Brake Wear and Performance Test Final Report

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

December 2009

FOREWORD

This study focuses on using a Performance-Based Brake Tester (PBBT) to determine selected commercial vehicles' brake performance over time and quantifying associated brake component wear as a function of mileage. Additionally, ORNL was tasked with assisting the State of Tennessee in identifying suitable PBBT machines, procuring a PBBT machine, installing the PBBT machine to be used in this research, and training Tennessee Department of Safety (TDOS) Staff on the operation of the PBBT machine.

The work performed under the project included:

- Drafting of the project Statement of Work
- Drafting of the Field Operation Test Plan
- Downselection of viable PBBT machines
- Providing PBBT procurement assistance
- Facilitating the PBBT installation
- Facilitating PBBT training and operator certification
- Developing industry partnerships
- Conducting the Field Operational Test
- Conducting supporting testing
- Analyzing the Field Operational Test data
- Drafting a Final Report

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Technical Report Documentation Page

1. Report No. **FMCSA-RRT-yy-###**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Brake Wear and Performance Test Final Report**		5. Report Date **December 2009**
		6. Performing Organization Code
7. Author(s) **Gary Capps, Oscar Franzese, Mary Beth Lascurain**		8. Performing Organization Report No.
9. Performing Organization Name and Address **Oak Ridge National Laboratory 1 Bethel Valley Road Oak Ridge, TN 37831**		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address **Federal Motor Carrier Safety Administration 1200 New Jersey Avenue, SE Suite W60-300 Washington, DC 20590**		13. Type of Report and Period Covered **Final Report, September 2005–September 2009**
		14. Sponsoring Agency Code **FMCSA**
15. Supplementary Notes **Contracting Officer's Technical Representative: Luke Loy**		

16. Abstract

This study focuses on using a Performance-Based Brake Tester (PBBT) to determine selected commercial vehicles' brake performance over time and quantifying associated brake component wear as a function of mileage. Additionally, ORNL was tasked with assisting the State of Tennessee in identifying suitable PBBT machines, procuring a PBBT machine, installing the PBBT machine to be used in this research, and training Tennessee Department of Safety (TDOS) Staff on the operation of the PBBT machine.

17. Key Words **Commercial motor vehicle, brakes, performance-based brake tester, brake wear, brake performance**		18. Distribution Statement **No restrictions**	
19. Security Classif. (of this report) **Unclassified**	20. Security Classif. (of this page) **Unclassified**	21. No. of Pages **188**	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS									
APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					AREA		
in2	square inches	645.2	square millimeters	mm2	mm2	square millimeters	0.0016	square inches	in2
ft2	square feet	0.093	square meters	m2	m2	square meters	10.764	square feet	ft2
yd2	square yards	0.836	square meters	m2	m2	square meters	1.195	square yards	yd2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi2	square miles	2.59	square kilometers	km2	km2	square kilometers	0.386	square miles	mi2
		VOLUME					VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	l	l	liters	0.264	gallons	gal
ft3	cubic feet	0.028	cubic meters	m3	m3	cubic meters	35.71	cubic feet	ft3
yd3	cubic yards	0.765	cubic meters	m3	m3	cubic meters	1.307	cubic yards	yd3
		MASS					MASS		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2,000 lbs)	0.907	megagrams	Mg	Mg	megagrams	1.103	short tons (2,000 lbs)	T
		TEMPERATURE (EXACT)					TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8 C + 32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m2	cd/m2	cd/m2	candela/m2	0.2919	foot-lamberts	fl
		FORCE AND PRESSURE OR STRESS					FORCE AND PRESSURE OR STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be done to comply with Section 4 of ASTM E380.

ACKNOWLEDGEMENTS

The Oak Ridge National Laboratory (ORNL) would like to thank the Brake Wear and Performance Test Fleet Partners for their cooperation and dedication to this commercial motor vehicle brake safety research effort. These partners are Greene Coach Tours, Pioneer Petroleum Co., Richard Diehl Inc., and Summers-Taylor Inc.

We would also like to thank the Tennessee Highway Patrol Commercial Motor Vehicle Enforcement staff in Nashville, Tennessee, and at the Greene County Commercial Motor Vehicle Inspection Station for their continued support of the safety-related research within the Commercial Motor Vehicle Roadside Technology Corridor (CMVRTC).

The project team would like to thank Science Undergraduate Laboratory Interns Amanda Blagg, Tabitha Voytek, and Rachel Andrews, along with Community College Institute interns Zane Pannell and Elizabeth Orlando for their invaluable contributions to this effort through appointments funded in part by the (DOE) Office of Science and administered by the Oak Ridge Institute for Science and Education.

Finally, we would like to extend a special thanks to our Commercial Motor Vehicle Roadside Technology Corridor subcontractor, Commercial Motor Carrier Consultants, for providing needed staff support and the brake-related hardware to make this effort a success.

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AAL	Artificial Axle Loading
AM	Aftermarket, referring to brake lining or other equipment or materials that meet original equipment specifications but are not sold as original equipment. This equipment or materials are typically sold at a lower cost than original equipment
BE	Brake Efficiency; braking force divided by weight
BF	Braking Force
BWPT	Brake Wear and Performance Test
CDL	Commercial Driver's License
CMV	Commercial Motor Vehicle
CMVRTC	Commercial Motor Vehicle Roadside Testing Corridor; a real-world test bed for testing vehicles and technology that includes the Knox County and Greene County, TN inspection stations and the ~70 miles of interstate highway that connects them.
Curb Weight	The weight of a vehicle with maximum capacity of all fluids necessary for operation of the vehicle, but without cargo or accessories that are ordinarily removed from the vehicle when they are not in use. It will, for the purposes of this testing, include the driver and instrumentation.
CV	Coefficient of Variation
CVE	Commercial Vehicle Enforcement
CVSA	Commercial Vehicle Safety Alliance
CVSP	Commercial Vehicle Safety Plan
DAS	Data Acquisition System
DOT	Department of Transportation
FMCSA	Federal Motor Carrier Safety Administration
FOT	Field Operational Test
GAWR	Gross Axle Weight Ratings; maximum weight an axle is rated to carry by the manufacturer. Includes both the weight of the axle and the portion of the vehicle's weight carried by the axle.
GC	Greene Coach Tours
GVW	Gross Vehicle Weight; the total weight of the vehicle and load
GVWR	Gross Vehicle Weight Ratings; the value specified by the manufacturer or up fitter as the loaded weight of a single vehicle.
HOS	Hours of Service
IS	Inspection Station
NAS	North American Standard
NHTSA	National Highway Traffic Safety Administration

NTRCI	National Transportation Research Center, Inc.
MCSAP	Motor Carrier Safety Assistance Program
MOU	Memorandum of Understanding
OE	Original Equipment - Brake components that are the same part number, manufacture, and materials as those that came on the vehicle when it was purchase in the new/unused state.
ORNL	Oak Ridge National Laboratory
OOS	Out of Service
Partner	A CMV carrier who has agreed to participate in the BWPT via MOU
PBBT	Performance-Based Brake Tester
POC	Point Of Contact
PP	Pioneer Petroleum Co.
PS	Portable Scales
RD	Richard Diehl Inc.
ST	Summers-Taylor Inc.
TDOS	Tennessee Department of Safety
TDOT	Tennessee Department of Transportation
THP	Tennessee Highway Patrol
TV	Test Vehicle; any one of the participating fleet CMVs
VUT	Vehicle Under Test - the specific vehicle undergoing testing at any particular time relative to this Test Plan

EXECUTIVE SUMMARY

Performance-Based Brake Testers (PBBTs) are devices that can be used to evaluate the current braking capabilities of a vehicle through the measurement of brake forces developed as a vehicle engages in a braking event while on a PBBT machine. The Federal Motor Carrier Safety Administration (FMSCA) passed legislation on February 5, 2003, allowing a PBBT that meets the FMCSA functional specifications to be used as an enforcement tool. Previously, citations could be written, although the test results could not be used to put a vehicle out-of-service (OOS). Failure to meet minimum braking efficiency as measured by a PBBT was added as an OOS criteria effective April 1, 2007. However, the few PBBT machines in the continental United States are used primarily for screening and conducting research.

The Oak Ridge National Laboratory (ORNL) was tasked by FMCSA in August of 2005 to: 1) assist the Tennessee Department of Safety (TDOS) in the procurement and installation of a PBBT machine; 2) train and certify PBBT machine operators; and 3) layout the framework for a Brake Wear and Performance Test (BWPT) project using the installed PBBT machine.

A PBBT machine was installed at the Greene County, Tennessee Commercial Motor Vehicle (CMV) Inspection Station (IS) located in Bulls Gap Tennessee. This CMV IS serves as the northeastern anchor of the FMCSA CMV Roadside Testing Laboratory (CMVRTC). This equipment is a roller dynamometer with the capability of measuring a vehicle's rolling resistance, weight, and brake force. In a typical PBBT test, the vehicle's tires are placed on and between the rollers which will start rolling the wheels as if the vehicle were traveling forward and will attain a rotational speed of approximately 2 mph. As the driver gradually depresses the brake, the PBBT measures the force exerted by the braking system on the axle under test. This data is sent directly to the PBBT desktop computer. This process is repeated for each axle until the entire vehicle has been tested. The overall result reported is the brake efficiency, the ratio of the total braking force to the gross vehicle weight (GVW).

As part of the training plan, ORNL and TDOS arranged for the supplier of the PBBT machine to conduct operational training and operator certification for all ORNL and TDOS staff responsible for operating the machine.

ORNL drafted the Brake Wear and Performance Test (BWPT) Test Plan in September 2007 with the approach of testing eight commercial vehicles from four vocations for a period of 12-to-18 months. Each vehicle would receive new foundation brake components before the start of the BWPT Field Operational Test (FOT) and then receive a PBBT test on a monthly basis to determine if the vehicle's ability to stop degrades over time. Additionally, ORNL would look at wear as a function of mileage and explore induced ovality within a vehicle's brake drums or rotors and the PBBT's ability to measure this induced ovality. For the BWPT, ORNL conducted specific training for each trooper participating in the data collection effort.

PURPOSE

As a fleet operates its vehicles over time, brake components wear and, in some cases, fail. To date, little is known regarding the effect of this wear and component failure on the vehicle's brake performance and safety. This study sought to measure these effects as the test vehicles carry out their normal vocation.

The goals of this evaluation were as follows:

1. To quantify, using a PBBT, the heavy vehicle braking performance of multiple vehicles over time in a real-world environment
2. To use the PBBT to detect a vehicle with a braking system failure or gross degradation (i.e., ruptured wheel seal, improperly functioning brake chamber, etc.)
3. To monitor the operational issues, failures, and acceptance levels of user personnel of an in-ground PBBT, over time
4. To measure the acceptance and operational ease of an in-ground PBBT by drivers, over time
5. To measure the total wear of brake linings, drums, and rotors at the end of their normal life, as a function of mileage
6. To explore drum ovality at the end of component life and to explore the possible correlation to PBBT ovality measurements

PROCESS

This study represents an examination of brake wear and performance in selected CMVs. Four CMV fleets (Partners) were asked to make available, on a semi-gratis basis, two class-8 CMVs from each fleet for the BWPT. ORNL used project funds to purchase (via contractor) the necessary brake components to bring the foundation brake system of the two test vehicles to "new condition." This included, at a minimum, new linings, drums, and/or rotors. Each participating test vehicle's braking system was required to be inspected by a certified mechanic to be sure that other foundation brake components (beyond linings, drums/rotors) were in good serviceable condition. The components inspected included air lines, brake cambers, slack adjusters, pushrods, camshafts, camshaft bushings, s-cams, wheel seals, etc. Any components found not to be serviceable were required to be replaced. The needed brake components were itemized by each Partner and the list was submitted to ORNL for approval prior to the actual purchasing and installation.

Four types of vehicles participated in the Field Operation Test (FOT): 1) class-8 combination tanker, 2) class-8 tri-axle dump, 3) class-8 combination dry-box van, and 4) class-8 motor coach. The testing included the following steps:

- Testing the participating vehicles on the PBBT machine prior to the start of the field test.
- Fitting these vehicles with new original equipment (OE) or new aftermarket (AM) brakes and drums or rotors and pads (of the type typically used by the owner fleet).
- Verifying that the vehicles have operational braking systems using the PBBT.
- Testing the vehicles on the PBBT to establish baseline brake performance at curb weight and 80% GVWR.

- Testing the participating vehicles weekly for one month to monitor changes to the brake system performance as the linings are burnished.
- Testing the vehicles monthly on the PBBT at their regular loaded weight or 80% GVWR using artificial axle loading of the PBBT when not loaded with regular cargo.

For the brake components:

- The new linings, drums, and rotors were measured at the beginning of the test to establish their baseline dimensions.
- The linings, drums, and rotors were measured again at the end of their service life to determine their total wear.

Besides investigating the brake performance and wear of the eight participating vehicles, other related studies were conducted in this project. Those included:

- A Level-1/PBBT Correlation Study to help identify trends in the data collected by researchers at the CMVRTC;
- A PBBT Valuation Study aimed at determining the PBBT's ability to increase the number of contacts with CMVs and exploring how the PBBT affects the CMV out-of-service (OOS) rate;
- A study to determine the accuracy of the EWJ PBBT machine in measuring axle weight and artificial axle load;
- A study comparing different methods to calculate brake efficiency; and
- A study to explore the effect of wear on ovality and eccentricity, and their effect on brake performance.

STUDY FINDINGS

Key findings from the investigation are as follows:

In 95% of the cases there was an increase in brake efficiency in the first part of the brake's life cycle. The single axle brake efficiency information collected showed that within 5,000 miles of the initial test there were gains in brake efficiency of 17.5%, on average.

The results of the FOT also showed that in 96% of the cases there was not a statistically significant degradation of the brakes during the length of the test conducted in this project.

The results of the wear analysis showed that on average the left and right end of any given axle presented similar wear of the brake linings, although there was a slight tendency in the data towards a faster wear of the linings of the right axles. Also, in 86% of the cases in which the brake shoes were arranged in a top-bottom layout, the linings of the bottom shoe wore at a faster rate than that of the top shoe (the remaining 14% of the cases included the tag axles, which are deployed only when needed).

The results of the wear analysis also showed that, in general, the axles that support less weight reflected less wear in the diameter of the drums over the test period.

The Level-1/PBBT Correlation Study showed than when vehicles were selected at random from the traffic stream, they were only 1.93% less likely to "pass" both a PBBT test and Level-1 inspection than when traditional vehicle selection methodologies were used.

The PBBT Valuation Study provided valuable information regarding time savings, OOS rates, and the number of vehicles which could be contacted using various inspection methods. The inspection pit was shown to be beneficial because its use doubled the OOS rate in the small sample of vehicles tested, although it did not appear to increase the number of vehicles contacted. This is explained by better access to the underside of the vehicle, allowing the officer to conduct a more thorough inspection.

