higher the friction coefficient of a lining-cast iron couple, the more the lining tends to wear. This trend, while not presenting an exact correlation, is nevertheless indicated in Figure 2.14 in which the Chase Test "normal" friction coefficient values are plotted as a function of the average lining wear, as measured by the percent loss in thickness.

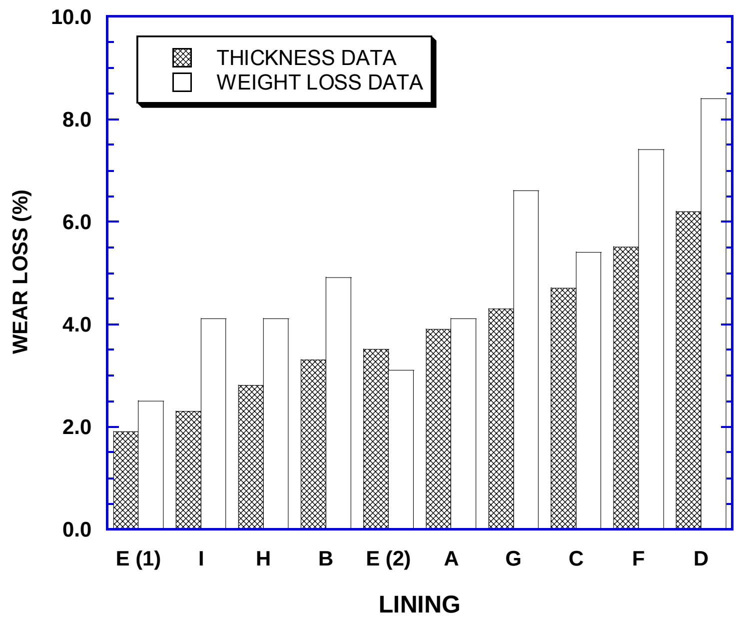

Figure 2.13 Relative Wear Loss for Linings Measured by Weight Loss (Open Bars) and Ranked by Reduction in Thickness (Hatched Bars).

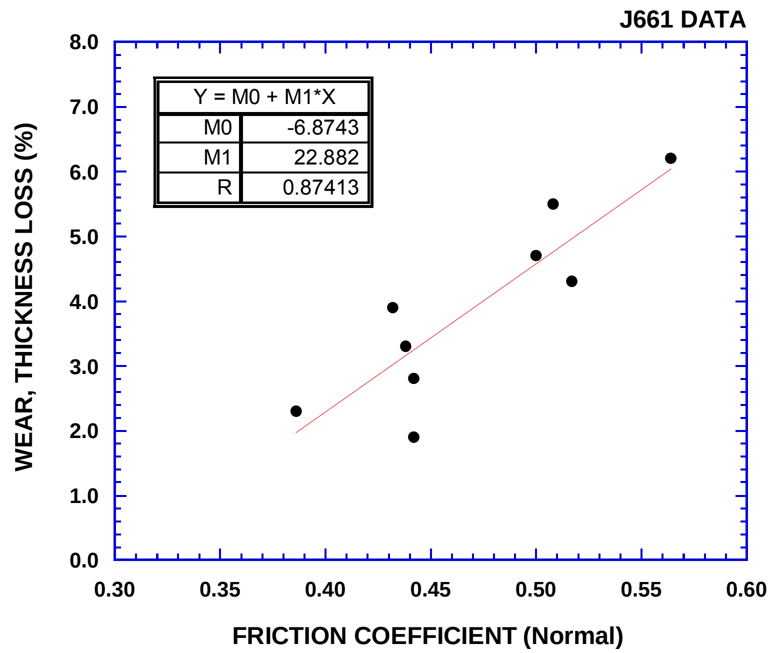

Figure 2.14 Relationship Between Lining Wear and "Normal" Coefficient of Friction.

The wear of the test drums was difficult to measure accurately since measurements varied considerably around the circumference of the drum. In some cases, the standard deviation of the measurements was similar to the average value. Therefore, drum wear is approximate, at best. Considering this limitation, the drum wear is plotted in ascending order in Figure 2.15. The test-to-test drum wear difference between the Lining "E" samples suggests that different samples of the same lining type can produce significant variations in data, although this particular case may not be typical of the variations for all lining products. It is interesting to note that Lining “E(1)” initially failed the SAE J661 friction criteria and had to be retested, but its wear was much lower than that for lining “E(2)” which did pass the friction criteria for the same test method. Lining “E(2),” which passed the friction test, was the most damaging to the drum (see Figure 2.15).

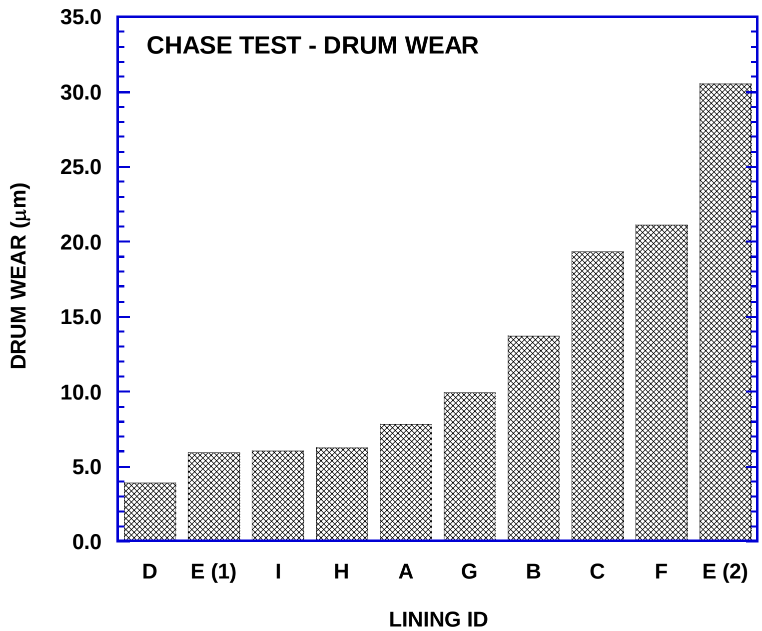

Figure 2.15 Drum Wear Loss in Ascending Order (Average of Five Tests).

2.2.4 Results

Friction and wear test results from the previous sections can be compared in terms of whether the lining was considered an OE lining or an AM, replacement lining. Data from Table 2.12 were resorted on the basis of this classification and presented in Table 2.16. Overall, the OE linings produced slightly higher average friction coefficients than did the AM linings in both the “Normal” and “Hot” categories; however, the result was significantly biased by the abnormally high friction coefficients for lining “D.” Without lining “D,” the averages for normal and hot friction coefficients for the OE would be 0.469, and 0.457 respectively – quite close to the values for the AM linings. It cannot be concluded that the friction of OE linings is consistently higher than AM linings based on the results of the current tests.

Wear loss, sorted with regard to OE and AM materials, is presented in Table 2.17. Based on the limited sample of data, the OE linings had higher average wear than the AM linings. However, there were only three OE linings, so each OE material had a larger effect on the average than each of the seven AM linings did. It cannot be concluded that OE linings had consistently more or less wear than AM linings based on the Chase data. In fact, the data overlapped and may be part of the same population.

Wear amounts tended to span a wider range of values than did the friction coefficients of the various brake materials. Therefore, it is especially important to repeat friction tests and to establish their variability, because even a small difference in friction coefficient, can significantly change a material's ranking within such a narrow overall range of results.

Table 2.16 Comparison of Friction Coefficient Data Based on OE and AM Designations

Lining Code		"Normal" COF	Overall Ranking*	"Hot" COF	Overall Ranking*
B	OE	0.438	7	0.462	4
C	OE	0.500	4	0.452	6
D	OE	0.564	1	0.539	1
Average	OE	0.501		0.484	
A	AM	0.432	8	0.415	8
E1	AM	0.442	6	0.376	9
E2	AM	0.477	5	0.376	9
F	AM	0.508	3	0.484	2
G	AM	0.517	2	0.464	3
H	AM	0.442	5	0.459	5
I	AM	0.386	9	0.424	7
Average	AM	0.458		0.428	

* Ranking from high (1) to low, equal values given equal rankings.

Table 2.17 Comparison of Lining Wear Based on OE and AM Designations

Lining Code		Lining Average Mass Loss (%)	Standard Deviation (%)	Lining Average Thickness Loss (%)	Standard Deviation (%)
B	OE	4.9	0.5	3.3	0.7
C	OE	5.4	0.3	4.7	1.3
D	OE	8.4	0.4	6.2	0.7
Average	OE	6.2		4.7	
A	AM	4.1	0.3	3.9	0.7
E (1)	AM	2.5	1.2	1.9	1.1
E (2)	AM	3.1	0.9	3.5	1.2
F	AM	7.4	0.6	5.5	1.9
G	AM	6.6	0.4	4.3	1.9
H	AM	4.1	0.5	2.8	0.5
I	AM	4.1	0.4	2.3	0.3
Average	AM	3.2		3.4	

2.2.5 Conclusion

The following conclusions were obtained from the Chase tests:

- The "normal" friction coefficients for all nine lining samples, each tested five times, ranged from 0.386 to 0.564. The average for all linings was 0.471 (standard deviation = 0.052).

- The "hot" friction coefficients for all nine lining samples, each tested five times, ranged from 0.376 to 0.539. The average for all linings was 0.445 (standard deviation = 0.050).

- In the second fade portion of the Chase tests, the friction coefficients reached a maximum near the mid-range of drum temperatures 302°F (150°C). The relationship between the friction coefficient and temperature could be represented by a third-degree polynomial expression and could be used to estimate the temperature for peak friction coefficient. Values ranged between 153 and 263°C.

- One lining type was tested twice and while the friction results were similar, the wear results were significantly different.

- In general, high lining wear tended to correlate with high friction, but variability in wear data, particularly for drums, was large.

- On average, the OE linings displayed slightly higher friction coefficients, but also slightly higher wear than the AM linings, although the small sample size in this study does not permit broad general conclusions about either trend to be made. Some AM lining materials were as good as, or better than OE lining materials in terms of their friction and wear behavior.

2.3 Test-Track Testing

2.3.1 Facilities Description

The Transportation Research Center (TRC), Inc., is an automotive proving ground located on 4,500 acres in East Liberty, Ohio. TRC conducts research and testing designed to study safety, energy, fuel economy, etc. (www.trcpg.com). Facilities include a 7.5-mile test track, a vehicle dynamics area (VDA), cobblestone road, skid pad, and a 9,000-foot all-terrain-vehicle (ATV) course. The 50-acre vehicle dynamics area (shown in Figure 2.16) contains a skid pad, allowing for brake testing on surfaces of varying friction. Vehicles may be tested for compliance on a number of testing standards, including FMVSS 121 [9].

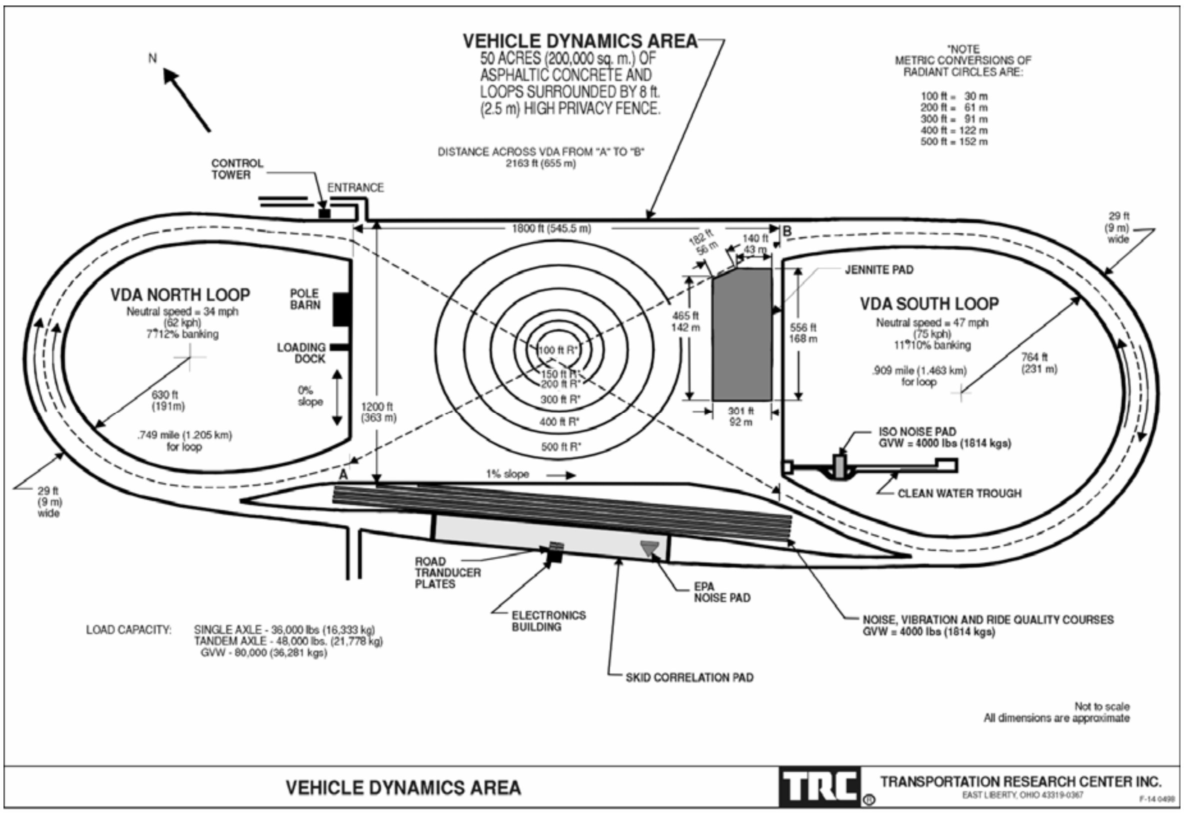

Figure 2.16 Transportation Research Center – Vehicle Dynamics Area.

Laurens Proving Grounds (LPG), Michelin's testing facility, is located on 3,000 acres in Mountville, South Carolina. The LPG consists of 13 individual test areas, consisting of 14 miles of track. Areas are dedicated to wet and dry handling, inside and outside noise testing, comfort, wet and dry braking, hydroplaning, dry and wet off-road capability, curb impacts, wet tread photography and dry and wet road holding. An aerial photograph of the LPG is shown in Figure 2.17.

Figure 2.17 Laurens Proving Grounds.

2.3.2 Description of TRC Testing

Truck #3212 (Class-7 single-axle dump truck) was sent to TRC to be tested under selected portions of FMVSS 121 at the request of NHTSA. FMVSS 121 requires heavy-duty vehicles to stop, on a high-coefficient-of-friction pavement, with properly working brakes, in a pre-determined distance based on load. The following sequence was selected and optimized to mitigate the number of vehicle load changes:

2.3.2.1 Perform brake build in accordance to FMVSS 121.
2.3.2.2 Perform 500, 40-20 mph Brake Burnish snub maneuvers at GVWR.
2.3.2.3 Perform six, 60 mph service brake effectiveness stops at GVWR.
2.3.2.4 Determine maximum drive through brake-in-curve speed at GVWR.
2.3.2.5 Determine maximum brake-in-a-curve lateral stability at GVWR (ability to remain within a 12 ft. wide lane as determined from visual observation).
2.3.2.6 Perform six, 30 mph split-mu stopping performance maneuvers at GVWR.
2.3.2.7 Perform six, 60 mph service brake effectiveness stops at LLVW.
2.3.2.8 Determine maximum drive through brake-in-curve speed at LLVW.
2.3.2.9 Perform six, brake-in-curve lateral stability maneuvers at LLVW (ability to remain within a 12 ft. wide lane as determined from visual observation).
2.3.2.10 Perform six, 30 mph split-mu stopping performance maneuvers at LLVW).
2.3.2.11 Complete a brake adjustment, if needed.
2.3.2.12 Perform final inspection.

The above procedure was followed for both the AM and OE brake materials listed in Table 1.3 for truck #3212. A test report #20020317 was issued by TRC. [10] Figures 2.18 and 2.19 show photographs taken during the testing of truck # 3212 at TRC.

Figure 2.18 Truck 3212 at GVWR.

Figure 2.19 Truck 3212 Passenger Side Rear Brake Build.

2.3.3 Description of LPG Testing

Truck #s 102 (Class-8 tandem-axle dump truck), 107 (Class-8 tri-axle dump truck), and 960 (Class-8 refuse hauler) were sent to LPG to be tested on the straight-line stopping portion of FMVSS 121 only, and were tested as follows:

2.3.2.1 Perform brake build in accordance to FMVSS 121.
2.3.2.2 Perform 500, 40-20 mph Brake Burnish snub maneuvers at GVWR.
2.3.2.3 Perform six, 60 mph service brake effectiveness stops at GVWR.
2.3.2.4 Perform six, 60 mph service brake effectiveness stops at LLVW.
2.3.2.5 Complete a brake adjustment, if needed.
2.3.2.6 Perform final inspection.

The above procedure was followed for both the AM and OE brake materials listed in Table 1.3 for truck #'s 102, 107, and 960. A report dated March 30, 2006, was issued by LPG [11]. Figures 2.20 and 2.21 show photographs of the brake build and instrumentation, taken during the LPG testing.

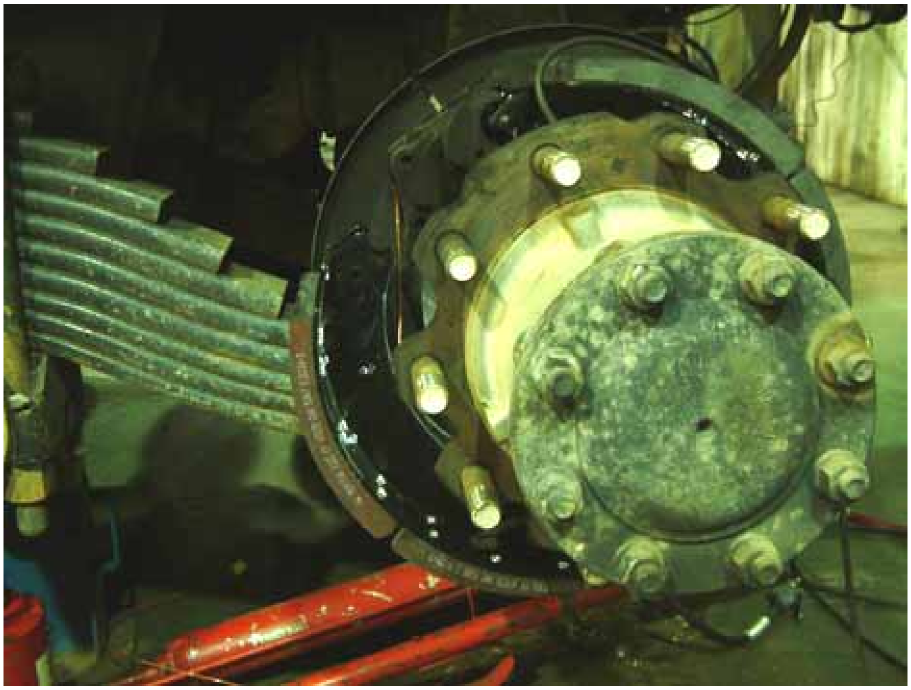

Figure 2.20 Brake Build at LPG.

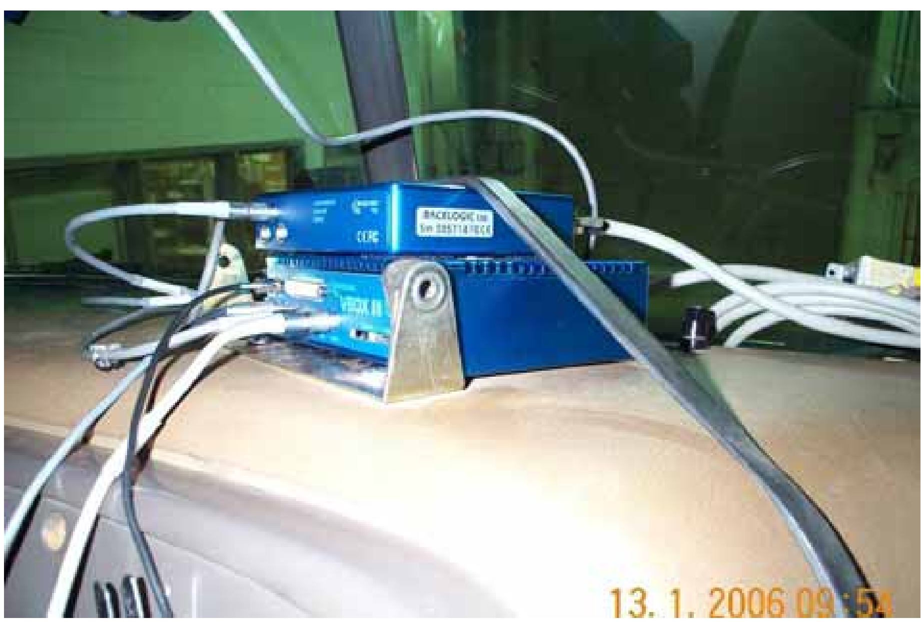

Figure 2.21 Instrumentation to Measure and Record Stopping Time and Distance at LPG.

2.3.4 Test-Track Data Collected (TRC and LPG)

As described previously, a battery of six stopping distance tests, following the FMVSS 121 specifications, were performed at the TRC and LPG research centers for each OE and AM brake lining. These tests were conducted with the trucks lightly loaded (LLVW) and fully loaded (GVWR). For all cases, speed information was collected at a resolution that varied from 100 Hz (TRC tests) to 20 Hz (LPG tests). The Class-7 vehicle was tested using an ADAT radar speed sensor that integrates speed (or change of speed) relative to time to produce a distance. The Class-8 vehicles were tested using a Vbox GPS type system interfaced with their braking software. The GPS system takes positions and measures the distance from the user defined start speed to ending speed. The positions are interpolated between the locations where the vehicle is just above and just below (or 0 for the end speed) the defined start and end speeds. The VBox Braking software does this interpolation. In addition to speed, TRC also collected treadle pressure for each one of the runs at a rate of 100 Hz. Raw temperature data was collected and is available upon request. GVWR tests were conducted with gravel as the ballast in all vehicles.

Results of these tests are presented in Tables 2.18 and 2.19, which show the stopping distance and times for each one of the six runs under each truck category tested (note: WC and W refer respectively to the Waste Connections and Walker Class-8 tandem-axle trucks that participated in this project; see Table 1.2). Notice that no data was collected for the WC Class-8 tandem-axle truck at the LLVW level. The reason for this was that during these tests the truck wheels locked up, making the stopping distance test invalid [2]. It was also noted that the stopping distances of the tandem axle trucks appeared to be very low in some cases. This anomaly was reported to the test engineer at LPG who confirmed data acquisition and reduction was conducted properly, and no errors in the equipment or process were found.

Table 2.18 Test Track Results for Aftermarket Brake Linings

	Run #	Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]
LLVW	1	4.80	214.8	N/A	N/A	2.88	123.7	5.24	235.0
	2	4.77	218.6	N/A	N/A	2.72	120.4	5.18	228.7
	3	4.60	210.8	N/A	N/A	2.77	120.1	5.39	232.7
	4	4.60	212.8	N/A	N/A	2.62	115.9	5.06	224.5
	5	4.59	211.2	N/A	N/A	2.73	121.8	5.17	231.3
	6	4.79	218.4	N/A	N/A	2.98	125.5	5.39	238.0
GVWR	1	7.79	345.9	4.42	202.1	5.07	216.5	7.68	351.4
	2	8.16	365.1	4.32	196.3	4.88	206.0	8.07	359.3
	3	7.71	343.9	4.27	194.1	5.08	201.5	8.24	358.8
	4	7.27	327.8	4.22	191.4	4.87	206.8	8.54	370.1
	5	7.23	324.8	4.32	197.6	5.13	212.3	8.16	367.7
	6	7.24	324.2	4.28	192.7	4.53	196.4	7.71	371.2

[2] With ABS, wheels lock-up should not have happened. However, this phenomenon was observed for this particular truck in the three attempts to run the stop-distance tests. The tests were therefore terminated to avoid damaging the truck tires.

Table 2.19 Test Track Results for Original Equipment Brake Linings

	Run #	Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]
LLVW	1	4.54	216.3	N/A	N/A	2.43	107.8	5.86	245.0
	2	4.16	188.5	N/A	N/A	2.43	111.4	5.17	232.1
	3	4.26	197.8	N/A	N/A	2.48	112.1	5.34	243.3
	4	4.22	185.4	N/A	N/A	2.43	108.3	5.49	241.2
	5	4.19	188.3	N/A	N/A	2.42	107.7	5.04	228.8
	6	4.32	198.8	N/A	N/A	2.43	107.5	5.39	234.4
GVWR	1	7.06	311.6	4.47	209.0	4.72	217.5	10.34	479.5
	2	6.61	294.6	4.38	203.2	4.52	203.7	9.37	391.3
	3	6.59	295.3	4.37	201.9	4.52	208.3	8.88	381.8
	4	6.28	288.8	4.32	203.2	4.57	208.8	8.96	405.1
	5	6.09	276.5	4.33	198.4	4.68	213.6	10.05	410.0
	6	6.10	280.5	4.33	199.0	4.57	210.4	8.89	412.4

2.3.5 Analysis of Test-Track Results (TRC and LPG)

Under carefully conducted tests, expectations would be to observe a constant deceleration rate for a constant braking pressure (i.e., a linear relationship between speed and time) during the stopping-distance tests. This was the case for most of the runs conducted at TRC. Figures 2.22 and 2.23 show one AM and one OE run, respectively, for the Class-7 single-axle truck under GVWR conditions. These figures show that in both cases speed (shown in blue) was a linear function of time (an ideal constant deceleration rate is shown in red). The graphs also show the treadle pressure (in green) which, except for the peak at the beginning of the deceleration regime, was constant during the test. Notice that at this peak in treadle pressure a variable deceleration rate was experienced. This rapidly changed to a constant deceleration rate once the pressure stabilized. This effect was more pronounced in the case of LLVW tests, in which the treadle pressure took longer to become stable, although the treadle pressure never reached constant regime (see Figures 2.24 and 2.25). Nevertheless, even in those LLVW TRC tests the registered deceleration rate was mostly constant.

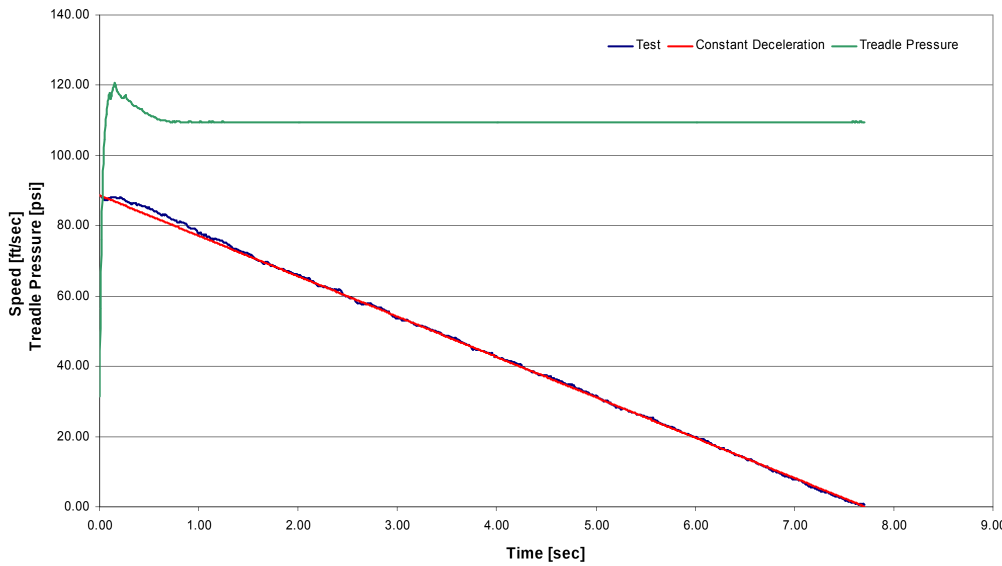

Figure 2.22 Speed vs. Time - Treadle Pressure vs. Time TRC AM/GVWR/Run #3.

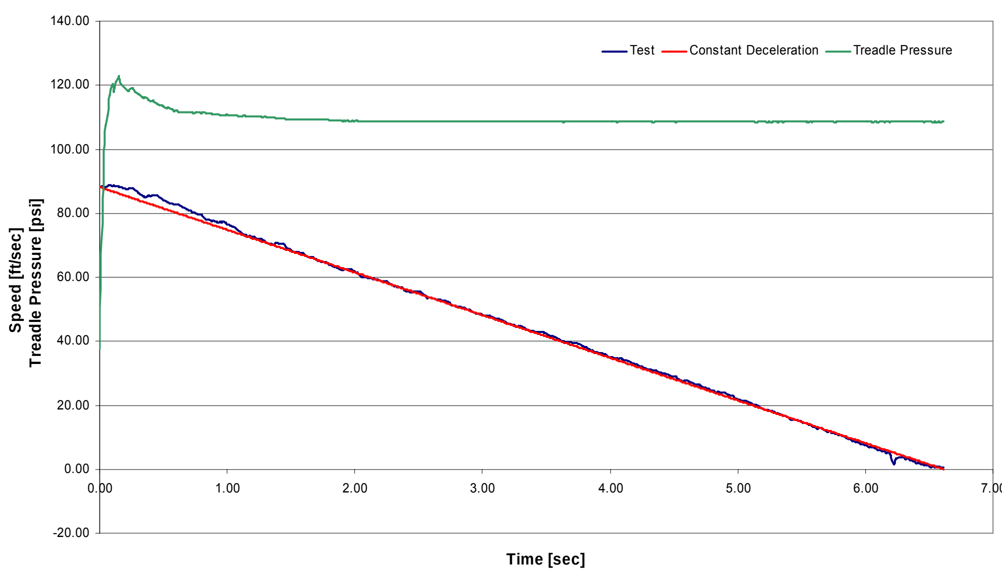

Figure 2.23 Speed vs. Time - Treadle Pressure vs. Time TRC OE/GVWR/Run #2.

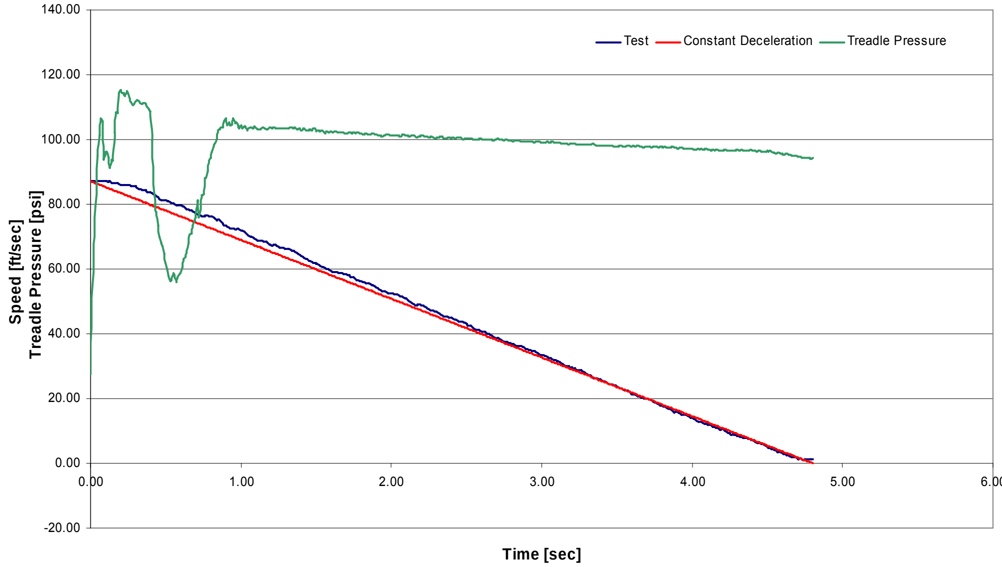

Figure 2.24 Speed vs. Time - Treadle Pressure vs. Time TRC AM/LLVW/Run #1.

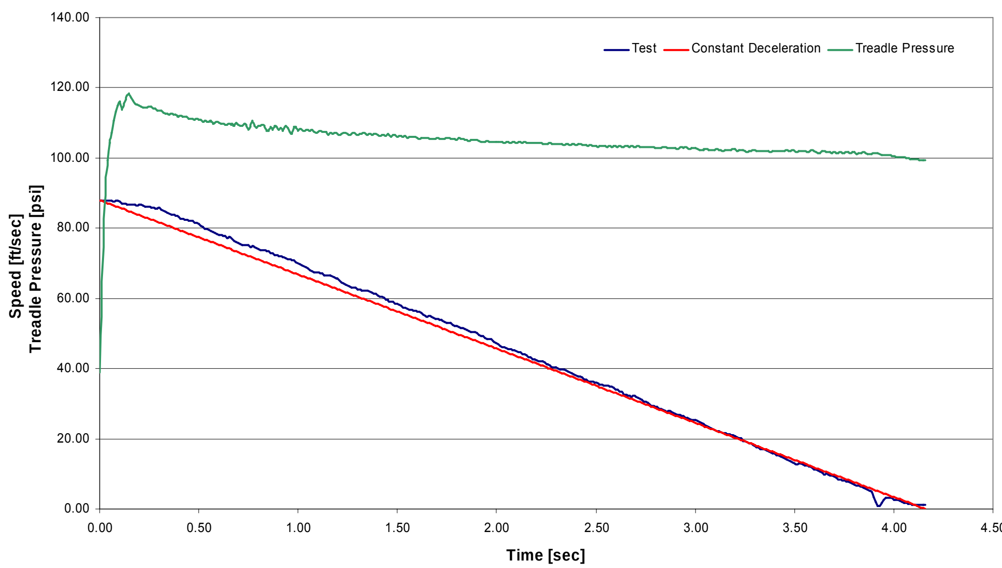

Figure 2.25 Speed vs. Time - Treadle Pressure vs. Time TRC OE/LLVW/Run #2.

The tests conducted at LPG resulted in deceleration rates that showed more variability than those observed at TRC. For instance, Figure 2.26 provides an example of a variable deceleration rate while Figure 2.27 shows a case of speed fluctuation during the stopping distance tests. In some of the cases, this speed fluctuation presented the form of a (decreasing) step function (see Figure 2.28) suggesting perhaps a malfunction of the braking system or the application of a variable treadle pressure (i.e., brake "pumping"). Unfortunately, in the case of the LPG tests, treadle pressure information was not collected so further elaboration on this phenomenon is not possible[3].

Similar to the TRC tests, some of the LPG runs also resulted in perfectly constant deceleration rates (see Figure 2.29), but the proportion was lower. That is, 67 percent of the TRC runs showed the expected constant deceleration rate, while this figure only reached 40 percent in the case of the LPG tests.

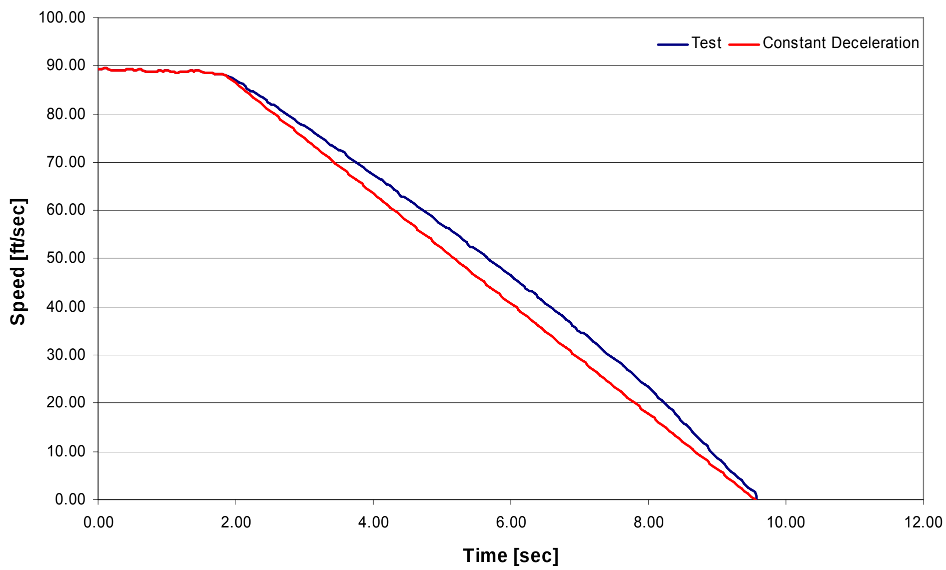

Figure 2.26 Speed vs. Time With Variable Deceleration LPG Class 8-Tri-Axle/AM/GVWR/Run #6.

[3] The test-track tests conducted at LPG focused on the straight-line stopping portion of FMVSS 121 only (see Section 2.3.3). Because of LPG's understanding of ORNL's requirements for these tests, only time and speed information were collected.

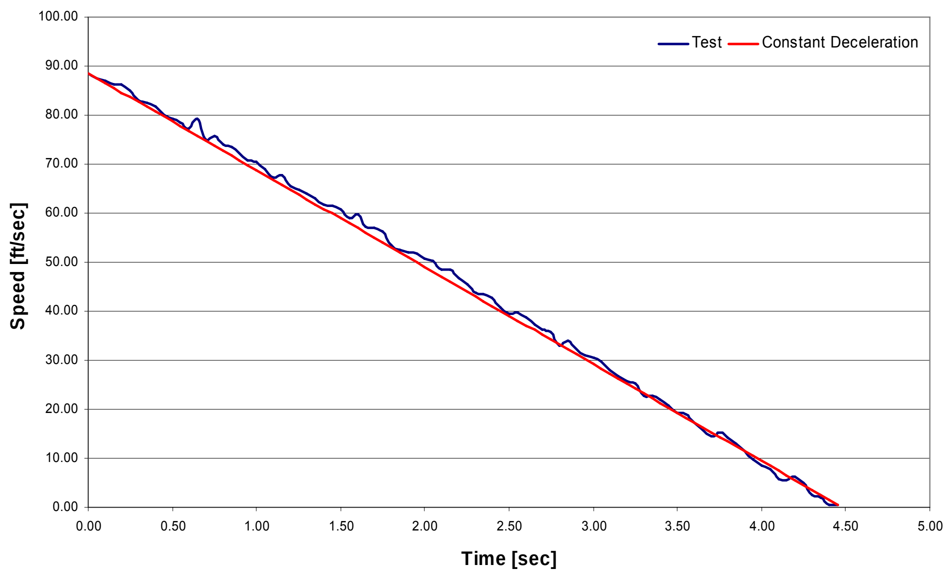

Figure 2.27 Speed vs. Time with Speed Fluctuations LPG WC Class 8-Tandem-Axle/AM/GVWR/Run #1.

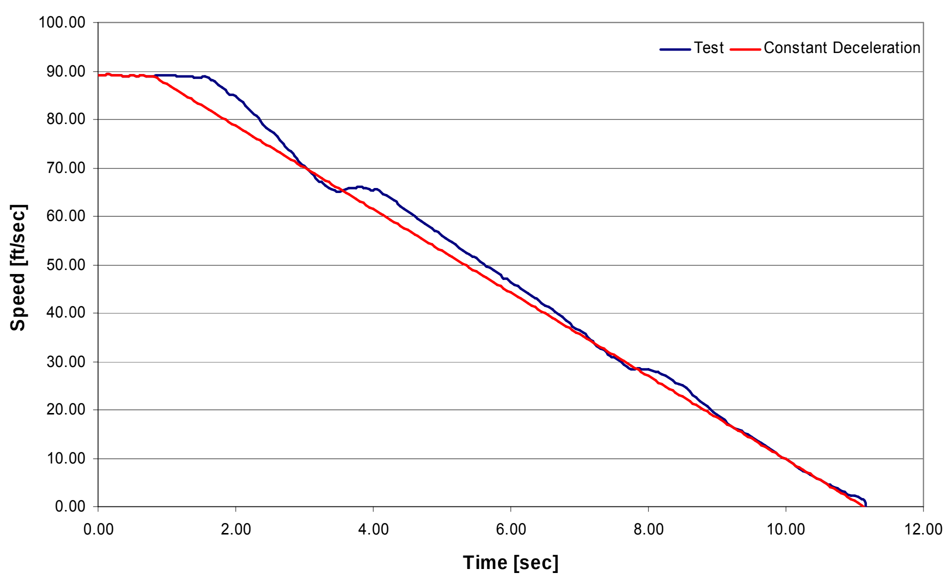

Figure 2.28 Speed vs. Time with Speed Fluctuations LPG Class-8 Tri-Axle/OE/GVWR - Run #1.

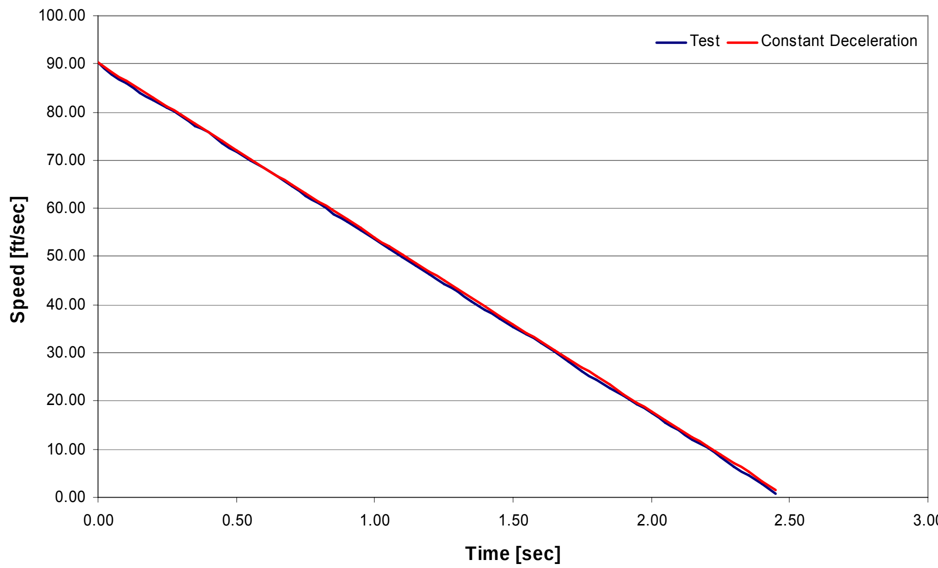

Figure 2.29 Speed vs. Time with Constant Deceleration Rate LPG W Class 8-Tandem-Axle/OE/LLVW/Run #2.

Using the speed vs. time information collected during these tests, it was possible to compute an average deceleration rate *DR* [= (Vi^2 – Vf^2) / (2 * d), where Vi = 88fps, Vf = 0, and d is the stopping distance]. The results of these calculations are shown in Tables 2.20 and 2.21 below (first column under each truck category). In the case of the TRC tests, it was also possible to compute a normalized deceleration rate *nDR* (i.e., a deceleration rate per unit of applied treadle pressure) which is shown in the second column under the Class-7 single-axle truck category. The other three truck categories in Tables 2.20 and 2.21 also show values of the variable *nDR*. However, since treadle pressure information for the LPG tests was not collected, in order to compute these normalized deceleration rates, the average treadle pressure collected in the TRC tests was used (see Table 2.22 below). Notice that it was possible to use this TRC average treadle pressure since the standard under which those tests were performed (i.e., FMVSS 121) requires the application of the maximum treadle pressure by the driver, making this variable a function of the truck's ABS. Moreover, considering that the air compressor of a brake system starts pumping air when the pressure falls below 100 psi –which assures a minimum of 100 psi, for braking systems in good conditions–, it may be feasible to assume that average treadle pressure observations similar to those of TRC would have been made if data on this variable had been collected at LPG. This assumption, however, may not hold in cases where brakes are not working properly.

Since both the TRC and LPG tests were performed under the FMVSS 121 standard, which calls for a specific procedure in the application of treadle pressure, the use of the variable *DR* or *nDR* in the statistical analysis of the results should, theoretically, make no difference. However, as discussed in the next section of this report, this is not the case for the field tests. Those tests were not (and could not have been) conducted under the FMVSS 121 standard, and therefore, the applied treadle pressure was not constant across field-tested truck categories and sometimes even across runs within the same category. This required a normalization of the deceleration rate, which strongly depends on the applied brake pressure (i.e., up to a certain threshold, the higher the treadle pressure, the larger the deceleration rate). For consistency reasons, the variable *nDR* was also used in the analysis of the test-track results.

Table 2.20 Deceleration Rate and Normalized Deceleration Rate Aftermarket Brake Linings

	Run #	Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		DR [ft/sec^2]	nDR [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]
LLVW	1	18.8	0.193	N/A	N/A	30.0	0.291	16.6	0.161
	2	19.0	0.178	N/A	N/A	32.5	0.315	16.9	0.164
	3	19.6	0.184	N/A	N/A	31.4	0.305	17.0	0.165
	4	19.7	0.186	N/A	N/A	33.1	0.322	17.6	0.170
	5	19.8	0.192	N/A	N/A	32.2	0.312	16.9	0.164
	6	19.3	0.195	N/A	N/A	29.5	0.287	16.2	0.157
GVWR	1	11.9	0.110	20.3	0.193	17.3	0.164	11.5	0.109
	2	11.2	0.114	20.3	0.192	18.0	0.171	11.0	0.104
	3	12.1	0.111	21.0	0.200	17.4	0.165	10.6	0.100
	4	12.8	0.123	20.0	0.190	18.0	0.171	10.2	0.097
	5	12.9	0.119	21.0	0.200	17.2	0.163	10.9	0.103
	6	12.7	0.122	20.6	0.196	19.4	0.184	11.3	0.107

*Normalized deceleration rate for LPG tests was calculated using average treadle pressure data from the TRC tests as this data was not taken during testing at LPG.

Table 2.21 Deceleration Rate and Normalized Deceleration Rate Original Equipment

	Run #	Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		DR [ft/sec^2]	nDR [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]	DR [ft/sec^2]	nDR* [ft/sec^2/psi]
LLVW	1	19.8	0.206	N/A	N/A	35.7	0.353	15.2	0.150
	2	21.5	0.205	N/A	N/A	36.3	0.358	17.1	0.169
	3	21.0	0.206	N/A	N/A	35.6	0.352	16.4	0.162
	4	20.8	0.201	N/A	N/A	35.6	0.352	15.9	0.157
	5	21.3	0.207	N/A	N/A	36.1	0.357	17.3	0.171
	6	20.9	0.213	N/A	N/A	35.9	0.355	16.1	0.159
GVWR	1	13.0	0.120	20.0	0.191	18.6	0.178	8.5	0.081
	2	14.0	0.128	20.7	0.197	19.2	0.183	9.4	0.090
	3	14.0	0.137	21.2	0.202	19.4	0.186	9.9	0.094
	4	14.5	0.144	21.3	0.204	19.2	0.184	9.9	0.095
	5	15.1	0.147	22.0	0.210	18.8	0.179	9.0	0.086
	6	15.1	0.144	21.6	0.207	19.2	0.183	9.8	0.093

*Normalized deceleration rate for LPG tests was calculated using average treadle pressure data from the TRC tests as this data was not taken during testing at LPG.

Table 2.22 TRC Tests Treadle Pressure (psi)

	LLVW		GVWR	
Run #	**AM**	**OE**	**AM**	**OE**
1	97.46	95.92	107.79	108.95
2	106.94	105.02	98.53	109.32
3	106.56	101.92	109.58	102.35
4	105.88	103.49	103.59	100.71
5	102.98	102.85	108.04	102.63
6	98.64	98.27	104.09	104.72
Mean	103.08	101.24	105.27	104.78

Statistical Analysis of Test-Track Data

The deceleration rates (*DR* and *nDR*) were used to perform statistical tests aimed at determining whether trucks with OE brake linings performed better than those fitted with AM brake linings. For those statistical tests, it was assumed that a brake lining that provides a higher deceleration rate – everything else being equal[4] – was better than one that produces a lower deceleration rate. A null hypothesis (H_o) specifying that there was no difference in the average deceleration rate obtained with AM and OE brake linings was tested against an alternative hypothesis (H_a) indicating that on the average, trucks mounted with OE brake linings provide higher deceleration rates than those mounted with AM brake linings. To evaluate these hypotheses, a two-sample t test was used since in many of the cases examined the sample sizes were small [12]. The two main assumptions required by this test are that the populations are normally distributed and that the sample variances are in the same order of magnitude. Both of these assumptions appeared to be reasonably met by the data collected. The t test was then used to determine the level of confidence at which the null hypothesis could be rejected in favor of the alternative hypothesis. A high level of confidence in rejecting H_o would be a strong indication that trucks mounted with OE brake linings performed better than trucks mounted with AM brake linings.

Table 2.23 presents the results of these statistical tests, when the deceleration rate *DR* was used for the comparison. The first five rows in the table present general statistics for each set of observations. The subsequent three rows include parameters (i.e., degrees of freedom of the data sample, difference between the observed OE and AM means, and the pooled estimator of the common variance) that permit the computation of the t statistic shown on the fourth row. This t statistic was then used to determine the confidence level at which the null hypothesis (i.e., no differences in deceleration rates between AM and OE equipment) could be rejected.

[4] Only technical aspects were analyzed here, no economical factors (i.e., installation and maintenance costs) were considered.

Table 2.23 Statistical Test Results When Using Deceleration Rate as the Comparison Variable (Test-Track Observations)

		Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		AM	OE	AM	OE	AM	OE	AM	OE
LLVW	Count	6	6	N/A	N/A	6	6	6	6
	Mean	19.4	20.9	N/A	N/A	31.4	35.9	16.9	16.3
	Std. Dev.	0.384	0.600	N/A	N/A	1.439	0.260	0.464	0.799
	Min	18.8	19.8	N/A	N/A	29.5	35.6	16.2	15.2
	Max	19.8	21.5	N/A	N/A	33.1	36.2	17.6	17.3
	N	10		N/A		10		10	
	Mean Diff	1.5		N/A		4.4		-0.5	
	Variance	0.254		N/A		1.068		0.427	
	t statistic	5.208		N/A		7.429		1.381	
	Reject H_o at	99.98%		N/A		100.00%*		90.13%**	
GVWR	Count	6	6	6	6	6	6	6	6
	Mean	12.3	14.3	20.5	21.1	17.9	19.1	10.9	9.4
	Std. Dev.	0.654	0.790	0.444	0.712	0.827	0.311	0.472	0.567
	Min	11.2	13.0	20.0	20.0	17.2	18.6	10.2	8.5
	Max	12.9	15.1	21.0	22.0	19.4	19.4	11.5	9.9
	N	10		10		10		10	
	Mean Diff	2.0		0.6		1.2		-1.5	
	Variance	0.526		0.352		0.391		0.272	
	t statistic	4.808		1.771		3.389		4.888	
	Reject H_o at	99.96%		94.65%		99.66%		99.97%**	

* Difference in sample variances slightly over an order of magnitude.
** This test corresponds to a reversed Alternative Hypothesis.

For the Class-7 single-axle truck, the null hypothesis (i.e., the AM and OE brake linings provided, on average, the same deceleration rate) could be rejected with over 99 percent confidence, for both the LLVW and GVWR load levels, in favor of the alternative hypothesis (i.e., the OE brake linings provided, on the average, higher deceleration rates than the AM brake linings). Similar results were obtained for the WC Class-8 tandem-axle GVWR test (the LLVW tests were not performed on this truck for reasons explained earlier), and the W Class-8 tandem-axle at the GVWR and LLVW.[5]

The Class-8 tri-axle tests showed reverse results, indicating that it was possible to reject the null hypothesis with 90 percent (LLVW) and 99.9 percent (GVWR) in favor of an alternative hypothesis postulating that AM brake linings produced higher deceleration rates than OE brake linings. Notice, however, that the Class 8 tri-axle truck is a particular truck in which the third axle (i.e., the drop axle) was mounted with AM brake linings for both OE and AM categories.[6] That is, the OE truck was really a hybrid configuration with two axles mounted with OE brake linings and the drop axle mounted with AM brake linings. In effect, this configuration was "closer" to an AM mounted truck than any of the other three cases. Given these conditions, it would be expected that the "OE" category performed worse, when compared to the AM category, than in the other three cases. Results for the field tests hinted similar results for this truck class, albeit at a much weaker level (see Section 2.4 of this report).

Similar statistical test results for the first three truck categories (both at the LLVW and GVWR load levels) as well as for the fourth truck class at the GVWR level were obtained when the normalized deceleration rate, *nDR*, was used (see Table 2.24). In the case of the Class-8 tri-axle truck loaded at LLVW, the statistical tests showed a reduction in the rejection confidence level (of the null hy-

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[5] In the case of the Class-8 Tandem Axle LLVW test, the sample variances were different by slightly over an order of magnitude, which could render this statistical test invalid.
[6] Since it was not possible to determine what was the original equipment installed on the drop axle, it was decided to use the typical AM linings that the fleet partner used for these brakes.

pothesis) from 90 percent to 72 percent, which was very close to the one obtained with the field test data (i.e., 71% as shown in Section 2.4 of this report). This provides a hint that if treadle pressure were collected during the LPG tests, the results would have been closer to those observed in the field (see next section) where it was possible to correct for this variable[7].

Table 2.24 Statistical Test Results When Using Normalized Deceleration Rate as the Comparison Variable (Test-Track Observations)

		Class-7 Single-Axle (TRC)		WC Class-8 Tandem-Axle (LPG)		W Class-8 Tandem-Axle (LPG)		Class-8 Tri-Axle (LPG)	
		AM	OE	AM	OE	AM	OE	AM	OE
LLVW	Count	6	6	N/A	N/A	6	6	6	6
	Mean	0.188	0.206	N/A	N/A	0.305	0.354	0.164	0.161
	Std. Dev.	0.007	0.004	N/A	N/A	0.014	0.003	0.005	0.008
	Min	0.178	0.201	N/A	N/A	0.287	0.352	0.157	0.150
	Max	0.195	0.213	N/A	N/A	0.322	0.358	0.170	0.171
	N	10		N/A		10		10	
	Mean Diff	0.018		N/A		0.049		-0.002	
	Variance	0.000		N/A		0.000		0.000	
	t statistic	5.769		N/A		8.514		0.588	
	Reject H_o at	99.99%		N/A		100.00%*		71.53%**	
GVWR	Count	6	6	6	6	6	6	6	6
	Mean	0.117	0.137	0.195	0.202	0.170	0.182	0.103	0.090
	Std. Dev.	0.006	0.011	0.004	0.007	0.008	0.003	0.005	0.005
	Min	0.110	0.120	0.190	0.191	0.163	0.178	0.097	0.081
	Max	0.123	0.147	0.200	0.210	0.184	0.186	0.109	0.095
	N	10		10		10		10	
	Mean Diff	0.020		0.007		0.013		-0.014	
	Variance	0.000		0.000		0.000		0.000	
	t statistic	3.989		2.051		3.633		4.730	
	Reject H_o at	99.87%		96.63%		99.77%		99.96%**	

* Difference in sample variances slightly over an order of magnitude.
** This test corresponds to a reversed Alternative Hypothesis.

2.4 Field Testing

2.4.1 Overview of Field Test

Field testing of the vehicles called out in Table 1.1 was conducted, using the OE and AM brakes in Table 1.2, by performing service brake straight-line stopping tests at the beginning (after a burnishing period) and near the end of the service life of the brakes under test. Each vehicle tested was fitted with new tires at the beginning of the field test period. The brake burnishing period is shown in Table 2.25 for each of the test vehicles.

Still images and video documentation of example of field braking event were recorded using a digital camera and video recorder. The cameras were attached to a tripod on the roadside.

[7] As explained previously, the average treadle pressure collected during the TRC test was used to compute the normalized deceleration rates for the LPG tests.

Table 2.25 Field Test Brake Burnishing Period

Vehicle Type	Identifying Number	Brake Burnishing Period
Class-7 Single-Axle Dump	#2879	2 Weeks
Class-7 Single-Axle Dump	#3212	2 Weeks
Class-8 Tandem-Axle Dump	#102	1 Week
Class-8 Tandem-Axle Dump	#105	1 Week
Class-8 Tri-Axle Dump	#107	1 Week
Class-8 Tri-Axle Dump	#108	1 Week
Class-8 Tandem-Axle Refuse	#960	1 Week
Class-8 Tandem-Axle Refuse	#961	1 Week

Table 2.26 lists the expected brake life and the actual brake life during the testing. Due to: a) the fact that all Class-8 vehicles' brakes lasted longer than the fleet owners' experience (3-times longer in the case of the refuse haulers) and b) timing issues with the test-track testing, the duration of the field test was shorter in many cases than the actual brake life. Note, the ">" sign is used to denote the brakes that were still serviceable at the end of the field test.

Table 2.26 Brake Change Frequency and Brake Life

TEST VEHICLES						
Vehicle Type	**Identifying Number**	**Type Brakes**	**Axle**	**Frequency of Installation**	**Expected Life of Brakes**	**Actual Life of Brakes**
Class-7 Single-Axle Dump	#2879	AM	All Axles	Once	2 years	> 11 months
Class-7 Single-Alxle Dump	#3212	OE	All Axles	Once		> 4 months
Class-8 Tandem-Axle Dump	#102	OE	Drive Axles	Once	4 to 6 months	6 months
		OE	Steer Axle	Once	8 to 12 months	> 6 months
Class-8 Tandem-Axle Dump	#105	AM	Drive Axles	Once	4 to 6 months	9 months
		AM	Steer Axle	Once	8 to 12 months	> 9 months
Class-8 Tri-Axle Dump	#107	OE	Drive Axles	Once	4 to 6 months	6 months
		OE	Drop Axle	Once	8 to 12 months	> 6 months
		OE	Steer Axle	Once	8 to 12 months	> 6 months
Class-8 Tri-Axle Dump	#108	AM	Drive Axles	Once	4 to 6 months	8 months
		AM	Drop Axle	Once	8 to 12 months	> 8 months
		AM	Steer Axle	Once	8 to 12 months	> 8 months
Class-8 Tandem-Axle Refuse	#960	OE	Drive Axles	Once	< 2 months	5 months
		OE	Steer Axle	Once	< 4 months	> 5 months
Class-8 Tandem-Axle Refuse	#961	AM	Drive Axles	Once	< 2 months	6 months
		AM	Steer Axle	Once	< 4 months	> 6 months

At the beginning of the field test, each test vehicle was fitted with new tires as called out in Table 2.27. Tire wear monitoring was not a part of this project.

Table 2.27 Tire Size, Tread Type, and Pressure

Truck		Steer Axle	Test Pressure	Drop Axle	Test Pressure	Front Drive Axle	Test Pressure	Rear Drive Axle	Test Pressure
Class-7 Single Axle Dump	Size	11R22.5	**100 psi**					11R22.5	**100 psi**
Truck #2879	Tread Type	Highway						All Season	
	Tread Number	ST 230						DR 444	
	Tire Brand	BF Goodrich						BF Goodrich	
Class-7 Single Axle Dump	Size	11R22.5	**100 psi**					11R22.5	**100 psi**
Truck #3212	Tread Type	Highway						All Season	
	Tread Number	ST 230						DR 444	
	Tire Brand	BF Goodrich						BF Goodrich	
Class-8 Tandem Axle Dump	Size	385/65R22.5	**120 psi**			11R24.5	**100 psi**	11R24.5	**100 psi**
Truck #102	Tread Type	Highway				Traction		Traction	
	Tread Number	ST565				DR444		DR444	
	Tire Brand	BF Goodrich				BF Goodrich		BF Goodrich	
Class-8 Tandem Axle Dump	Size	11R24.5	**100 psi**			11R24.5	**100 psi**	11R24.5	**100 psi**
Truck #104	Tread Type	Highway				Traction		Traction	
	Tread Number	ST230				DR444		DR444	
	Tire Brand	BF Goodrich				BF Goodrich		BF Goodrich	
Class-8 Tri-Axle Dump	Size	385/65R22.5	**120 psi**	11R22.5	**90 psi**	11R24.5	**100 psi**	11R24.5	**100 psi**
Truck #107	Tread Type	Highway		Highway		Traction		Traction	
	Tread Number	ST565		TR134		DR444		DR444	
	Tire Brand	BF Goodrich		BF Goodrich		BF Goodrich		BF Goodrich	
Class-8 Tri-Axle Dump	Size	385/65R22.5	**120 psi**	11R22.5	**90 psi**	11R24.5	**100 psi**	11R24.5	**100 psi**
Truck #108	Tread Type	Highway		Highway		Traction		Traction	
	Tread Number	ST565		TR134		DR444		DR444	
	Tire Brand	BF Goodrich		BF Goodrich		BF Goodrich		BF Goodrich	
Class-8 Rufuse	Size	315/80R22.5	**130 psi**			315/80R22.5	**130 psi**	315/80R22.5	**130 psi**
Truck #960	Tread Type	Highway				Traction		Traction	
	Tread Number	R296				DBM		DBM	
	Tire Brand	Bridgestone				Bandag		Bandag	
Class-8 Rufuse	Size	315/80R22.5	**130 psi**			315/80R22.5	**130 psi**	315/80R22.5	**130 psi**
Truck #961	Tread Type	Highway				Traction		Traction	
	Tread Number	R296				DBM		DBM	
	Tire Brand	Bridgestone				Bandag		Bandag	

2.4.2 Testing Protocols

In order to conduct the required straight-line service brake stopping tests, the vehicle under test (VUT) was instrumented with the equipment listed in Table 2.28. The test instrumentation is shown in Figure 2.30.

Table 2.28 Field Test Instrumentation

Equipment	Purpose
Racelogic VBOX	Measurement of Velocity and Stopping Distance from 55 mph to 0 mph
Laptop Computer with USB to Serial Interface	Used to Record VBOX Data
Brake Application Pressure Gauge (Permanently mounted to each test vehicle)	Used by Driver to Assure Consistent Brake Stopping Force
DC Power Pack	To Power VBOX and Computer

Figure 2.30 Field Test Instrumentation.

The field test instrumentation was mounted to a common backplane and rested in the test engineer's lap during testing. The instrumentation was self-contained and required only that the GPS antenna be attached to the VUT via magnet or tape.

A warm-up period was required before each series of testing. The VUT was operated for a period of 30 minutes prior to the start of test. Tire pressure was requested to be maintained by the fleet to +/- 3 psi as called out in Table 2.26.

The applicable sections of FMVSS 121 were used as a guide for the performance of the service brake straight-line stopping event. The testing speed was limited to 55 mph (instead of 60 mph in FMVSS 121) due to the fact that the testing was being conducted on a public roadway. The tests were conducted in a controlled manner using the Tennessee Highway Patrol as an escort during the stopping events.

The field test procedure was as follows:

2.4.2.1 Prior to arriving at the test area, the trucks were loaded to GVWR as listed in Table 2.29 and weighed to determine GVW prior to arrival for testing. This information was recorded on the Field Test Stopping Event Log Sheet shown in Figure 2.31.

2.4.2.2 Installed and initialized VBOX and associated peripherals.

2.4.2.3 The driver ensured that the placement of the instrumentation and peripherals did not interfere with the safe operation of the vehicle.

2.4.2.4 Working with State or local governments, secured a 0.5 mile section of roadway (test area) and made it safe to local traffic and the VUT for the maneuver called out below. (The test area was required to be flat, straight, and have turn lanes to allow the VUT to loop around for multiple stopping events. A vehicle staging area was used near the test site to keep test vehicles safely off the road-side and to allow testing staff a safe place to record tire and brake temperature data.)

2.4.2.5 Verified that the tire pressures for the VUT were within the limits set for vehicle in Table 2.26.

2.4.2.6 The driver attained a speed of greater that 55 mph (56 to 60 mph).

2.4.2.7 The driver initiated the stopping maneuver once they were in the approved test lane by depressing the brake pedal. (The DAS will begin recording data once the vehicle decelerates to 55 mph.)

2.4.2.8 The driver attained (as best they could) the predetermined brake application pressure as quickly as possible and held the pressure steady (by observing the brake application pressure gauge) until the vehicle came to a complete stop. These pre-determined pressures are listed in Table 2.30. (These pressures were pre-determined by completing several non-data collection runs for the driver to pick a pressure at which he was comfortable stopping.)

2.4.2.9 Once the vehicle came to a complete stop, the system was reset and ready for the next stopping test.

2.4.2.10 The vehicle traveled ~3.5 miles to cool the brakes before the next stopping test (cool-down loop).

2.4.2.11 A total of six stops were made for each vehicle (if time permitted).

2.4.2.12 The test instrumentation was removed.

2.4.2.13 Tire and drum temperatures were recorded.

Table 2.29 Test Vehicle GVWR

Vehicle Type	Vehicle Number	Curb Weight	GVWR
Class-7 Single-Axle Dump	#2879	16,620 lbs	30,000 lbs
Class-7 Single-Axle Dump	#3212	16,460 lbs	33,000 lbs
Class-8 Tandem-Axle Dump	#102	24,320 lbs	68,000 lbs
Class-8 Tandem-Axle Dump	#105	26,360 lbs	68,000 lbs
Class-8 Tri-Axle Dump	#107	27,200 lbs	74,000 lbs
Class-8 Tri-Axle Dump	#108	25,760 lbs	74,000 lbs
Class-8 Tandem-Axle Refuse	#960	39,200 lbs	64,000 lbs
Class-8 Tandem-Axle Refuse	#961	39,180 lbs	64,000 lbs

Date:		GVW:		
Truck #:		Steer Axle Wt:		
Driver:		Drop Axle Wt:		
Engineer:		Front Drive Axle Wt:		
Air Temperature:		Rear Drive Axle Wt:		
Mileage:		Brake Condition at Test:		
Brake App. PSI:		Tire Pressure Verified:	YES	No
Data Set ID#:				

Driver Comments :

Engineer Comments:

Drum Temps (At end of testing; Degrees F)					Tire Temps (At end of testing; Degrees F)				
	DS		PS			DS		PS	
	DD		PD			DD	/	PD	/
	DFD		PFD			DFD	/	PFD	/
	DRD		PRD			DRD	/	PRD	/
							Inner/Oute r		Inner/Outer

Run Number	Time	Stopping Distance	Run Number	Time	Stopping Distance
1			5		
2			6		
3			7		
4			8		

Figure 2.31 Service Brake Straight-Line Stopping Test Log Sheet.

Table 2.30 Service Brake Application Pressure

Vehicle Type	Identifying Number	Pre-Determined Service Brake Application Pressure
Class-7 Single-Axle Dump	#2879	30 PSI
Class-7 Single-Axle Dump	#3212	30 PSI
Class-8 Tandem-Axle Dump	#102	30 PSI
Class-8 Tandem-Axle Dump	#105	30 PSI
Class-8 Tri-Axle Dump	#107	40 PSI
Class-8 Tri-Axle Dump	#108	30 PSI
Class-8 Tandem-Axle Refuse	#960	25 PSI
Class-8 Tandem-Axle Refuse	#961	50 PSI

Figures 2.32 through 2.35 show photographs of the field test in progress.

Figure 2.32 Safety Briefing.

Figure 2.33 Truck # 960 Initiates Stop.

Figure 2.34 Truck # 107 in Cool-Down Loop.

Figure 2.35 Trucks in Staging Area.

2.4.3 Data Collected

A total of 98 observations (stopping distance tests) were made during the field testing phase of this study, 50 on trucks mounted with AM brake linings and 48 on trucks using OE brake linings. Out of the 50 AM observations, 27 were gathered at the beginning of the study (new brakes) and 23 near the end of brake life. Similarly, 23 of the 48 OE observations were collected at the start of the study and the remaining 25 near the end of brake life. In all cases, the final stopping times, stopping distances, and brake pressures were recorded. Tables 2.31 and 2.32 present the first two variables for the AM and OE mounted trucks, respectively, while Table 2.33 shows the "average" brake pressure during the test runs. Notice that, as opposed to the test-track data where speed and other variables were saved at a very high frequency (100 Hz and 20 Hz for the TRC and LPG tests, respectively), no intermediate information was recorded in the field tests. Both stopping time and distance were measured by on-board equipment, and the treadle pressure was read from a dashboard-mounted gage registered by the researcher supervising the tests. That researcher also noted other information such as brake noises, vibrations, and maneuver execution descriptions when relevant.