The independent testing of the EWJ PBBT machine strongly suggested that the PBBT is very accurate at measuring both actual –i.e., axle weight– and artificial loads (note: at present, the brake performance criterion found in FMCSR 393.52 specifies that the vehicle be tested in the "as-is" condition of loading; as such, the use of artificial axle load does not come into play).

CONCLUSIONS

The main conclusion from the data collected in the FOT is that well maintained brakes result in consistently high performing brakes, even after a considerably large number of miles logged (the result of the analysis suggested that there was not a statistically significant degradation of the brakes during the length of the test conducted in this project).

Regarding the selection of vehicles to be inspected, and based on a small sample, there are only minor differences (2%) between traditional methodologies and randomly selecting vehicles from the stream of traffic that pass both PBBT and Level-1inspections.

The availability of the PBBT inspection pit doubled the OOS rate (in the small sample of vehicles tested), but it did appear to increase the number of vehicles contacted.

DEPLOYMENT STRATEGIES

A set of functional specifications currently exists for a PBBT machine to be purchased using Motor Carrier Safety Assistance Program (MCSAP) grant funding. Thus, a funding mechanism is in place for states to purchase PBBT machines. However, changes will need to be made in the North American Standard (NAS) Inspection guidelines in order to give weight to the PBBT inspection, making it on par with the current Level-1 and -2 vehicle inspections. Also, changes will be needed in the MCSAP Commercial Vehicle Safety Plan (CVSP) that will accept a PBBT inspection as part of the performance-based criteria in lieu of or in support of NAS Level-1 and -2 inspections. These changes would allow state enforcement staff to get "credit" for PBBT testing and will be necessary for states to be willing to purchase and utilize PBBT machines.

1. INTRODUCTION

1.1 BACKGROUND

1.1.1 Performance-Based Brake Tester

Performance-Based Brake Testers (PBBTs) are devices that can evaluate the current braking capabilities of a vehicle through the measurement of brake forces developed as a vehicle engages in a braking event while on a PBBT. PBBT devices are typically in-ground, but can also be in portable configurations. The common types of PBBTs include roller dynamometers, flat-plate testers and breakaway torque testers. Some PBBTs are equipped with the capability for artificial axle loading. This capability can ensure constant wheel loadings and repeatable testing despite the actual load of the vehicle.

The PBBT installed at the Greene County Commercial Motor Vehicle (CMV) Inspection Station (IS) is a roller dynamometer with the capability of measuring a vehicle's rolling resistance, weight, and brake force. The vehicle's tires are placed on and between the red rollers shown in Figure 1. The driver is asked to maintain a minimum of 90-100 psi of system air pressure at all times. The PBBT will start rolling the wheels as if the vehicle were traveling forward and attain a rotational speed of approximately 2 mph. As the driver gradually depresses the brake, the PBBT records the force being activated in lbf. This data is sent directly to the PBBT desktop computer. This process is repeated for each axle until the entire vehicle has been tested. The overall result reported is the brake efficiency: the ratio of the total braking force to the gross vehicle weight (GVW). Figure 1 shows the parts of the Greene County CMV IS's PBBT, the machine used for all of the PBBT testing in this report.

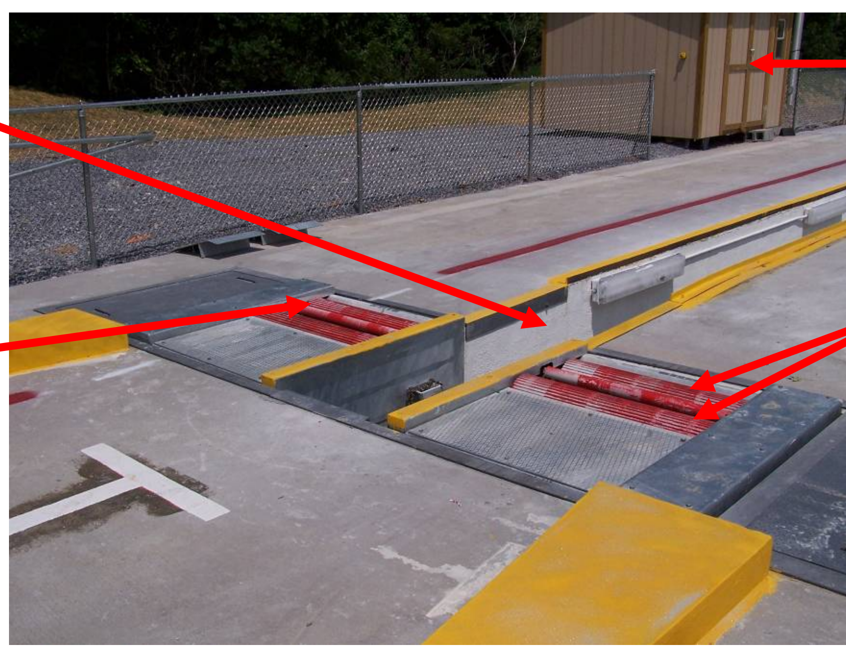

Figure 1. Diagram of a PBBT

Figure 2 Legend	
1. Dynamometer rollers	3. Inspection pit
3. Tachometer roller	4. Location of PBBT computer

The overall vehicle brake efficiency is calculated from the sum of the wheel-end brake forces divided by the total vehicle weight. In order to pass a PBBT test, the overall vehicle has to score a 43.5 or higher. Anything less than a 43.5 is failing. An invalid test may occur because the driver slams on the brakes (brake application is too fast) or the trailer is too lightly loaded (potentially resulting in scores over 100). Figure 2 shows the PBBT display with its dials indicating the brake forces being applied by the right and left wheel-ends during a PBBT test.

Figure 2. PBBT Display

Motor carrier communities and law enforcement can benefit from PBBT technologies because they can reduce overall inspection times, and can provide a consistent and objective measure of the braking performance of a vehicle.

Although PBBTs have been in general use in Europe and Australia for over 25 years, the experience has not been the same in the US. However, this may be due to the short amount of time since the Federal Motor Carrier Safety Administration (FMCSA) issued its final rule establishing performance criteria for use with PBBTs (effective February 5, 2003 and is applicable to all commercial motor vehicles and commercial vehicle combinations weighing over 10,000 pounds).

Because of the significant benefits of utilizing PBBT technologies (time/labor savings, error reduction, objective measures, consistency, enhanced fleet safety), FMCSA has an interest in assessing a vehicle's long-term brake performance using PBBT technology to measure (for each vehicle in the test fleet) the brake force for the overall vehicle, and for each individual wheel-end over a sufficiently long period of time. Such an effort would provide experiential data, and would quantitatively assess benefits from long-term brake performance data.

1.1.2 Legislation

FMSCA passed legislation on February 5, 2003, allowing a PBBT that meets the FMCSA functional specifications and has been certified to be used as an enforcement tool. Citations could be written, although the test results could not be used to put a vehicle out-of-service (OOS). Thus, the few PBBT machines in the continental United States were used for screening and conducting research.

In the fall of 2007 the Commercial Vehicle Safety Alliance (CVSA) added the PBBT test results to the OOS criteria. This ruling took affect in April 2008 as part of the North American Standard (NAS) OOS criteria dated April 1, 2008. According to this ruling, a vehicle may be put out of service for failing to develop a total brake force as a percentage of gross vehicle or combination weight of 43.5 or more on an approved PBBT (393.53(a)). In order to be returned to service, the vehicle must meet the following criteria: 1) If an approved PBBT is available, the vehicles shall be retested on an approved PBBT and achieved a total brake force as a percentage of gross vehicle or combination weight of 43.5 or more; or 2) If an approved PBBT is unavailable, each of the brake fault areas indentified on the inspection report shall be inspected and repaired.

1.1.3 ORNL Efforts Leading up to the BWPT

ORNL was tasked by FMCSA in August of 2005 to: 1) assist the TDOS in the procurement and installation of the PBBT machine; 2) train and certify PBBT machine operators; and 3) layout the framework for a BWPT project using the installed PBBT machine. The statement of work and authorization to begin the effort was approved by FMCSA in September 2005.

1.1.3.1 Procurement and Installation

Site Selection: The effort was initiated with a visit to the CMV IS facilities in Knox County and Greene County Tennessee to determine the best site for the PBBT installation. Images of the truck inspection areas of these sites are shown in Figure 3, Figure 4, and Figure 5 with callouts for proposed locations for the PBBT machine. A letter report assessing the Knox County sites was drafted and submitted by ORNL to FMCSA in October 2005. A letter report assessing the Greene County site was drafted and submitted by ORNL to FMCSA in November 2005. The Greene County site was ultimately chosen due the space limitations at the Knoxville sites.

Figure 3. Knoxville CMV IS on Eastbound I-40

Figure 4. Knox County CMV IS Westbound I-40

Figure 5. Greene County CMV IS Southbound I-81

PBBT Machine Procurement: ORNL conducted a market survey of companies that produced PBBT machines with artificial axle loading (AAL) capability. Artificial axle loading is typically accomplished by securing straps to the vehicle under test (VUT) and applying force to these straps to simulate a vehicle cargo load. Three companies with sales offices in the United States were indentified. They were:

- Link-Radlinski, Inc; Representing B&M; East Liberty, Ohio
- Infinity Test; Representing EWJ Teknik A/S; Canada
- VIS; Orlando, Florida

Visits and demonstrations were arranged to allow ORNL to analyze the features and capabilities of the machines. Additionally, ORNL arranged for the identified companies to visit the Greene County site to make recommendations as to a potential installation location(s) of the PBBT machine and express concerns and issues related to the site condition, available power, and vehicle access.

The PBBT machine was funded via a Motor Carrier Safety Assistance Program (MCSAP) grant from FMCSA and procured through the TDOS procurement office. ORNL prepared a set of procurement specifications for the PBBT machine in January 2006 and participated in the procurement process.

Installation: As a part of the installation of the PBBT machine, it was decided to install an inspection pit to allow for easier application of the AAL straps to the VUT. Construction of the pit began in May 2007 and was completed in July 2007. The excavation of the pit is shown in Figure 6 and Figure 7. The completed pit is shown in Figure 8 and the installed PBBT machine is shown in Figure 9.

Figure 6. Excavation for the CMV Inspection Pit

Figure 7. Inspection Pit Progress in June 2007

Figure 8. Finished CMV Inspection Pit

Figure 9. Finished PBBT Machine

1.1.3.2 Training

ORNL and TDOS arranged for the supplier of the PBBT machine to conduct operational training and operator certification for all ORNL and TDOS staff responsible for operating the machine. ORNL conducted Brake Wear and Performance Test (BWPT) specific training for each trooper participating in the data collection for the BWPT effort.

1.1.3.3 BWPT Framework

ORNL Drafted the BWPT Test Plan in September 2007 with the approach of testing eight commercial vehicles from four vocations. Each vehicle would receive new foundation brake components before the start of the BWPT Field Operational Test (FOT) and then receive a PBBT test on a monthly basis to determine if the vehicle's ability to stop degrades over time. Additionally, ORNL would look at wear as a function of mileage and potentially explore induced ovality within a vehicle's brake drums or rotors, and the PBBT machines ability to measure this induced ovality.

1.1.4 CMVRTC

On August 7, 2007, FMCSA launched the Commercial Motor Vehicle Roadside Technology Corridor (CMVRTC) at a keynote address given by then FMCSA Administrator John Hill. He indicated that the FMCSA established the CMVRTC for the purpose of testing and promoting new truck and bus safety inspection technologies and will work in partnership with the Tennessee Departments of Safety and Transportation, ORNL, and the University of Tennessee (UT). ORNL was requested to take the lead role for coordination and management of CMVRTC activities as part of a multi-year interagency agreement with the FMCSA.

The CMVRTC is currently bounded by the Knoxville CMV IS located on I-40 (east and west bound) and the Greene County CMV IS located on I-81 southbound. There is approximately 70 miles of interstate highway between the two facilities. Figure 10 shows an illustrated map of the CMVRTC including its research partners.

The vision for the CMVRTC is to have established and ready testing facilities at the ISs bounding the corridor to demonstrate, test, evaluate, and showcase innovative safety technologies in real-world conditions in an effort to improve commercial truck and bus safety by increasing the adoption of these technologies by public and private stakeholders.

The CMVRTC provides a platform to showcase inspection technologies and highlight their systematic integration with existing enforcement operations and highway information systems by State partners at the TDOS and the Tennessee Department of Transportation (TDOT). Data gathered from experiments and field tests along the corridor will be used to support FMCSA enforcement and compliance programs, state safety programs, policy research and future rulemaking activities.

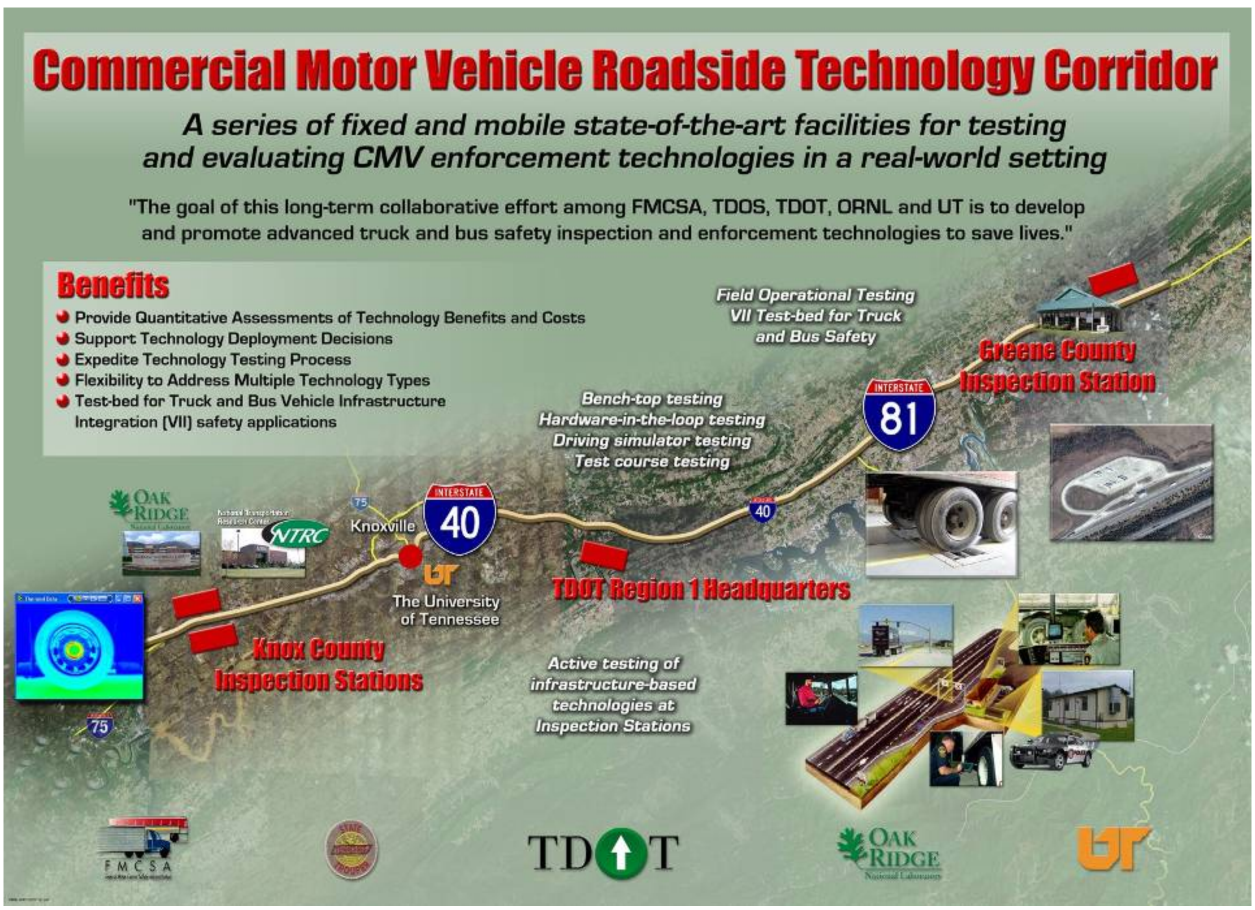

Figure 10. Illustrated Map of CMVRTC

1.2 GOALS

As a fleet operates its vehicles over time, brake components wear and in some cases fail. Little is known regarding the effect of this wear and component failure on the vehicle's brake performance and safety. This evaluation seeks to measure these effects as the test vehicles carry out their normal vocation.