Table 2.31 Field Test Results for Aftermarket Brake Linings

	Run #	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]
Initial	1	9.59	379.2	19.25	680.3	22.35	928.3	18.85	768.4
	2	8.32	344.1	18.26	754.0	25.35	1020.5	18.06	732.6
	3	7.68	269.9	18.26	733.8	23.21	919.3	18.73	763.2
	4	7.43	248.9	19.47	810.7	19.33	747.8	21.95	905.8
	5	8.44	325.0	22.92	1000.2	20.88	816.8	24.51	952.5
	6	6.09	244.1			26.06	943.6		
	7	4.56	181.2			20.61	787.3		
	8	5.74	233.2			20.88	785.7		
	9	6.67	266.0						
Final	1	20.98	814.8	6.41	265.9	17.50	713.9	22.25	919.4
	2	19.16	769.2	6.30	240.2	21.37	854.5	20.54	812.2
	3	20.08	765.4	5.85	242.1	22.23	890.8	26.12	1104.8
	4	21.75	838.0	5.83	241.3	25.00	974.2	29.60	1358.8
	5	18.81	749.2	6.11	250.3	24.94	940.9	25.64	976.4
	6	20.03	778.3	5.93	247.0	24.19	921.2		

Table 2.32 Field Test Results for Original Equipment Brake Linings

	Run #	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]
Initial	1	20.73	864.9	16.85	658.1	17.83	722.6	11.61	473.3
	2	18.48	750.6	15.42	580.8	19.79	729.6	12.27	494.9
	3	20.96	818.9	13.59	509.7	17.81	665.0	13.79	559.8
	4	20.99	830.2	18.38	677.0	18.34	699.8	12.20	477.8
	5	20.34	791.7	16.45	606.7	19.29	757.5	12.09	489.9
	6	19.25	760.5	20.23	617.0			12.19	475.5
Final	1	18.99	756.0	16.19	605.9	20.77	775.0	23.50	895.8
	2	21.98	914.3	18.09	732.4	13.81	581.2	27.41	996.4
	3	24.85	1026.0	16.49	620.5	14.31	541.9	30.85	1126.8
	4	21.62	865.1	15.85	655.1	14.71	564.3	24.84	925.2
	5	20.34	874.1	18.26	655.1	12.91	462.3	24.99	922.3
	6	19.25	769.9	16.86	642.3	14.90	583.0	30.40	1147.9
	7	21.11	817.8						

[Note: because not every test run was acceptable (due to, for example, incorrect stopping pressure, failure to completely stop, and equipment problems) and the test vehicles were from a working fleet (i.e., there was a time constraint), it was not always possible to obtain six or more test runs on a given vehicle.]

Table 2.33 Field Test Treadle Pressure and Truck Weight

		Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]
AM	Initial	90	26,340	30[1]	63,360	30	56,020	30	72,700
	Final	30	33,700	90	39,180	30	60,500	30	70,500
OE	Initial	30	32,720	30	39,060	30	71,820	40	70,500
	Final	30	38,900	30	55,000	30	67,760	30	69,940
Avg. Weight			32,915		49,150		64,025		70,910

[1]Some data collected at 50 psi.

2.4.4 Analysis/Results

By their own nature, field tests cannot be conducted under strictly controlled conditions. For example, the truck drivers participating in the field-test part of this study, although professional drivers, did not have test-driving training which may have resulted in runs with variable, instead of uniform, deceleration rates. In addition, the weight of the trucks at the time of the tests could not be controlled (these were real-world trucks hauling loads for real customers) to make it uniform across the truck class tested.

Any comparison of results requires that, except for the variable of interest, all the other relevant variables be constant. Both the variability in the deceleration rates across runs and the difference in truck weights within a given tested truck class introduce differences in the variable of interest (i.e., stopping distance or deceleration rate) which need to be eliminated, or at least minimized, to allow a fair comparison of the different brake-lining materials tested. These corrections are discussed below.

Variable Deceleration Rates Due to Variable Treadle Pressures

The test track experiments (see Section 2.3.5 above) showed that when the treadle pressure was constant, the relationship between speed and time during the stopping distance test is linear. That is, under perfect testing conditions, the speed vs. time diagram for a stopping distance test should be similar to the one shown in Figure 2.36. In that diagram, V_0 represents the initial speed at time 0 (i.e., the speed at which the brakes are applied) and t_f is the final time at which the vehicle came to a complete stop. The area under the line $(0, V_0) – (t_f, 0)$ represents the stopping distance.

For the test-track cases, it was possible to check whether this linear relationship between time and speed was present in the data since these variables were collected at a very high resolution during the stopping-distance tests. For the field tests, on the other hand, only two points of the speed-time diagram were recorded; the time at which the trigger speed (i.e., 55 mph) for the test was reached and the time when the vehicle came to a complete stop (the difference was the stopping time t_f). The stopping distance for each run was also noted (see Tables 2.31 and 2.32 above).

Field-test collected data that reflects a more or less constant deceleration rate would be an indication that the treadle pressure applied by the driver during the test was uniform, making the measured stopping distance or deceleration rate a valid observation (i.e., an observation where any effect introduced by the driver is minimized) that can be used in the statistical analysis. Conversely, data showing a highly variable deceleration rate would suggest that a non-uniform treadle pressure was applied during the particular test run. For such a case, the observation would have to be discarded since it would be impossible to separate the effects introduced by the driver in the measured stopping distance from those attributed to the brake linings.

Because no intermediate speed-time points were recorded for the field test observations, it was not possible to conduct a visual inspection of the data to determine how far from a linear relationship (and in consequence, from a constant deceleration) the speed-time diagram was. However, it is still possible to determine whether a particular run produced a linear relationship in the speed-time diagram. This can be done by comparing the recorded stopping distance (*RSD*) against the constant-deceleration rate stopping distance (*CRSD*), which can be computed as the area under the line connecting the known points $(0, V_0)$ – $(t_f, 0)$. Any reported distance different from *CRSD* implies a non-constant deceleration rate. For example, if *RSD*>*CRSD*, this points to an evolution in which the deceleration rate (brake pressure) increases with time, while if *RSD*<*CRSD*, this is an indication of a deceleration rate (brake pressure) decreasing with time (see Figure 2.37).

Other more complicated evolutions may also apply, for example, one in which the deceleration rate increases with time and then decreases[8]. However, all of them have to be within a certain area, or envelope, in the time-speed diagram. This envelope is delimited by the maximum (and minimum = 0) possible deceleration rates and the recorded stopping time t_f,. It is also assumed that while conducting the braking maneuver the driver will not accelerate (the cut-off speed device, set at 55 mph assured that stopping time and stopping distance would only be recorded when this speed was reached and the truck continued to decelerate).

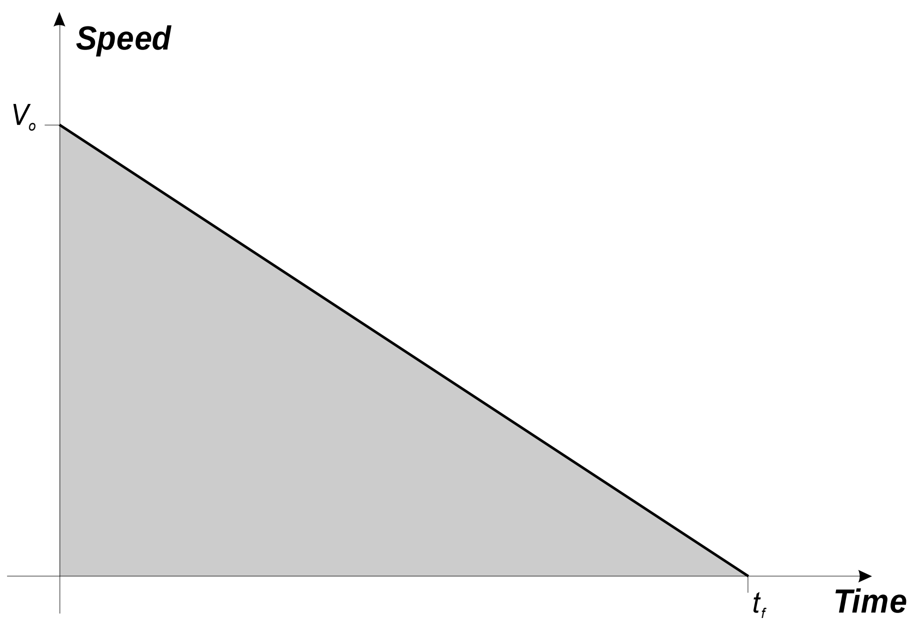

Figure 2.36 Speed vs. Time - Constant Deceleration Rate.

[8] If this type of evolution is perfectly symmetrical, or $A_1 = A_2$ (where A_1 is the area of the portion of the evolution that is above the straight line, and A_2 the area of the portion below), then *RSD = CRSD*.

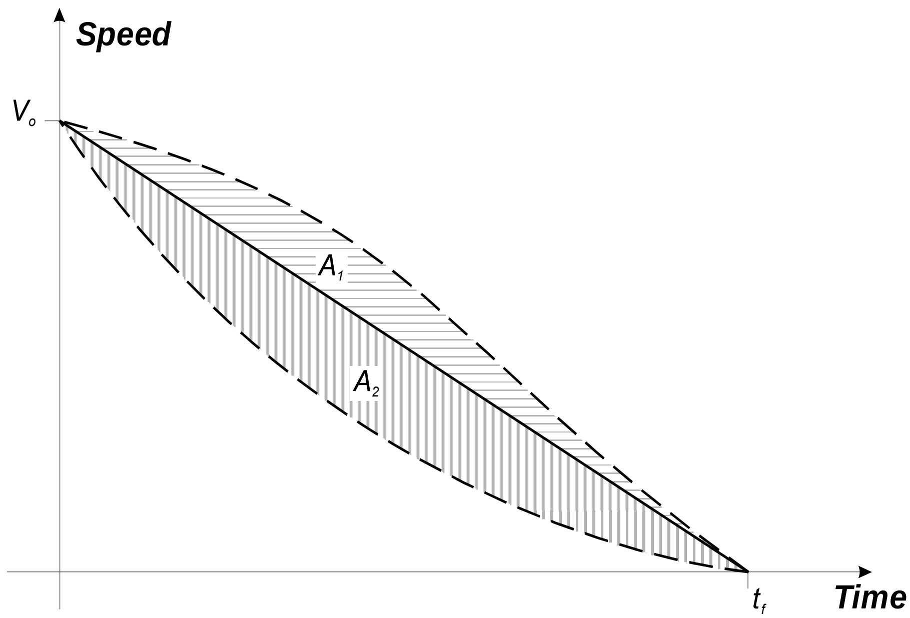

Figure 2.37 Speed vs. Time - Variable Deceleration Rates.

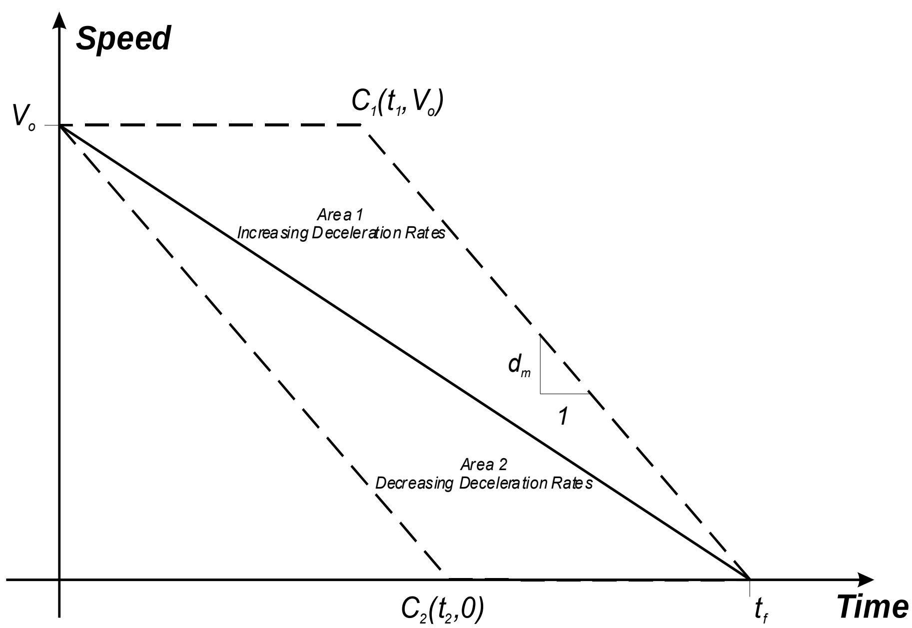

Figure 2.38 Speed vs. Time - Deceleration Rate Envelope.

Figure 2.38 shows this envelope for increasing (A_1) and decreasing (A_2) deceleration rates. Areas 1 and 2, therefore, show the maximum departure possible in stopping distance from a constant deceleration rate starting at 55 mph and lasting t_f seconds. To compute these areas A_1 and A_2 it was assumed that the maximum deceleration rate achievable (d_m) was 15 ft/sec^2 [13] for loaded trucks and 22.5 ft/sec^2 for empty trucks.

For any given test run, it is then possible to compute an indicator *SDDI* (Stop Distance Difference Indicator) as:

$$SDDI = (RSD - CRSD) / MSD * 100 \qquad (2.2)$$

which gives the percentage difference between the recorded stopping distance *RSD* and the ideal constant rate stopping distance *CRSD* as a percentage of the maximum stopping distance, *MSD*. *SDDI* for any given run *i* provides a measurement of how much departure was in run *i* from a constant deceleration rate.

In order to establish a threshold that permits the elimination of runs that are "too far apart" from the prescribed constant deceleration run, some carefully conducted tests (i.e., driver keeping the brake pressure constant at 25 psi during the entire braking maneuver as much as humanly possible) were performed. The results of these controlled experiments are shown in Table 2.34, while Table 2.35 shows the computations of the *SDDI* index.

Table 2.34 Controlled Experiment: Field Test Raw Data

Run #	Run 1 (30 mph)		Run 2 (30 mph)		Run 3 (40 mph)	
	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]	Stop Time [sec]	Stop Dist [ft]
1	3.92	87.7	4.02	87.2	5.08	150.5
2	4.03	89.4	3.71	84.0	5.21	153.6
3	3.54	78.2	3.57	78.1	5.18	152.3
4	4.42	99.8	3.78	84.2	5.32	153.3
5	4.16	92.3	4.18	90.5		
6	4.02	87.3	3.93	87.0		
7	4.27	96.9				

Table 2.35 Controlled Experiment: Stopping Distance Difference Indicator Index

Run #	Run 1 (30 mph)					Run 2 (30 mph)					Run 3 (40 mph)				
	CRSD	RSD	CRSD-RSD	MSD	SDDI	CRSD	RSD	CRSD-RSD	MSD	SDDI	CRSD	RSD	CRSD-RSD	MSD	SDDI
1	86.2	87.7	-1.5	43.2	-3.4%	88.4	87.2	1.2	45.4	2.6%	149.0	150.5	-1.5	72.5	-2.1%
2	88.7	89.4	-0.8	45.6	-1.7%	**81.6**	**84.0**	**-2.4**	**38.6**	**-6.2%**	152.8	153.6	-0.8	76.3	-1.0%
3	77.9	78.2	-0.3	34.9	-0.8%	78.5	78.1	0.5	35.5	1.4%	151.9	152.3	-0.3	75.5	-0.5%
4	97.2	99.8	-2.6	54.2	-4.7%	83.2	84.2	-1.0	40.1	-2.6%	156.1	153.3	2.8	79.6	3.5%
5	91.5	92.3	-0.7	48.5	-1.5%	92.0	90.5	1.4	48.9	2.9%					
6	88.4	87.3	1.1	45.4	2.5%										
7	93.9	96.9	-2.9	50.9	-5.8%										

Table 2.35 shows that, in most cases, the *SDDI* index is less than 6 percent (in absolute value). A slightly less conservative threshold (10%) was adopted for the field test runs. Any observation for which the *SDDI* was larger than this threshold was assumed to present a high degree of deceleration variation and was eliminated from the analysis data set. Tables 2.36 and 2.37 present the deceleration rate (*DR*) and the *SDDI* index for each one of the field-test runs. The deceleration rate shown in these two tables is an average deceleration rate[9] computed using the known kinematic equation relating distance, speed, acceleration, and time:

$$DR = (V_0 * t_f - MSD) * 2 / t_f^2 \qquad (2.3)$$

[9] In the case of constant deceleration rate, this ***DR*** coincides with the slope of the speed-time line.

In Tables 2.36 and 2.37, entries in bold indicate observations that presented an *SDDI* larger than 10 percent (in absolute value) and therefore were eliminated from the database used for the analysis due to their high variability in deceleration rate (brake pressure). Other runs, shown in italicized boldface type, were eliminated due to observations made by the researcher during the tests (e.g., noisy brakes, abrupt braking pressure applied by the driver). Out of the 98 field test runs, 18 were eliminated from further analysis (14 because of a high *SDDI* index and four based on observations made by ORNL personnel during the test).

Table 2.36 Field Test: Deceleration Rate and SDDI - Aftermarket Brake Linings

	Run #	Class-7 Single Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]
Initial	1	8.6	3.1	**4.7**	**15.2**	3.5	-3.6	4.2	-1.3
	2	9.5	-4.4	4.3	-3.0	3.2	0.2	4.4	-0.7
	3	**11.9**	**24.2**	4.4	0.5	3.5	2.1	4.3	-1.3
	4	**12.7**	**32.8**	***4.0***	***-4.0***	4.3	5.0	3.6	-2.8
	5	10.0	7.9	***3.2***	***-9.7***	4.0	3.6	3.4	4.3
	6	13.3	1.5			**3.4**	**11.9**		
	7	18.0	6.8			4.1	6.4		
	8	14.0	-1.9			4.1	8.1		
	9	12.2	2.4						
Final	1	4.0	4.5	12.2	-6.4	4.6	-1.4	3.5	-2.9
	2	4.2	0.6	**13.5**	**12.7**	3.8	1.0	4.0	2.4
	3	4.2	6.7	13.4	-6.8	3.7	0.8	2.9	-5.6
	4	3.9	5.4	13.5	-6.7	3.3	4.0	**2.4**	**-15.7**
	5	4.3	1.6	13.0	-3.8	3.4	7.6	3.3	6.5
	6	4.2	4.5	13.2	-8.2	3.5	6.6		

Table 2.37 Field Test: Deceleration Rate and SDDI - Original Equipment Brake Linings

	Run #	Class-7 Single Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]	DR [ft/sec^2]	SDDI [%]
Initial	1	3.8	-4.2	4.9	4.0	4.5	-0.6	6.9	-1.5
	2	4.3	-0.9	5.6	8.6	**4.4**	**10.5**	6.6	0.0
	3	4.0	3.8	6.4	9.5	4.9	9.3	5.8	-0.9
	4	3.9	2.3	**4.8**	**10.8**	4.6	6.7	6.8	4.1
	5	4.1	4.3	**5.3**	**10.9**	4.3	3.2	6.6	-0.7
	6	4.3	2.5	**5.0**	**29.6**			6.8	4.7
Final	1	4.3	1.6	5.3	9.3	4.2	9.1	3.6	6.5
	2	***3.6***	***-3.7***	4.4	-0.5	5.6	-5.9	**3.2**	**11.4**
	3	***3.2***	***-2.8***	5.2	8.6	6.0	8.2	**2.9**	**10.7**
	4	3.8	0.9	5.0	-3.2	5.8	6.5	3.5	8.9
	5	3.7	-8.0	**4.9**	**13.8**	**7.0**	**15.5**	3.5	9.9
	6	4.2	1.0	5.1	7.0	5.6	4.0	2.8	7.2
	7	4.0	4.8						

Corrections Due to Differences in Test-Run Treadle Pressures

Treadle pressure plays an important role in the length of the stopping distance and in the deceleration rate achieved. That is, up to a certain threshold, the higher the treadle pressure, the larger the deceleration rate achieved; or similarly, the shorter the stopping distance attained.

For reasons discussed previously, it was not possible to maintain perfectly constant conditions across all field-test runs. One variable that varied across different runs and/or truck categories was the treadle pressure applied by the driver during the stopping distance tests. The drivers were instructed to keep that pressure at a constant level of 30 psi by checking a gage installed on the dashboard for that purpose. In some cases, while the drivers did maintain a constant treadle pressure, the pressure was higher than the specified 30 psi and, in consequence, shorter stopping distances (or higher deceleration rates) were recorded. Table 2.38 shows the treadle pressures that were recorded for each one of the tests, as well as the load level of the truck during those tests. Notice that while for most of the runs the applied treadle pressure was 30 psi (75 runs out of 98), there was one case where that pressure reached 40 psi (6 runs), and 2 cases were it registered 90 psi (15 runs). For the initial observations made on the WC Class-8 tandem-axle truck with AM brake linings there were two runs (out of five) for which the observed treadle pressure was 50 psi, with the other three runs conducted at 30 psi. This was the only case in which there was a mixed treadle pressure level within a battery of runs.

Table 2.38 Field Test: Treadle Pressure and Truck Weight
Aftermarket and Original Equipment Brake Linings

		Class-7 Single Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]	Pressure [psi]	Weight [lb]
AM	Initial	90	26,340	30[1]	63,360	30	56,020	30	72,700
	Final	30	33,700	90	39,180	30	60,500	30	70,500
OE	Initial	30	32,720	30	39,060	30	71,820	40	70,500
	Final	30	38,900	30	55,000	30	67,760	30	69,940
Avg. Weight			32,915		49,150		64,025		70,910

[1]Some data collected at 50 psi.

Figure 2.39 shows a representation of the deceleration rate versus the treadle pressure (in psi) for the observations with an absolute value of the *SDDI* index smaller than 10 percent. The graph indicates a positive correlation between the deceleration rates and treadle pressure, with the best fitting line presenting a slope of 0.1391 ft/sec^2/psi. That is, as might be expected, the field test data show that it is possible to achieve higher deceleration rates as more pressure is applied to the brakes. Since it may also be expected that “superior brakes” will produce higher deceleration rates than “inferior brakes,” this variable (deceleration rate, or the recorded stopping distance for that matter) cannot be used to compare the performance of the different brake linings used in the test. In other words, for observations with treadle pressure > 30 psi, it is not possible to differentiate if a higher deceleration rate is due to “better brakes” or to a higher treadle pressure.

In an attempt to eliminate this correlation between deceleration rate and treadle pressure, a new variable was defined by dividing the calculated deceleration rate by the (more or less) constant treadle pressure maintained during each test run. Figure 2.40 shows a representation of this variable (deceleration rate/treadle pressure, *dr/tp*) as a function of the observed treadle pressure. It can be seen that this new variable is independent of the applied treadle pressure (the slope of the "best fit" line is -0.00002).[10] Hence, this variable (the normalized deceleration rate, or *nDR*) was selected for the statistical analysis of the field test collected information. (Note: this variable was also used to analyze data collected during the test-track experiments; however, in that analysis, it was not as relevant as in the current analysis since the treadle pressures were more-or-less constant across all runs.)

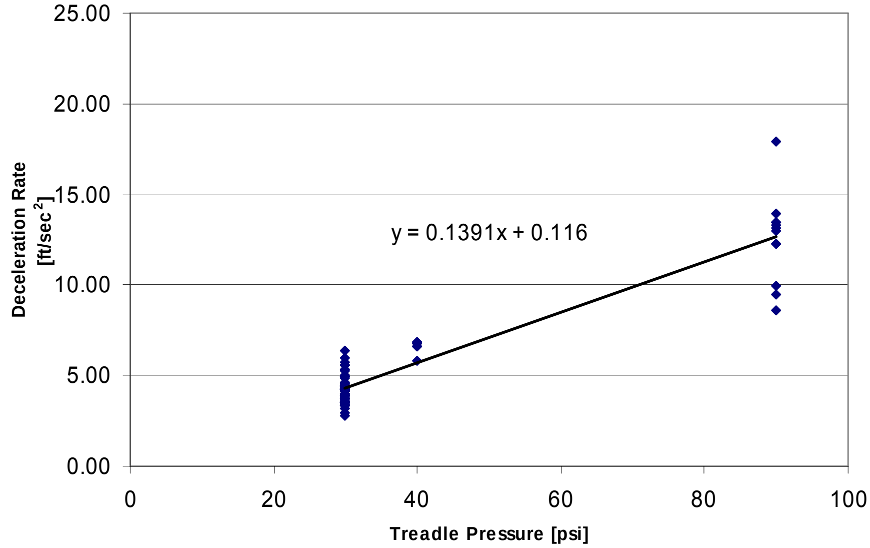

Figure 2.39 Deceleration Rate vs. Treadle Pressure (SDDI<10%).

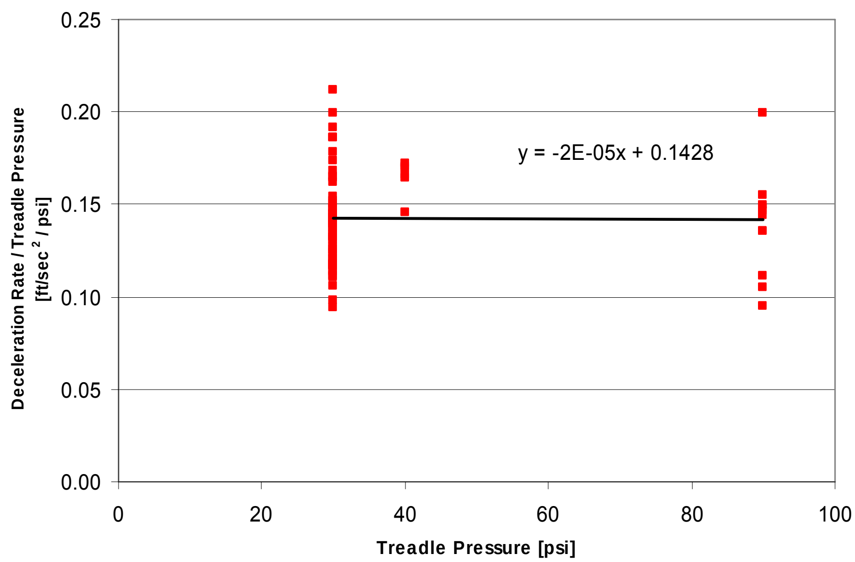

Figure 2.40 Deceleration Rate/Treadle Pressure vs. Treadle Pressure (SDDI<10%).

[10] A different approach to correct for differences in treadle pressure, presented in Section 3.3, arrived at similar results in terms of a linear correspondence between the variables under consideration.

Corrections Due to Differences in Truck Weight

As discussed earlier, the weight of the trucks that participated in the field tests could not be controlled. Ideally, the trucks within a given category (e.g., Class-7 single-axle, with AM and OE brake linings, for the initial and final tests) should have weighed the same, in order to eliminate any influence that this variable could have in the recorded deceleration rates. The recorded weights of all trucks participating in the experiment are presented in Table 2.38, which was introduced earlier in this section. The information in some instances shows significant weight differences within each of the four battery of tests (i.e., initial and final AM, and initial and final OE) under each truck class. For example, the WC Class-8 tandem-axle truck showed the largest difference in weight (24,300 lb difference between the initial runs for the truck mounted with AM and OE brake linings), while the Class 8-tri-axle truck presented the smallest difference (2,760 lb between the initial AM run and the final OE run). On the average, the trucks mounted with OE brake linings were heavier than those using AM brake linings (55,713 lb vs. 52,788 lb).

Results from the carefully conducted tests at TRC (see Sections 2.3.4 and 2.3.5 above) showed that, as may be expected, differences in weight accounted for considerable differences in the maximum deceleration rates (and deceleration rate over treadle pressure) registered. Figure 2.41 graphs the deceleration rate over treadle pressure as a function of the truck weight for both AM and OE runs conducted at TRC. A Class-7 single-axle truck, used to conduct these tests, was loaded at two different levels: at a LLVW with 16,840 lb and at the GVWR with 33,010 lb. These results show average decreases of about 38 percent and 34 percent in *nDR* between the LLVW and GVWR conditions when the truck was mounted with AM and OE brake linings, respectively.

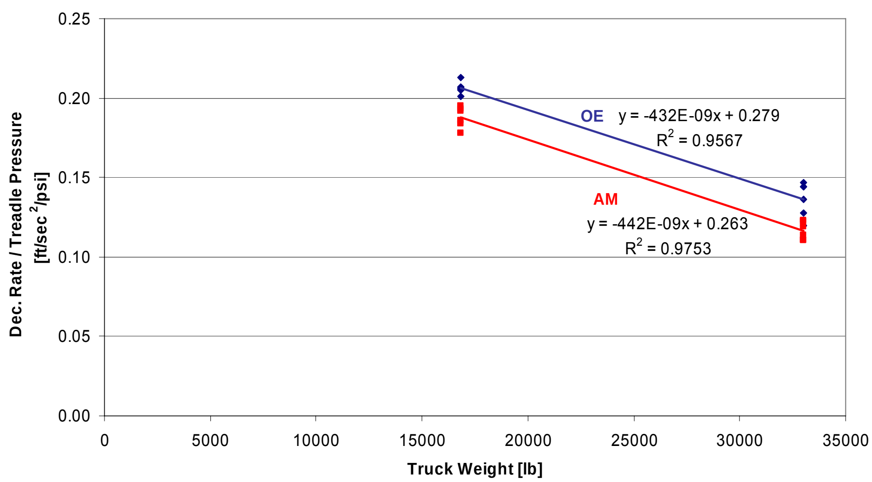

Figure 2.41 Deceleration Rate/Treadle Pressure vs. Treadle Pressure (TRC Tests).

These significant decreases in the variable of interest due to vehicle load-level differences require the normalization of field test results to a uniform vehicle weight within each of the four truck classes analyzed. To accomplish this, a "weight-correction" function was derived from the TRC results. The form of this function, for lack of intermediate data points between the LLVW and the GVWR, was assumed to be linear and its slope (-0.00000432 and -0.00000442, for the OE and AM cases, respectively) was used to adjust the field test observed *nDR* to a certain uniform truck weight. Within each of the four truck categories analyzed in the field test, and to minimize the corrections, the average weight was used as the normalized weight, and corrections were made to the recorded *nDR* from the actual truck weight to this normalized weight. To illustrate how these corrections were made, consider, for example, the final run for the Class-7 single-axle truck mounted with AM brake linings. The average weight for this category was 32,915 lb, while the weight of the truck with AM brake linings for the final run was 33,700 lb (see Table 2.38). Therefore, corrections in the recorded *nDR* variable for this run were made to account for a weight difference (weight decrease) of -785 lb. Using the "weight correction" function derived from the TRC runs, a factor of 0.003473 (= -785 * -0.00000442) was added to all the observed *nDR* for this run. The results of these weight corrections are shown in Tables 2.39 and 2.40 below. All the field-test collected observations are shown in those tables; however, for the statistical analysis that follows, the observations shown in bold typeface were discarded (refer to the discussion regarding variable treadle pressure presented above).

Table 2.39 Field Test: Normalized Deceleration Rate With and Without Weight Correction – Aftermarket Brake Linings

	Run #	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction
Initial	1	0.095	0.066	**0.157**	**0.220**	0.117	0.081	0.141	0.149
	2	0.105	0.076	0.144	0.207	0.106	0.071	0.148	0.156
	3	**0.132**	**0.103**	0.148	0.211	0.118	0.083	0.142	0.150
	4	**0.141**	**0.112**	***0.080***	***0.143***	0.145	0.109	0.120	0.128
	5	0.111	0.082	***0.065***	***0.128***	0.133	0.097	0.114	0.122
	6	0.148	0.119			**0.114**	**0.078**		
	7	0.199	0.170			0.137	0.102		
	8	0.155	0.126			0.137	0.102		
	9	0.136	0.107						
Final	1	0.133	0.136	0.136	0.092	0.152	0.136	0.118	0.116
	2	0.141	0.145	**0.150**	**0.106**	0.127	0.111	0.134	0.132
	3	0.141	0.145	0.149	0.105	0.122	0.106	0.098	0.096
	4	0.129	0.133	0.150	0.106	0.111	0.096	**0.078**	**0.077**
	5	0.145	0.148	0.144	0.100	0.115	0.099	0.111	0.109
	6	0.139	0.143	0.146	0.102	0.117	0.102		

Table 2.40 Field Test: Normalized Deceleration Rate With and Without Weight Correction - Original Equipment Brake Linings

	Run #	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction	wo/Weight Correction	w/Weight Correction
Initial	1	0.125	0.124	0.165	0.121	0.150	0.184	0.172	0.170
	2	0.145	0.144	0.186	0.142	**0.148**	**0.181**	0.164	0.163
	3	0.132	0.132	0.212	0.168	0.162	0.196	0.145	0.144
	4	0.131	0.130	**0.159**	**0.115**	0.155	0.188	0.170	0.168
	5	0.137	0.136	**0.177**	**0.134**	0.143	0.177	0.166	0.164
	6	0.143	0.142	**0.165**	**0.122**			0.171	0.169
Final	1	0.143	0.169	0.178	0.203	0.139	0.155	0.121	0.117
	2	***0.119***	***0.144***	0.148	0.173	0.186	0.202	**0.108**	**0.104**
	3	***0.106***	***0.132***	0.174	0.199	0.199	0.216	**0.095**	**0.091**
	4	0.125	0.151	0.165	0.191	0.192	0.208	0.117	0.112
	5	0.124	0.149	**0.164**	**0.189**	**0.232**	**0.248**	0.117	0.113
	6	0.141	0.167	0.168	0.194	0.186	0.202	0.094	0.090
	7	0.132	0.158						

Statistical Analysis of Field Test Data

The weight-corrected *nDR* variable was used to perform statistical tests aimed at determining whether trucks with OE brake linings performed better than those mounted with AM brake linings. For those statistical tests, it was assumed that a brake lining that provides a higher deceleration rate –everything else being equal[11]– was better than one that supplies a lower deceleration rate. A null hypothesis (H_o) specifying that there was no difference in the average *nDR* obtained with AM and OE brake linings was tested against an alternative hypothesis (H_a) indicating that on average, a truck mounted with OE brake linings provides higher deceleration rates than the same truck mounted with AM brake linings. To evaluate these hypotheses, a two-sample t test was used since in many of the cases examined the sample sizes were small [12]. The two main assumptions required by this test are that the populations are normally distributed and that the sample variances are in the same order of magnitude. Both of these assumptions appear to be reasonably met by the data collected (see Figures 2.42 and 2.43 for a histogram of the variable *nDR* for both AM and OE observations).[12] The t test was then used to determine the level of confidence at which the null hypothesis could be rejected in favor of the alternative hypothesis. A high level of confidence in rejecting H_o would be a strong indication that trucks mounted with OE brake linings performed better than those mounted with AM brake linings.