The goals of this evaluation were to do the following:

- Quantify, using a PBBT, heavy vehicle braking performance of multiple vehicles over time in a real-world environment,
- Use the PBBT to detect a vehicle with a braking system failure or gross degradation (i.e., ruptured wheel seal, improperly functioning brake chamber, etc.),
- Monitor the operational issue, failures, and acceptance level of user personnel of an in-ground PBBT over time,
- Measure the acceptance and operational ease of an in-ground PBBT by drivers over time,
- Measure the total wear of brake lining, drums, and rotors at the end of their normal life as a function of mileage, and
- Explore drum ovality at the end of component life and explore possible correlation to PBBT ovality measurements.

1.3 PARTNERSHIPS

1.3.1 Commercial Motor Vehicle Enforcement

Within the CMVRTC, ORNL partnered with the Tennessee Highway Patrol Commercial Vehicle Enforcement Division (THP CVE) to assist with the needed data collection for this research. For the purposes of this testing, the Knox County and Greene County CMV ISs were selected as locations for data collection by the THP. The majority of the data collection was accomplished at the Greene County site. Images of the sites can be seen in Figure 11 and Figure 12.

Figure 11. Knox County CMV IS

Figure 12. Greene County CMV IS

THP officers operated the PBBT machine for the data collection portion of the BWPT and conducted the NAS Level-1, -2, and -3 inspections needed for the other support efforts within the BWPT effort.

1.3.2 Fleet Partnerships

1.3.2.1 Rational for Fleet Partnerships

In order to gather the needed "real-world" data necessary to analyze fleet brake wear and performance over time and mileage, ORNL formed partnerships with fleets of interest to FMCSA. These partnerships were formed to:

1. Gain access to the needed commercial motor vehicles (CMV),
2. Mitigate the cost of operating eight (8) CMVs over a 12 to 18-month period, and
3. Gather data from actual working vehicles in their normal vocation.

1.3.2.2 Mechanism for the Fleet Partnerships

ORNL used a Memorandum of Understanding (MOU) as the mechanism to define the scope of the effort and the roles relative to four commercial fleets (Section 1.3.2.4) and ORNL. A sample MOU can be found in Appendix A.

1.3.2.3 Terms of the Fleet Partnerships

The four CMV fleets (Partners) were asked to make available, on a gratis basis, two Class-8 CMVs from each fleet for the BWPT. ORNL provided for the cost of the necessary brake components to bring the foundation brake systems of the two test vehicles to “as-new" condition. This included, at a minimum, new linings, drums, and/or rotors. Each participating test vehicle’s braking system was required to be inspected by a certified mechanic to be sure that other foundation brake components (i.e., beyond linings, drum/rotors) were in good serviceable condition. The components inspected included air lines, brake cambers, slack adjusters, pushrod, camshaft, camshaft bushings, s-cams, wheel seals, etc.). Any components found not to be serviceable were required to be replaced. The needed brake components were itemized by each Partner and submitted to ORNL for approval prior to their purchase and installation.

ORNL elected that in the event that a particular fleet CMV (test vehicle) needed a brake component(s) replaced due to wear during the course of the testing, ORNL would review the data collected and the total time that particular vehicle had been in the test and make a determination on a case-by-case basis whether or not to replace the brake component or remove the vehicle from the testing. This occurred only once during the FOT and that particular trailer was retired from the test because its brake linings were determined to be at the end-of-life.

For test vehicles that did not have a glad-hand connection on the vehicle's service brake line, a pressure port was required to be installed by the Partner to monitor the test vehicle's brake application pressure during the PBBT test event.

The THP CVE agreed not to issue monetary fines against vehicles participating in this test (while at the IS specifically for the purposes of this test). When an OOS violation was identified while a test vehicle is at the IS, the officer notified the driver, the Partner, and ORNL. The violation was then corrected by the Partner before the vehicle was allowed to return to service. Partners were encouraged to access the condition of their vehicles prior to the vehicle's arrival at the IS for testing.

Any repairs or adjustments made to the test vehicle's brakes or braking system during the 18-month test period were requested to be noted by the Partner regarding date, mileage, and type of work done, and then reported to ORNL.

1.3.2.4 Fleet Partners

Partnerships were formed with the following Class-8 vocational fleets:

1. Dry-Box Van
2. Motor Coach
3. Tanker
4. Tri-Axle Dump

Dry-Box Van: Richard Diehl, Inc., a refrigerated carrier based in Jonesborough, TN was selected as the dry-box van vocation Partner and supplied two Class-8 tractor-trailers. These vehicles are shown in Figure 13 and Figure 14. Richard Diehl has over 30 tractor-trailers and specializes in the transportation of grain and feed ingredients as well as refrigerated loads.

Figure 13. Richard Diehl Inc. Truck # 375

Figure 14. Richard Diehl Inc. Truck # 379

Motor Coach: Greene Coach Tours based in Greeneville, Tennessee, provided two Class-8 motor coaches for this research effort. They are shown in Figure 15 and Figure 16. Greene Coach Tours is a provider of Charter and specialty tours service in the continental U.S. and Canada.

Figure 15. Greene Coach Tours Unit #190

Figure 16. Greene Coach Tours Unit #194

Tanker: Pioneer Petroleum Co. based in Morristown, Tennessee provided two Class-8 tanker tractor-trailers. These vehicles are shown in Figure 17 and Figure 18. Pioneer Petroleum is an oil petroleum wholesaler operating in East Tennessee.

Figure 17. Pioneer Petroleum Co. Unit #1

Figure 18. Pioneer Petroleum Unit #2

Tri-Axle Dump: Summers-Taylor, Inc. of Elizabethton, Tennessee supplied two Class-8 tri-axle dump trucks. These vehicles are shown in Figure 19 and Figure 20. Summers-Taylor is the largest heavy and highway construction contractor in the Northeast Tennessee with operations in Tennessee, North Carolina, and Virginia.

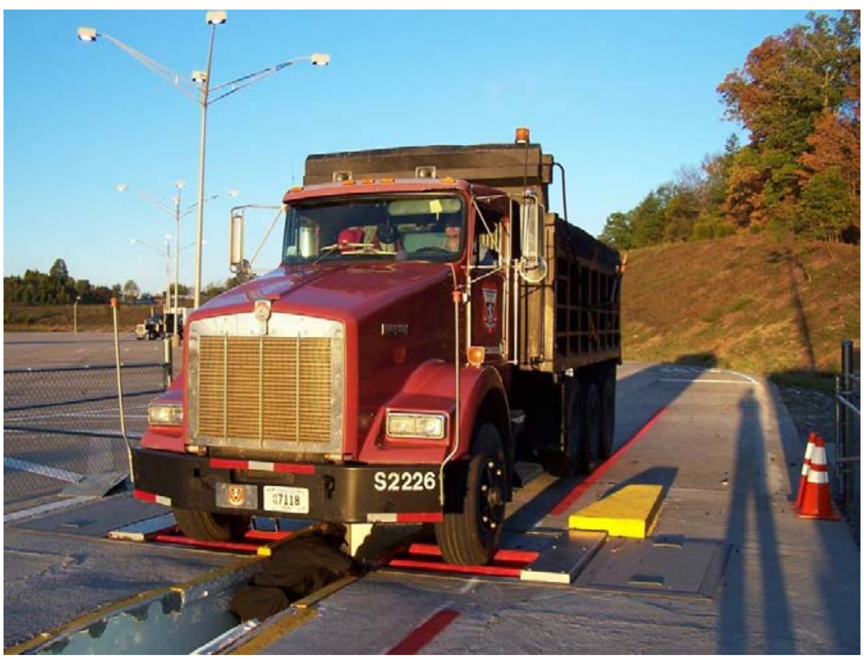

Figure 19. Summers-Taylor Inc. Truck Number S2226

Figure 20. Summers-Taylor Inc. Truck Number S2235

2. METHODOLOGY

As called out in Section 1.3.2.4, four types of vehicles were chosen from area fleets for participation in the FOT. They are: Class-8 combination tanker, Class-8 tri-axle dump, Class-8 combination dry-box van, and Class-8 motor coach. Two vehicles from each of these vocations were utilized for this testing. These vehicles were

- Tested on the PBBT machine prior to the start of the field test,
- Fitted with new original equipment (OE) or new aftermarket (AM) brakes and drums or rotors and pads (of the type typically used by the owner fleet),
- Verified as having operational braking systems using the PBBT,
- Tested on the PBBT to establish baseline brake performance at curb weight and 80% GVWR,
- Tested weekly for one month to monitor changes to the brake system performance as the linings are burnished, and
- Tested monthly on the PBBT at regular loaded weight or 80% GVWR using artificial axle loading of the PBBT when not loaded with regular cargo.

For the brake components:

- The new linings, drums, and rotors were measured at the beginning of the test to establish baseline dimensions.
- The lining, drums, and rotors were measured again at the end of their service life to determine total wear.

2.1 TEST VEHICLES AND BRAKE COMPONENTS

Although the scope of this study only focused on the lining/drum/rotor components of the foundation brakes, every effort was made to ensure that foundation brakes of the test vehicles were rebuilt to "as new," thus allowing for optimum performance and wear of the brake linings. Table 1 shows the brake components used on the test vehicles.

Table 1. Brake Materials by Test Vehicle

Vehicle Type	Vehicle ID #	Axle #	Brake Mfg /Size (in)	Brake Style	Brake Chamber Size (in)	Slack Adjuster Size (in)	Drum/Rotor Mfg/Size (in)	Drum/Rot Part Number
Tanker	#1	1	Haldex 15x4	4702QR	24	5 1/2	Webb 15.0	61528B
		2	Haldex 16.5x7	4707QR	30-30	5 1/2	Webb 16.5	66884B
		3	Haldex 16.5x7	4707QR	30-30	5 1/2	Webb 16.5	66884B
		4	Haldex 16.5x7	4515QR	30-30	6	Webb 16.5	67518F
		5	Haldex 16.5x7	4515QR	30-30	6	Webb 16.5	67518F
	#2	1	Haldex 15x4	4702QR	24	5 1/2	Webb 15.0	61528B
		2	Haldex 16.5x7	4707QR	30-30	5 1/2	Webb 16.5	66884B
		3	Haldex 16.5x7	4707QR	30-30	5 1/2	Webb 16.5	66884B
		4	Haldex 16.5x7	4515QR	30-30	6	MotorWheel 16.5	89996B
		5	Haldex 16.5x7	4515QR	30-30	6	MotorWheel 16.5	89996B
Tri-Axle Dump	#2226	1	Fleet Pride 16.5x6	47425 E2	24	5 1/2	Webb 16.5	65266B
		2	Fleet Pride 16.5x7	4515Q	24	6	Webb 16.5	67518F
		3	Fleet Pride 16.5x7	4709 E2	30-30	5 1/2	Webb 16.5	63032F
		4	Fleet Pride 16.5x7	4709 E2	30-30	5 1/2	Webb 16.5	63032F
	#2235	1	Fleet Pride 16.5x6	4715Q	24	6	Webb 16.5	65152B
		2	Fleet Pride 16.5x7	4515Q	24	6	Webb 16.5	66864F
		3	Fleet Pride 16.5x7	4515Q	30-30	6	Webb 16.5	66864B
		4	Fleet Pride 16.5x7	4515Q	30-30	6	Webb 16.5	66864B
Motor Coach	#190	1	Fleet Pride 16.5X6	4715Q	30L	5 1/2	Webb 16.5	65600B
		2	Haldex 16.5x8 5/8	4711QR	30-30	5 1/2	Webb 16.5	66845B
		3	Fleet Pride 16.5x6	4715Q	24-24	5 1/2	Webb 16.5	65600B
	#194	1	Meritor	04-01-1019	30	N/A	Meritor ~17.25	3218Z1404
		2	Meritor	04-01-1019	24-24	N/A	Meritor ~17.25	3218Z1404
		3	Meritor	04-01-1019	24-24	N/A	Meritor ~17.25	3218Z1404
Dry-Box Van	#375	1	Meritor	4702QP	24	5 1/2	Meritor 15	53123567002
		2	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B
		3	Meritor	4707	30	5 1/2	Webb 16.5	66884B
		4	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B
		5	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B
	#379	1	Meritor	4702QP	24	5 1/2	Meritor 15	53123567002
		2	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B
		3	Meritor	4707	30	5 1/2	Webb 16.5	66884B
		4	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B
		5	Meritor	4707	30-30	5 1/2	Webb 16.5	66884B

2.2 MEASUREMENTS

2.2.1 Performance

PBBT tests were performed on each vehicle prior to the installation of the new brake components to establish a baseline for the vehicle. Once the new brakes were installed, these tests were performed weekly to capture the burnish period. After the first month, the tests were carried out monthly for the remainder of the FOT. Each vehicle remained in the FOT for approximately 18 months before the final tests were performed. From these tests, ORNL determined the change in braking performance over the course of the FOT.

To maintain consistent vehicle axle loading throughout the FOT, artificial axle loading was used when the vehicles arrived at the PBBT unloaded. A detailed description of the testing procedures may be found in the project test plan.