Different aggregation levels were used to perform the statistical tests. The first test, which included all the *nDR* values for both the AM and OE observations, was designed to analyze whether or not there were any differences (in deceleration rates) when using one or the other type of brake linings. This aggregation helped increase the total size of the sample, which gives more power to the statistical tests, since some of the assumptions about the data can be relaxed. Although different types of trucks with different characteristics participated in the test, the overall aggregation is valid since it is unbiased. That is, the aggregation of the data does not favor the AM or the OE linings, since for any given truck class, both AM and OE linings were tested.

Results of this first statistical test are presented in Table 2.41. The first main column in that table includes the results obtained when all the observations were included (i.e., a total sample size of 80 observations). Results corresponding to the initial observations (i.e., those that were made at the beginning of the field tests with new linings) and final observations (i.e., those performed at the end of the field test after the trucks had been mounted with the brake linings for several months) are shown in the second and third main columns. The first five rows in the table present general statistics for each set of observations. The subsequent three rows include parameters (i.e., degrees of freedom of the data sample, difference between the observed OE and AM means, and the pooled estimator of the common variance) that permit the computation of the t statistic shown on the fourth row. This t statistic was then used to determine the confidence level at which the null hypothesis (i.e., no differences in deceleration rates between AM and OE brake linings) could be rejected. Table 2.41 shows that in all cases the null hypothesis could be rejected with close to 100 percent confidence in favor of the alternative hypothesis, indicating that on average the deceleration rates obtained when trucks were mounted with OE brake linings were larger than when AM brake linings were used.

[11] Only technical aspects were analyzed here, no economical factors (i.e., lining installation and maintenance costs) were considered.
[12] Two cases, Class 7 Single Axle and Class 8 Tandem, both for the initial observations, presented sample variances that were slightly over one order of magnitude of each other (1.2 and 1.6, respectively).

Table 2.41 Statistical Test Results for *nDR*
All Truck Categories Combined

	All Observations		Initial Observations		Final Observations	
	AM	OE	AM	OE	AM	OE
Count	42	38	21	19	21	19
Mean	0.118	0.161	0.120	0.156	0.117	0.167
Std. Dev.	0.032	0.031	0.042	0.023	0.019	0.038
Min	0.066	0.090	0.066	0.121	0.092	0.090
Max	0.211	0.216	0.211	0.196	0.148	0.216
N	78		38		38	
Mean Diff	0.043		0.036		0.050	
Variance	0.001		0.001		0.001	
t statistic	6.084		3.371		5.352	
Reject H_o at	100.00%		99.91%		100.00%	

To complement Table 2.41, Figures 2.42 and 2.43 show a histogram of the data for both the AM and OE observations, corresponding to the first main column of the table (all observations). These graphs show that the distribution of the data is approximately normal, and clearly indicates that the OE distribution is to the right – higher deceleration rates – of the AM distribution (the mean of each the distribution is indicated in the graph by an arrow).

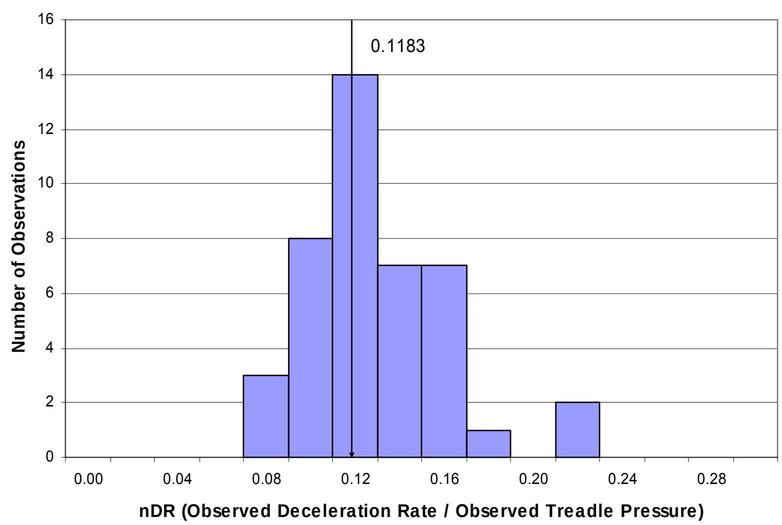

Figure 2.42 Aftermarket Brake Linings
(All Observations, Corrected for Weight Differences).

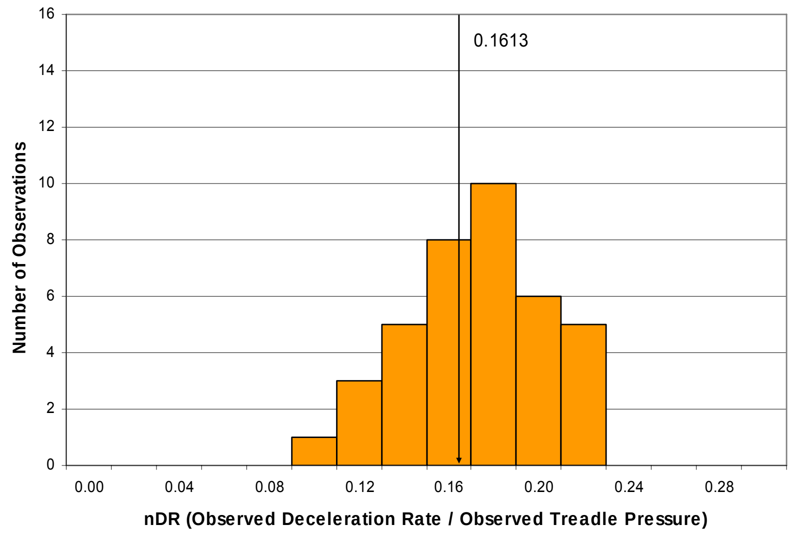

Figure 2.43 Original Equipment Brake Linings (All Observations, Corrected for Weight Differences).

Using the results shown in Table 2.41, it is possible to perform comparisons of the expected stopping distance when using AM vs. OE brake linings. Table 2.42 presents these expected stopping distances for two constant treadle pressures representing a normal braking maneuver (30 psi) and a more abrupt braking maneuver (70 psi), assuming an initial speed of 60 mph. The table also includes a row showing the percentage difference between the stopping distance calculated with the average AM and OE normalized and weight-corrected deceleration rate (only one value is shown since the stopping distance is proportional to the treadle pressure and a constant deceleration rate is assumed). The results show that, on average, the truck equipped with OE brake linings is able to go from 60 mph to a stop in about two-thirds of the distance resulting from the use of AM brake linings.

Table 2.42 Expected Stopping Distances (in ft) for Normal and Emergency Braking Maneuvers

Treadle Pressure	All Observations		Initial Observations		Final Observations	
	AM	OE	AM	OE	AM	OE
30	1091	800	1079	828	1103	774
70	467	343	462	355	473	332
% Diff.	36.3%		30.2%		42.6%	

A second series of statistical tests was conducted for each one of the four types of trucks that participated in the field test. Table 2.43 presents those results, when all the observations were taken into account (first main row in the table), and for the initial (second main row) and final (third main row) observations. When all the observations were considered, the null hypothesis could be rejected in favor of the alternative hypothesis with 100 percent, 98 percent, and 96 percent confidence for the W Class-8 tandem-axle truck, the Class-7 single-axle, and the WC Class-8 tandem-axle trucks, respectively, indicating that on the average the OE brake linings performed better than the AM brake linings. For the Class-8 tri-axle truck, the null hypothesis could only be rejected at 84 percent confidence level, not showing a clear superiority of the OE against the AM brake linings as in the other three cases. Notice, however, that the Class-8 tri-axle truck is a particular truck in which the third axle (the drop axle) was mounted with AM brake linings for both OE and AM categories. That is, the OE truck was really a hybrid configuration with two axles mounted with OE brake linings and the drop axle mounted with AM brake linings. This configuration was therefore "closer" to an AM-mounted truck than any of the other three cases. Given these conditions (and the results discussed above for the other tucks), it would be expected that, for this particular truck, the "AM" category performed better (i.e., closer to the "OE" category) than the "AM" category in the other three cases. The results confirm this expectation; that is, the two average deceleration rates for the Class-8 tri-axle truck are closer to one another than in the other three cases (thus the null hypothesis could only be rejected at a relatively low level of confidence), although the OE case still shows, on the average, larger deceleration rates than the AM case.

The other two main rows in Table 2.43 show the results of the statistical tests when the data is disaggregated into the observations made at the beginning and end of the field test (approximately, six months apart). One of the negative consequences of disaggregating the data, from the standpoint of the statistical analysis, is that the sample sizes become very small. Nevertheless, the results obtained are in agreement with those observed when all the observations were included.

Consider the second main row in Table 2.43; Initial Observations. For the W Class-8 tandem-axle and the Class-8 tri-axle trucks, it was possible to reject the null hypothesis at 100 percent and 99 percent confidence level, respectively, in favor of the alternative hypothesis (i.e., the OE brake linings performed better than the AM brake linings). In the case of the WC Class-8 tandem-axle truck, the sample size was very small (presenting only three degrees of freedom) and the sample variances were apart by about 1.6 order of magnitude, thus violating one of the assumptions of the two-sample t test. For this reason, the statistical test was not performed in this case. Similarly, for the Class-7 truck, the sample variances were apart by a slightly over one order of magnitude (i.e., 1.2), which again violated one of the assumptions of the two-sample t test. However, when the two outliers (i.e., the minimum and maximum) for the AM case were eliminated, the sample variances were within an order of magnitude (the new standard deviation for the AM case was 0.0222) and therefore the t statistic (= 3.4095) allowed rejection of the null hypothesis at a 99-percent confidence level.

For the "final observations" case (third main row in Table 2.43), although the sample sizes in the different categories were small, all the sample variances were within an order of magnitude of one another. The t tests permitted the rejection of the null hypothesis at over 99 percent confidence for the Class-7, the WC Class-8 tandem-axle and the W Class-8 tandem-axle trucks. For the fourth type of truck, the result showed that the AM Class-8 tri-axle truck configuration presented on the average, higher deceleration rates than the hybrid truck mounted with OE and AM (drop axle) brake linings. For this case, while maintaining the same null hypothesis, the alternative hypothesis was reversed (i.e., the "AM" case presented, on the average, larger deceleration rates than the "OE" case). The t statistic showed that it was only possible to reject the null hypothesis at a 70-percent confidence level, suggesting that, on the average, there were no differences in deceleration rates when using the hybrid OE/AM linings or the AM brake linings exclusively.

Table 2.43 Statistical Test Results for *nDR* by Truck Category

		Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
		AM	OE	AM	OE	AM	OE	AM	OE
All Observations	Count	13	11	7	8	13	9	9	10
	Mean	0.123	0.146	0.132	0.174	0.100	0.192	0.129	0.141
	Std. Dev.	0.032	0.015	0.053	0.029	0.016	0.018	0.020	0.030
	Min	0.066	0.124	0.092	0.121	0.071	0.155	0.096	0.090
	Max	0.170	0.169	0.211	0.203	0.136	0.216	0.156	0.170
	N	22		13		20		17	
	Mean Diff	0.023		0.042		0.092		0.012	
	Variance	0.001		0.002		0.000		0.001	
	t statistic	2.208		1.953		12.493		1.034	
	Reject H_o at	98.10%		96.37%		100.00%		84.22%	
Initial Observations	Count	7	6	2	3	7	4	5	6
	Mean	0.107	0.135	0.209	0.144	0.092	0.186	0.141	0.163
	Std. Dev.	0.036	0.007	0.003	0.024	0.014	0.008	0.015	0.010
	Min	0.066	0.124	0.207	0.121	0.071	0.177	0.122	0.144
	Max	0.170	0.144	0.211	0.168	0.109	0.196	0.156	0.170
	N	11		SAMPLE TOO SMALL TO TEST		9		9	
	Mean Diff	0.028				0.094		0.022	
	Variance	0.001				0.000		0.000	
	t statistic	1.855				12.138		2.910	
	Reject H_o at	95.47%*		*		100.00%		99.13%	
Final Observations	Count	6	5	5	5	6	5	4	4
	Mean	0.142	0.159	0.101	0.192	0.108	0.197	0.113	0.108
	Std. Dev.	0.006	0.009	0.006	0.012	0.015	0.024	0.015	0.012
	Min	0.133	0.149	0.092	0.173	0.096	0.155	0.096	0.090
	Max	0.148	0.169	0.106	0.203	0.136	0.216	0.132	0.117
	N	9		8		9		6	
	Mean Diff	0.017		0.091		0.088		-0.005	
	Variance	0.000		0.000		0.000		0.000	
	t statistic	3.906		15.867		7.564		-0.560	
	Reject H_o at	99.82%		100.00%		100.00%		70.23%**	

* Difference in sample variances slightly over an order of magnitude.
** This test corresponds to a reversed Alternative Hypothesis.

2.5 Wear Measurement

During the field test, information was also collected regarding brake-lining wear for all the lining materials and mating drums listed in Table 1.2 relative to each vehicle in the field test.

2.5.1 Overview

Prior to installation onto the respective test vehicle, all brake and drum components were measured and marked as to brake material, vehicle, wheel position, and component position. A coding scheme was devised to allow parts to be easily identified once they were removed from the vehicle. An example part number is show in Table 2.44 for the driver's side front drum of truck #2879.

Table 2.44 Sample Part Labeling Scheme

Field (F)/Test Track (T)	Brake Set # (#)	OE(OE)/ Aftermarket (AM)	Truck Number (#)	Type	Axle	Axle Number (X#)	Vehicle Side (Driver's D or Passenger's P)	Part (Drum D, Top Shoe T, or Bottom Shoe B)	Label
Field	1	AM	2879	Class-7 Single Axle Dump	Steer	1	Driver's	Drum	F1AM2879X1DD

Upon removal from the test vehicle, all brake and drum components were again measured to assess the total wear of the components during the test period. An example of a brake that has been marked and made ready for installation is shown in Figure 2.44.

Figure 2.44 Example of Brake Part Labeling.

2.5.2 Test Protocol

After each drum was marked, it was measured for its initial (new condition) internal diameter (ID) using a 24 in Preisser Digimate digital caliper as shown in Figure 2.45. The measurements were taken 2.0 inches from the outside edge of the drum and recorded on the Shoe and Drum Measurements Log Sheet shown in Figure 2.46. Each drum was labeled on the outside wheel face using a yellow paint pen (Sandford Gold Coat or Dykem Texpen). At the end of the field test each drum was removed and measured again for its ID. Drum wear for the field test was found to be minimal as reflected in Section 2.5.3.

Figure 2.45 Drum Measurement.

Driver's Side Steer Axle

Drum — Identification # : F1AM108X1DD

	Initial	Final	Wear
Diameter:	16.515		
Temperature:	67.000		

WEBB 65152B

Top Shoe — Identification # : F1AM108X1DT

	Initial	Final	Wear
S-Cam End Thickness:	0.453		
Pivot End Thickness:	0.221		

Bottom Shoe — Identification # : F1AM108X1DB

	Initial	Final	Wear
S-Cam End Thickness:	0.453		
Pivot End Thickness:	0.226		

Driver's Side Drop Axle

Drum — Identification # : F1AM108X2DD

	Initial	Final	Wear
Diameter:	16.514		
Temperature:	76.000		

WEBB 66884B

Top Shoe — Identification # : F1AM108X2DT

	Initial	Final	Wear
S-Cam End Thickness:	0.385		
Pivot End Thickness:	0.205		

Bottom Shoe — Identification # : F1AM108X2DB

	Initial	Final	Wear
S-Cam End Thickness:	0.381		
Pivot End Thickness:	0.196		

Driver's Side Front Drive Axle

Drum — Identification # : F1AM108X3DD

	Initial	Final	Wear
Diameter:	16.516	16.523	0.007
Temperature:	67.000	69.000	

WEBB 66884B

Top Shoe — Identification # : F1AM108X3DT

	Initial	Final	Wear
S-Cam End Thickness:	0.380	0.231	0.149
Pivot End Thickness:	0.226	0.197	0.029

Bottom Shoe — Identification # : F1AM108X3DB

	Initial	Final	Wear
S-Cam End Thickness:	0.369	0.273	0.096
Pivot End Thickness:	0.200	0.179	0.021

Driver's Side Rear Drive Axle

Drum — Identification # : F1AM108X4DD

	Initial	Final	Wear
Diameter:	16.515	16.535	0.020
Temperature:	67.000	69.000	

WEBB 66884

Top Shoe — Identification # : F1AM108X4DT

	Initial	Final	Wear
S-Cam End Thickness:	0.382	0.220	0.162
Pivot End Thickness:	0.220	0.147	0.073

Bottom Shoe — Identification # : F1AM108X4DB

	Initial	Final	Wear
S-Cam End Thickness:	0.362	0.293	0.069
Pivot End Thickness:	0.206	0.132	0.074

Truck # :	108
Type:	Class-8 Tri-Axle

FIELD TEST

Aftermarket Brakes
Test Series 1
Front Shoe
OTR II FF ANC - 4715D

INITIAL INSPECTION	
Date:	8Apr05; 3May05
Driver:	
Engineer:	Capps
Air Temperature:	70.0
Odometer:	224879
Engine Hours:	

FINAL INSPECTION	
Date:	2-Feb-06
Driver:	
Engineer:	Capps/Massimini
Air Temperature:	69
Odometer:	260708
Engine Hours:	

Drop Axle Kit
CNB 4515EQ21

Rear Shoe Kit
CNB 4515EQ21

A4 PS shoes had mud on them
shoes and drums were oxidized

Passenger's Side Steer Axle

Drum — Identification # : F1AM108X1PD

	Initial	Final	Wear
Diameter:	16.511		
Temperature:	67.000		

WEBB 65152B

Top Shoe — Identification # : F1AM108X1PT

	Initial	Final	Wear
S-Cam End Thickness:	0.448		
Pivot End Thickness:	0.226		

Bottom Shoe — Identification # : F1AM108X1PB

	Initial	Final	Wear
S-Cam End Thickness:	0.459		
Pivot End Thickness:	0.227		

Passenger's Side Drop Axle

Drum — Identification # : F1AM108X2DD

	Initial	Final	Wear
Diameter:	16.516		
Temperature:	76.000		

WEBB 66884B

Top Shoe — Identification # : F1AM108X2DT

	Initial	Final	Wear
S-Cam End Thickness:	0.372		
Pivot End Thickness:	0.204		

Bottom Shoe — Identification # : F1AM108X2DB

	Initial	Final	Wear
S-Cam End Thickness:	0.370		
Pivot End Thickness:	0.203		

Passenger's Side Front Drive Axle

Drum — Identification # : F1AM108X3PD

	Initial	Final	Wear
Diameter:	16.511	16.533	0.022
Temperature:	67.000	69.000	

WEBB 66884B

Top Shoe — Identification # : F1AM108X3PT

	Initial	Final	Wear
S-Cam End Thickness:	0.376	0.201	0.175
Pivot End Thickness:	0.216	0.146	0.070

Bottom Shoe — Identification # : F1AM108X3PB

	Initial	Final	Wear
S-Cam End Thickness:	0.373	0.199	0.174
Pivot End Thickness:	0.215	0.130	0.085

Passenger's Side Rear Drive Axle

Drum — Identification # : F1AM108X4PD

	Initial	Final	Wear
Diameter:	16.515	16.515	0.000
Temperature:	67.000	69.000	

WEBB 66884B

Top Shoe — Identification # : F1AM108X4PT

	Initial	Final	Wear
S-Cam End Thickness:	0.360	0.351	0.009
Pivot End Thickness:	0.207	0.214	-0.007

Bottom Shoe — Identification # : F1AM108X4PB

	Initial	Final	Wear
S-Cam End Thickness:	0.364	0.311	0.053
Pivot End Thickness:	0.209	0.206	0.003

Figure 2.46 Wear Data Log Sheet and Sample Data.

Each shoe was labeled to identify the vehicle, shoe location (wheel end position and orientation), and test event. The labeling was done on the web of the shoe adjacent to the shoe table. This area remained cool enough during the testing for the markings to survive and be useful in identifying the brake components after they were removed from the test vehicles. Using a Presisser Digimate digital depth gauge, the thickness of the brake lining from the rivet head to the top surface of the shoe was measured on the right side of the shoe at two points (anchor end and S-cam end) as shown in Figure 2.47. Measurements were taken before installation onto the test vehicle (new, unburnished condition) and at the end of the field test.

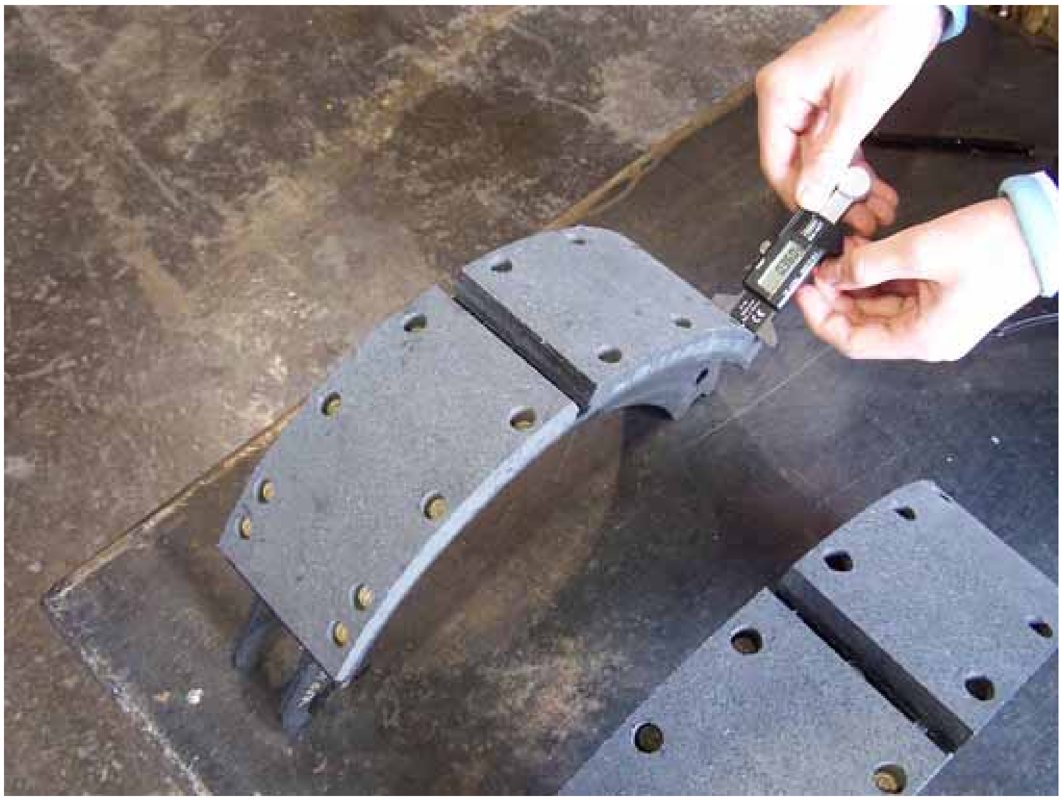

Figure 2.47 Shoe Lining Thickness Measurements.

Figure 2.48 shows the brake build for truck #2879 (driver's side rear) prior to the start of the field test. Figure 2.49 shows the brakes and drums being readied for the tri-axle and tandem-axle dump trucks.

Figure 2.48 Truck #2879 Brake Build.

Figure 2.49 Field Test Brakes for Tandem-Axle and Tri-Axle Dumps.

2.5.3 Data Collected

Measurements of the lining material were made for each shoe on each axle at the beginning and at the end of the field test; the difference between these two readings, *dW*, was used as a measure of the lining wear. The variable *dW* strongly depends on the frequency with which the brakes are applied; that is, it would be expected that a higher braking frequency would result in more wearing of the lining material than a lower frequency. Therefore, this variable cannot be used for comparison between AM and OE linings, unless adjustments that take into consideration the number of braking cycles applied to the material are made. While information about the frequency of braking was not collected in this test, the number of miles traveled during the interval extending from the beginning to the end of the field test was. This information, a proxy for braking frequency[13] (i.e., the higher the mileage, the larger the number of braking cycles) was used to normalize *dW*, thus obtaining a brake-lining wear in inches per mile traveled, *dWmt*. This variable, which was later scaled to inches per million miles traveled, was used in the analysis. Table 2.45 shows, for each one of the four truck classes studied and each type of linings, the number of miles traveled between the initial and final measurements and the length, in days, of that interval of time between these two measurements.

Table 2.45 Miles Traveled and Time Elapsed Between Initial and Final Wear Measurements

	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
	Miles Traveled	Time Int. [days]	Miles Traveled	Time Int. [days]	Miles Traveled	Time Int. [days]	Miles Traveled	Time Int. [days]
AM	12,560	334	14,083	190	29,494	278	35,829	250
OE	6,201	139	10,657	164	18,270	182	28,979	187

Tables 2.46 and 2.47 present the results of the wear measurements observed on the linings and on the brake drums, respectively, during the field test. Notice that some observations show negative numbers, indicating that the linings were thicker at the end than at the beginning (Table 2.46) or that the drums had a smaller inside diameter at the end than at the beginning (Table 2.47). Both of these phenomena seem to be in contradiction to expectations. However, they could be explained by considering that the lining materials, when new, are not completely cured and may expand with usage (up to a certain point), and that the diameter of the drums was measured at one or two points only. Further study of these phenomena would need to be performed to reject or accept these explanations.

[13] Since in each of the four truck categories both the AM- and the OE-mounted trucks performed the same operations, it was assumed that they would experience, in the long run, the same braking frequency. Therefore, miles traveled by the AM and OE truck within a given category would capture this information and could be used as a proxy for it.

Table 2.46 Brake-Lining Wear Measurements (Inches per Million Miles Traveled)

					Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle*	
					AM	OE	AM	OE	AM	OE	AM	OE
Front Axle	Driver Side	Axle 1	Front Shoe	S Cam	0.398	1.290	N/A	17.453	N/A	0.055	N/A	1.242
				Pivot	1.752	-0.968	N/A	2.346	N/A	-0.164	N/A	-0.173
			Back Shoe	S Cam	0.717	-0.806	N/A	15.764	N/A	0.712	N/A	0.932
				Pivot	-0.398	-0.484	N/A	4.316	N/A	0.000	N/A	-0.069
	Passenger Side	Axle 1	Front Shoe	S Cam	0.717	-1.290	N/A	13.700	N/A	0.328	N/A	1.104
				Pivot	-0.159	-0.806	N/A	6.193	N/A	-0.602	N/A	0.000
			Back Shoe	S Cam	0.319	-0.968	N/A	18.579	N/A	0.110	N/A	0.897
				Pivot	0.000	0.484	N/A	5.818	N/A	0.110	N/A	0.000
Back Axles	Driver Side	Axle 2	Front Shoe	S Cam	3.901	2.903	18.604	18.392	-0.237	2.080	4.159	5.659
				Pivot	-0.637	-0.806	4.616	5.255	2.712	-0.274	0.809	0.035
			Back Shoe	S Cam	1.831	-0.968	16.900	17.266	2.000	2.244	2.679	4.797
				Pivot	0.398	-1.290	8.379	9.759	0.373	0.055	0.586	1.829
		Axle 3	Front Shoe	S Cam	N/A	N/A	20.024	18.767	0.610	1.368	4.522	3.485
				Pivot	N/A	N/A	5.610	11.260	0.949	-0.055	2.038	2.830
			Back Shoe	S Cam	N/A	N/A	20.592	21.301	1.187	1.752	1.926	5.452
				Pivot	N/A	N/A	9.586	4.973	1.390	0.766	2.065	1.001
	Passenger Side	Axle 2	Front Shoe	S Cam	0.796	-0.484	16.616	10.416	0.814	1.040	4.884	3.244
				Pivot	0.319	-0.645	5.823	-0.094	1.255	-0.055	1.954	-0.207
			Back Shoe	S Cam	2.548	-1.613	16.403	6.287	0.780	1.861	4.856	3.761
				Pivot	-0.876	-1.451	6.959	1.501	1.763	-0.328	2.372	-0.138
		Axle 3	Front Shoe	S Cam	N/A	N/A	21.586	19.236	1.221	2.135	0.251	4.417
				Pivot	N/A	N/A	7.030	4.879	1.187	-0.547	-0.195	0.518
			Back Shoe	S Cam	N/A	N/A	24.498	19.049	-0.136	1.806	1.479	5.418
				Pivot	N/A	N/A	9.728	3.566	0.746	-0.110	0.084	0.725
Mean					0.727	-0.494	13.310	10.666	1.038	0.595	2.154	1.948

* No measurements were made on the drop-axle of these trucks. Axle 2 and Axle 3 measurements refer to the fixed axles.

Table 2.47 Brake-Drum Wear Measurements (Inches per Million Miles Traveled)

		Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle*	
		AM	OE	AM	OE	AM	OE	AM	OE
Axle 1	Driver Side	0.239	0.484	N/A	5.161	N/A	0.219	N/A	0.380
	Passenger Side	0.239	-1.451	N/A	6.099	N/A	0.110	N/A	0.069
Axle 2	Driver Side	0.000	0.000	3.266	2.534	0.814	0.657	0.195	0.966
	Passenger Side	0.796	0.323	3.124	2.534	1.085	0.438	0.614	0.794
Axle 3	Driver Side	N/A	N/A	3.408	2.440	1.051	0.712	0.558	0.518
	Passenger Side	N/A	N/A	3.266	2.815	0.949	0.438	0.000	1.449
Mean		0.319	-0.161	3.266	3.597	0.975	0.429	0.342	0.696

* No measurements were made on the drop-axle of these trucks. Axle 2 and Axle 3 measurements refer to the fixed axles.

2.5.4 Analysis of Results

A statistical analysis similar to the one used to compare the deceleration rates provided by the AM and OE brake linings was used to analyze the wear of the brake-lining materials. As in the previous case, two levels of aggregation were considered: all observations, and by truck category.

Consider first the highest aggregation level. Figures 2.50 and 2.51 show histograms of the distribution of the observed brake-lining wear per million miles traveled for the AM and OE cases, respectively. In each of these charts it is possible to see that the distribution appears to be bimodal (i.e., there are two distinct values of the variable under consideration around which the measurements tend to center). Further analysis of the data clearly showed that this was the case. The WC Class-8 tandem-axle truck showed a degree of brake-lining wear, for both the AM and the OE cases that was an order of magnitude larger than those recorded within the other three truck categories (see Table 2.46). A plausible explanation for this large difference in wearing resides in the fact that this was a refuse truck. In general, these type of trucks make more frequent stops than the other types of trucks in the study.

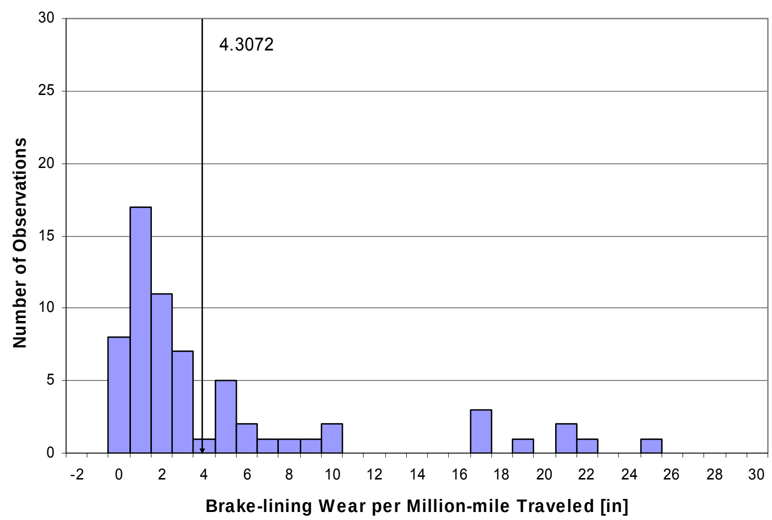

Figure 2.50 Brake-Lining Wear per Million Miles Traveled All Observations – Aftermarket Brake Linings.

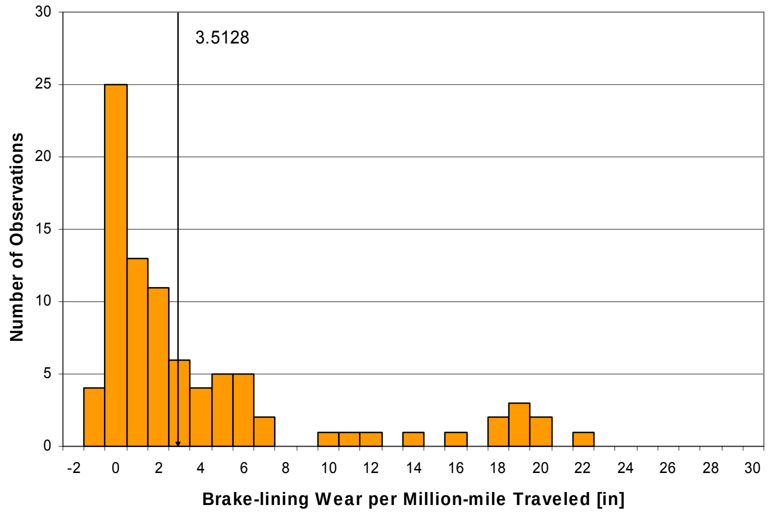

Figure 2.51 Brake-Lining Wear per Million Miles Traveled
All Observations – Original Equipment Brake Linings.