2.2.2 Wear

In addition to regular PBBT tests for performance data, a number of physical dimensions were measured at the beginning and end of the FOT to obtain wear data for the brake components. These dimensions include rotor thicknesses, pad thicknesses, drum diameters, and lining thicknesses. Figure 21 shows the depth gauge used to take the lining thickness measurements on one of the test components prior to the FOT.

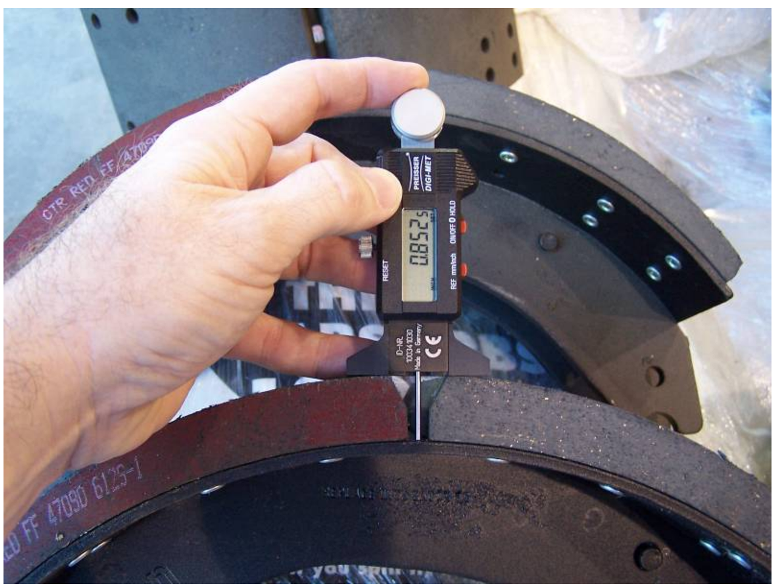

Figure 21. Lining Thickness Measurement Prior to the FOT for ST 2226

3. FOT DATA ANALYSIS

As described previously, eight vehicles participated in the 20 month test. During that period, 90 PBBT tests were conducted which resulted in 367 axle evaluations. Table 2 presents a summary of the tests conducted on each of the 8 participating vehicles, including the total miles logged during the tests period (i.e., the difference in the vehicle odometer between the first and last test), the number of days between the first and the last test, and the average vehicle weight.

Table 2. Tests Summary by Vehicle

Vehicle	PBBT Tests	PBBT Tests w/Air Pressure Measurements	Total Miles	Total Days	Average Veh. Weight* [lbs]
GC 190	17	12	77,771	564	50,060
GC 194	12	11	57,098	589	50,387
PP 1	9	7	154,254	508	71,038
PP 2	9	7	134,392	398	71,346
RD 375	12	9	174,454	469	73,061
RD 379	6	5	131,808	326	74,373
ST 2226	13	12	33,794	562	53,362
ST 2235	12	10	39,173	562	53,192
Total	90	73			

* Does not include tests with empty vehicles and no Artificial Axle Load

Table 2 also shows that in 73 out of the 90 PBBT tests, brake-line air pressure data was collected in real-time as the PBBT test progressed. To collect this data, a pressure tap, installed by the driver in the service air line between the tractor and the trailer via the glad-hand connectors, was used (see Figure 22). A pressure transducer attached to the device permitted sampling the air pressure in the system at 10 Hz –i.e., a sampling rate of one observation every 0.1 sec.

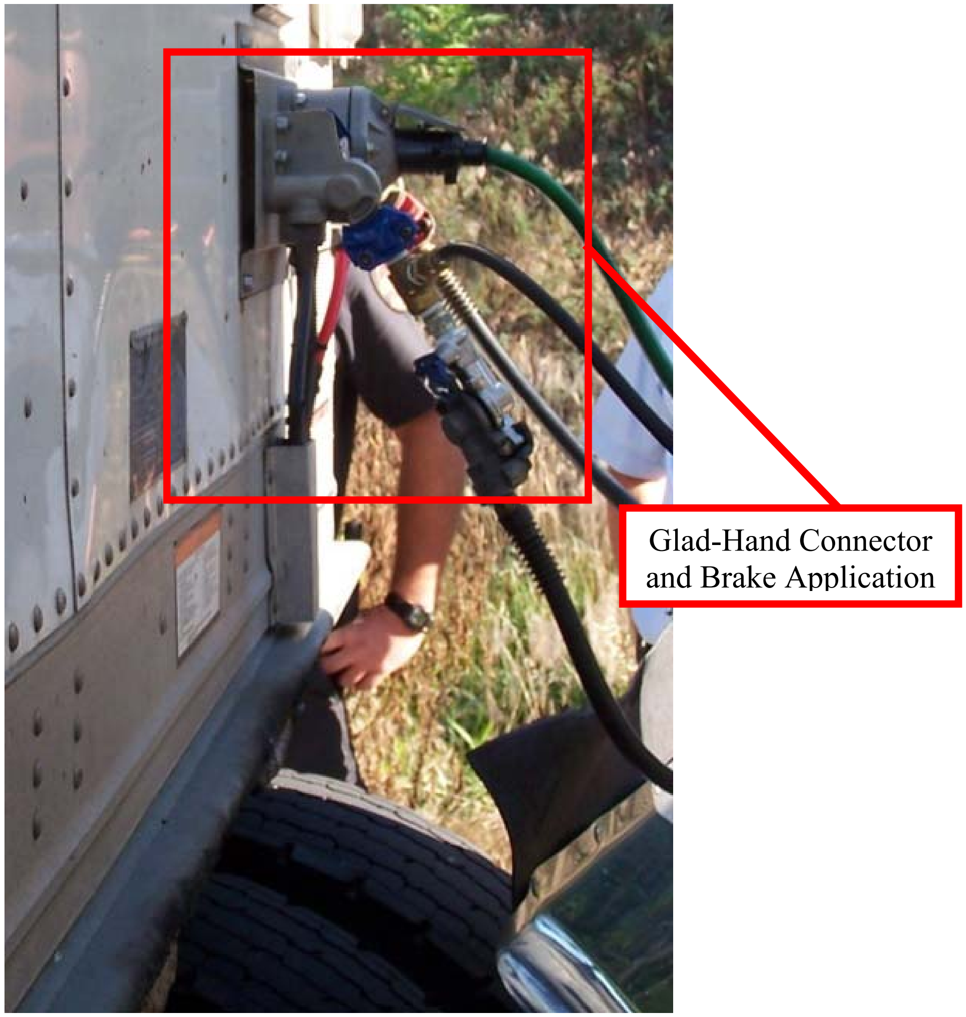

Figure 22. Glad-Hand Pressure Tap

3.1 VEHICLE BRAKE EFFICIENCY

The results of the PBBT tests are presented in Table 3 to Table 6, for each pair of vehicles, respectively. These tables show the date when the test was conducted, the vehicle mileage, and the result of the PBBT test for the vehicle in terms of vehicle brake efficiency (note: efficiencies below 0.435 are highlighted).

Table 3. Test Date, Vehicle Mileage and Vehicle Brake Efficiency (GC 190 and GC 194)

Test	GC 190			GC 194		
	Date	Mileage	Brake Eff.	Date	Mileage	Brake Eff.
1	10/04/07	367,473	0.4822	11/08/07	169,418	0.4697
2	10/11/07	368,402	0.4914	11/15/07	171,493	0.5443
3	10/23/07	369,969	0.5216	02/12/08	180,947	0.5558
4	11/28/07	376,922	0.5372	04/25/08	189,255	0.5459
5	02/12/08	385,253	0.5317	05/27/08	194,126	0.5560
6	04/01/08	396,569	0.6123	07/30/08	199,340	0.5450
7	05/27/08	410,155	0.5665	08/29/08	205,562	0.5170
8	06/19/08	412,813	0.5736	09/25/08	207,551	0.4788
9	07/30/08	415,571	0.5450	10/14/08	209,711	0.5130
10	08/29/08	420,188	0.5569	11/20/08	209,893	0.5793
11	09/25/08	423,093	0.5779	12/05/08	211,431	0.4681
12	10/16/08	425,861	0.6241	06/19/09	226,516	0.4956
13	11/05/08	428,446	0.5547			
14	12/16/08	432,143	0.5331			
15	01/13/09	432,659	0.6436			
16	02/17/09	436,322	0.5973			
17	04/20/09	445,244	0.5266			
Avg.			0.5574			0.5224

Table 4. Test Date, Vehicle Mileage and Vehicle Brake Efficiency (PP 1 and PP 2)

Test	PP 1			PP 2		
	Date	Mileage	Brake Eff.	Date	Mileage	Brake Eff.
1	10/11/07	40,812	0.5161	03/28/08	185,600	0.7058
2	10/18/07	42,500	0.5070	04/02/08	187,288	0.4695
3	10/30/07	45,400	0.5883	06/06/08	208,428	0.4906
4	01/29/08	65,625	0.4815	06/17/08	212,443	0.5061
5	05/13/08	98,734	0.5654	07/31/08	227,067	0.3658
6	07/23/08	120,627	0.4858	11/17/08	266,890	0.5321
7	09/03/08	134,315	0.4853	01/13/09	285,538	0.4089
8	01/21/09	183,657	0.5652	03/11/09	304,299	0.4718
9	03/02/09	195,066	0.4536	04/30/09	319,992	0.4693
Avg.			0.5165			0.4911

Table 5. Test Date, Vehicle Mileage and Vehicle Brake Efficiency (RD 375 and RD 379)

Test	RD 375			RD 379		
	Date	Mileage	Brake Eff.	Date	Mileage	Brake Eff.
1	01/31/08	351,322	0.5009	05/22/08	279,163	0.5314
2	02/12/08	356,200	0.4822	07/17/08	301,642	0.4887
3	04/25/08	387,184	0.4701	09/09/08	323,793	0.4560
4	05/23/08	398,157	0.5011	11/17/08	348,569	0.5440
5	06/25/08	409,058	0.4934	02/16/09	381,012	0.5127
6	08/01/08	420,592	0.4173	04/13/09	410,971	0.4970
7	08/21/08	426,044	0.4971			
8	09/04/08	431,443	0.4788			
9	11/17/08	460,743	0.5377			
10	01/09/09	481,672	0.5301			
11	03/04/09	500,212	0.5222			
12	05/14/09	525,776	0.4509			
Avg.			0.4901			0.5050

Table 6. Test Date, Vehicle Mileage and Vehicle Brake Efficiency (ST 2226 and ST 2235)

Test	ST 2226			ST 2235		
	Date	Mileage	Brake Eff.	Date	Mileage	Brake Eff.
1	10/16/07	282,513	0.5884	10/16/07	97,968	0.4984
2	10/23/07	283,580	0.4859	10/23/07	99,001	0.5789
3	10/30/07	284,180	0.6039	10/30/07	99,785	0.5783
4	11/28/07	286,246	0.6158	11/15/07	102,760	0.5234
5	12/11/07	286,739	0.5877	12/11/07	104,604	0.5415
6	01/29/08	287,103	0.6114	03/13/08	104,921	0.6060
7	05/02/08	290,835	0.6091	05/02/08	106,261	0.5721
8	06/27/08	295,767	0.5861	06/27/08	113,950	0.5452
9	07/23/08	298,197	0.4765	07/23/08	116,924	0.4499
10	09/09/08	303,458	0.4118	09/09/08	122,409	0.4381
11	11/20/08	309,280	0.6037	11/20/08	126,501	0.6240
12	01/12/09	311,972	0.6515	04/30/09	137,141	0.5117
13	04/30/09	316,307	0.5788			
Avg.			0.5700			0.5390

The information presented in these tables show that the average vehicle brake efficiency ranged from 0.490 (RD 375) to 0.570 (ST 2226), and for single test the minimum and maximum were 0.366 and 0.706, respectively (both for PP 2). This information is also shown in Figure 23 which presents the distribution of the vehicle brake efficiencies. Notice that in 86 out of the 90 tests conducted (or 95.5% of the cases) the vehicles passed the PBBT test (i.e., the vehicle overall brake efficiency was larger than 0.435).

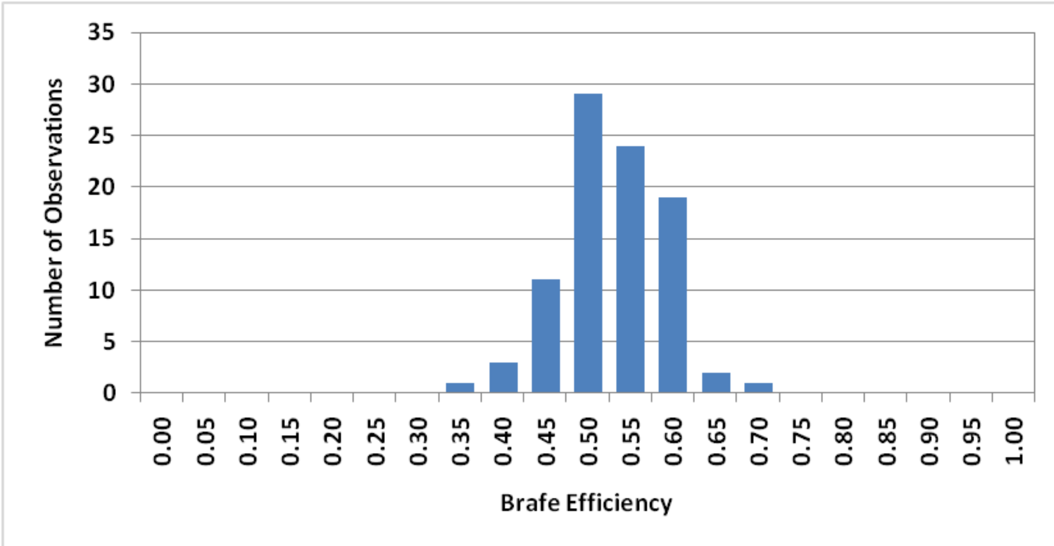

Figure 23. Distribution of Vehicle Brake Efficiencies

Figure 24 is similar to Figure 23, but in this case the distribution of brake efficiencies was built using all of the information (i.e., wheel-end brake efficiencies) collected during the tests (note: detailed information about the results of the PBBT tests by vehicle, mileage, and wheel end as well as axle weight information can be found in Appendix X of this report). As expected, at the axle level the dispersion of brake efficiencies is higher than at the vehicle level (the latter are averages of the former), with 17% of the observations below 0.435 but also with 26% above 0.60 (as opposed to 4% and 14%, respectively, for the vehicle-level brake efficiencies).