Figures 2.52 and 2.53 show the same information as in the previous two charts, but in these figures, the observations corresponding to the WC Class-8 tandem-axle truck have been separated and are shown in a different color. The mean of the two distributions in each chart are also represented.

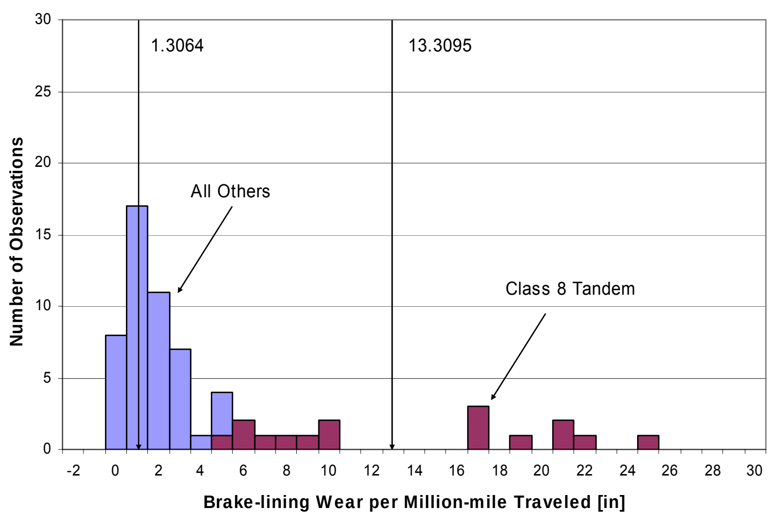

Figure 2.52 Brake-Lining Wear per Million Miles Traveled
WC Class-8 Tandem-Axle and the Other Three Truck Categories Aggregated
Aftermarket Brake Linings.

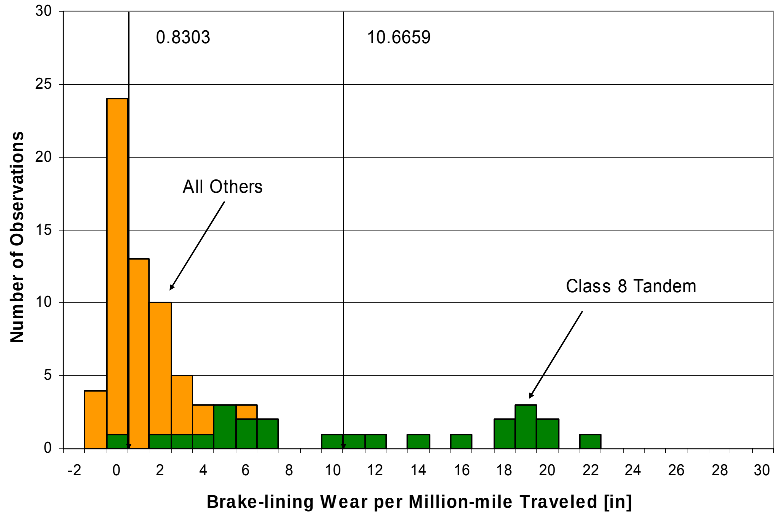

Figure 2.53 Brake-Lining Wear per Million Miles Traveled WC Class-8 Tandem-Axle and the Other Three Truck Categories Aggregated Original Equipment Brake Linings.

Due to these large differences in wear, the data was first aggregated into two groups: the WC Class-8 tandem-axle truck and all others (i.e., Class-7 single-axle, W Class-8 Tandem–Axle, and Class-8 tri-axle). The results of this high-level aggregation are shown in Table 2.48 below. The statistical tests indicate that it is possible to reject the null hypothesis with 88-percent and 94-percent confidence level for the WC Class-8 tandem-axle truck and the "All Others" category, respectively, in favor of the alternative hypothesis of a higher degree of brake-lining wear for the AM-equipped trucks than for those using OE brake linings.

Table 2.48 Statistical Test Results for *dWmt* for the WC Class-8 Tandem-Axle and the Remaining Three Truck Categories

	WC Class-8 Tandem-Axle		All Others	
	AM	OE	AM	OE
Count	16	24	48	64
Mean	13.310	10.666	1.306	0.830
Std. Dev.	6.708	6.879	1.403	1.767
Min	4.616	-0.094	-0.876	-1.613
Max	24.498	21.301	4.884	5.659
N	38		110	
Mean Diff	2.644		0.476	
Variance	46.403		2.631	
t statistic	1.202		1.537	
Reject H_o at	88.17%		93.64%	

A more disaggregated summary of the data is shown in Table 2.49. Again, the results of the statistical tests allow for the rejection of the null hypothesis of equal brake-lining wear for AM and OE brake linings at the 99-percent, 88-percent, and 94-percent confidence level for the Class-7 single-axle, WC Class-8 tandem-axle, and W Class-8 Tandem–Axle, respectively. For the Class-8 Tri–Axle it was only possible to reject the null hypothesis at a very low (63%) level of confidence. As explained previously, the OE case for this particular category was really a hybrid configuration with the drop axle using AM brake linings.

Table 2.49 Statistical Test Results for *dWmt* by Truck Category

	Class-7 Single-Axle		WC Class-8 Tandem-Axle		W Class-8 Tandem-Axle		Class-8 Tri-Axle	
	AM	**OE**	**AM**	**OE**	**AM**	**OE**	**AM**	**OE**
Count	16	16	16	24	16	24	16	24
Mean	0.727	-0.494	13.310	10.666	1.038	0.595	2.154	1.948
Std. Dev.	1.244	1.158	6.708	6.879	0.746	0.939	1.693	2.054
Min	-0.876	-1.613	4.616	-0.094	-0.237	-0.602	-0.195	-0.207
Max	3.901	2.903	24.498	21.301	2.712	2.244	4.884	5.659
N	30		38		38		38	
Mean Diff	1.220		2.644		0.443		0.206	
Variance	1.444		46.403		0.753		3.684	
t statistic	2.872		1.202		1.582		0.333	
Reject H_o at	99.63%		88.17%		93.90%		62.94%	

Notice that in Table 2.48 and 2.49 some of the minimum values, and even one mean value, are negative. This seems to be a contradiction since those numbers represent the difference in brake lining thickness between the start of the field test (new linings) and the end (worn linings). The explanation for this phenomenon may reside in the theory that these lining materials are not entirely cured when they are new, and complete their curing phase while being used. During this process, the material may expand and therefore the linings may be thicker after some usage than when they are newly installed.

3.0 Correlational Analysis

3.1 SSBT/Chase Test

3.1.1 Comparison of Friction Coefficients

Table 3.1 compares data for the various linings tested using the J 661 (Chase test) and the SSBT tests. The various correlations between test conditions are plotted in Figures 3.1-3.3 to facilitate comparison. The terms Low-PV and High-PV refer, respectively, to the low-load/low-speed and high-load/high-speed conditions described in Section 2.

Table 3.1 Comparison of Chase Test Friction Coefficients With Those Using the ORNL SSBT

Lining Code	Type	Chase Test "Normal"	Chase Test "Hot"	SSBT Low-PV	SSBT High-PV
A	AM	0.432	0.415	0.505	0.265
B	OE	0.438	0.462	0.535	0.269
C	OE	0.500	0.452	0.534	0.226
D	OE	0.564	0.539	0.649	0.407
E	AM	0.477	0.376	0.399	0.352
F	AM	0.508	0.484	0.576	0.305
G	AM	0.517	0.464	0.551	0.314
H	AM	0.442	0.459	0.444	0.249
I	AM	0.386	0.424	0.491	0.166

As shown in Figure 3.1, except for linings "E" and "H" there was a reasonable correlation between the Chase "Normal" friction coefficients and the SSBT Low-PV data. The average ratio of the corresponding friction coefficients is found from the slope of the plot. It is 0.869, with a reasonable standard deviation of 0.056. Therefore, one could approximate the value of the Chase test's "Normal" friction coefficient by multiplying the average SSBT friction coefficient for the last drag in the series of Low-PV drags by a factor of 0.87.

Figure 3.2 data indicate that, except for lining "H" there was an even better correlation between the Chase "Hot" friction coefficients and the SSBT Low-PV data. The ratio of Chase "Hot" friction coefficients to the SSBT Low-PV data was a steady 0.856 with a standard deviation of only 0.038 with respect to that ratio. A reasonable estimate (within 5%) of the value of the Chase test's "Hot" friction coefficient can be obtained by multiplying the average SSBT friction coefficient for the last drag under less severe conditions, by 0.86. As shown in Figure 3.3, with the exception of linings "A" and "E," there was good correlation between the Chase "Hot" friction coefficients and the SSBT High-PV results.

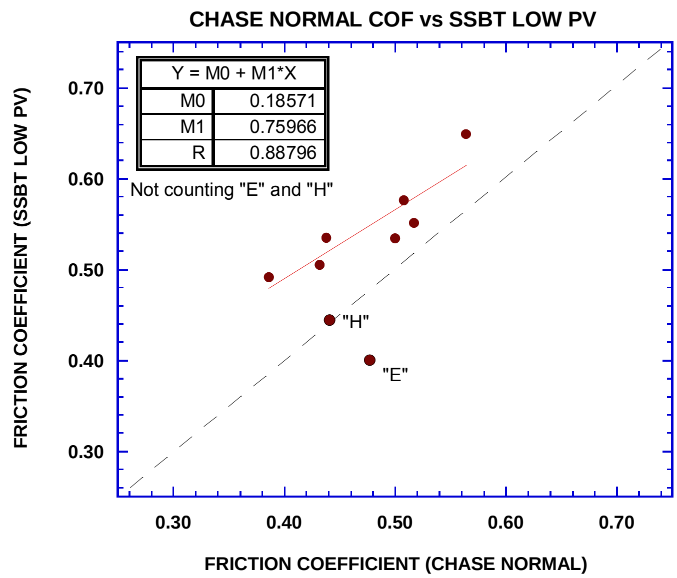

Figure 3.1 Relationship Between the "Normal" Friction in the SAE J661 Test And the Average Friction Coefficient for the Last Drag Interval n the SSBT Low-PV Condition.

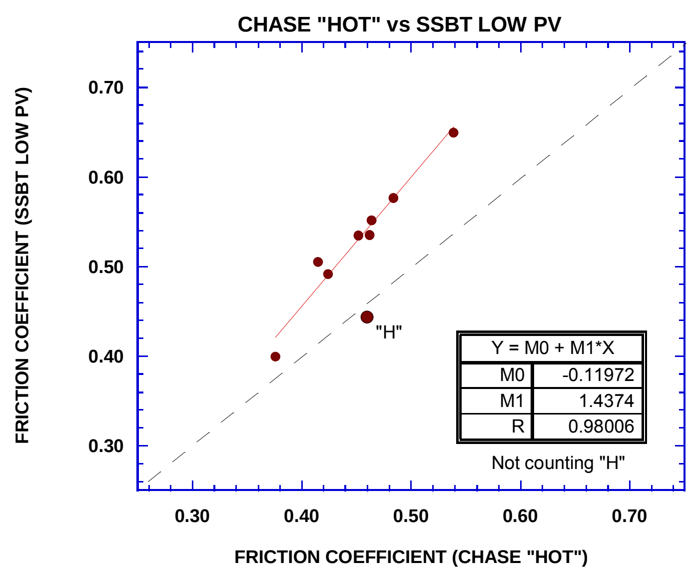

Figure 3.2 Relationship Between the "Hot" Friction in the SAE J661 Test And the Average Friction Coefficient for the Last Drag Interval On the SSBT Low-PV Condition.

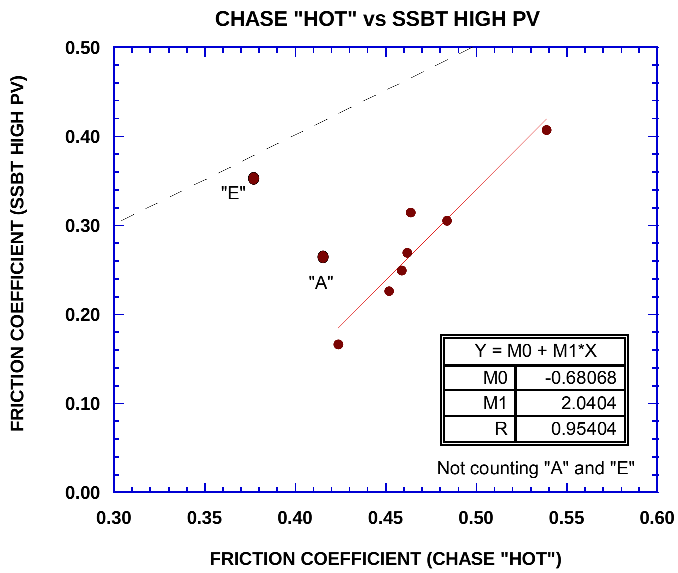

Figure 3.3 Relationship Between the "Hot" Friction in the SAE J661 Test And the Average Friction Coefficient for the Last Drag Interval On the SSBT High-PV Condition.

Aftermarket materials "A", "E," and "H" deviated most from the well-correlated SSBT/Chase results displayed by other lining materials. All three of the lining materials that did not correlate well happened to be "aftermarket" products. Since the selection of linings was based on the preferences of the participating fleets, it is not known whether a different set of aftermarket linings would also have included any that deviated from the general trends in Figures 3.2 and 3.3. These deviations from the normal trend of other linings are more evident when considering the general ranking of frictional performance, as is discussed in the following section.

3.1.2 Comparison of Relative Rankings

The relative rankings of lining materials from low to high friction are given in Table 3.2. In every test condition, OE lining "D" was highest in friction, and AM lining "F" was relatively high as well. The most consistent overall rankings were obtained between the "Hot" Chase test results and the Low-PV SSBT test results (note the similarity of the rankings in bold-face fonts).

Lining materials "D" (OE), "F" (AM), and "G" (AM) consistently ranked higher than most, irrespective of test method. Similarly, lining material type-I tended to rank in the lower friction group regardless of the test method employed. Other lining materials, those that fell more within the middle of the group, varied in performance depending on the severity of conditions and type of test.

Lining material "E" (underlined in Table 3.2) displayed particularly inconsistent behavior. While most of the other linings rank at about the same position within the listing in companion columns, lining "E" shows a major difference between normal and hot rankings and between Low-PV and High-PV rankings. There are a number of possible reasons. Discounting the possibilities that the operator(s) made errors while running the test or that there was an undetected equipment problem, it may be that the material itself is sensitive to the differences in imposed testing conditions between Chase tests and SSBT tests. The problem with this hypothesis is that the more severe conditions evoke opposite responses in material "E," and there is no physical basis to explain such a phenomenon.

Table 3.2 Relative Rankings of Friction Coefficients in Chase and SSBT Tests

Rank (9 is highest)	Chase "Normal"	Chase "Hot"	SSBT Low-PV	SSBT High-PV
1	I	**E**	**E**	I
2	A	A	H	C
3	B	**I**	**I**	H
4	H	C	A	A
5	E	H	C	B
6	C	**B**	**B**	F
7	F	**G**	**G**	G
8	G	**F**	**F**	E
9	D	**D**	**D**	D

Lining material "A" ranked similarly in the normal and hot Chase results, and higher on the two SSBT results. Material "C" ranked lower under more severe testing conditions in both Chase and SSBT tests; however, material "H" had slightly higher friction when more severe testing conditions were applied.

If data for the three problematic lining materials ("A," "E," and "H") were excluded, the ranking of the other linings would appear as in Table 3.3. Lining I consistently ranked lowest and lining "D" ranked consistently highest in friction. There are small variations in the rank order in the middle of the grouping, but results are remarkably consistent considering that the two test methods were independently performed at different locations, with different machines, using different testing protocols, and with a factor of four difference in the nominal pad contact area.

Table 3.3 Relative Rankings of the Friction of Six Lining Materials In Chase and SSBT Tests

Rank (Note 1)	Chase "Normal"	Chase "Hot"	SSBT Low-PV	SSBT High-PV
1	I	I	I	I
2	B	C	C	C
3	C	B	B	B
4	F	G	G	F
5	G	F	F	G
6	D	D	D	D

Note 1: Rank 1 is the lowest friction coefficient and 6 is the highest friction coefficient.

Overly high friction can produce grabby brakes that jerk the driver and cause violent stops or skids. Low friction coefficients imply that more pedal force is required to stop the vehicle. Therefore, one cannot say that high friction is necessarily best for a given application. It depends entirely on the intended service for the vehicle. The primary goal for lining formulation is that the friction of the linings remains steady and reliable over a wide range of temperatures and operating conditions. In the current study, the purpose was to determine whether the various test methods showed similar friction coefficient values and/or lining rankings.

3.1.3 Rankings Based on Original Equipment or Aftermarket Designation

The frictional rankings of OE and AM materials are separately given in Table 3.4. The OE materials, all produced by the same company, ranked nearly in the same order, irrespective of test method. The AM linings, however, ranked in more widely different order from one test method to another. Lining "E," for example, seemed quite sensitive to test conditions; ranking lowest in two cases, and highest in two others. There are a number of possible reasons for this including the possibility that the specimens were cut from different parts of the lining. If the lining was not uniform from place to place, it is possible that the cut-out samples were not identical in composition.

Table 3.4 Relative Rankings of Friction Coefficients Based On OE and AM Designation

Designation of Lining Type	Rank (1=Low)	Chase "Normal"	Chase "Hot"	SSBT Low-PV	SSBT High-PV
OE	1	B	C	C	C
	2	C	B	B	B
	3	D	D	D	D
AM	1	I	E	E	I
	2	A	A	H	H
	3	H	I	I	A
	4	E	H	A	F
	5	F	G	G	G
	6	G	F	F	E

3.1.4 Comparison to Published Data From Recommended Practice RP 628

In response to a strong trucking industry demand for improved measures to help select replacement linings for S-cam drum-type vehicle brakes, a study group within the Technology and Maintenance Council of the American Trucking Associations developed and published Recommended Practice (RP) 628 [14]. Submission of commercial products to be evaluated by this procedure is voluntary among manufacturers of aftermarket linings. The basis of the practice was the dynamometer portion of the existing Federal Motor Vehicle Safety Standard FMVSS 121. RP 628 reports only a single torque value associated with a 40 psi control line pressure (see Section B of the test summary, below). The additional data is kept on file but not reported in the trade industry summaries.

The outline in Table 3.5 summarizes the main procedures conducted within the dynamometer portion of FMVSS 121. The abbreviation IBT refers to the initial temperature of the brake drum prior to brake application. The test typically requires full-sized 16.5 x 7 S-cam drum brake hardware. References indicated in brackets [ ] refer to sections of the published standard. Including burnishing, 438 brake applications are performed during the course of this protocol.

In 1994, the Society of Automotive Engineers established the Brake Lining Review Institute, and within it a Brake Lining Review Committee was formed to develop and administer the program which evaluated commercial linings using RP 628. In early 2000, the evaluation of linings was transferred to the Performance Review Institute an SAE-affiliated organization with an established track record of managing third-party product review programs in the ground and aerospace transportation sectors. Today, the PRI has a heavy-duty brake lining qualification program that involves periodically evaluating FMVSS 121 dynamometer test results on brake lining products and publishing lists of lining performance metrics in accordance with TMC RP 628. Further information may be found on the website: http://www.pri.sae.org/NADCAP/brakes.htm.

RP 628 data were available for five of the lining materials evaluated in this project. It is presented in Table 3.6 listed from lowest to highest RP 628 torque value and compared to the relative rankings (from 1-to-9, low-to-high) for the same grade of lining materials evaluated in the Chase and SSBT tests. Note that the range in RP 628 torques varied less than 10 percent between the lowest and highest values; much less than the range in friction coefficients reported within each series of laboratory-scale tests. The laboratory tests, therefore, seem more effective in discriminating between different levels of performance even though they do not agree with the RP 628 results in terms of rank order.

As seen in Table 3.6, lining material "E" that ranked highest in RP 628, also ranked near the top (8 of 9) in three out of the four laboratory test methods. Interestingly, lining "E" was one of those that least well conformed to the trends discussed in Sections 2.1-2.3. Lining "A" had the lowest RP 628 torque and was also ranked second to the lowest in the Chase test.

Considering that the RP 628 torque value is one of several hundred values that are generated during a full FMVSS 121 dynamometer test, the likelihood that this particular value would happen to correlate with either the Chase or SSBT data is small. Furthermore, it must be noted that the linings used for RP 628 testing would be from different batches of lining material than those used for the current tests (Chase and SSBT tests were conducted using samples from the same brake shoe for each type of lining).

Table 3.5 Summary of the FMVSS 121 Dynamometer Test From Which RP 628 Data are Extracted

(Note: references refer to paragraphs in the standard. The outlined procedure should be considered a summary of the more comprehensive requirements in the standard.)

A. Burnish [ref. §S6.2.6]: (total applications = 400)

- Make 200 stops from 40 mph at 10 ft/s^2 with 315^o F ≤ IBT ≤385^o F
- Make 200 stops from 40 mph at 10 ft/s^2 with 450^o F ≤ IBT ≤500^o F

(To increase IBT, stop from 40 mph at 10 ft/s^2; to decrease IBT, rotate the drum / disc at 30 mph).

B. Brake Retardation Force Factor. [§ 5.4.1.1] (total applications = 7)

With 125^o F ≤ IBT ≤200^o F, and beginning with 20 psi chamber pressure:

- Decelerate from 50 to 0 mph. Record average torque.
- Increase chamber pressure by 10 psi, rotate the drum or disc until the temperature drops into the specified range and repeat (six times).

Total of seven decelerations 20, 30, <u>40</u>, 50, 60, 70, 80 psi.

C. Brake Power. [§ 5.4.2] (total applications = 11)

Begin with 125^o F ≤ IBT ≤200^o F for the first application.

- Conduct 10 decelerations from 50 to 15 mph at 9 ft/s^2 at equal intervals of 72 s counting from the start of deceleration of the previous application. (Line pressure not to exceed 100 psi for any application.)
- After last deceleration and running at 20 mph, decelerate to stop at 14 ft/s^2.

D. Brake Recovery. [§ 5.4.3] (total applications = 20)

Begin 2 minutes after completing 5.4.2.

- Make 20 stops from 30 mps at 12 ft/s^2 with (20 psi ≤ line air pressure ≤ 85 psi) for non-antilock system or (12 psi ≤ line pressure) for an anti-lock system.

Exception = neither the front axle brake of a bus or a truck or a truck-tractor combination.

Table 3.6 Summary and Comparison of Published RP 628 Torque Data With Chase and SSBT Data

	Lining Code	RP 628 Torque (in-lb)*	Chase "Normal"	Chase "Hot"	SSBT Low-PV	SSBT High-PV
1	A	57,625	2	2	4	4
2	G	58,581	8	7	7	7
3	I	62,475	1	3	3	1
4	F	62,746	7	8	8	6
5	E	63,916	5	1	1	8

* published on the PRI website (http://www.pri-network.org/Brake-Lining-Program.id.29.htm)

The friction coefficient equivalents of the torques shown in Table 3.6 can also be estimated from the standard braking force equation described by L. Strawhorn [15].

A dynamometer-based, recommended procedure RP 628 was developed by the TMC to characterize aftermarket brake linings. It reports only a single torque value (at 40 psi line pressure, average of three tests) from within the more extensive data set produced by a standardized FMVSS 121 procedure that is used for OE truck brake linings. Torque values for five of the selected linings used in this work were obtained from the table of RP628 data published on the internet. Those values were converted to friction coefficients in order to compare them with the SSBT and Chase test results. The friction coefficients based on RP 628 dynamometer data tended to fall into a narrower range (0.265 – 0.295) than those obtained for either Chase tests or SSBT tests. The narrow range of RP 628 data is within typical frictional variations from test-to-test. In only one case, the high-load high-speed tests on the SSBT, was there a hint of correlation between laboratory results and RP628-derived friction coefficients, but the relationship was not strong. We can conclude, therefore, that friction coefficients derived from RPM 628 data did not discriminate between lining frictional characteristics as well as the two types of lab tests which showed a more self-consistent and wider range of frictional values for the same set of five linings. The fact that only one of the SSBT laboratory test conditions (high-load, high-speed) seemed to correlate with RPM 628 data may have been fortuitous because of the small range in RP 628-derived friction coefficient for these five linings.

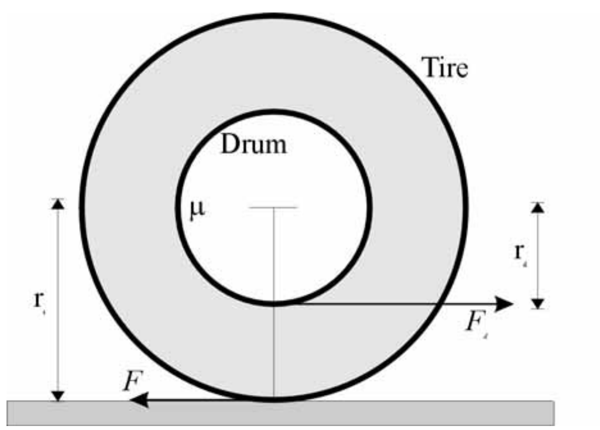

Figure 3.4 Forces and Radii Designations for the Brake Drum and Tire.

The braking force F_b is calculated from the following quantities, some of which are illustrated in Figure 3.4:

p = air line pressure (psi)
A = cross-sectional area of the actuator (in^2)
S = length of the slack adjuster (in)
r_d = radius of the brake drum (in)
r_c = radius of the cam (in)
r_t = mean static rolling radius of the tire (in)
μ = mean friction coefficient

In addition, we can define

F_d = reaction force on the drum due to friction (lbs-f)
T = braking torque (in-lbs)
P_d = effective normal force acting on the drum (lbs-f)

The standard equation for braking force, using the above nomenclature, is:

$$F_b = \frac{2pAS\mu r_d}{r_c r_t} \tag{3.1}$$

From the equations of static equilibrium, and the definition for torque, we have

$$T = F_b\, r_t = F_d\, r_d \tag{3.2}$$

Equation (3.1) can be rearranged as follows:

$$F_b r_t = T = \frac{2pAS\mu}{r_c} r_d \tag{3.3}$$

and,

$$F_d = \frac{2pAS}{r_c} \mu \tag{3.4}$$

From the definition of the friction coefficient, we can find the equivalent normal force,

$$\mu = \frac{F_d}{P_d} \tag{3.5}$$

and, therefore,

$$P_d = \frac{2pAS}{r_c} \tag{3.6}$$

Therefore, the friction coefficient for the lining against the drum is estimated from:

$$T = F_d r_d = \mu\left(\frac{2pAS}{r_c}\right) r_d \tag{3.7}$$

or,

$$\mu = \left(\frac{T}{p}\right)\left(\frac{r_c}{2ASr_d}\right) \tag{3.8}$$

Conveniently, the first factor on the right hand side of the equation is the ratio of the torque to the line pressure, and the dimensions of the mechanical components are grouped into the second factor, which is called "K_A", where A is the chamber size.

$$\mu = K_A\ (T/p). \tag{3.9}$$

For a typical S-cam drum with a 30 in^2 chamber or a 24 in^2 chamber, the constant K becomes

$K_{30} = 0.0001837$ $\qquad$ $K_{24} = 0.0002296$

Results of the calculation for the lining types are shown in Table 3.7. The fact that the High-PV data and the estimated friction coefficient for lining "A" agreed to the third significant figure is felt to be a fortuitous occurrence. The apparent lack of correlation is shown in Figure 3.5. On the other hand, considering only linings "A" and "G" (the lowest torques from RP 628 data), there was a remarkable similarity in the change in friction coefficients for the laboratory tests even though the magnitudes were offset.

Table 3.7 Estimated Friction Coefficients From Published RP 628 Torque Data and Comparison With SSBT and Chase Data for the Same Linings

Lining Code	RP 628 Torque (in-lb)	Estimated Friction Coefficient	Chase "Normal"	Chase "Hot"	SSBT Low-PV	SSBT High-PV
A	57,625	0.265	0.432	0.415	0.505	0.265
G	58,581	0.269	0.517	0.464	0.551	0.314
I	62,475	0.287	0.386	0.424	0.491	0.166
F	62,746	0.289	0.508	0.484	0.576	0.305
E	63,916	0.294	0.477	0.376	0.399	0.352

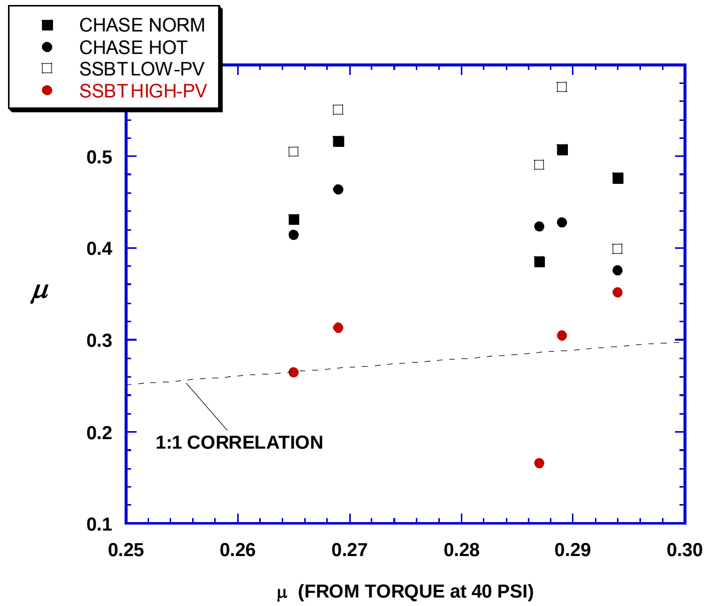

Figure 3.5 Plot of the Data in Table 3.7 Showing a Slightly Better Correlation With SSBT High-PV Data.

3.1.5 Conclusions Regarding the Chase, SSBT, and RP 628 Friction Correlations

The following can be concluded from a comparison of Chase, SSBT, and RP 628 results:

- Friction coefficients estimated for linings for which RP 628 torque data were available fell into a much narrower range than values measured in the other types of laboratory tests.

- With only a few exceptions, laboratory tests produced higher friction coefficients than those calculated from RP 628 torque data.

- The High-PV SSBT data tended to correlate with calculated friction coefficients from RP 628 tests slightly better than any of the other laboratory tests, but that correlation was fair at best.
- For the linings that were examined, there was no evidence for a systematic correlation or similar ranking between RP 628 data and either Chase test data or SSBT data.

3.1.6 Correlation of Chase and SSBT Wear Results

Wear measurements from the Chase test were determined in two ways: change in thickness of the pad expressed as a percentage, and mass change of the pad, also expressed as a percentage. Wear measurements for the SSBT tests were determined by the mass change of the slider.

Table 3.8 compares the wear data from both tests. Lining "D", and the OE lining that had the highest friction in both Chase and SSBT tests, also had the highest amount of wear in both Chase and SSBT tests. Likewise, lining "I" had the least wear in both tests. In order to evaluate the relative rankings of wear in both tests, the wear amount of each lining was divided by the wear amount for lining "I" in the respective type of test. Figure 3.6 displays that result. With the exception of lining

"E," the general wear trend for SSBT and Chase tests seem to agree well on the basis of mass change.

There was an even better correlation between the percent thickness change measured in Chase tests and the mass loss in SSBT tests; as shown in Figure 3.7. One data point, for lining "E", was well off the trend and was not included in the curve fit to the other eight linings shown in Figure 3.7.

Table 3.8 Comparison of Chase Test Lining Wear Measurements With Those From the ORNL SSBT

Lining Code	Type	Chase Test Thickness Loss (%)	Chase Test Mass Loss (%)	SSBT Mass Loss (mg)
B	OE	4.9	3.3	34.6
C	OE	5.4	4.7	30.5
D	OE	8.4	6.2	135.8
A	AM	4.1	3.9	28.2
E	AM	3.1	3.5	83.4
F	AM	7.4	5.5	53.1
G	AM	6.6	4.3	57.0
H	AM	4.1	2.8	18.2
I	AM	4.1	2.3	15.8

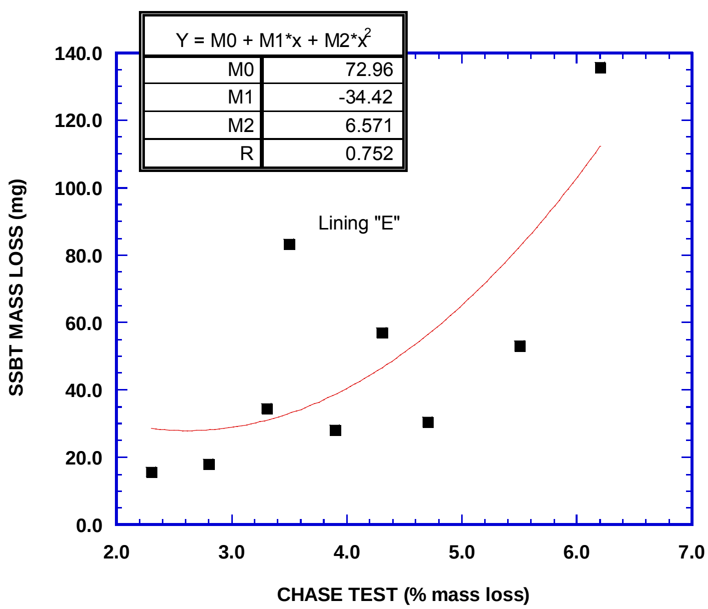

Figure 3.6 Non-Linear Relationship Between Lining Wear Results of Chase and SSBT Tests Based on Mass Loss.
(The fitted curve ignores data for lining "E.")

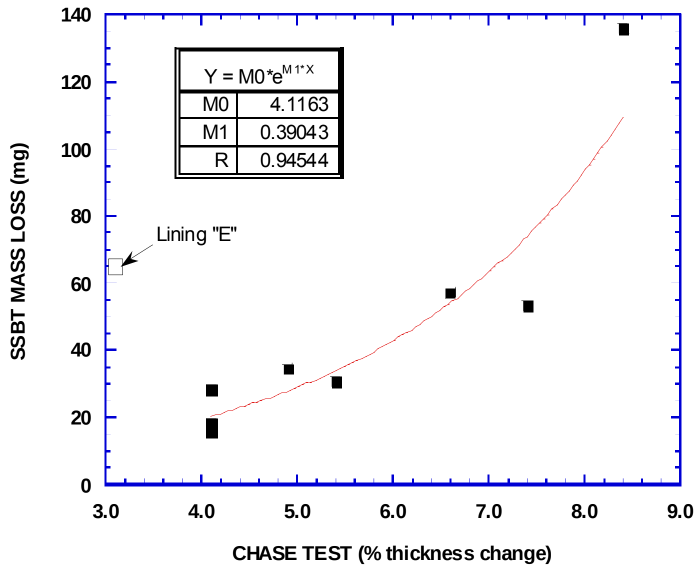

Figure 3.7 Exponential Relationship Between the Mass Loss in SSBT Tests and The Thickness Change in Chase Tests.
(Lining "E" results were anomalous and were not included in the fit to the data.)

3.1.7 Overall Conclusions of the Correlation Between Chase and SSBT Test Data

Based on a distillation of a substantial volume of friction and wear data, and the selection of certain quantities with which to conduct correlations, the following general conclusions can be drawn:

- There was a fair correlation of relative rankings in friction coefficient between the Chase and SSBT test results, but a few lining materials ranked in quite different order between the two testing protocols.

- The Chase "Hot" friction coefficients were in best agreement with the SSBT Low-PV rankings. One can approximate the value of the Chase test's "Hot" friction coefficient by multiplying the average SSBT friction coefficient for the last drag in the series of Low-PV drags by a factor of 0.86.

- There was no apparent correlation between RP 628 dynamometer test data and either the Chase or the SSBT friction results. Recall that the 40 psi retardation torque value selected for RP 628 tests represents the judgment of a committee and was not intended to represent either mild or severe braking conditions, but rather a compromise value. Had some other air pressure or speed been chosen for testing, there might have been a better correlation with Chase or SSBT tests.

- With the exception of one lining, there was an excellent correlation between the mass loss by wear in SSBT tests and the percent thickness loss for linings in Chase tests. The correlation between Chase and SSBT wear data could be represented by an exponential function.

- In general, the OE and AM linings performed comparably in the Chase and SSBT tests. One OE lining, however, had significantly higher friction coefficients and higher wear than any of the other eight linings.

Considering all performance criteria (coefficient of friction, lining wear, fade, etc.), it cannot be stated from the results of the present investigation that OE linings perform better as a class than AM linings; however, the U.S. brake linings market is witnessing a growing infusion of inexpensive aftermarket products, and the current study did not include tests of any of the low-cost imports.

3.2 SSBT/Test Track

Data were available for an OE (Type B in Table 3.1) and an AM lining (Type A from Table 3.1) tested on the same truck at TRC, Inc. While OE and AM data were also available on the same truck at LPG, SSBT/test-track correlations were confined to the results provided by TRC because of a more complete information database. For the TRC data a correlation was found to exist between stopping distances at TRC and the SSBT and Chase test results.

Figure 3.8 compares the results of four different laboratory friction tests performed on each of two different linings that were also tested on the same truck at TRC. Data for the OE lining is plotted on the left and data for the AM lining is plotted on the right. As indicated in the legend, the four laboratory tests were: SSBT average friction coefficients for Low-PV conditions, the SSBT average friction coefficients at High-PV conditions, Chase test friction coefficients designated as “Normal” and Chase test friction coefficients designated as “Hot”. The average stopping distance measured at TRC was shorter for the OE lining (292 feet) than for the AM lining (339 ft). Note that the Chase “Normal” and SSBT High-PV data were not significantly different for OE and AM linings, so they would not reflect the differences in stopping distance. On the other hand, the friction coefficients for the Chase “Hot” and the SSBT Low-PV data were both lower for AM linings than for OE linings, as would be expected for the longer stopping distance for the AM linings. The important conclusions of this are:

1) It is improper to state unequivocally that the results from one testing machine or another correlate, or do not correlate with full-scale vehicle performance. As shown here, with diligence, the investigator can find specific testing conditions to apply to a given laboratory testing machine that will improve its ability to correlate with full-scale vehicle performance. Therefore, the selection of both the laboratory testing machine and the parameters to be applied to it are equally important in generating relevant laboratory data.

2) Two sets of laboratory test conditions correlated with the trend in test track stopping distances between an OE and an AM lining: the Chase test “Hot” data, and the SSBT Low-PV data. Considering just these data, the 14-percent reduction in stopping distance for OE linings over AM linings corresponded to a 10-percent increase in the “Hot” friction coefficient for the Chase test but only a 5.6-percent increase in the Low-PV friction coefficient on the SSBT test. Thus, the “Hot” friction coefficient obtained from the Chase test was slightly more sensitive than the SSBT Low-PV friction coefficient in reflecting differences in test track stopping distance.

3) There was only about a 0.05 difference between the average friction coefficients for laboratory tests on OE and AM linings (see Figure 3.8). That small but definite difference was enough to distinguish between shorter and longer test-track stopping distances for the two linings. The typical standard deviations for five SSBT friction tests for the same lining materials was 0.06 to

0.07, and that for five Chase tests was 0.02 to 0.04. In light of the small magnitude of the differences in friction between the OE and AM linings relative to the typical test-to-test variability, it is important to conduct multiple repeated tests in order that the small differences in the friction of these linings can be detected from amongst the typical test-to-test variation.

The information obtained from the lab tests was also correlated with the average *nDR* values gathered from the track tests, for the LLVW and GWVR load levels (see Tables 2.24 for the average *nDR* and 2.10 and 2.16 for the friction coefficients used in the correlational analysis). Since the brakes were not replaced between these two batteries of track tests, only for one of them (i.e., either LLVW or GWVR tests) the brakes were in new condition. In the case of the Class-8 tri-axle/AM category, the LLVW condition was tested first, while for the other seven truck-class/brake-lining combinations the tests started with the GVWR load condition. For this preliminary correlation analysis, only the test-track observations collected under the load level tested first were used; however, because deceleration rates under GVWR load conditions are different from those observed when the truck is loaded at the LLVW level, the Class-8 tri-axle/AM observation was not included in the analysis. In the case of the SSBT tests, only the Low-PV condition produced a positive correlation between friction coefficient and normalized deceleration rate (a regression line with a slope value equal to 0.1301), indicating that linings that showed higher friction coefficients in the lab produced higher deceleration rates in the test-track tests. For the Chase tests, this correlation was more pronounced under the “Normal” condition than under “Hot” conditions (regression line slopes equal to 0.3041 and 0.2026, respectively).

None of these three regression lines (SSBT Low-PV vs. *nDR*, Chase “Normal” vs. *nDR*, and Chase “Hot” vs. *nDR*) presented a statistically significant “goodness of fit” of the data (i.e., low R^2 regression coefficient). However, when a more comprehensive correlation analysis, involving this time SSBT lab data and test-track and field-testing *nDR* observations, was performed, then the Low-PV data produced a significant correlation (i.e., $R^2 = 0.94$; see Appendix).

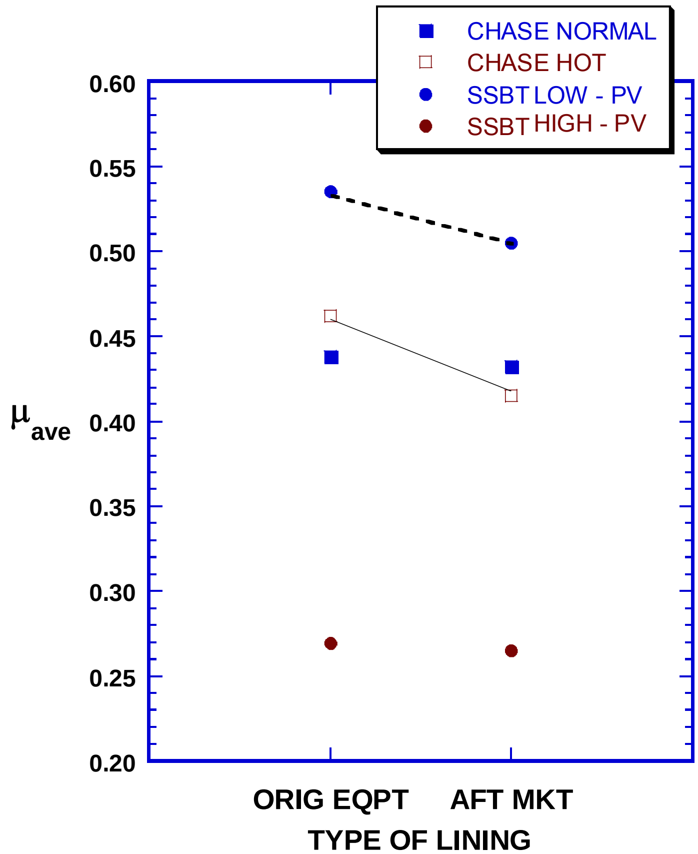

Figure 3.8 Correlation Between Chase/SSBT/ and Test-Track Data for an OE and an AM Lining on the Same Truck.

3.3 SSBT/Field Test

Correlation of the field test results with SSBT results was complicated by the fact that several drivers failed to follow instructions in the road test, and departed from the requested 30 psi line pressure during the stops. To help compensate for this, a compensatory strategy was developed. Data for the effects of line pressure, *p*, on the brake retardation ratio, *RR* [ratio of the sum of the braking torques to the sum of the gross axle weight ratings] were collected from commercial literature on the internet and from a series of FMVSS 121 dynamometer tests funded by the DOT/NHTSA on a prior project with ORNL [16].

The data in Figure 3.9 were fitted to a linear relationship to estimate the effect of higher or lower than requested pressure on stopping distance. Based on the following linear fit to the data, for line pressure in units of psi,

$$RR = m_o + m_1(p)$$

The curve fit parameters for the six data sets are given in Table 3.9.

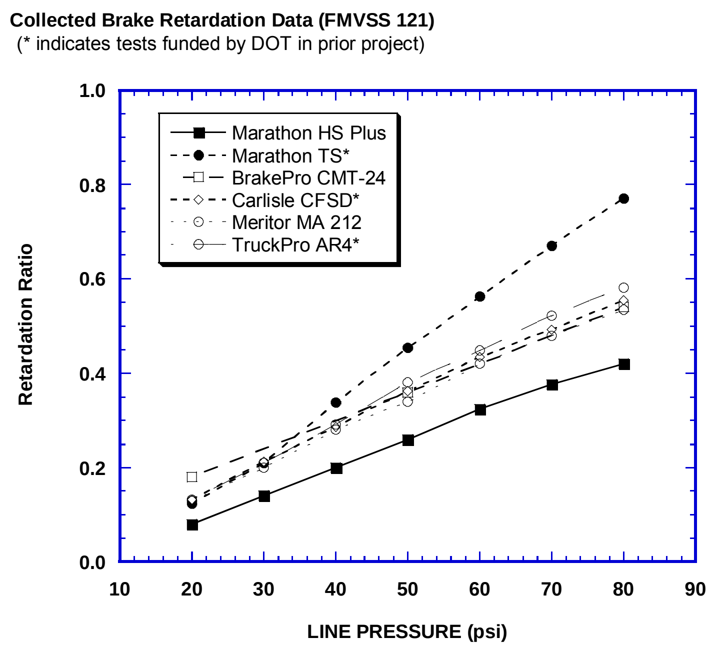

Figure 3.9 Line Pressure vs. Retardation Ratio for Six Linings.

Table 3.9 Curve Fit Parameters for Retardation Force and Line Pressure

Lining Material*	m_o	m_1	Correlation Coeff. (R)
Marathon HS Plus	- 0.03170	0.00578	0.9986
Marathon TS*	- 0.10390	0.01102	0.9993
BrakePro CMT-24	- 0.06000	0.00600	1.0000
Carlisle CFSD	0.00086	0.00706	0.9985
Meritor MA 212	-0.00125	0.00684	0.9987
TruckPro (Armada) AR4	-0.01380	0.00761	0.9986
Averages	-0.03500	0.00739	0.9990

* Lining data represent an average of two FMVSS 121 dynamometer tests per sample and do not necessarily represent the general characteristics of these products.

To approximate the effects of overpressure on the stopping distance, one could assume that the retardation ratio is proportional to the stopping distance and scale the stopping distance to the appropriate pressure using the averages from Table 3.9. Thus,

$$RR = -\,0.035 + 0.00739\,p \qquad (3.10)$$

and the ratio of the given stopping distance, S, for pressures, p, other than the requested 30 psi could be roughly estimated from:

$$\frac{RR_{30\,psi}}{RR_{xpsi}} = \frac{m_0 + 30m_1}{m_0 + pm_1} = \frac{0.187}{-0.035 + 0.00739\,p} \qquad (3.11)$$

Ignoring the differences in vehicle weight, and assuming that the ratio of *RR*s is the same as the ratio of stopping distances, then stopping distances from field tests conducted at lower or greater pressures than 30 psi could be adjusted to correspond to those for 30 psi line pressure. Therefore, the estimated stopping distance in feet for a line pressure of 30 psi, S_{30}, corrected for a field trial using p other than 30 psi, and with a measured stopping distance of S_p (feet) is given by:

$$S_{30} = S_{\mathrm{p}} (0.0396p - 0.1875) \qquad (3.12)$$

Stopping distances for various vehicles used in the field trials were corrected for actual pressure and shown in Table 3.10. Corrected stopping distances for OE and AM linings are plotted in Figure 3.10 and 3.11.

Table 3.10 Stopping Distances for Drivers – Corrected for 30 psi Line Pressure

Truck Number	Lining: Front/Rear (Type)	Condition (N = New, W = Worn)	Actual Applied Pressure (psi)	Measured Stopping Distance (ft)	30 psi Corrected Stopping Distance (ft)
3212	B/B (OE)	N	30	802.8	802.8
		W	30	816.8	816.8
960	D/C (OE)	N	25	608.3	488.5
		W	30	651.9	651.9
961	E/E (OE)	N	30 (3 stops)	722.7	722.7
		N	50 (2 stops)	905.5	1623.5
		W	90	247.8	836.8
102	C/C (OE)	N	30	714.9	714.9
		W	30	584.6	584.6
107	C/C (OE)	N	40	495.2	825.3
		W	30	1003.4	1003.4
2879	A/A (AM)	N	90	276.8	934.8
		W	30	785.8	785.8
105	F/G (AM)	N	30	868.7	868.7
		W	30	882.6	882.6
108	H/I (AM)	N	30	824.5	824.5
		W	30	1034.3	1034.3

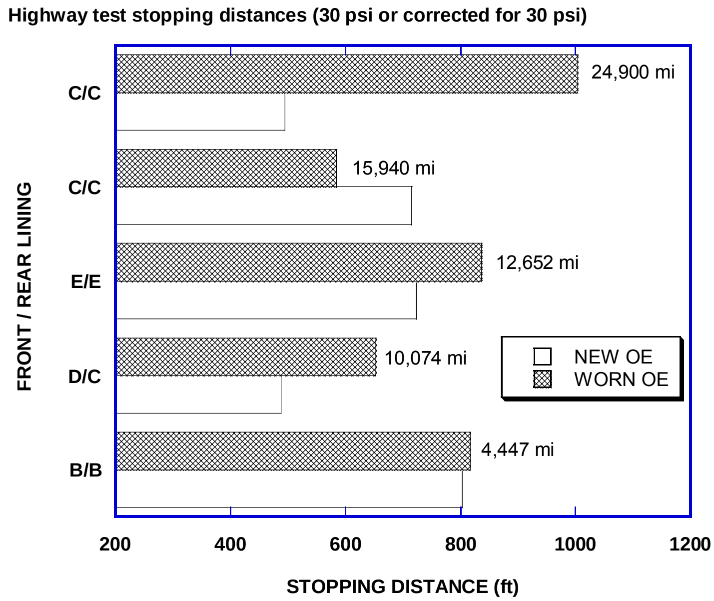

Figure 3.10 Pressure-Corrected Stopping Distances for OE Linings Before and After Wear.

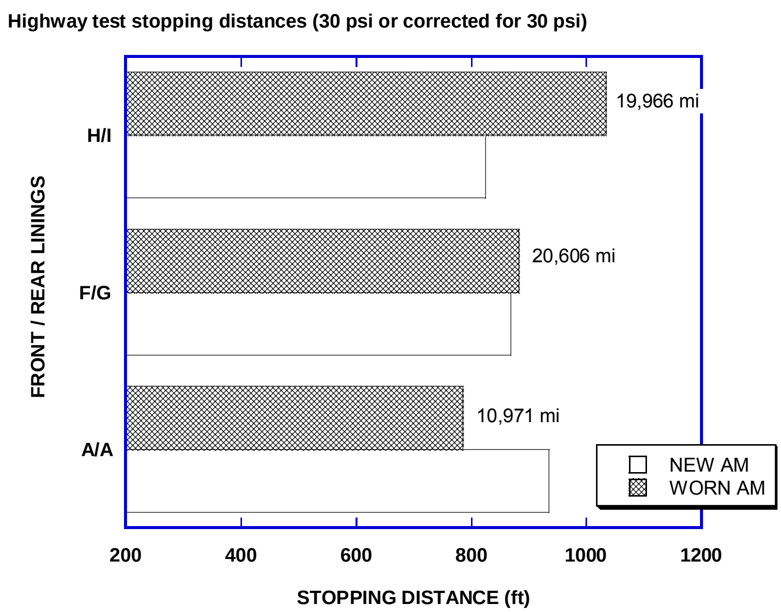

Figure 3.11 Pressure-Corrected Stopping Distances for AM Linings Before and After Significant Use.

Except for one lining, the data in Figure 3.10 for OE linings indicates that some worn linings produced longer stopping distances, as might be expected. The exception is notable, however, because it indicates that in-use conditioning of a lining can improve the stopping distance during its lifetime, but prior to its wearing out. Similar statements can be made for AM linings, as shown in Figure 3.11.

Having provided a means to correct for differences in braking pressure correlations, such corrections could be applied to braking distances and the friction coefficients obtained from Low-PV and High-PV SSBT tests. Figures 3.12 and 3.13 show the relationships between SSBT friction data under two test conditions and the pressure-corrected stopping distances of field tested trucks with new (a) and worn (b) linings. The best linear correlation (R = 0.877) was obtained for SSBT Low-PV tests versus the stopping distance of new linings (Figure 3.12). Other data were not as well correlated.

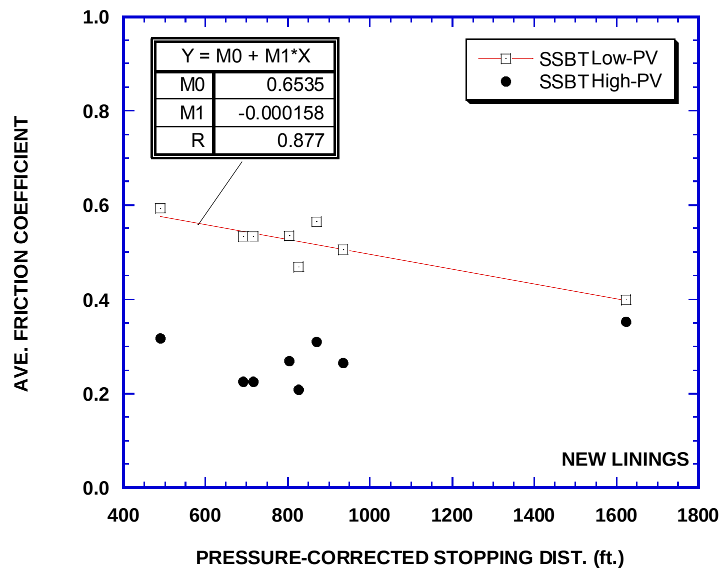

Figure 3.12 Relationship Between SSBT Friction Data and Stopping Distance for New Linings.

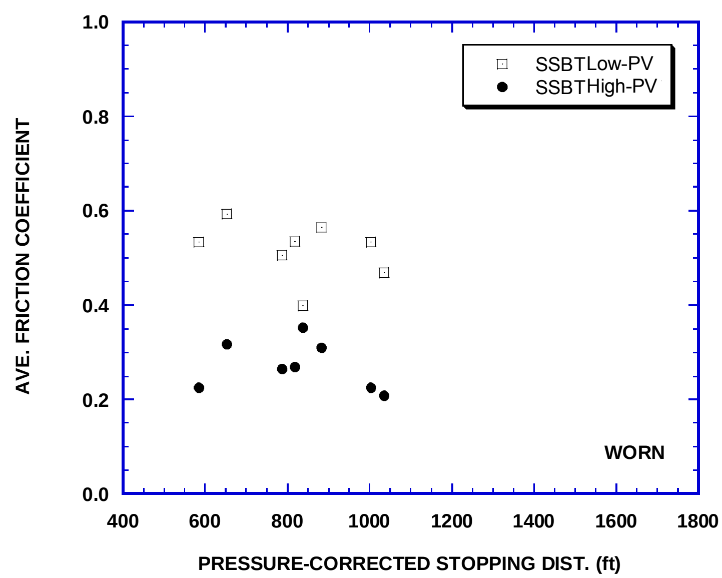

Figure 3.13 Relationship Between SSBT Friction Data and Stopping Distance for Worn Linings.

Within this portion of the overall study, it cannot be stated that OE linings as a class consistently performed either better or worse that AM linings. Tests on relatively new and worn linings produced mixed results. Some linings braked more effectively after they had been run for a period of time and others behaved better when they were newer. This may have been due to differing service conditions experienced by the different kinds of vocational trucks and the environment in which they normally operate.

A linear correlation was observed between the friction coefficients obtained for SSBT tests conducted under low pressure and low sliding speed conditions and the pressure-corrected stopping distances of field-tested trucks. The ability to maintain highly-controlled testing conditions on the highway was an issue since the condition of the vehicle, the degree of lining wear, and importantly, the ability of the driver to follow instructions introduced additional variables into the results of the highway tests. The laboratory-based SSBT tests were considerably more controllable than field tests but they did not completely simulate full-scale truck braking conditions.

In summary, it is important to realize that the stopping performance of a truck on a test track or on the road is not uniquely determined by the friction coefficient between the linings and drums. Even if the driver's reaction time and uniformity of braking is taken out of the equation, the stopping distance once the pedal is applied is a function of all of the following to some degree:

1) The slope of the road on which braking occurs (uphill, level, downhill, tilted).
2) The design and condition of the braking system.
3) The distribution of the braking forces carried by each axle and each braked wheel end.
4) The wind speed and direction relative to the drag characteristics of the vehicle.
5) The initial and final temperature of the braking surfaces.
6) The condition of the tires and road surfaces.
7) The weather conditions.
8) Whether the vehicle is braking on a straight line or on a curve.
9) The grip and traction of the friction materials (linings), as influenced by their composition and state of wear.
10) The weight of the vehicle and its initial speed.

Any attempt to correlate to friction coefficients between lining and drum materials (as implied by items 5 and 9 above) with stopping distance, even under relatively controlled conditions, must presume that the effects of the other variables are either secondary in importance or held sufficiently constant so as to isolate the effects of lining friction. Since the vehicles used in this study varied in a number of aspects other than the lining choices, the ability to correlate laboratory friction test results with vehicle stopping performance was made much more difficult. Despite these issues, it was still possible to obtain a measure of correlation between SSBT test data and the field performance of new linings, as shown in Figure 3.11(a), and with the test track data, as shown in Figure 3.8.[14] It is expected that even better correlations could have been obtained if the same truck and driver were used.

[14] See the Appendix of this report for a correlation analysis involving SSBT lab data and test-track and field-testing *nDR* observations.

3.4 Test Track/Field Test Correlations

Because similar information was collected in the field and test-track tests, it is possible in principle to investigate if the less-controlled conditions of the former type of testing introduce any statistically significant difference in the results. As explained elsewhere in this report, one very important variable affecting stopping distance, and in consequence deceleration rates, is the load level of the truck being tested. While in the test-track tests this variable could be, and was, finely controlled (in fact, these tests were conducted at LLVW and GVWR levels), this was not the case for the field test in which the load level of the tested truck could not be changed. In fact, only 1 of the field tests was conducted at LLVW level and 2 at GVWR level, with all the remaining 13 at some intermediate load level (although most of the time closer to the GVWR level than to the LLVW level).

For the analysis of the field test results (see Section 2.4.4), this disparity in weight was corrected by selecting an ideal load level for each one of the four truck categories (i.e., the average load of the initial and final observations for both the OE and AM equipment), and then adjusting the observed deceleration rates using equations derived from the TRC tests. As explained earlier, the form of the weight-deceleration rate function was not known and a linear form was adopted. The errors introduced by adopting a given function (linear in this case) were not large because the difference between the average load for any given truck category and the actual weight of any truck tested in that category was comparatively small (less than 7,800 lb in 75% of the cases). However, using the same procedure to make corrections, for example, to go from an actual field measured weight (close to a GVWR level) to the corresponding LLVW for that truck would introduce significant errors. This, in turn, would make it difficult to differentiate between errors introduced in the analysis by these weight corrections and anomalies that are attributable to the less-controlled conditions of the field test. For this reason, no weight adjustments were made to the observed normalized deceleration rates collected in the field. However, only those field observations in which the truck-load level was close to either the corresponding LLVW level or the GVWR level were used for this comparison.

Tables 3.11 to 3.14 present the results of the comparison of the normalized deceleration between field and test-track tests. In those tables, the two rows labeled “Weight Diff.” show the difference in weight between the actual field-tested trucks, and the load level shown at the top of the table. For example, in Table 3.11 the load level of the field-tested AM-mounted truck was 26,340 lb during the initial observations. Since for this particular truck the LLVW was set at 16,620 lb (see Table 2.33), the entry in Table 3.11 for this row (i.e., “Weight Diff.-Initial Obs.”) and column “LLVW-AM-Field Test” is shown as 9,720 lb, or 26,340-16,620 lb. On the other hand, the same entry under the column labeled “TRC tests” shows a 0 since the TRC test was conducted at LLVW or, in other words, with the truck loaded at 16,620 lb. The remaining entries in these four tables are similar to those presented in previous statistical tests in this report, except for the entry labeled “% Mean Diff.” which shows the difference between the test-track and field test average *nDR* as a percentage of the test-track average *nDR*. Notice also that some entries in Tables 3.11 to 3.14 are marked as N/A. The WC Class -8 tandem-axle LLVW case has already been discussed (i.e., no test-track information was collected, and therefore no comparison with the corresponding field test is possible). In the remaining cases, every time the difference in truck weight between the field test and the test-track test was large (i.e., more than 10,000 lb for the LPG tests or more than 16,500 lb for the TRC tests), then no comparison was performed and a “N/A” label was assigned to the field test.

Table 3.11 Statistical Test Results for *nDR* Field vs. Track Tests (Class-7 Single-Axle Truck)

		LLVW				GVWR			
		AM		OE		AM		OE	
		Field Test	TRC Test	Field Test	TRC Test	Field Test	TRC Test	Field Test	TRC Test
Weight Diff.	Initial Obs.	9,720	0	16,260	0	3,660	0	280	0
	Final Obs.	17,080		22,440		0		0	
Count		7	6	6	6	13	6	11	6
Mean		0.179	0.188	0.206	0.206	0.128	0.117	0.134	0.137
Std Dev.		0.036	0.007	0.007	0.004	0.028	0.006	0.008	0.011
Min		0.138	0.178	0.195	0.201	0.079	0.110	0.124	0.120
Max		0.242	0.195	0.215	0.213	0.183	0.123	0.143	0.147
N		11		10		17		15	
Mean Diff		0.009		0.001		0.012		0.003	
% Mean Diff		4.98%		0.37%		-9.90%		2.06%	
Variance		0.001		0.000		0.001		0.000	
t statistic		0.625		0.221		1.003		0.625	
Reject H_o at		45.53%*		17.01%		67.02%*		45.86%	

* Difference in sample variances slightly over an order of magnitude.

Table 3.12 Statistical Test Results for *nDR* Field vs. Track Tests (WC Class-8 Tandem-Axle Truck)

		LLVW				GVWR			
		AM		OE		AM		OE	
		Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test
Weight Diff.	Initial Obs.	24,180	N/A	140	N/A	640	0	24,940	0
	Final Obs.	0		15,800		24,820		9,000	
Count		5	N/A	3	N/A	2	6	5	6
Mean		0.145	N/A	0.187	N/A	0.143	0.195	0.128	0.202
Std Dev.		0.006	N/A	0.024	N/A	0.003	0.004	0.012	0.007
Min		0.136	N/A	0.164	N/A	0.141	0.190	0.109	0.191
Max		0.150	N/A	0.211	N/A	0.145	0.200	0.139	0.210
N		N/A		N/A		6		9	
Mean Diff		N/A		N/A		0.052		0.074	
% Mean Diff		N/A		N/A		26.72%		36.59%	
Variance		N/A		N/A		0.000		0.000	
t statistic		N/A		N/A		15.882		13.233	
Reject H_o at		N/A		N/A		100.00%		100.00%	

Table 3.13 Statistical Test Results for *nDR* Field vs. Track Tests (W Class-8 Tandem-Axle Truck)

		LLVW				GVWR			
		AM		OE		AM		OE	
		Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test
Weight Diff.	Initial Obs.	29,660	0	47,500	0	11,980	0	3,280	0
	Final Obs.	34,140		43,440		7,500		240	
Count		N/A	6	N/A	6	6	6	9	6
Mean		N/A	0.305	N/A	0.354	0.091	0.170	0.175	0.182
Std Dev.		N/A	0.014	N/A	0.003	0.015	0.008	0.018	0.003
Min		N/A	0.287	N/A	0.352	0.078	0.163	0.138	0.178
Max		N/A	0.322	N/A	0.358	0.119	0.184	0.198	0.186
N		N/A		N/A		10		13	
Mean Diff		N/A		N/A		0.079		0.007	
% Mean Diff		N/A		N/A		46.46%		3.99%	
Variance		N/A		N/A		0.000		0.000	
t statistic		N/A		N/A		11.557		0.950	
Reject H_o at		N/A		N/A		100.00%		64.06%*	

* Difference in sample variances slightly over an order of magnitude.

Table 3.14 Statistical Test Results for *nDR* Field vs. Track Tests (Class-8 Tri-Axle Truck)

		LLVW				GVWR			
		AM		OE		AM		OE	
		Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test	Field Test	LPG Test
Weight Diff.	Initial Obs.	46,940	0	43,300	0	3,500	0	3,500	0
	Final Obs.	44,740		42,740		1,300		4,060	
Count		N/A	6	N/A	6	9	6	10	6
Mean		N/A	0.164	N/A	0.161	0.115	0.103	0.128	0.090
Std Dev.		N/A	0.005	N/A	0.008	0.020	0.005	0.030	0.005
Min		N/A	0.157	N/A	0.150	0.082	0.097	0.077	0.081
Max		N/A	0.170	N/A	0.171	0.142	0.109	0.157	0.095
N		N/A		N/A		13		14	
Mean Diff		N/A		N/A		0.012		0.038	
% Mean Diff		N/A		N/A		-11.09%		-42.00%	
Variance		N/A		N/A		0.000		0.001	
t statistic		N/A		N/A		1.349		2.987	
Reject H_o at		N/A		N/A		79.95%*		99.02%*	

* Difference in sample variances slightly over an order of magnitude.

With the information available after the elimination of those observations that presented a large weight difference, a null hypothesis specifying that the average *nDR* measured in the field and in the test-track were the same was tested against an alternative hypothesis indicating that these two measurements were different (a two-tail test). For the Class-7 single-axle truck, the results of the statistical tests indicate that the null hypothesis could only be rejected with a very low confidence level (less than 67%) thus strongly suggesting that, on average, measurements of the *nDR* variable in the field were the same as those obtained from the TRC test-track tests.

This result indicates a high correlation between field and test-track observations, which is illustrated graphically in Figure 3.14. In that figure the average of the variable *nDR* obtained from the field observations is plotted against the same variable gathered from the TRC test-track runs (mean values in Table 3.11). Notice that two of the matching field/test-track observations are located almost on top of the 45-degree red line in Figure 3.14, indicating a perfect correlation. The other two observations are very close to that line, also indicating a strong correlation between the observations made in the field and those obtained in the more controlled environment of the TRC test track.

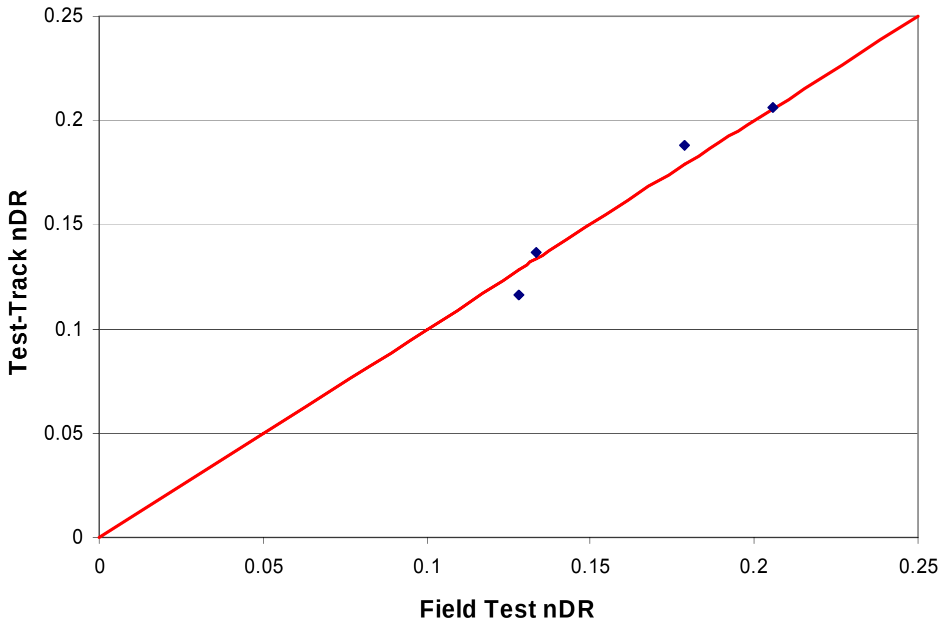

Figure 3.14 Field Test vs. Test Track Normalized Deceleration (TRC, Class-7 Single-Axle Truck).