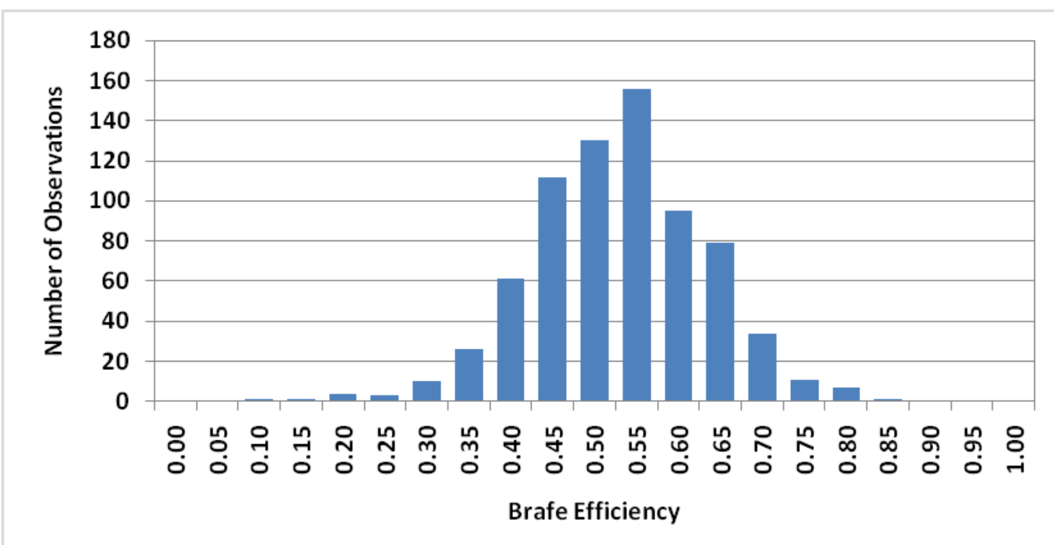

Figure 24. Distribution of Wheel-end Brake Efficiencies

3.1.1 Brake Efficiency Variability

As discussed in the previous chapter, all of the participating vehicles were equipped with automatic slack adjusters. Therefore, under perfect conditions, and on a theoretical basis, it would be expected that the measured brake efficiencies for a given vehicle and a specific wheel end would not vary over the life of the brakes (or a shorter period). In reality, there are many factors that affect the brake efficiency of a wheel end, including wear of brake components, brake maintenance, axle weight, variability in brake application pattern by the driver, different drivers performing the tests, brake and drum temperature at the time of the test, and other factors (e.g., noise in the data collection system). In order to study the variability that those factors introduce, the coefficient of variation (CV), defined as the ratio between the standard deviation and the mean of a distribution, was computed for each vehicle and wheel end. The results are presented in Table 7 which also shows the minimum and maximum brake efficiency values (note: CVs larger than 20% are highlighted).

The coefficient of variation provides a normalized measure of dispersion of a distribution, allowing a comparison of the degree of variation from one data series (wheel-end brake efficiencies) to another. Notice that in Table 7 the CV is not uniformly distributed across vehicles and axles; but two sets of vehicles (i.e., PP and ST) present larger CVs than the other two (i.e., GC and RD). Out of 10 CVs that are larger than 20%, 9 correspond to PP 1 and PP 2 (3 for PP 1 and 6 for PP 2) and 1 to ST 2226. The highest variability of the brake efficiency during the tests were observed for vehicle PP 2, axle 3 right (CV = 49%) followed by vehicle ST 2226 axle 1 left (CV = 35%). Notice that in the PP 2 case, the first test was conducted without artificial axle load and with an empty vehicle (25,410 lbs), while all of the other subsequent tests were performed with the vehicle's weight around 71,000 lbs (see Appendix B). As a consequence, the initial-test brake efficiencies were significant larger than those observed in the following tests (see Appendix B), which resulted in a higher variability in the data.

Table 7. Axle-end Brake Efficiency Variability

Vehicle	Axle #	Left Side Brake Efficiency					Right Side Brake Efficiency				
		Min	Max	Mean	St Dev	CV [%]	Min	Max	Mean	St Dev	CV [%]
GC 190	A1	0.421	0.685	0.535	0.068	12.78	0.460	0.700	0.546	0.058	10.54
	A2	0.465	0.610	0.524	0.038	7.24	0.522	0.801	0.616	0.070	11.41
	A3	0.446	0.610	0.523	0.046	8.74	0.399	0.741	0.610	0.099	16.23
GC 194	A1	0.455	0.612	0.530	0.052	9.79	0.430	0.655	0.536	0.054	10.05
	A2	0.427	0.596	0.510	0.052	10.13	0.440	0.672	0.536	0.082	15.39
	A3	0.410	0.516	0.488	0.030	6.21	0.387	0.614	0.538	0.057	10.66
PP 1	A1	0.565	0.753	0.655	0.059	8.98	0.570	0.783	0.670	0.061	9.17
	A2	0.329	0.428	0.389	0.033	8.60	0.301	0.675	0.484	0.121	25.07
	A3	0.170	0.473	0.353	0.098	27.65	0.272	0.624	0.456	0.123	27.06
	A4	0.428	0.558	0.490	0.044	9.05	0.477	0.636	0.562	0.053	9.39
	A5	0.539	0.673	0.587	0.041	7.04	0.573	0.749	0.645	0.060	9.31
PP 2	A1	0.482	0.759	0.637	0.086	13.42	0.504	0.805	0.649	0.089	13.77
	A2	0.213	0.454	0.341	0.074	21.75	0.207	0.533	0.376	0.094	25.14
	A3	0.256	0.481	0.405	0.076	18.65	0.279	0.981	0.433	0.214	49.35
	A4	0.324	0.819	0.541	0.137	25.39	0.362	0.790	0.544	0.117	21.49
	A5	0.284	0.709	0.490	0.125	25.48	0.498	0.869	0.614	0.105	17.17
RD 375	A1	0.482	0.700	0.601	0.065	10.73	0.473	0.698	0.624	0.064	10.18
	A2	0.387	0.600	0.460	0.058	12.71	0.462	0.609	0.528	0.045	8.44
	A3	0.413	0.551	0.483	0.046	9.49	0.453	0.628	0.525	0.045	8.56
	A4	0.330	0.497	0.408	0.050	12.29	0.374	0.493	0.443	0.032	7.31
	A5	0.356	0.529	0.422	0.051	12.11	0.377	0.561	0.481	0.048	10.04
RD 379	A1	0.441	0.661	0.565	0.076	13.50	0.475	0.731	0.643	0.096	14.94
	A2	0.455	0.628	0.518	0.061	11.73	0.519	0.564	0.542	0.017	3.23
	A3	0.463	0.555	0.508	0.034	6.71	0.513	0.665	0.585	0.053	9.09
	A4	0.372	0.453	0.406	0.034	8.30	0.419	0.483	0.457	0.023	5.10
	A5	0.406	0.431	0.414	0.009	2.16	0.391	0.618	0.483	0.086	17.89
ST 2226	A1	0.108	0.649	0.479	0.166	34.60	0.415	0.735	0.565	0.100	17.76
	A2	0.394	0.668	0.520	0.077	14.86	0.392	0.685	0.558	0.080	14.35
	A3	0.406	0.669	0.571	0.088	15.38	0.439	0.697	0.617	0.075	12.19
	A4	0.483	0.742	0.595	0.077	12.94	0.469	0.809	0.651	0.106	16.29
ST 2235	A1	0.419	0.612	0.516	0.067	12.90	0.404	0.676	0.573	0.072	12.52
	A2	0.371	0.554	0.463	0.056	12.02	0.412	0.533	0.490	0.036	7.33
	A3	0.392	0.627	0.532	0.071	13.34	0.413	0.692	0.584	0.096	16.51
	A4	0.394	0.626	0.552	0.075	13.53	0.402	0.708	0.579	0.089	15.32

Figure 25 shows the distribution of the coefficient of variation corresponding to wheel-end brake efficiencies. The distribution is skewed to the left, with a mean coefficient of variation around 13.8%. That is, based on the tests conducted in this project, when measurements of brake efficiencies for the same vehicle and same axle are repeated over the life of well-maintained brakes, these measurements are expected to have a standard deviation that is approximately 14% of their mean value.

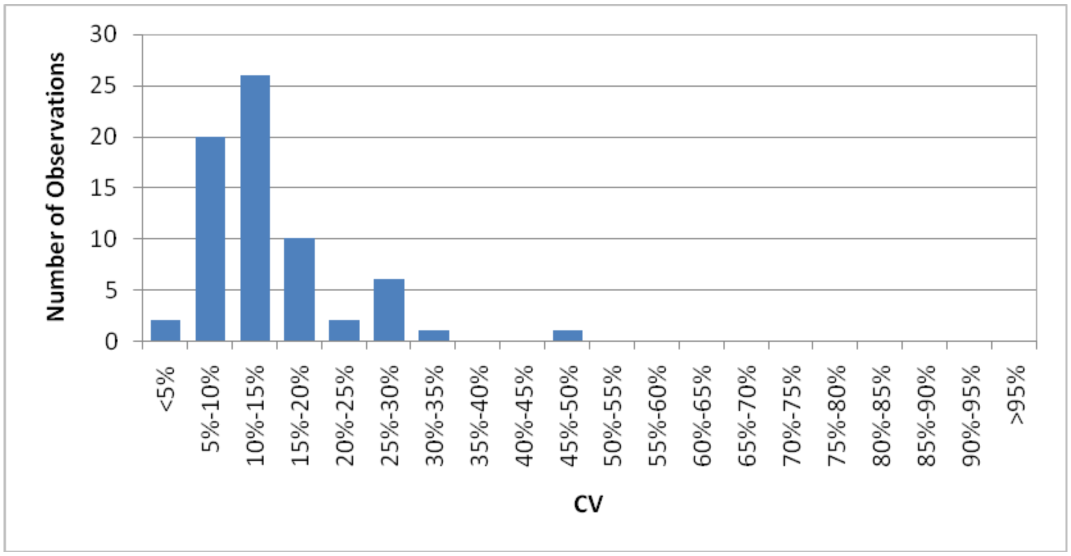

Figure 25. Distribution of the Coefficient of Variation Corresponding to Wheel-end Brake Efficiencies

The data also shows that at the beginning of the life cycle of the brakes, there was an increase in brake efficiency, which can account for some of the variability observed in the wheel-end brake efficiencies. Before the tests started, the participant vehicles were equipped with new brakes and shortly thereafter, the first PBBT test was conducted. In most cases, the second and, sometimes, the third PBBT tests were conducted within a few days of the first one, with subsequent tests performed at varying intervals which, depending on the vehicle, ranged from one to several months (see Table 3 to Table 6). The data showed that for the cases in which a second (or third) PBBT test was conducted within 5,000 miles of the initial test, there was almost always (94.4% of the cases) an increase in the brake efficiency with respect to the first (or second) test. Table 8 presents this information for each one of the vehicles participating in the tests. The table shows the difference in vehicle weight between the second (or third) test and that of the first test, as well as the number of miles logged by the vehicle. Cases in which the difference in vehicle weight was excessive –i.e., PP 2, RD 375, and RD 379– were not considered (heavier weights tend to generate lower brake efficiencies, and therefore if there are large weight differences between tests those brake efficiencies are expected to be different and cannot be used in the comparisons). One vehicle, RD 379, also logged a large number of miles (i.e., more than 22,000 miles) between the first and second PBBT tests. For the remaining vehicles, Table 8 shows the percentage change in brake efficiency which was computed as shown below:

$$\Delta BE = \frac{(BEf - BEi)}{BEi} \times 100$$

where ΔBE is the percentage change in brake efficiency between that which was measured in the second (third) test, BEf, and that measured at the initial test, BEi. Table 8 shows that 36 out of 38 wheel-end brake efficiency measurements were larger in the second (or third) test than in the first test; in some cases by a substantial amount (e.g., 49% for ST 2226 axle 4R). The table also shows that for the two cases in which the brake efficiency actually decreased in the second test, the percentage change was very small (0.4% and 1.9%).

Table 8. Wheel-end Brake Efficiency Change with Respect to the First PBBT Test

Vehicle	Delta Weight [lbs]	Delta Miles	A1L	A1R	A2L	A2R	A3L	A3R	A4L	A4R	A5L	A5R
GC 190	690	2,496	12.0%	11.6%	-0.4%	4.7%	19.4%	5.8%				
GC 194	340	2,075	11.8%	17.4%	3.2%	17.1%	25.8%	29.0%				
PP 1	-420	4,588	14.4%	3.8%	14.1%	16.8%	11.7%	30.0%	21.7%	4.2%	11.3%	15.5%
PP 2	45,450	1,688	Significantly lower weight in the first test: 25,950 lbs vs. 71,400 lbs.									
RD 375	14,050	4,878	Significantly lower weight in the first test: 65,650 lbs vs. 79,700 lbs.									
RD 379	15,850	22,479	Significantly lower weight in the first test: 62,990 lbs. vs. 78,840 lbs. and also a large number of miles traveled between the first and second test.									
ST 2226*	6,410	1,667	15.9%	27.3%	17.2%	37.9%	23.1%	18.4%	29.1%	48.7%		
ST 2235	-830	1,817	2.8%	-1.9%	16.0%	3.6%	44.7%	67.4%	6.1%	13.2%		

* Calculations made between fourth and second tests (first test had a 12% lower weight than subsequent tests).

In order to determine whether this observation of increasing brake efficiencies at the beginning of the brake life cycle is a random occurrence or is a real phenomenon, consider the following binomial experiment. Assume that the variations in brake efficiencies between the first and second PBBT tests are simply noise. Assume further that there is an equal chance ($p = 0.5$) that the second measurement can be smaller or larger than the first one (i.e., just noise in the measurements). Under these assumptions, the likelihood of observing 36 instances of brake efficiency increases out of 38 cases is 0.0000000026, a very rare event. This result suggests that brakes become better (i.e., brake efficiency increases) during the first period of their life cycle (i.e., 5,000 miles in the tests conducted in this project).

3.1.2 Change in Brake Efficiency during the Length of the Test

In order to analyze if there was a loss of brake efficiency during the test period, a linear regression analysis was performed on the data collected for each wheel-end. That is, the wheel-end brake efficiency measurements were regressed against the vehicle mileage such that the slope of the linear regression line measured the change in brake efficiency as a function of the miles traveled by the vehicle. Because the brake efficiency almost always increased at the beginning of the life cycle of the brakes (see the subsection above), the results of the very first (and in some cases the second) test were not used in the regression analysis. As an example, Figure 26 and Figure 27 show plots of brake efficiency measurements vs. the vehicle mileage for GC 194 axle 1 left and right, respectively. The figures also present the linear regression line which for the left axle shows a slight decrease in brake efficiency (i.e., a degradation of the brakes) as the vehicle mileage increases and a slight increase in brake efficiency for the right axle. Statistical tests were also performed to determine whether the slopes of these trend lines were different from zero [3]. That is, the null hypothesis (Ho) stating that the slope was equal to zero (i.e., no effect of the vehicle mileage on brake efficiency) was tested against the alternative hypothesis (Ha) of the slope being different from zero (i.e., the vehicle mileage had a positive – upward slope of the regression line– or negative –downward slope of the regression line– effect on the brake efficiency.