For the other three truck categories (i.e., all the LPG track tests), the results allowed to reject the null hypothesis with levels of confidence of 64 percent (one case), 80 percent (one case), and over 99 percent (four cases). Except for the first, and perhaps second cases (64-percent and 80-percent levels of confidence in rejecting the null hypothesis), those results are opposite to the ones obtained when comparing the TRC and Field tests. This is illustrated in Figure 3.15 which shows the average of the variable *nDR* obtained from the LPG tests plotted against the same variable gathered from the filed test runs (mean values in Tables 3.12 to 3.14 for those columns highlighted in yellow). The graph shows that four points are located far from the red line (those correspond to the observations in which H_o could be rejected with almost 100% confidence), which is the locus of perfect correlated observations.

The graph also shows that three of the six points are high above the red line, indicating that the test-track observations resulted in much higher normalized deceleration rates than the field observations. One explanation for this is that, as discussed previously, no treadle information was collected in the LPG tests and average values (from the TRC tests) were used to generate the *nDR* variable used to compare track and field results. This may have introduced some errors in *nDR* for the test-track information. However, to make these three points closer to the red line, the treadle pressure at LPG should have been much higher than the one observed in the TRC tests, particularly for the WC Class-8 tandem-axle for the GVWR, which seems to present very high deceleration rates that are more attune with a LLVW test. If those WC Class-8 tandem-axle observations are discarded and only observations that present weight differences that are less than 1,500 lb are considered, then the rejection level of the null hypothesis falls to 20 percent for the W Class-8 tandem-axle/GVWR/OE category and to 45 percent for the Class-8 tri-axle/GVWR/AM category. This is also illustrated in Figure 3.16, which shows the two remaining field/track-test matching observations.

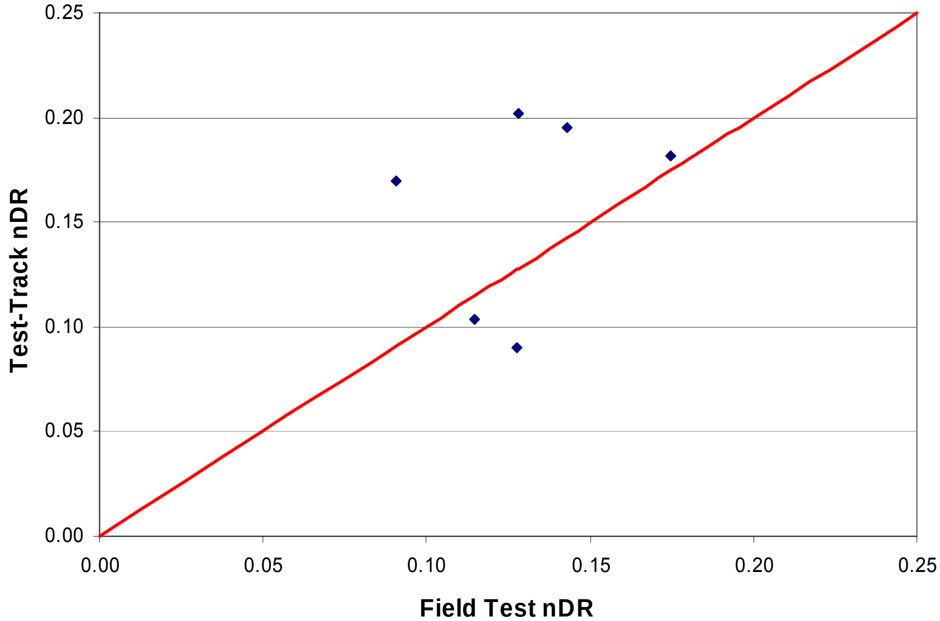

Figure 3.15 Field Test vs. Test Track Normalized Deceleration (LPG Tests).

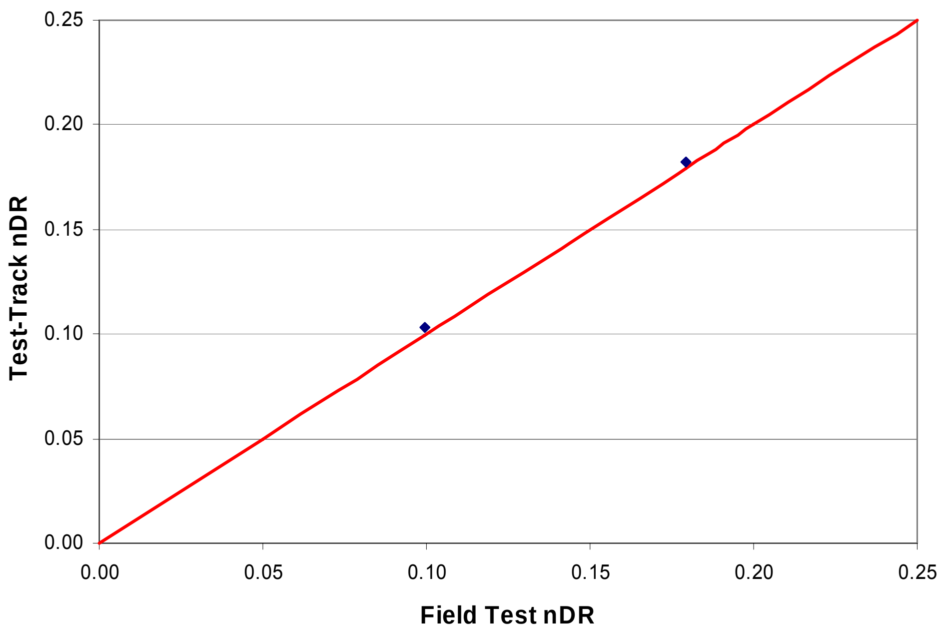

Figure 3.16 Field Test vs. Test Track Normalized Deceleration (LPG, W Class-8 Tandem-Axle/GVWR/OE and Class-8 Tri-Axle/GVWR/AM).

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4.0 Lessons Learned

- Determining the original equipment manufacturer of the brakes and the specific aftermarket brake materials for each of the four test vehicles was a slow and difficult task. Information received from the local dealer (it was the same dealer for all of the participating trucks) proved to be incorrect on three of the four test vehicles requiring OE brakes. Final certification of an SUT is usually done by the body builder who installs the appropriate body for the end customers application. The OE brakes at point of delivery could very likely be different from the brakes installed by the OEM. In future tests of this nature, a mechanism needs to be established to determine what brakes were on the truck at time of delivery to the end customer.

- The local dealer did not stock OE brakes, which therefore resulted in long lead times (up to six weeks) and delays in fielding the test vehicles. In the future, establishing a relationship directly with the OE brake providers would assure faster delivery of materials.

- This project required that OE brake materials be used in the testing. In dealing with the local brake material dealer, they attempted to provide remanufactured brakes that met the same specifications as the OE brakes. For this research, this substitution was not acceptable. This point was not well communicated with the dealer, and resulted in additional inefficiencies. In the future, all parties must be clear as to the nature of the project, the necessity for the exact material requested, and that substitutions are not allowed.

- For one of the OE brake linings, the local dealer shipped the wrong OE brake material. This resulted in one of the test vehicles having to be recalled from the test and resulted in additional costs and project time. Each box of brakes received should be checked to ensure they have the correct lining (not just by manufacturer, but also by lining type).

- The OE 301 brake material was being phased out by the manufacturer. This made obtaining the material difficult. Once a brake material is determined, the manufacturer should immediately be contacted to determine any supply issues and not rely on the dealer to determine and communicate this.

- The OE 402 brake material, while specified as the OE material for the refuse hauler was not currently available in finished shoe form. The local dealer had to request that the 402 lining material be assembled onto shoes. The special request caused delays in getting materials for testing. Again, once a brake material is determined, the manufacturer should immediately be contacted to determine any supply issues and not rely on the dealer to determine and communicate this.

- For the field test, it was very difficult for the drivers to maintain constant stopping pressure using the analog brake application air gauges. Furthermore, it was difficult for them to hit the target stopping pressures. This caused great inconsistencies in the field test straight-line stopping data. A performance-based brake tester is suggested for future performance testing to remove variability of real-world field stopping test. However, if real-world field stopping tests are conducted, it is recommended that measurements of speed versus time during the tests be collected at a reasonable sampling rate (i.e., 10 to 20 Hz) and the information saved to help with the analysis. For the test track tests, besides speed vs. time, treadle pressure should also be measured and saved.

- Because the field test involved active fleets going about their normal vocation, there was considerable variability in the vehicle loading as they arrived for the field test straight-line stopping tests. In particular, the refuse hauler had the greatest weight discrepancies. Depending on the time of the particular stopping test, the refuse hauler might arrive for the test empty or fully loaded. This was an additional inconsistency that had to be addressed in the data analyses. Again, a performance-based brake tester is suggested for future performance testing. Vehicles could be delivered to the tester unloaded and a repeatable simulated load could be added using artificial axle loading.

- Brake wear measurements were taken at the pivot and s-cam ends of the brake linings. In some cases measurements indicated a thicker brake measurement at these positions after it had been in service. Conjecture regarding this “growth” phenomenon may be attributable to material swelling, material migration, or the build up of brake material residue. It is believed that better wear indications could have been realized had they been taken at the opposite end of the lining near the center of the shoe.

5.0 Summary of Results/Conclusions

This study focused on heavy truck drum brake performance for selected Class-7 and Class-8 single-unit trucks. Specifically, the project studied the performance of OE and AM brake lining materials in three different test settings: laboratory, test-track, and field tests. Nine different brake lining materials (three OE and six AM, all of them manufactured or distributed by well-established U.S. or Canadian companies) were tested in the lab using the sub-scale brake testing capability available at ORNL and Chase testing at Link Engineering. Besides these nine linings, and due to efficient utilization of funds of the project, ORNL was also able to conduct a limited study (i.e., SSBT tests and correlation analysis, but no test-track or field testing).on a low-cost imported replacement lining material.

For the field tests, eight different trucks (two Class-7 single-axle dump trucks, two Class-8 Tandem-Axel dump trucks, two Class-8 tri-axle dump trucks, and two Class-8 refuse haulers) were mounted with brake linings corresponding to these nine materials studied. Four of these eight trucks (one in each of the four categories) were mounted with OE and the other four with aftermarket brake linings. For the test-track studies, one of each of these four classes of vehicles were tested. Test-track testing was conducted at the Transportation Research Center in East Liberty, Ohio (Class-7 single-axle dump), and at the Laurens Proving Grounds in Mountville, South Carolina (for testing of the remaining vehicles); the field tests were conducted at several locations in east Tennessee.

The results of the SSBT lab tests on the nine lining materials did not provide strong evidence that OE linings performed better or worse than AM linings, although the tests showed that the low-cost import replacement lining material presented a lower friction coefficient than the other brake linings (both OE and OM) studied in this project. Data were obtained for specific lining materials under specific test conditions, but there were an insufficiently large number of different lining materials involved in this study to draw any general conclusions about these two classes. One particular OE lining exhibited extremes in both traction and wear loss; this tended to bias the average for the two remaining OE linings toward higher values. Considering the other two OE linings, their friction coefficients and wear values fell within the expected range of the AM linings tested.

The Chase tests showed that, overall, the OE linings produced slightly higher average friction coefficients than did the AM linings in both the “Normal” and “Hot” categories; however, the result was significantly biased by the abnormally high friction coefficients of one particular lining. Without that lining, the averages for normal and hot friction coefficients for the OE would have been quite close to the values for the AM linings. Based on the results of the lab tests which focused on brake lining friction performance, it could not be concluded that the friction of OE linings was consistently higher than AM linings, nor that OE linings had consistently more (or less) wear than AM linings.

Stopping distance tests, based on FMVSS 121 specifications, were performed at the TRC and LPG research centers for each OE and AM brake lining and truck class studied in this project. These tests were conducted with the trucks lightly loaded (LLVW) and fully loaded (GVWR) conditions. Six runs were conducted for each combination of brake-lining/truck-class/truck-load, except for the Class-8 refuse haulers (AM and OE) under the LLVW load level. The reason for this was that during the LLVW tests, the brakes of the Class-8 refuse hauler would lock up, making the stopping-distance test invalid.

From the information collected at the test tracks, the deceleration rate per unit of treadle pressure was used to conduct statistical analyses comparing the performance of AM and OE lining materials (this variable was used because of consistency reasons with the field test analyses). In these statistical tests, a null hypothesis stating that the AM and OE brake linings provided, on average, the same deceleration rate, was tested against an alternative hypothesis specifying that the OE brake linings provided, on the average, higher deceleration rates than the AM brake linings. For the stopping distance tests conducted at TRC (Class-7 single-axle dump truck), the null hypothesis could be rejected with over 99.9 percent confidence, for both the LLVW and GVWR load levels, which provided supporting evidence that the OE brake linings achieved higher deceleration rates than the AM brake linings. Similar results were obtained for the Class-8 refuse hauler for the GVWR test, and the Class-8 Tandem-Axel dump trucks at the GVWR and LLVW levels. The Class-8 tri-axle dump truck tests showed reverse results, indicating that it was possible to reject the null hypothesis with 72 percent (LLVW) and 99.9 percent (GVWR) in favor of an alternative hypothesis postulating that AM brake linings produced higher deceleration rates than OE brake linings. However, the Class 8 tri-axle dump truck is a particular truck in which the third axle (the drop axle) was mounted with AM brake linings for both OE and AM categories.[15] That is, the OE truck was really a hybrid configuration with two axles mounted with OE brake linings and the drop axle mounted with AM brake linings. In effect, this configuration was "closer" to an AM mounted truck than any of the other three cases. Given these conditions, it would be expected that the "AM" category performed relatively better (closer to the OE category) than in the other three cases.

Stopping distance tests were also conducted under field test settings. A total of 98 observations were made during the field testing phase of this study, 50 (27 gathered at the beginning of the study and 23 near the end of brake life) on trucks mounted with AM brake linings and 48 (23 gathered with new brakes and 25 with worn brakes) on trucks using OE brake linings. In all cases, the final stopping times, stopping distances, and brake pressures were recorded. However, and as opposed to the test-track data where speed and other variables were saved at a very high sampling frequency, no intermediate information was recorded in the field tests.

By their own nature, field tests cannot be conducted under strictly controlled conditions. For example, the truck drivers participating in the field-test part of this study, although professional drivers, did not have test-driving training. This may have resulted in runs with variable, instead of uniform, deceleration rates. In addition, the weight of the trucks at the time of the tests could not be controlled (these were real-world trucks hauling loads for real customers) in order to assure uniformity across the truck class tested. This issue required the development of a methodology to normalize the collected data such that statistical comparisons could be made.

The raw data collected in the field was corrected for variations in the observed deceleration rates (they should have been uniform), load discrepancies between the AM and OE trucks belonging to the same class (information collected from the carefully conducted test-track tests were used as a basis), and for discrepancies in applied treadle pressure between runs. The resulting analysis variable was a normalized deceleration rate (i.e., deceleration rate/treadle pressure). Through this methodology, it was necessary to eliminate 18 observations because they reflected highly variable deceleration rates (as opposed to the expected constant deceleration rate); the remaining 80 observations were corrected for weight and treadle pressure variances and used in the analysis.

Statistical analyses, similar to those conducted for the test-track tests, were performed on the collected field data. In all the cases where there was sufficient data for the statistical analysis (i.e., all the cases, except the initial observations made on the Class-8 refuse haulers), the null hypothesis could be rejected with over 95 percent confidence in favor of the alternative hypothesis, indicating that on the average, the deceleration rates obtained when the trucks were mounted with OE brake

[15] Since it was not possible to identify the OE that originally came with the drop axle, the AM equipment that the fleet partner normally uses was mounted on the drop axle of both the AM and OE trucks.

linings were higher than when they were mounted with AM brake linings. The one exception was the Class 8 tri-axle truck during field observations made close to the end of the study. In that case, the null hypothesis could only be rejected with 70 percent confidence (84% confidence if both the initial and final observations were aggregated) thus not showing enough evidence that the OE brake linings performed better than the AM brake linings. However, and as discussed earlier, this was a hybrid configuration truck (the drop axle was mounted with AM linings in the OE configuration), and it was expected that both OE and AM would show less differences than the other three truck categories.

During the field test, information was also collected regarding brake-lining wear. Measurements of the lining material were made for each shoe on each axle at the beginning and at the end of the field test; the difference between these two readings was used as a measure of the lining wear. Statistical tests were conducted on the collected wear data. The results of these statistical tests allowed for the rejection of the null hypothesis of equal brake-lining wear for AM and OE brake linings at the 99-percent, 88-percent, and 94-percent confidence level for the Class-7 single-axle, the Class-8 refuse hauler, and Class-8 tandem–axle dump truck, respectively. For the Class-8 tri–axle dump truck it was only possible to reject the null hypothesis at a very low (63%) level of confidence. Once more, and as pointed out previously, the OE case for this particular category was really a hybrid configuration with the drop axle using AM brake linings.

During this project, it was also observed that the brakes on the Class-8 refuse haulers lasted longer (24 weeks or longer) than what the partner indicated to be their experience (7 to 9 weeks). A plausible explanation for this result could be attributed to an exhaustive maintenance of the brakes, as opposed to simply replacing brake shoes. That is, at the beginning of the tests, all participating trucks were mounted with new brakes and new drums, provided to the partner fleets as part of this project. In addition, the participating refuse haulers underwent a complete foundation brake built that was provided by the company that owned the trucks. This comprehensive brake maintenance might have allowed the brake linings to last longer. Further studies need to be conducted to determine whether this is the case.

As part of this study, correlation analyses were also conducted in an attempt to determine any correspondences between the SSBT and Chase lab tests, the lab tests and the road tests (field and test-track), and between the field and test-track observations. The correlation analysis of the lab tests showed that, except for two linings there was a reasonable correlation between the Chase "Normal" friction coefficients and the SSBT Low-PV data. The average ratio of the corresponding friction coefficients was found to be 0.869, with a reasonable standard deviation of 0.056. The results also indicated that there was an even better correlation between the Chase "Hot" friction coefficients and the SSBT Low-PV data (except for one lining). The ratio of Chase "Hot" friction coefficients to the SSBT Low-PV data was a steady 0.856 with a standard deviation of only 0.038 with respect to that ratio.

The frictional rankings of OE and AM materials were also studied. The OE materials, all produced by the same company, ranked nearly in the same order, irrespective of the test method (SSBT or Chase). The AM linings, however, ranked in more widely dispersed order from one test method to another. One particular lining seemed quite sensitive to test conditions; ranking lowest in two cases, and highest in two others. There are a number of possible reasons for this including the possibility that the specimens were cut from different parts of the lining. If the lining was not uniform from place to place, it is possible that the cut-out samples were not identical in composition. The correlation results also showed that friction coefficients estimated for linings for which RP 628 torque data were available fell into a much narrower range than values measured in the other types of laboratory tests.

While data were available for OE and an AM linings tested on the same truck at TRC and LPG, SSBT/test-track correlations were confined to the results provided by the former because of a more complete information database. For the TRC data a correlation was found to exist between stopping distances at TRC and the SSBT and Chase test results. The average stopping distance measured at TRC was shorter for the OE lining (292 feet) than for the AM lining (339 ft). Note that the Chase "Normal" and SSBT High-PV data were not significantly different for OE and AM linings, so they would not reflect the differences in stopping distance. On the other hand, the friction coefficients for the Chase "Hot" and the SSBT Low-PV data were both lower for AM linings than for OE linings, as would be expected for the longer stopping distance for the AM linings.

Correlation of the field test results with SSBT results was complicated by the fact that several drivers failed to follow instructions in the road test, and departed from the requested 30 psi line pressure during the stops. To help compensate for this, a compensatory strategy was developed. Data for the effects of line pressure on the brake retardation ratio were collected from commercial literature on the internet and from a series of FMVSS 121 dynamometer tests. Once these corrections were applied, a linear correlation was observed between the friction coefficients obtained for SSBT tests conducted under low pressure and low sliding speed conditions and the pressure-corrected stopping distances of field-tested trucks (note: further analysis, correlating both test-track and field observations with SSBT results confirmed these results by showing a significant correlation between Low-PV friction coefficients and observed deceleration rates). The ability to maintain highly-controlled testing conditions in the field was an issue since the condition of the vehicle, the degree of lining wear, and importantly, the ability of the driver to follow instructions, introduced additional variables into the results of the field test. The laboratory-based SSBT tests were considerably more controllable than field tests but focused on frictional behavior. As a result, they did not completely simulate full-scale truck braking conditions.

Similar information was collected in the field and test-track tests, and therefore it was possible, in principle, to investigate if the less controlled conditions of the former type of testing introduced any statistically significant differences in the results. However, one very important difference between these two test settings resided in the truck load level, which strongly affects the stopping distance and deceleration rate. While in the test-track tests the truck weight could be, and was, finely controlled, this was not the case for the field test that involved trucks engaged in their normal vocational activities. As a result, the load level of the tested truck could not be guaranteed. In fact, only one of the field tests could be considered to have been conducted at the LLVW level and two at GVWR level, with all the remaining 13 at some intermediate load level (although most of the time closer to the GVWR level than to the LLVW level). Weight corrections similar to those applied in the case of the field data analysis were not warranted here since they could introduce systematic errors in the correlation analysis. Therefore, no weight adjustments were made to the observed normalized deceleration rates collected in the field for the correlation analysis. However, only those field observations in which the truck-load level was close to either the corresponding LLVW level or the GVWR level were used for this comparison. With this information, a null hypothesis specifying that the average deceleration rates measured in the field and at the test-track were the same was tested against an alternative hypothesis indicating that these two measurements were different. For the Class-7 single-axle truck, the results of the statistical tests indicated that the null hypothesis could only be rejected with a very low confidence level (less than 67%), thus strongly suggesting that, on average, measurements of the deceleration rate (or stopping distance) in the field were the same as those obtained from the TRC test-track tests. For the other three truck categories (i.e., all the LPG test-track tests), the results allowed the rejection of the null hypothesis with levels of confidence of 64 percent (one case), 80 percent (one case), and over 99 percent (four cases). Except for the first, and perhaps the second cases (64% and 80% null hypothesis rejection level of confidence) those results are opposite to the ones obtained when comparing the TRC and field tests.

In conclusion, the results of this study indicate that trucks mounted with OE brake linings perform better (in terms of achieving higher deceleration rates, and in consequence shorter stopping distances) than the same trucks mounted with AM brake linings. This superior OE performance was observed in both the field (after the data was corrected) and in the test-track tests, although they were less pronounced for the LPG track tests. The lab tests provided some indication that this was also the case, although not in all of the tests conducted. Results from preliminary tests conducted on one low-cost imported replacement lining material indicated a lower friction coefficient than the other brake linings (both OE and OM) studied in this project. The predicted deceleration rate was also found to be at the lower end of those observed during the test-track and field testing experiments.

The correlation analysis of the lab tests showed that there was a reasonable correlation between the Chase and SSBT data, at least for some of the conditions tested. The analysis also showed a correlation between stopping distances at TRC and the SSBT and Chase test results, and when all the test-track and field observations were combined, a strong correlation between SSBT "Low-PV" friction coefficients and deceleration rates. The data collected at TRC also showed a strong correlation to the deceleration rates measured during the field tests.

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6.0 Suggested Future Research

Of primary concern to a heavy vehicle's braking system is the quality of the brake materials. This effort has shown that the process of quantifying and correlating brake material quality and relevance to other existing materials is difficult and costly. Test-track testing gives the best "head-to-head" comparison of a given lining due to the fact that it mimics real-world stopping events to the extent that tests are recorded on actual vehicles being operated by human drivers. Additionally, variables like vehicle GW, road surface friction coefficient, and brake treadle pressure can be controlled. However, practical access to the test facilities for large-scale brake testing (multiple lining on multiple vehicles) and test facility costs are prohibitive.

With this in mind, future research is suggested that combines the control of the test track with the long-term brake performance measurements that are obtainable from field testing. This "optimized" testing could be accomplished by using a Performance-Based Brake Tester (PBBT) which measures the braking force of a vehicles braking system both in terms of the total vehicle and individual wheel end. Using the PBBT would eliminate the variability of results from varying brake treadle pressure and varying road surface friction coefficient and slope, while allowing a true metric of brake performance (braking force) to be monitored over time.

A PBBT inspection station is planned for the fall of 2007 at the Greene County Commercial Vehicle Inspection Station on I-81 in northeast Tennessee. This facility is being funded by the Federal Motor Carrier Safety Administration (FMCSA) and in partnership with the Tennessee Department of Safety (TDOS) and ORNL. For the first 18 to 24 months the facility will be designated a research facility and could be used for additional lining characterization studies. Also, NTRC has a multiplate PBBT [17] that may be used in this project to perform a correlation with PBBT equipment that meets the FMCSA Functional Specifications.

By eliminating the test-track and field test straight-line stopping test, time and resources could be directed at looking at a larger sample of OE and AM brakes as well as "knock-off" brands and "foreign" independent-labeled brakes. Coupled with the PBBT and wear testing, it is suggested that some form of bench-top testing be conducted to understand a lining's propensity to fade due to heat. As an initial phase of follow-on work, a large set of brake linings could be tested on the bench, say 30- to- 50 linings, and correlated to the results from this effort. Then a smaller set of linings of interest could be selected for field testing on the PBBT.

It is clear from this project that as a brake material heats up, it's braking performance changes. Further, it is clear that there is a need to better understand brake material performance over time and subsequent wear. These needs could be addressed using the PBBT, bench-top testing, and field wear measurements.

This study has shown that under specific sets of applied conditions, Chase tests and SSBT tests can provide similar frictional rankings for a series of linings, even if the friction coefficients themselves differed in magnitude between linings. The SSBT's High-PV condition seems to provide lower friction coefficients and correlates less well with the Chase or field test results because it imposed higher energy stopping conditions (i.e., fade) than did the other methods used in this study. Therefore, the correlation of field and test track data with SSBT High-PV data was not as evident as it was for SSBT Low-PV data. It is recommended that in future studies, rather than using the Chase test, the dynamometer portion of FMVSS 121 be used. While more expensive than Chase testing, it is less expensive than test track or field tests, and it uses full-size linings and drums. A correlation between that dynamometer method, SSBT data, and field tests would provide additional, useful information to establish the relationship between laboratory and field braking performance. In addition, and in contrast with Chase tests, the FMVSS 121 data include results for different line pressures, so it would be easier to compensate the analysis to account for pressure variations that occurred in the current field tests.

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Appendix

A1. Evaluation of a Low-Cost, Imported Aftermarket Brake Lining Material by Sub-Scale Testing

A1.1. Summary and Overview

During the course of this project, the team engaged in discussions with several industry representatives (including R. Diemer of BrakePro) about a growing concern on the part of the U.S. brake lining manufacturers that the use of low-cost, imported replacement brake linings was growing. The issue is not simply one of market share, but could have a serious impact on the safety of the traveling public. Recent test results, provided by private communication from BrakePro, suggest that some of the low-cost imports from Asia and South America can have much longer stopping distances, far exceeding the federal requirements for original equipment (OE) linings.

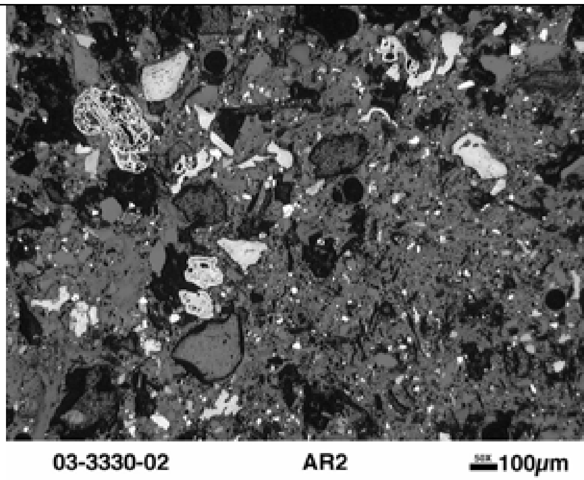
The supplementary study described in this Appendix was performed to obtain SSBT data on a sample of one of the low-cost imported lining products and to compare it to the data obtained under the same test conditions used for OE and aftermarket (AM) products described elsewhere in this report. Overall, the low-cost import reflected a lower friction coefficient than the other brake linings (both OE and AM) studied in this project. Further work is suggested to define the nature and extent of this threat to public safety.

A1.2. Material

Similar to the other linings tested, the mating disk in all cases was gray cast iron. BrakePro provided a sample of a Chinese-made, low-cost imported replacement lining material (LCIL) that had previously been dynamometer-tested by them, that had raised some concerns. The material itself had no product name identification marked on it other than the following edge code: “HT 4515 CD ML.” According to the SAE Standard, J866, the “C” in the edge code means that the normal friction coefficient was ≤ 0.15 and the “D” implies that the friction coefficient was > 0.15 but ≤ 0.25 when hot. This fact alone should be cause for concern since friction coefficients for linings typically range from 0.35 to 0.55 (i.e., ratings E, F, or G). The fact that the “hot” friction was higher than the normal value does not indicate a resistance to fade, but rather typifies the situation when the brakes are warmed up by use. Fade is a more severe condition that occurs during emergency stops or during abnormally long or repetitive drags.

A specimen of the LCIL was removed from the brake block, polished, and its microstructure was compared to that of AR2, another aftermarket lining material tested in this project and one which had been previously polished for study in another brakes-related project at ORNL. The block of LCIL was polished in an orientation that would be parallel to the plane of the sliding face against the rotor surface. Photomicrographs of the two materials are shown in Figure A.1. The AR2 shows a typical, multi-component microstructure containing large and small additive particles. Some of the darker-appearing areas in the AR2 are not voids, but rather non-metallic phases. Bright flecks and smaller bright, curved particles are probably metallic chips to enhance thermal conductivity. The typical void content of friction materials like this is about 4-6 percent.

By contrast, there was a relatively high proportion of open voids and cavities in the LCIL and evidence of glass fiber bundles (regions of small ovals in the center of Figure A.1). The presence of so much porosity raises concerns about the strength and durability of the material. The scope of the present project did not allow a chemical analysis to be made of the material, but visually, the LCIL seems to have higher porosity levels, and a lower concentration of angular hard particles that would decrease its "grip".



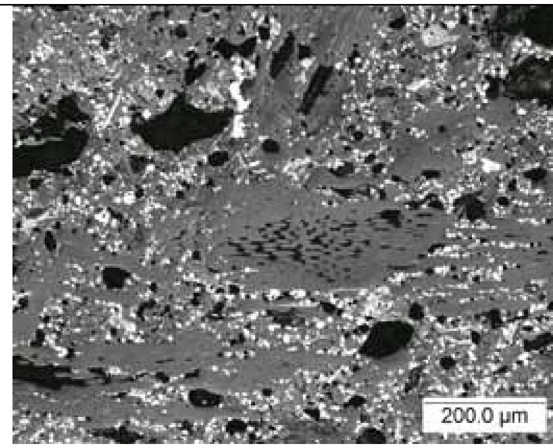


Figure A.1 Microstructure of Armada AR2 Lining Material (Left) and the LCIL (Right).

A1.3. Testing Conditions

The SSBT system was used to conduct tests of the LCIL material. A description of the apparatus is given in Section 2.1.1 of this report. To reiterate, two testing conditions were applied after first burnishing for five drags to condition the sliding surfaces. Each of the two testing sequences consisted of a series of 10 constant speed drags of 20 s on, and 10 s off. As with the other lining materials tested in the SSBT, five blocks of the LCIL material were tested to assess the repeatability of the results and to establish an average friction coefficient for the material. The same cast iron disc was used for all tests, without reconditioning between runs.

Two different degrees of severity of contact were applied. The Low-PV level was intended to simulate the conditions in the Chase test. The High-PV level was intended to test the material response of frictional heating and its susceptibility to fade.

Low-PV: 167 N normal force and 6 m/s sliding speed.

High-PV: 320 N normal force and 15 m/s sliding speed.

The weight of the test block was measured after burnishing, but before the Low-PV sequence, and at the conclusion of the High-PV. The difference in mass was used to calculate wear. Tests were insufficiently long to enable measurement of the disk wear.

A1.4. Friction Coefficients and Temperature Rises

As with the other linings investigated in this project, five tests of the LCIL were planned. However, as will be explained subsequently, there were clear differences between the results of the first two tests and the latter three. Three additional, confirmatory runs were subsequently performed of the same disk and their results were also considered. Results for the five tests are first described, and then the results of the three additional confirmatory tests are included.

The average friction coefficient for each drag of the LCIL material on cast iron is shown for Low-PV and High-PV sliding conditions in Figures A.2 and A.3, respectively. The suffixes “A” and “B” in the legends in these figures refer to Low-PV, and High-PV tests, respectively. There appeared to be a significant variation in the sample-to-sample behavior and they appeared to fall into two classes: relatively low friction and higher friction. The order in which the runs were performed was examined to ensure that the observed trends were not due simply to a time-dependent drift in force sensor readings. However, the latter runs (LCB3, LCB4, and LCB5) had higher friction in both the Low-PV and High-PV tests. This suggests that friction improved as a thicker transfer film was built up on the cast iron disc. The decreasing friction following the third drag in High-PV tests suggests the onset of fade.

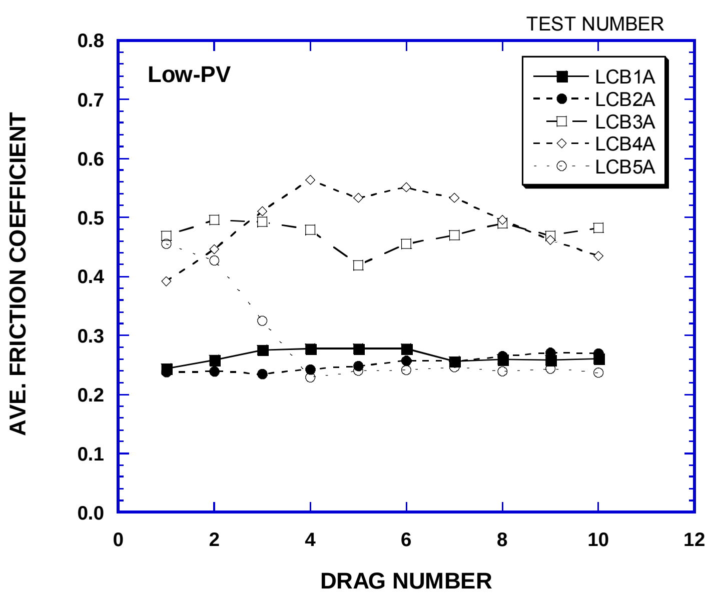


Figure A.2 Low-PV Friction Coefficient Data for the LCIL.

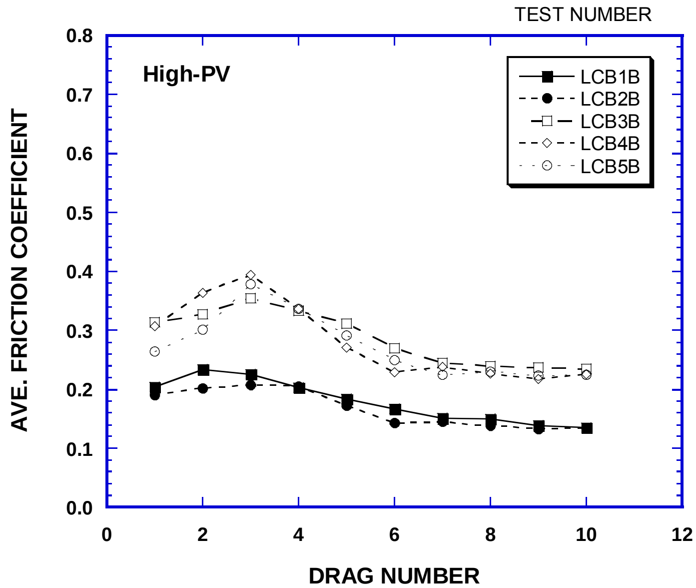


Figure A.3 High-PV Friction Coefficient Data for the LCIL.

A summary of the friction coefficients and temperature rises for the LCIL material is shown in Table A.1. It includes the first five planned runs as well as the three additional runs (identified as tests 6, 7, and 8) that were performed to verify the behavior of the material. Each value represents the average of the ten drags conducted at Low-PV and High-PV conditions for each of the five specimens of LCIL. Note that the friction coefficients are generally lower for the High-PV conditions when fade is likely to be more prominent. The temperature rise for each drag is relatively consistent for both Low-PV and High-PV conditions. Therefore, the temperature ratchets up by about the same amount for each subsequent drag.

In Figure A.4, the average temperature per drag is plotted versus the corresponding friction coefficient for the first five runs. Two groupings of curves are evident, with the higher values of friction corresponding to the latter runs in which the transfer film on the cast iron disc was better established. Figure A.5 shows the data only for runs 3-8. There is considerable scatter at the Low-PV conditions, but the trend of decreasing friction above about 165^{o}C becomes more pronounced when runs 1 and 2, that did not have a fully-formed transfer film, are excluded. There were a few isolated values of low-friction coefficient even among the data that did not include runs 1 and 2. These anomalously low values are circled in Figure A.5. All were recorded during run 5, and may be due to a variation in the properties of that particular test specimen.

The High-PV friction data, represented by solid symbols on Figures A.4 and A.5, show relatively low friction at low average temperatures; then an increase to a maximum friction coefficient at intermediate temperatures; and then a decline again at the highest temperatures. The observation that brake linings perform better when slightly warm is also seen in dynamometer test data for a range of commercial linings[A1] and is not unusual in and of itself.

[A1] "A Proposed Marking System for Aftermarket Heavy Truck Brake Linings," sponsored by DOT/NHTSA (2002-2004), and conducted at Oak Ridge National Laboratory under an interagency Work for Others agreement.

Note that the friction coefficients for individual drags at higher temperatures are in the range of 0.14 to 0.24, in agreement with the “CD” rating stamped on the edges of the lining material test block. The average friction coefficients in Table A.1 reflect the entire series of ten drags for each specimen, but Figure A.4 data for individual drags indicates that a significant reduction occurs when the highest temperatures occur.

Table A.1 Average Friction Coefficients and Temperature Rise Data for the LCIL Material (10 repeated drags in each set of conditions)

	Test	Low-PV Conditions	High-PV Conditions
Average Friction Coefficient	1	0.264	0.179
	2	0.252	0.167
	3	0.472	0.286
	4	0.492	0.281
	5	0.288	0.272
	6	0.452	0.268
	7	0.534	0.318
	8	0.550	0.316
Standard Deviation in Friction Coefficient	1	0.012	0.036
	2	0.014	0.032
	3	0.023	0.046
	4	0.056	0.065
	5	0.085	0.054
	6	0.055	0.052
	7	0.029	0.053
	8	0.028	0.064
Mean Temperature Rise per Drag (^{o}C)	1	16.5	58.3
	2	15.6	55.4
	3	18.4	56.9
	4	19.1	54.6
	5	13.8	56.1
	6	18.7	56.9
	7	17.8	58.2
	8	19.8	55.2
Maximum Temperature, Last Drag (^{o}C)	1	102.9	267.8
	2	100.5	255.2
	3	106.1	260.3
	4	117.2	264.6
	5	91.8	256.4
	6	119.2	257.0
	7	111.2	259.9
	8	120.5	264.1

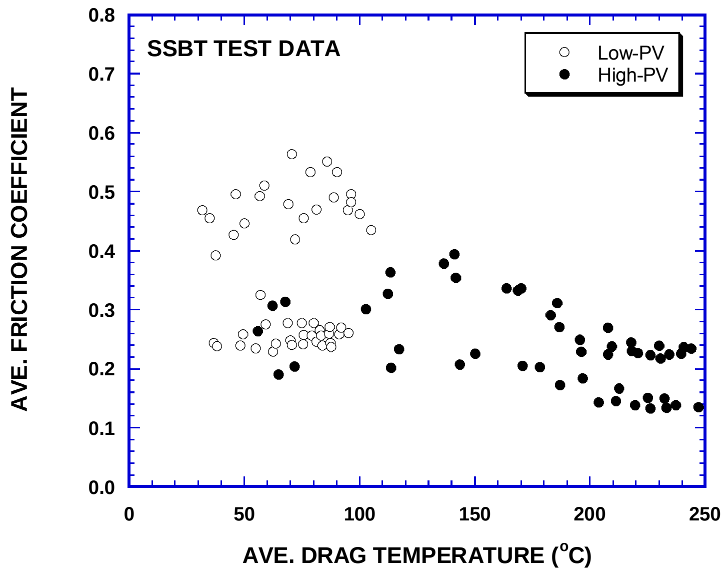


Figure A.4 Compilation of Average Friction Coefficients and Corresponding Average Disc Track Temperatures for Low-PV and High-PV Tests (Runs 1 to 5).

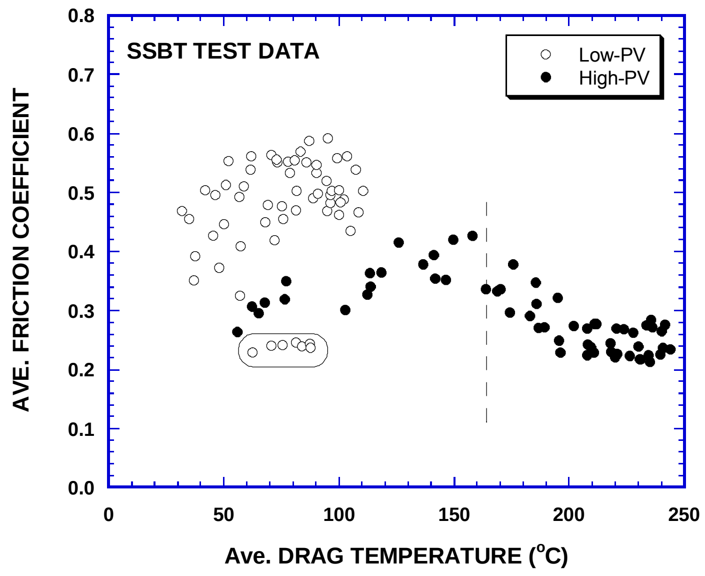


Figure A.5 Compilation of Average Friction Coefficients and Corresponding Average Disc Track Temperatures for Low-PV and High-PV Tests (Runs 3 to 8). Circled Data Were All From Run 5.

A1.5. Comparison of LCIL Data with Data for OE and Other AM Linings

The friction coefficients for the tenth drag on all linings tested are given in Table A.2, based on data from Tables 2.5 and 2.6, and the more recent data on the LCIL material. Since there were apparently two populations of data for the LCIL materials, separate averages were computed for the first two tests, for the last six tests, and for the overall average.

Table A.2 data indicate that:

- With one exception, the High-PV and Low-PV friction coefficients for the LCIL fall below the average friction coefficients for the OE linings.
- High-PV friction coefficients for LCIL are lower than those for all AM lining friction coefficients except AM lining "I."
- Low friction was observed on the first two LCIL runs, and for a period of time on a later Low-PV run (run 5). This indicated that more sliding time (running-in) may have been required for LCIL linings to reach steady-state performance than did either the OE linings or the other AM linings. Alternatively, there may have been a specimen-to-specimen variation in performance. Those issues remain a subject for future investigation.

Table A.2 Friction Coefficients (μ) for the 10th Drag During Low-PV and High-PV Tests

Lining Code	Product Name	Low-PV 10^{th} Drag Avg. μ	High-PV 10^{th} Drag Avg. μ
B	ARVIN 212	0.535	0.269
C	ARVIN 301	0.534	0.226
D	ARVIN 402	0.649	0.407
	Avg. (OE linings)	0.573	0.301
A	ABEX 6008-1	0.505	0.265
E	BrakePro CM24	0.399	0.352
F	Armada AR3	0.576	0.305
G	Armada AR2	0.551	0.314
H	Fleet Pride OTR II	0.444	0.249
I	Carlisle MB21	0.491	0.166
	Avg. (AM linings)	0.494	0.275
LCIL	(Avg. of first 2 runs)	0.266	0.135
LCIL	(Avg. of last 6 runs)	0.434	0.241
LCIL	(Avg. of all 8 runs)	0.392	0.214

A1.6. Comparison of LCIL Wear Data With That of Other Linings

The lining weight change was determined between the as-burnished pad, just prior to the Low-PV tests, and the final weight after both Low-PV and High-PV tests had been run. Individual weight losses are given in Table A.3. The average LCIL value is compared with the wear of the OE and AM linings (as reported in Table 2.9) and is shown in Table A.4. The average LCIL value falls very near the average value for all AM linings. The aggressive OE lining (Lining D), with its high friction, remains the highest wearing material of those tested and skewed the average mass loss for the three OE linings to a larger value. Discounting lining D, linings B and C would otherwise have averaged about 25 percent less mass loss than the average of the AM linings.

Table A.3 Wear Data for LCIL Specimens

Test	Mass Loss (mg)
1	40.1
2	42.7
3	44.3
4	39.3
5	38.9
6	43.0
7	47.7
8	49.1
Average	43.2

Table A.4 Wear and Relative Rankings of Linings Tested on the SSBT

Lining Code	Average Mass Loss (mg)	Relative Ranking*
B	34.6	5
C	30.5	4
D	135.8	10
Avg. OE	67	
A	28.2	3
E	83.4	9
F	53.1	7
G	57.0	8
H	18.2	2
I	15.8	1
Avg. AM**	42.6	
LCIL Avg.	43.2	6

* Relative ranking: 1 = least wear, 9 = most wear
** Average does not include the LCIL

A1.7. Summary and Conclusions

The influx of low-cost replacement brake linings for heavy trucks is an issue of increasing concern both from the standpoint of domestic lining sales and highway safety. Limited SSBT tests were performed on a sample of a low-cost, imported AM truck brake lining material (LCIL) of Chinese origin, using the same test method as was used for the OE and AM linings addressed earlier in this project. The purpose of this supplemental investigation was to determine whether the LCIL material displayed low friction behavior on the SSBT, and then to relate its results to those for the OE and AM linings similarly tested. In summary:

1) The friction coefficients of the LCIL were in general significantly lower than those of the OE and other AM materials investigated in the course of this project, especially at the more severe testing conditions.

2) The first five runs of LCIL seemed to separate into two groups with the first two runs having lower friction than the latter three. Individually, each group showed a similar trend in response to frictional heating at High-PV conditions. Friction data from three additional tests were obtained on the same test disk and agreed well with the data of the latter runs. A possible explanation is that the first two runs were needed to develop a transfer layer of lining material on the cast iron disk. Once that layer was developed, the friction stabilized at a higher level; though still underperforming most of the other linings. Perhaps, the LCIL required a longer conditioning period to develop a stable layer than the other linings tested.

3) Fade behavior was exhibited by the LCIL at frictionally-induced temperatures exceeding approximately 165^{o}C. After fade set in, friction coefficients were as low as 0.135, a value that is within the range of powdered lubricants, like graphite.

4) The wear of the LCIL material was comparable to, but no worse than that of the other AM materials tested, despite the significant porosity displayed in a polished cross-section of the material. However, the SSBT test protocol used here was primarily aimed at friction characterization. To generate better wear data, the sliding time would have to be much longer; long enough to generate measurable wear on the disk as well as on the lining material.

While the work described here involved only one brake block of one LCIL material, the results were sufficiently disturbing to raise concerns over the growing use of such materials in the replacement truck brake lining market. It is therefore recommended that a more comprehensive follow-on study be conducted to determine the extent to which such LCIL materials would have an impact on U.S. highway safety; especially if their use spreads to the independent owner-operators across the country.

A2. Estimation of Deceleration Rates for the Low-Cost, Imported Aftermarket Brake Lining Material

A2.1. Overview

The SSBT experiments conducted on the low-cost, imported aftermarket lining material provided insights on the friction coefficients that would be expected for these types of brakes under lab conditions. Field and test-track experiments, on the other hand, were not performed on these LCILs due to budget and time constraints, and therefore no "real-world" data on the performance of these brakes was collected. However, with the information gathered for the AM and OE brake linings in this project (see the main body of this report) it is possible to construct a statistical model that could correlate lab-obtained friction coefficients with field-observed deceleration rates. This model, then, would provide an estimation of what could potentially be observed, in terms of deceleration rates, if similar field and test-track experiments as those described in Sections 2.3 and 2.4 of this report were to be conducted on this particular LCIL material.

The purpose of the following subsections is to develop such a model and to use it to predict expected deceleration rates for this type of AM material. An attempt to develop this type of correlation model was described in Section 3 of the main report, particularly in Section 3.3. However, and in contrast to the model described in that section, which already hinted a correlation between Low-PV friction coefficients and pressure-corrected stopping distances of field-tested trucks, the model developed in this appendix investigates the relationship between lab-obtained friction coefficients and normalized deceleration rates measured during the field and test-track experiments.

The other main difference is that here, both the lab and field/test-track observations were screened for outliers. Outliers are defined as observations that appear to be inconsistent with the remainder of the collected data [18]. Those observations were carefully analyzed and an unbiased procedure was developed to filter out these outliers.

A2.2. Regression Analysis

Translating lab conditions (i.e., speed and pressures) in which the friction coefficient for the different lining materials were measured, to field/test-track conditions (truck speed and brake pressure) is beyond the scope of this project. Therefore, it is not possible to determine which one of the two real-world experiments (field or test-track) more closely resembles the conditions observed in the lab environment.

Because of this, all the observations (field and test-track) were used for the analysis that follows. The inclusion of both field and test-track information allows for the capture, within the data set, a wider range of conditions; but on the other hand, it creates a higher variability in the data. Higher variability also existed in the friction coefficient measurements since the specimens were cut from different parts of the lining which, not being a homogeneous material, provided very dissimilar values in some cases.

One way of diminishing the variability in the data is by eliminating outliers. That is, by eliminating from the dataset observations that are too “distant” from the mean, the standard deviation of the distribution decreases. As more observations are eliminated, the variability decreases, but so does the number of remaining observations and the power of any statistical test, including regression analysis. There is therefore a tradeoff between the gain in decreasing variability and the loss of data points.

In an attempt to balance variability reduction with total number of observations available for the analysis, the following methodology was used and included the field and test-track observations (normalized deceleration rates), the next-to-the-last and last drags for the SSBT Low-PV tests, and the tenth drag for the SSBT High-PV friction coefficient tests. First, for each set of repeated observations belonging to each analyzed category *c* (e.g., *nDR* for the single-axle truck mounted with AM equipment, or Low-PV friction coefficient measurements for the Arvin Meritor 301), the mean m_c and standard deviation SD_c of all the observations were calculated. The number of original observations No_c for each category c was also recorded, as well as the ratio

$$R_c = SD_c / No_c \qquad \text{(A1)}$$

(i.e., the standard deviation per observation).

Second, for each data point, the absolute value of the difference between the observed value and the sample mean divided by the sample mean was computed. That is, for each observation *i* for category *c*, a variable

$$dV_{ci} = Abs(m_c - o_{ci}) / m_c \qquad \text{(A2)}$$

was computed, where m_c is the mean of the set of repeated observations, o_{ci} is the value of observation *i* within category *c*, and *Abs* is the absolute value of the quantity in parentheses. The variable dV_{ci} was used to “screen out” those observations that were above a certain threshold (three such thresholds were selected: 15%, 20% and 25%). For example, for a threshold level of 15 percent, any observation i for which $dV_{ci} >= 0.15$ was eliminated from the data set. With the observations that showed $dV < .15$, a new mean (nm_c) and standard deviation (*nSDc*) were calculated. The number of remaining observations Nr_c was also recorded, as well as the ratio

$$nR_c = nSD_c / Nr_c \qquad \text{(A3)}$$

(i.e., the standard deviation per remaining observation).

This process was repeated for all the categories in the data set (e.g., all trucks, all linings Low-PV friction coefficients), and an average of the ratio R across all the categories for both the original (Eq. A4) and the remaining (Eq. A5) observations were computed. The total number of original ($No = \Sigma_c No_c$) and remaining ($Nr = \Sigma_c Nr_c$) observations across all categories *c* were also recorded.

$$mR = \Sigma_c R_c / No_c \qquad \text{(A4)}$$

$$mnR = \Sigma_c nR_c / Nr_c \qquad \text{(A5)}$$

Table A.5 below shows these values for all the different datasets at the three thresholds analyzed.

Table A.5 Data Variability Reduction Through Data Outlier Elimination

	nDR			Low PV			High PV		
	Threshold Level			Threshold Level			Threshold Level		
	25%	20%	15%	25%	20%	15%	25%	20%	15%
mR	0.0020	0.0020	0.0020	0.0048	0.0048	0.0048	0.0056	0.0056	0.0056
mnR	0.0015	0.0013	0.0010	0.0045	0.0042	0.0036	0.0051	0.0037	0.0037
mnR/mR *100	76.79%	67.48%	51.66%	93.34%	88.68%	74.74%	91.48%	65.56%	65.56%
No	88	88	88	90	90	90	45	45	45
Nr	71	67	58	87	83	79	44	39	39
Nr/No *100	80.68%	76.14%	65.91%	96.67%	92.22%	87.78%	97.78%	86.67%	86.67%

Entries in the third and sixth row of Table A.5 present the percentage of the statistic corresponding to the remaining observations to the same statistics for the original observations. Consider for example the sixth row for a 25-percent threshold for the *nDR* observations. The value in this cell indicates the percentage (i.e., 80.68%) of remaining observations (71) to the original number of observations after applying a 25-percent threshold to screen out outliers. For the same column, the third row measures the decrease in data variability when comparing the variability in remaining observations versus the variability when all the observations were taken into account. As expected, when the threshold decreases, the variability in the data diminishes since more outliers are screened out. Notice than when going from 25 percent to 20 percent, there is a decrease of about 9 percent in the variability of the *nDR* collected data and about 4 percent of the observations are discarded. When going from 20 percent to 15 percent, these figures are 16 percent and 11 percent, respectively. The latter "jump" produces a higher decrease in the variability of the data, but also eliminates a larger number of observations. A closer inspection of the data indicated that an optimum could be found at a threshold of 18 percent. At that level, the *mnR* is 0.001085 with 65 remaining observations, and therefore the corresponding values of the third and sixth rows become 54.68 percent and 73.86 percent, respectively. Then, when the threshold decreases from 20 percent to 18 percent there is a decrease in variability of 12.8 percent (67.48-54.68%) while the number of remaining observations only decreases by 2.3 percent (76.14-73.86%, or 2 observations). Going from 18 percent to 15 percent would require eliminating 8 percent more observations to produce an additional 3 percent decrease in variability. Therefore, the 18-percent threshold was adopted for screening out outliers from the dataset (24% of the observations) which resulted in a 45-percent reduction in variability.

In the case of the High-PV observations, this type of analysis indicated a substantial decrease in the variability of the data when the threshold was changed from 25 percent to 20 percent, with a comparatively small number of discarded observations. Going from 20 percent to 15 percent did not produce any decrease in the variability of the data or diminish the number of remaining observations (any threshold level from 20 to 15% presented the same data variability and number of observations). The decreases in variability for the Low-PV data were smaller than in the other two cases, with a maximum observed at 15 percent. However, and for consistency reasons, an 18-percent threshold level was adopted for all the data (i.e., *nDR*, Low-PV, and High-PV observations). The filtered information was used to conduct a linear regression analysis to correlate the friction coefficients obtained from lab experiments with the normalized deceleration rates observed in the real-world experiments conducted in this project. However, before conducting the regression analysis, it was necessary to "aggregate" the lab obtained friction coefficients since many of the participating trucks used different brake linings in the front and rear axles.

Consider for example the W tandem-axle truck (truck #960) retrofitted with OE brakes. Table 1.3 shows that the brake linings with which this truck was retrofitted were the same (i.e., Arvin Meritor 301) for both the front and rear axles. In this case, the lab results for the friction coefficient for this particular brake lining could be used as representative of this particular truck and can be correlated with the field and test-track measured deceleration rates. However, this is not the case for the W tandem-axle truck (truck #961) retrofitted with AM equipment, since as Table 1.3 indicates; the front axle was equipped with Armada AR3 linings while the rear axles were mounted with Armada AR2 brakes (two different brake linings with two different friction coefficients). For cases like this, an overall friction coefficient for the truck was calculated by averaging the friction coefficients of the different linings weighted by the number of axles. That is, for truck #961 the overall friction coefficient was computed as

$$fc_{961} = [fc(AR3) + 2 * fc(AR2)] / 3 \qquad \text{(A6)}$$

where *fc(AR3)* and *fc(AR2)* are the lab measured friction coefficient for the Armada AR3 and AR2 linings, respectively. In the equation above, *fc(AR2)* is multiplied by 2 since there are 2 rear axles for this particular truck[A2]. Table A.6 shows the overall friction coefficients for the Low PV tests for information collected during the next-to-the-last and last drags (after the data was screened as explained before), while Table A.7 shows the same information but this time for the tenth drag of the High-PV tests (also after the data was filtered). Both tables also show the average normalized deceleration rates, obtained from the field and test-track information after applying the 18-percent threshold to eliminate outliers from the data set.

The information presented in these tables was used to run a linear regression analysis correlating the truck friction coefficient and its deceleration rate (note: because of anomalies explained earlier in this report, the friction coefficient derived from lining material E was not used in the regression analyses). Figures A.6 and A.7 present this information in graphical form, including the parameters of the linear function obtained from the regression analysis. Notice that in the case of the Low-PV friction coefficients, the R^2 (a measure of the "goodness of fit" of the data[A3]) was high indicating that the data presented a very good correlation between friction coefficients and deceleration rates. On the other hand, the High-PV friction coefficients presented a very low R^2 indicating poor correlation between the two variables of interest. That is, the data indicates that the Low-PV friction coefficient may be a good predictor of expected deceleration rates (under similar conditions as those of this study), while the High-PV friction coefficient does not appear to be correlated to the observed deceleration rates.

[A2] Perhaps a more accurate overall friction coefficient would have taken into account the axle loads as the weighting variable. However, at the time of this analysis this information was not available.

[A3] R^2 gives the proportion of the total variation in the dependent variable (*nDR* in this case) explained by the independent variable (Low-PV friction coefficients).

Table A.6 Low-PV Friction Coefficients (μ) and nDR by Truck and Brake Category

Truck ID	Truck Description	Equipment	Lining Material*	Low-PV μ	Truck μ	Truck nDR**
3212	Class-7 Single-Axle	OE	B		0.526	0.136
2879	Class-7 Single-Axle	AM	A		0.500	0.120
960	WC Class-8 Tandem-Axle	OE			0.587	0.197
		OE	D	0.651		
		OE	C	0.556		
		OE	C	0.556		
961	WC Class-8 Tandem-Axle	AM	E		0.400	0.195
102	W Class-8 Tandem-Axle	OE	C		0.556	0.170
105	W Class-8 Tandem-Axle	AM			0.552	0.154
		AM	F	0.574		
		AM	G	0.541		
		AM	G	0.541		
107	Class-8 Tri-Axle	OE			0.536	0.145
		OE	C	0.556		
		AM	I	0.475		
		OE	C	0.556		
		OE	C	0.556		
108	Class-8 Tri-Axle	AM			0.466	0.107
		AM	H	0.440		
		AM	I	0.475		
		AM	I	0.475		
		AM	I	0.475		

* Refer to Table 2.1
** Two decimal digits are significant in this column.

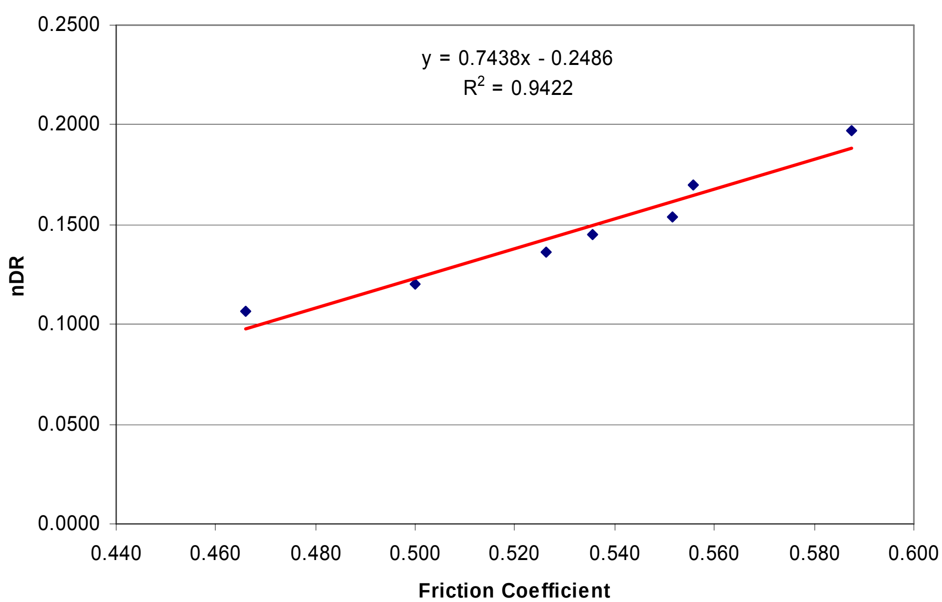


Figure A.6 Low-PV Friction Coefficients vs. nDR

Table A.7 High-PV Friction Coefficients (μ) and nDR by Truck and Brake Category

Truck ID	Truck Description	Equipment	Lining Material*	Low-PV μ	Truck μ	Truck nDR**
3212	Class-7 Single-Axle	OE	B		0.269	0.136
2879	Class-7 Single-Axle	AM	A		0.265	0.120
960	WC Class-8 Tandem-Axle	OE			0.305	0.197
		OE	D	0.407		
		OE	C	0.255		
		OE	C	0.255		
961	WC Class-8 Tandem-Axle	AM	E		0.352	0.195
102	W Class-8 Tandem-Axle	OE	C		0.255	0.170
105	W Class-8 Tandem-Axle	AM			0.311	0.154
		AM	F	0.305		
		AM	G	0.314		
		AM	G	0.314		
107	Class-8 Tri-Axle	OE			0.235	0.145
		OE	C	0.255		
		AM	I	0.175		
		OE	C	0.255		
		OE	C	0.255		
108	Class-8 Tri-Axle	AM			0.191	0.107
		AM	H	0.239		
		AM	I	0.175		
		AM	I	0.175		
		AM	I	0.175		

* Refer to Table 2.1
** Two decimal digits are significant in this column.

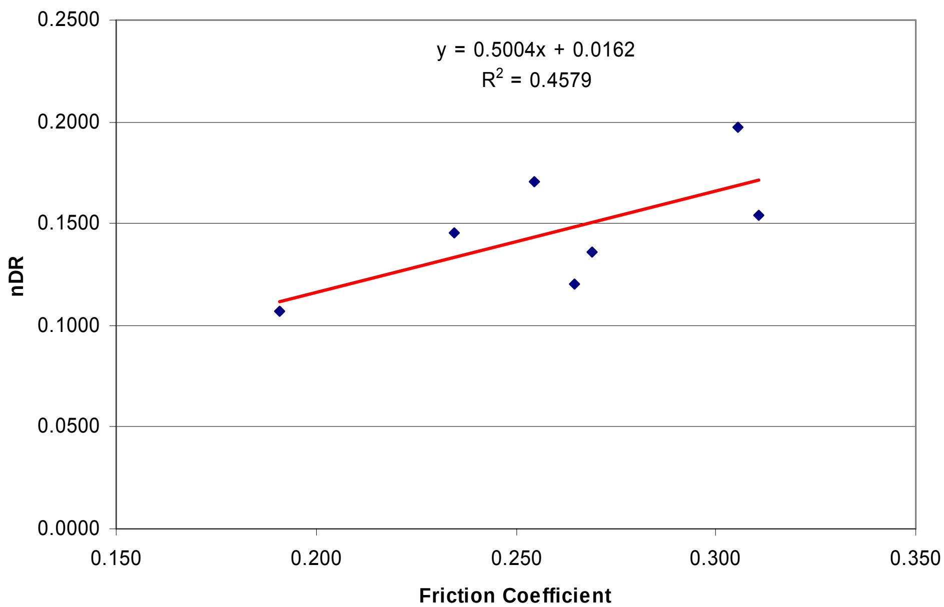


Figure A.7 High-PV Friction Coefficients vs. nDR

A2.3. Deceleration Rate Predictions for the Low-Cost, Imported Aftermarket Brake Lining Material

The information obtained from the SSBT lab tests conducted on the low-cost, imported AM brake lining material was used to predict an expected deceleration rate for a truck mounted with this brand of brakes. For the Low-PV tests, the friction coefficients measured in the ninth and tenth drags for specimens 3 to 8 (see Section A1.4. above) were used. These two particular drags were selected because the prediction model described in the last section was developed using the next to last and last drag information for the nine lining materials described in Section 2 of this report.

The data collected in the lab for the LCIL material was also filtered with an 18-percent threshold as explained previously, to eliminate any outliers and to impose on the data the same conditions used in the development of the deceleration rate prediction model. The resulting average Low-PV friction coefficient was 0.477, a value that was at the lower end of the lining material analyzed in Section 2 of this report, but not the lowest. This value was plugged into the linear equation shown in Figure A.6 to obtain a predicted normalized deceleration rate of 0.1059 ft/sec^2/psi. This value was also at the lower end of the observed deceleration rates.

Similarly, and average High-PV friction coefficient was computed using the same methodology as before, but this time using only the tenth (or last) drag, since in the development of the prediction model only information from the last drag was used. The resulting High-PV friction coefficient was 0.241, again a value located in the lower end of the values observed in Section 2, but not the lowest. As explained previously, since the data does not indicate that the High-PV friction coefficient is a good estimator of the deceleration rate, this friction coefficient was not used to obtain a predicted normalized deceleration rate.

A2.4. Summary and Conclusions

Sub-Scale Braking Tests were conducted on a sample of a low-cost, imported aftermarket brake lining material, using the same methodology as for the lab tests performed on OE and AM linings. However, as opposed to the latter, no real-world (field or test-track) experiments were conducted on this LCIL material. In lieu of real-world experiments, a statistical model was developed to predict expected *nDR* under conditions similar to those of the field and test-track tests discussed in the main body of this report.

After filtering outliers from the friction coefficient data gathered under Low-PV and High-PV procedures, as well as from the *nDR* information collected during the field and test-track experiments, two linear regression models were developed. The first statistical model correlated the Low-PV friction coefficients to *nDR*, while the second did the same for the High-PV friction coefficients. While the first model presented a high R^2 value (i.e., 0.94), indicating that the model fit the data very well, the same was not true for the second one which presented a very low R^2 value (i.e., 0.46).

The LPVM was used to predict values of *nDR* that could be expected, given the lab obtained Low-PV friction coefficients for the LCIL brake material (note: as with the original data, and for consistency reasons, these friction coefficients were also screened out for outlier values). The resulting average Low-PV friction coefficient was 0.477, a value that was at the lower end of the lining material analyzed in Section 2 of this report, but not the lowest. This value was plugged into the LPVM to obtain a predicted normalized deceleration rate of 0.1059 ft/sec2/psi, which was at the lower end of the field/test-track observed deceleration rates, but close to other observed values.

These results suggest that although these LICL materials seem to be at the lower end of the brake lining tested in this study, they are not completely out of range with respect to calculated deceleration rates. However, to verify these results, field and test-tracks experiments should be conducted to obtain real-world deceleration rates and stopping distances when these types of brake linings are used. Also, as was the case with the OE and AM equipment tested in this study, wear measurements should also be performed on these LCIL materials to determine how they compare to the brake linings tested in this project.

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