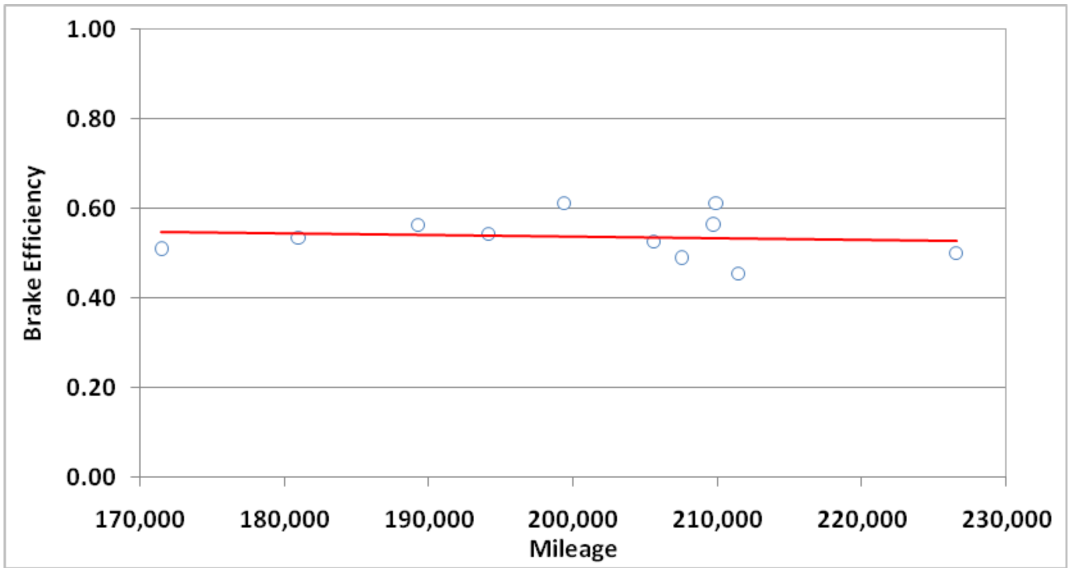

Figure 26. Brake Efficiency vs. Mileage (GC 194 - Axle 1 Left)

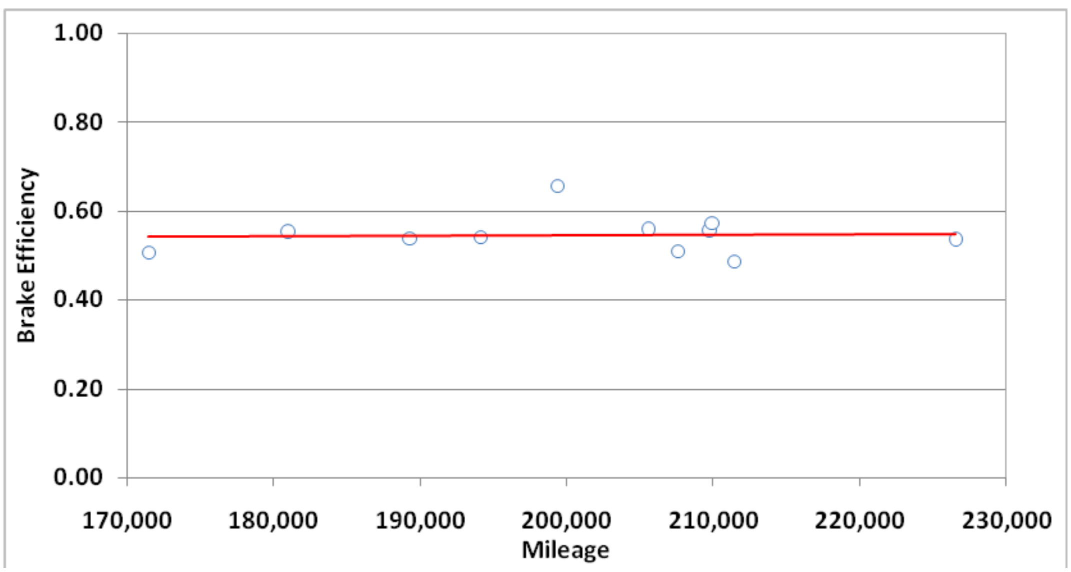

Figure 27. Brake Efficiency vs. Mileage (GC 194 - Axle 1 Right)

The results of the statistical tests showed that the null hypothesis stating that the slopes were equal to zero could only be rejected at a very low confidence level (i.e., less than 75%), indicating that the vehicle mileage did not have an effect on the measured brake efficiencies. Similar analyses were conducted for all the vehicles and wheel ends. The results of these statistical analyses are presented in Table 9, which for each vehicle and wheel end shows the slope of the regression line (i.e., the change in brake efficiency per 100,000 miles1) and below that number and in parenthesis the confidence level at which the null hypothesis of the slope being equal to zero could be rejected. Table 9 shows that in only four cases (i.e., GC 194 Axle 2 and Axle 3 Left, ST 2226 Axle 1 Right, and ST 2235 Axle 4 Left) it was possible to reject the null hypothesis of the slope of the regression line being equal to zero with a high level of confidence (more than 97%). Notice that in the ST 2226 case the slope was positive indicating an improvement in brake efficiency with mileage.

In all the other cases (i.e., 64 out of 68 cases), the null hypothesis could only be rejected at low levels of confidence (less than 95%). This result suggests that there was not a statistically significant degradation of the brakes during the length of the test conducted in this project. This in turn shows that the automatic slack adjusters, which all the participant vehicles had, performed well. Notice also that all of the participant companies indicated that they conducted regular brake maintenance, and one of them (RD) pointed out that their vehicle brakes were always checked and, if needed adjusted, before the PBBT tests. Hence, this result was not unexpected. However, it confirmed that careful maintenance of the brake system results in consistently high performing brakes, even after a considerably large number of miles (more than 170,000 miles for RD 375).

[1] The slope of the regression line was computed as change in brake efficiency per mile, as very small number. Table 8 shows that number multiplied by 100,000.

Table 9. Axle-end Brake Efficiency vs. Vehicle Mileage – Slope of Linear Regression Line

Vehicle		A1L	A1R	A2L	A2R	A3L	A3R	A4L	A4R	A5L	A5R
GC 190	Slope	0.0058	0.0042	0.0523	0.1005	0.0308	0.1811				
	RCL =*	(<75%)	(<75%)	(<75%)	(76.9%)	(<75%)	(91.6%)				
GC 194	Slope	-0.0353	0.0115	-0.2646	-0.3183	-0.0782	0.0583				
	RCL =*	(<75%)	(<75%)	(99.4%)	(93.7%)	(97.1%)	(<75%)				
PP 1	Slope	-0.0322	0.0471	-0.0114	-0.0373	-0.0974	-0.0772	-0.0094	-0.0085	-0.0590	-0.0101
	RCL =*	(<75%)	(<75%)	(<75%)	(<75%)	(75.2%)	(<75%)	(<75%)	(<75%)	(92.4%)	(<75%)
PP 2	Slope	0.0074	0.0386	0.0047	-0.0215	0.0194	-0.0601	-0.1108	-0.0077	0.0974	0.0122
	RCL =*	(<75%)	(<75%)	(<75%)	(<75%)	(75.2%)	(76.9%)	(86.1%)	(<75%)	(76.9%)	(<75%)
RD 375	Slope	-0.0340	-0.0596	0.0482	0.0339	0.0182	0.0405	0.0127	0.0164	0.0201	0.0002
	RCL =*	(<75%)	(84.2%)	(80.0%)	(<75%)	(<75%)	(83.0%)	(<75%)	(<75%)	(<75%)	(<75%)
RD 379	Slope	0.0215	0.1057	-0.0694	0.0197	0.0194	0.0376	-0.0102	0.0403	-0.0044	0.1124
	RCL =*	(<75%)	(<75%)	(<75%)	(<75%)	(<75%)	(<75%)	(<75%)	(81.0%)	(<75%)	(<75%)
ST 2226	Slope	-0.4724	0.5720	0.1225	-0.4203	-0.1157	-0.0705	-0.0048	-0.3868		
	RCL =*	(<75%)	(96.8%)	(<75%)	(94.3%)	(<75%)	(<75%)	(<75%)	(80.0%)		
ST 2235	Slope	-0.0778	-0.1383	-0.0220	0.0121	-0.1845	-0.3275	-0.4484	-0.2660		
	RCL =*	(<75%)	(<75%)	(<75%)	(<75%)	(<75%)	(82.4%)	(97.5%)	(<75%)		

*Confidence level at which the null hypothesis of the slope being zero could be rejected.

3.2 BRAKE FORCE AND AIR PRESSURE

As mentioned earlier, in 73 out the 90 tests conducted on the eight vehicles participating in this project, brake-line air pressure was measured at the same time that the PBBT tests were performed. Figure 28 shows a typical representation of brake force (in lbs) as a function of the air pressure applied (in psi). Three different regimes can be clearly identified in the figure: two flat regions (i.e., no change in brake force as the air pressure increases) at the beginning and end of the test, and a linear region in which the brake force increases proportionally to the air pressure applied. For the particular case shown in Figure 28, the three regions are defined by the 0-10 psi, 10-90 psi, and 90-100 psi intervals, with the brake force increasing at a rate of 45.5 lbs/psi in the middle region of the plot.

Everything else being equal, a steeper line in the middle region would be an indication of stronger brakes than in a case where that line is more level (i.e., for a given brake force level, it would take a higher air pressure in the second case to achieve that brake force level than in the first case). This linear region was observed to exist in all of the tests performed in this project (see Appendix C for 3D plots of this information by vehicle and wheel-end), and the slope of this line was used to analyze how the brakes at the wheel end performed over time as well as to determine variations among different type of brakes.

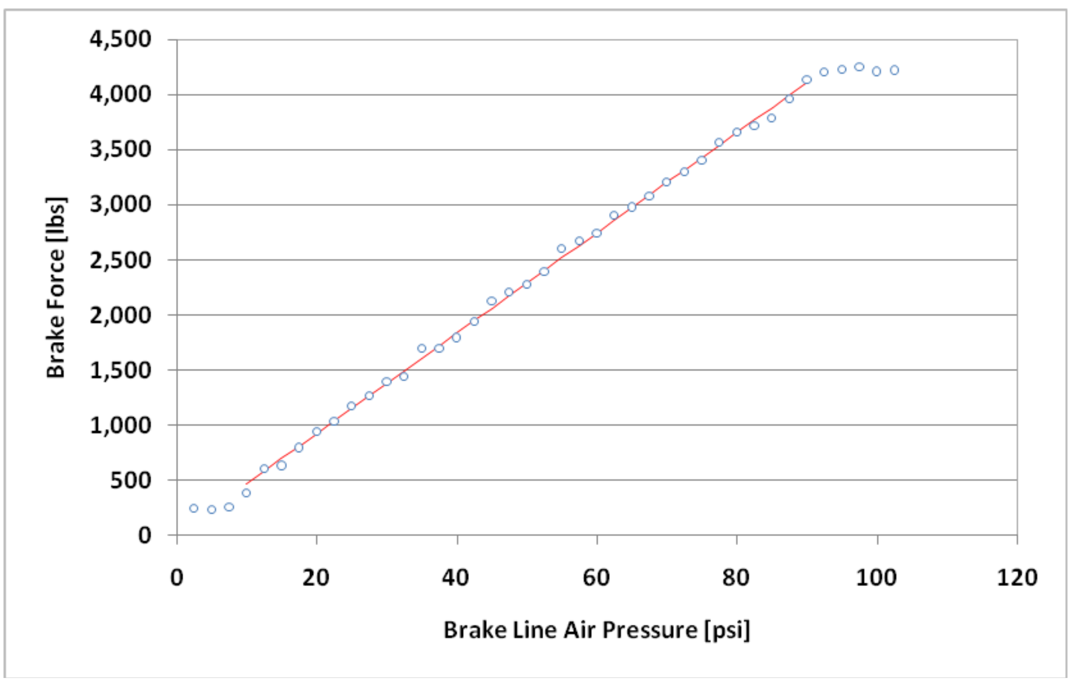

Figure 28. Brake Force vs. Air Pressure (ST 2235 - Axle 1 Left - 99,785 miles)

In the example shown in Figure 28, the data in the middle region presented a very low level of "noise"; however, there were other tests in which this was not the case. Figure 29 shows the data collected for the left end of axle 1 during the fifth PBBT test performed on ST 2226. Notice that there is a linear region starting at about 15 psi, and there are data points, such as those marked with arrows in Figure 29, that are clearly outliers; probably caused by disturbances in the data collection system (note: at the sampling of 10 Hz, these two points were observed within a 0.2 sec interval).

In order to calculate the slope of the proportionality region of the brake force vs. air pressure relationship, it was necessary to identify and eliminate not only those outliers, but also the “flat” regions at the beginning and end of the tests. Without taking these precautions, the slope of the linear regression line in the proportionality region would have been incorrect (in general, it would have been smaller, indicating a more level line than what it really was).

Visual inspection of the data would have permitted identifying the “flat” regions as well as the outliers, and eliminating them from the data set. However, there were 594 wheel-end tests in which brake force and air pressure information was collected, which made a manual cleansing of the data impractical. In order to solve this problem, an algorithm used in machine vision to recognize patterns and edges was used to identify the data belonging to the proportionality region of the brake force-air pressure relationship.

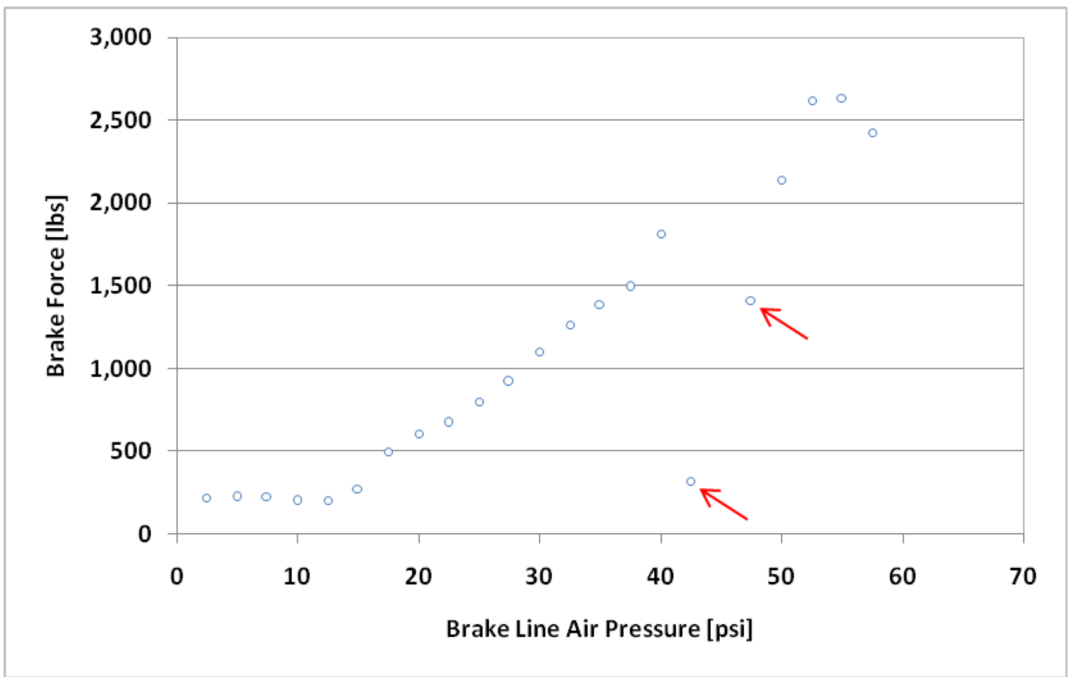

Figure 29. Brake Force vs. Air Pressure (ST 2226 - Axle 1 Left - 286,739 miles)

The RANdom SAmple Consensus (RANSAC) algorithm, originally proposed by Fischler and Bolles [4], is a general parameter estimation approach designed to handle large proportions of outliers in the input data. This algorithm is now commonly used within the computer vision community [5]. It basically consists of a re-sampling technique that generates candidate solutions by using the minimum number observations (data points) required to estimate the underlying model parameters (linear region in our case). The algorithm uses the smallest set possible (two points in our case since we are trying to identify a line) and proceeds to enlarge this set with consistent data points.

Figure 30 shows the results of the algorithm when applied to the data presented in Figure 29. The distance between the two outside lines (shown around the linear regression line) is a parameter (i.e., tolerance) that is an input to the RAMSAC algorithm. With this user defined parameter, the algorithm finds all of the points that fit the proposed model (a line in our case) and eliminates any point that is outside of the tolerance boundaries.

The results of applying the RANSAC algorithm to the data collected in this project and subsequent computation of the slope of the line in the proportionality region of the brake force-air pressure relationship are presented in Appendix B. Figure 31 shows a distribution of these slopes for all of the vehicles and wheel ends. The average slope was 77 lbs/psi, and ranged from 13 lbs/psi to 160 lbs/psi.

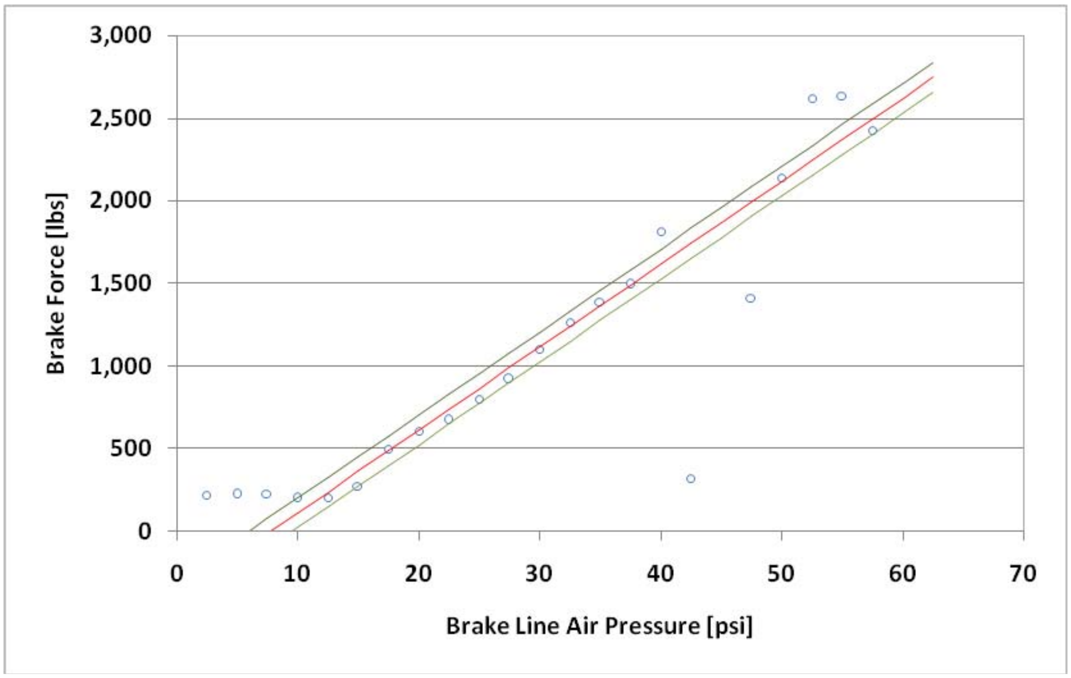

Figure 30. Brake Force vs. Air Pressure RANSAC Algorithm Boundaries (ST 2226 - Axle 1 Left - 286,739 miles)

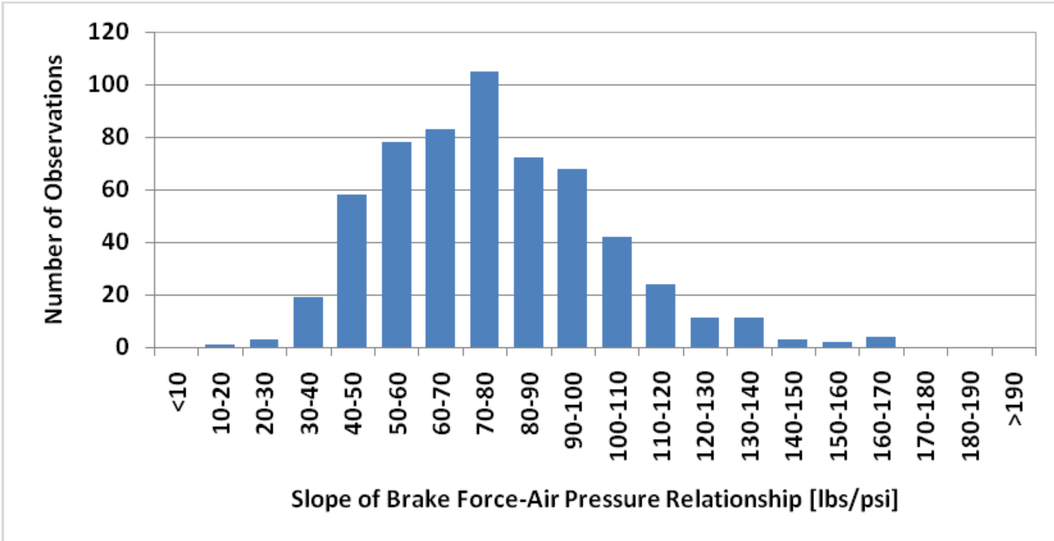

Figure 31. Distribution of the Slope of the Brake Force-Air Pressure Linear Relationship

For each one of the vehicles, all of the data selected by the RANSAC algorithm for all of the tests corresponding to a given wheel end were used to run a two dimensional (air pressure and mileage vs. brake force) linear regression analysis. This linear regression permitted the computation of an overall slope of the brake force-air pressure relationship for each vehicle and wheel end. Table 10 presents these results, including the R2 (or coefficient of determination[2]) and the overall slope of the brake force-air pressure linear relationship for vehicle and each axle, as well as the number of miles logged between the first and last test (note: air pressure was not measured in all of the PBBT tests, therefore the number of miles logged between the first and last PBBT test in which that information was collected was in some cases different from the information shown in Table 2). All of the slopes presented in Table 10 were shown to be statistically significant at the 99.99% confidence level.

[2] The coefficient of determination compares the estimated and actual variable dependent values. It ranges in value from 0 to 1; indicating that the sample has higher correlation (i.e., the estimated and the actual values are very similar) as it approaches 1.

Table 10. Wheel-end Brake Efficiency vs. Vehicle Mileage - Slope of the Linear Regression Line

Vehicle	Total Miles	Axle	Left		Right	
			R2	Slope [lbs/psi]	R2	Slope [lbs/psi]
GC 190	75,275	1	0.95758	53.27	0.95239	52.64
		2	0.96141	84.52	0.93221	95.30
		3	0.93319	55.71	0.96220	58.61
GC 194	57,098	1	0.88797	60.30	0.90164	59.93
		2	0.86842	74.74	0.90142	69.25
		3	0.90503	45.38	0.85823	43.09
PP 1	152,566	1	0.98675	47.67	0.98661	44.35
		2	0.96619	71.01	0.96529	70.50
		3	0.98160	94.40	0.95900	66.16
		4	0.94658	85.13	0.91424	88.91
		5	0.91735	72.53	0.92375	76.67
PP 2	132,704	1	0.95358	49.49	0.95305	51.98
		2	0.97222	70.50	0.97351	71.42
		3	0.97921	84.78	0.94431	66.51
		4	0.98183	113.30	0.93341	122.24
		5	0.95041	111.72	0.96644	119.01
RD 375	174,454	1	0.94447	37.73	0.92299	35.86
		2	0.87056	71.38	0.96530	70.27
		3	0.92744	79.42	0.96206	79.21
		4	0.87398	76.66	0.89419	77.68
		5	0.94475	81.64	0.92398	87.04
RD 379	131,808	1	0.97435	36.98	0.99215	42.37
		2	0.97196	66.30	0.98580	68.30
		3	0.94578	77.00	0.97251	68.66
		4	0.97600	60.31	0.81654	57.02
		5	0.85280	75.83	0.95947	64.09
ST 2226	32,727	1	< 0.8000	N/A	0.93203	60.92
		2	< 0.8000	N/A	< 0.8000	N/A
		3	0.98059	93.93	0.96841	98.37
		4	0.91884	106.51	0.94045	111.50
ST 2235	27,500	1	0.95678	50.67	0.95254	49.38
		2	0.90218	63.12	0.90883	76.33
		3	0.92447	82.09	0.95756	85.28
		4	0.93464	85.17	0.91570	84.30

There were three cases in which the R2 was low (R2 less than 0.8), all of them corresponding to vehicle ST 2226. This indicates a poor correlation between the data and the model (the linear regression plane); therefore, in these cases, no slope information (i.e., N/A) is shown in the table. For the remaining cases, the correlation was high, and in several cases very close to 1 (perfect correlation). Notice that in general, for each type of vehicle and axle, the slopes are similar for the left and right wheel ends, but are different for different axles in the same vehicle. This simply reflects the fact that different axles carry different weight, and therefore the brakes have to provide, at any given time, a larger brake force for those axles that support higher weights.

Since the air pressure is the same for any wheel end (under normal conditions) then those axles carrying a heavier weight will show a steeper slope in Table 10.

Because in the case described here there were two independent variables (air pressure and vehicle mileage), the linear regression also provides an overall slope (i.e., variation) of the brake force as a function of the vehicle mileage. The results were similar to those observed in the case of the variation of the wheel-end brake efficiencies with respect to the vehicle mileage. That is, there were no observable changes in brake force as the vehicle mileage increased.

3.3 BRAKE LINING WEAR AND DRUM DIAMETER ELONGATION

As part of the research conducted under this project, measurements of the thickness of brake pads and drum diameters were made at the beginning and at the end of the tests to study the wear of these components and to determine how fast (in terms of miles logged) different type of brakes wear. Notice that although the vehicles had different brands of brake components (in some cases even for vehicles that belonged to the same trucking company), the PBBT test results discussed previously showed that there was no discernible degradation of the brakes during the test period.

As discussed in Chapter 2, brake pads and drums were measured at the beginning of the tests; before those components were installed in the eight participant vehicles. It would have been desirable to make these measurements at the moment the components were installed to know exactly where (i.e., which wheel end) each one of them was installed. However, because of the way the companies operate and maintain their vehicles, it was not possible to schedule the brake replacement for a specific date and time, and therefore it was unfeasible to try to perform the measurements at the time of installation. On the other hand, the measurements made at the end of the tests were precisely identified in terms of wheel end and position.

In order to determine the wear of any component, it is necessary to know its parameters (thickness for the brake pads and diameter for the drums) at the beginning and at the end of the test period. As explained above, these parameters were known with precision for the measurements performed at the end. For the starting measurements, all of the components were measured and therefore it was possible to create a distribution of the relevant parameters, which in general had very low standard deviations (i.e., for any given component brand there is, in general, a very small tolerance). Table 11 presents these parameters for the brake linings and drums used in this project.

Table 11. Brake Lining Thickness and Drum Diameter Mean and Standard Deviation of Initial Measurements

Vehicle	Lining				Drum				Axle
	Type	Lining Thickness			Type	Drum Diameter			
		No of Obs.	Mean [in.]	St Dev [in.]		No of Obs.	Mean [in.]	St Dev [in.]	
GC 190	OTR 4715Q	8	0.820	0.0022	N/A	6	16.500	0.0000	Steer/Tag
	Halidex GG4711QR	4	0.813	0.0061					Drive
GC 194	Disk Brakes (OEM Lining - Meritor)	12	0.784	0.0049	N/A	3	1.751	0.0010	All
PP 1	Haldex GG47020-3020-1FF	4	0.724	0.0047	Webb 61528B	2	15.010	0.0042	Steer
	Haldex GG47070HX-3020-1FF	8	0.826	0.0076	Webb 65884B	4	16.509	0.0026	Drive
	Haldex GG 4515ED-HX3020-2FF	8	0.697	0.0041	Webb 67518F	4	16.514	0.0026	Trailer
PP 2	Haldex GG47020-3020-1FF	4	0.724	0.0047	Webb 61528B	2	15.010	0.0042	Steer
	Haldex GG47070HX-3020-1FF	8	0.826	0.0076	Webb 65884B	4	16.509	0.0026	Drive
	Haldex GG 4515ED-HX3020-2FF	8	0.697	0.0041	Webb 67518F	4	16.514	0.0026	Trailer
RD 375	Meritor SMA 210	8	0.740	0.0024	N/A	2	15.017	0.0014	Steer
	Meritor SMA 210	13	0.816	0.0019	N/A	2	16.500	0.0000	Drive/Trailer
RD 379	Meritor SMA 210	8	0.740	0.0024	N/A	2	15.017	0.0014	Steer
	Meritor SMA 210	13	0.816	0.0019	N/A	2	16.500	0.0000	Drive/Trailer
ST 2226	Fleet Pride OTR Red 4725 E2	2	0.853	0.0007	Webb 67518F	2	16.507	0.0028	Steer
	Fleet Pride OTR Red 4515Q	1	0.724	0.0000	Webb 67518F	1	16.500	0.0000	Tag
	Fleet Pride OTR Red 4707 E2	8	0.851	0.0035	Webb 63032F	4	16.514	0.0025	Drive
ST 2235	Fleet Pride OTR Red 4715Q	4	0.822	0.0041	Webb 65152B	2	16.507	0.0028	Steer
	Fleet Pride OTR Red 4515Q	1	0.724	0.0000	Webb 66864F	1	16.500	0.0000	Tag
	Fleet Pride OTR Red 4515Q	8	0.724	0.0057	Fleet Pride OTR Red 4515Q	4	16.509	0.0018	Drive

The issue then was how to assign a given starting measurement to a specific component. A Monte Carlo simulation, i.e., a method for iteratively evaluating a deterministic model using sets of random numbers as inputs, was adopted to solve this problem. The methodology is very simple and consists initially in generating a large set of random numbers (100 in this case) between 0 and 1. Assuming that the lining thickness drum diameters are normally distributed, the mean and standard deviation of the measurements presented in Table 11 were used to build cumulative probability distributions of the parameters of each of the brake components (i.e., thickness of the brake linings and diameter of the drums). Each one of the generated random numbers is then used to draw an observation of the brake lining thickness or drum diameter using the cumulative probability distributions built for that component. The average of these 100 observations was then used as the initial measurement of the component in question, and by subtracting from that the final measurement, the wear of the brake lining was determined (for the drums, the initial diameter was subtracted from the one measured at the end of the test).

The results of the brake lining wear are presented in Table 12 to Table 15. Each table presents the wear of the brake lining for each brake shoe position on the left and right axles. On average, the left and right end of any given axle showed similar wear of the linings, although the data seems to indicate a slightly faster wear of the linings of the right axles (this observation is further investigated later in this section). In 86% of the cases in which the brake shoes are arranged in a top-bottom layout, the linings of the bottom shoe wears at a fast rate than that of the top shoe. The remaining 14% of the cases include the tag axles of the ST 2226 and ST 2235, which are deployed only when required and when deployed carry less weight than the drive axles.

Table 12. Brake Lining Wear – GC 190 and GC 194

GC 190				GC 194			
Brake Shoe Position	**Left [in.]**	**Right [in.]**	**Lining**	**Brake Shoe Position**	**Left [in.]**	**Right [in.]**	**Lining**
Steer Top	0.120	0.132	OTR 4715Q	Steer Caliper	0.141	0.115	Disc Brakes
Steer Bottom	0.149	0.187	OTR 4715Q	Steer Piston	0.161	0.141	Disc Brakes
Drive Front	0.112	0.104	Halidex GG4711QR	Drive Caliper	0.156	0.099	Disc Brakes
Drive Rear	0.172	0.225	Halidex GG4711QR	Drive Piston	0.171	0.115	Disc Brakes
Tag Top	0.089	0.152	OTR 4715Q	Tag Caliper	0.098	0.160	Disc Brakes
Tag Bottom	0.178	0.231	OTR 4715Q	Tag Piston	0.126	0.187	Disc Brakes
Average	0.137	0.172			0.142	0.136	
Avg/1,000 miles	0.0018	0.0022			0.0025	0.0024	

The tables also show the average lining wear per 1,000 miles traveled, which was computed by dividing the average lining wear for a given vehicle and wheel end by the number of miles logged by that vehicle in the test and multiplied by 1,000 miles. The smallest lining wears per 1,000 miles traveled were registered by the RD vehicles, which were equipped with OEM linings (Meritor). When the RDs' wear rates are compared against those of other vehicles, the brake linings of the latter are wearing off between 2 and more than 4 times faster. Of course, this not only depends on the quality of the brake linings, but also on the way the vehicle operates in terms of their braking patterns. For example, it is expected that the RD vehicles would brake less often than the ST vehicles, and therefore the latter would naturally show a faster wear of the linings. Nevertheless, the differences in wear rates per 1,000 miles traveled between the RD vehicles and the other vehicles are significant.

Table 13. Brake Lining Wear – PP 1 and PP 2

PP 1				PP 2			
Brake Shoe Position	**Left [in.]**	**Right [in.]**	**Lining**	**Brake Shoe Position**	**Left [in.]**	**Right [in.]**	**Lining**
Steer Top	0.162	0.154	Haldex GG47020-3020-1FF	Steer Top	0.057	0.034	Haldex GG47020-3020-1FF
Steer Bottom	0.174	0.149	Haldex GG47020-3020-1FF	Steer Bottom	0.060	0.102	Haldex GG47020-3020-1FF
Ax 2 Top	0.199	0.237	Haldex GG47070HX-3020-1FF	Ax 2 Top	0.102	0.128	Haldex GG47070HX-3020-1FF
Ax 2 Bottom	0.215	0.278	Haldex GG47070HX-3020-1FF	Ax 2 Bottom	0.132	0.151	Haldex GG47070HX-3020-1FF
Ax 3 Top	0.239	0.310	Haldex GG47070HX-3020-1FF	Ax 3 Top	0.120	0.108	Haldex GG47070HX-3020-1FF
Ax 3 Bottom	0.252	0.308	Haldex GG47070HX-3020-1FF	Ax 3 Bottom	0.153	0.150	Haldex GG47070HX-3020-1FF
Ax4 -LngA_1	0.233	0.160	Haldex GG 4515ED-HX3020-2FF	Ax 4 Top	0.245	0.202	Haldex GG 4515ED-HX3020-2FF
Ax4 -LngA_2	0.191	0.236	Haldex GG 4515ED-HX3020-2FF	Ax 4 Bottom	0.309	0.305	Haldex GG 4515ED-HX3020-2FF
Ax4 -LngB_1	0.197	0.227	Haldex GG 4515ED-HX3020-2FF				
Ax4 -LngB_2	0.170	0.277	Haldex GG 4515ED-HX3020-2FF				
Ax5 -LngA_1	0.280	0.211	Haldex GG 4515ED-HX3020-2FF	Ax 5 Top	0.258	0.301	Haldex GG 4515ED-HX3020-2FF
Ax5 -LngA_2	0.233	0.198	Haldex GG 4515ED-HX3020-2FF	Ax 5 Bottom	0.372	0.426	Haldex GG 4515ED-HX3020-2FF
Ax5 -LngB_1	0.285	0.334	Haldex GG 4515ED-HX3020-2FF				
Ax5 -LngB_2	0.249	0.364	Haldex GG 4515ED-HX3020-2FF				
Average	0.220	0.246			0.181	0.191	
Avg/1,000 miles	0.0014	0.0016			0.0013	0.0014	

Table 14. Brake Lining Wear – RD 375 and RD 379

Brake Shoe Position	RD 375		RD 379		Lining
	Left [in.]	Right [in.]	Left [in.]	Right [in.]	
Steer Top	0.033	0.024	0.033	0.053	Meritor SMA 210
Steer Bottom	0.047	0.049	0.039	0.079	Meritor SMA 210
Ax 2 Top	0.060	0.045	0.029	0.041	Meritor SMA 210
Ax 2 Bottom	0.085	0.054	0.044	0.040	Meritor SMA 210
Ax 3 Top	0.059	0.068	0.038	0.052	Meritor SMA 210
Ax 3 Bottom	0.084	0.084	0.079	0.040	Meritor SMA 210
Ax 4 Top	0.095	0.078	0.086	0.102	Meritor SMA 210
Ax 4 Bottom	0.116	0.145	0.129	0.120	Meritor SMA 210
Ax 5 Top	0.147	0.170	0.115	0.115	Meritor SMA 210
Ax 5 Bottom	0.160	0.216	0.117	0.122	Meritor SMA 210
Average	0.089	0.093	0.071	0.076	
Avg/1,000 miles	0.0005	0.0005	0.0005	0.0006	

Table 15. Brake Lining Wear – ST 2226 and ST 2235

Brake Shoe Position	ST 2226		ST 2235		Lining
	Left [in.]	Right [in.]	Left [in.]	Right [in.]	
Steer Top	0.004	0.007	0.069	0.074	Fleet Pride OTR Red 4725 E2
Steer Bottom	0.025	0.018	0.117	0.099	Fleet Pride OTR Red 4725 E3
Tag Top	0.045	0.018	0.048	0.055	Fleet Pride OTR Red 4515Q
Tag Bottom	0.003	0.032	0.059	0.010	Fleet Pride OTR Red 4515Q
Ax 3 Top	0.067	0.074	0.115	0.119	Fleet Pride OTR Red 4707 E2
Ax 3 Bottom	0.100	0.076	0.168	0.169	Fleet Pride OTR Red 4707 E3
Ax 4 Top	0.090	0.126	0.161	0.151	Fleet Pride OTR Red 4707 E4
Ax 4 Bottom	0.081	0.114	0.149	0.170	Fleet Pride OTR Red 4707 E5
Average	0.052	0.058	0.111	0.106	
Avg/1,000 miles	0.0015	0.0017	0.0028	0.0027	

Table 16 presents the results of the drum diameter change during the test period. For each axle, the drum elongation was similar for the left and right end, although once again there was a slight tendency in the data (58% of the cases) to show larger diameter elongation on the right wheel end. This finding is further investigated in the next section.

Table 16. Brake Drum Diameter Change – All Vehicles

Vehicle	Axle	Left [in.]	Right [in.]	Drum Type
GC 194	Steer	0.0141	0.0169	N/A
	Drive	0.0180	0.0129	
	Tag	0.0128	0.0141	
	Average/1,000 miles	0.00026	0.00026	
PP 1	Steer	0.0476	0.0363	Webb 61528B
	Ax 2	0.0668	0.0806	Webb 65884B
	Ax 3	0.0836	0.0576	
	Ax 4	0.0280	0.0316	Webb 67518F
	Ax 5	0.0288	0.0317	
	Average/1,000 miles	0.00033	0.00031	
PP 2	Steer	0.0199	0.0228	Webb 61528B
	Ax 2	0.0256	0.0657	Webb 65884B
	Ax 3	0.0350	0.0401	
	Ax 4	0.0392	0.0310	Webb 67518F
	Ax 5	0.0395	0.0304	
	Average/1,000 miles	0.00024	0.00028	
RD 375	Steer	0.0051	0.0050	N/A
	Ax 2	0.0610	0.0430	
	Ax 3	0.0470	0.0460	
	Ax 4	0.0460	0.0590	
	Ax 5	0.0680	0.0600	
	Average/1,000 miles	0.00026	0.00024	
RD 379	Steer	0.0069	0.0052	N/A
	Ax 2	0.0220	0.0320	
	Ax 3	0.0210	0.0310	
	Ax 4	0.0340	0.0370	
	Ax 5	0.0410	0.0330	
	Average/1,000 miles	0.00019	0.00021	
ST 2226	Steer	0.0086	0.0140	Webb 65266B
	Tag	0.0130	0.0150	Webb 67518F
	Ax 2	0.0173	0.0214	Webb 63032F
	Ax 3	0.0268	0.0287	
	Average/1,000 miles	0.00049	0.00058	
ST 2235	Steer	0.0129	0.0179	Webb 65266B
	Tag	0.0260	0.0290	Webb 67518F
	Ax 2	0.0370	0.0350	Webb 63032F
	Ax 3	0.0362	0.0361	
	Average/1,000 miles	0.00072	0.00075	

In general, Table 16 shows that the axles that support less weight showed a smaller elongation of the diameter of the drums over the test period. For PP 2, the two RD vehicles, and the two ST vehicles, the steer axle drum (left and right sides) presented less deformation than any of the other axle drums. This was also the case for axles 2 and 3 of PP 1, and the left drive drum of vehicle GC 194. The table also provides information about the average drum elongation per 1,000 miles traveled, which was computed in a similar manner as the brake lining wear rates discussed above. Vehicle RD 379 presented the smallest drum diameter elongation per 1,000 miles for both the left and right sides. When this drum diameter elongation rate was compared to that of the other vehicles, it was found that GC 194, PP 1 and PP 2, and RD 375 presented elongation rates that were, in the majority of the cases, less than 1.5 (1.7 for PP 1 left side) that of RD 379. However, when compared to the ST vehicles, the latter showed a rate of drum diameter elongation per 1,000 traveled that was between 2.6 and 3.8 of that of vehicle RD 379.

3.4 STATISTICAL COMPARISON OF LEFT AXLE VS. RIGHT AXLE CHARACTERISTICS

3.4.1 Brake Lining Wear and Drum Diameter Elongation

As discussed in the previous subsection, the results of the brake lining wear analysis seem to indicate that there was a larger wear on the right axle than on the left wheel end. In order to determine if this was a statistically significant observation, a paired, two sample (i.e., left vs. right) t-test was performed on the lining wear data collected in the project. The paired t-test is actually a test that the differences between the two observations is zero (i.e., the wear of the brake linings on the left wheel ends are the same as the wear of the brake linings on the right wheel ends) . Therefore, if D represents the mean of the difference between the left and right wheel-end observations [i.e., $D = \sum (WRij - WLij) / n$ where WRij is the brake lining wear for the ith right wheel end of vehicle j, WLij the null hypothesis is the brake lining wear for the ith left wheel end of vehicle j, and n is the number of observations] then the null hypothesis is:

Ho: D = 0 (the difference between the two observations is zero)

and the alternative hypothesis is:

Ha: D > 0 (the difference is larger than zero)

The paired t-test provides the level of confidence at which the null hypothesis can be rejected in favor of the alternative hypothesis. A high confidence level (greater than 95%) would indicate that the null hypothesis can be rejected in favor of the alternative hypothesis, thus indicating that the right wheel end linings wear at a faster rate than those of the left wheel end. The same statistical technique can be applied to study whether or not the drums on the right wheel end presented larger elongations than those on the left side.

The results of the statistical tests are presented in Table 17. The table shows the mean of the distribution of the differences in lining wear between the right and left wheel ends, the standard deviation of that distribution, the number of observations n, the t-paired statistic, and the level of confidence at which the null hypothesis can be rejected. Similar statistics are presented for the drum diameter elongation. In the case of the lining wear, the null hypothesis could be rejected with more than 98% confidence, indicating that there is strong evidence in the data that the brake linings on the right side of the vehicle wear faster than those on the left side. In the case of the drum diameter elongation, the test indicates that there is not a statistically significant difference between the deformation of the left and right side drums.

Table 17. Brake Lining Wear and Brake Drum Diameter Change Statistical Comparison of Left vs. Right Wheel Ends

	Brake Linings	Drums
	Delta Wear (WR - WL)	Delta DDC* (DDCR - DDCL)
Mean [in.]	0.0104	0.0010
St Dev [in.]	0.0380	0.0112
No of Obs.	72	31
t paired Statistic	2.3184	0.5059
Reject Ho at	98.83%	69.17%

*DDC: Drum Diameter Change

3.4.2 Brake Efficiency and Axle Weight

The brake efficiency data collected during the test also seems to indicate that there is a difference between the left and right side of the vehicle, with the right side showing higher brake efficiencies than the left. Since higher axle weights tend to produce lower brake efficiencies, a subset of the data in which the left and right wheel-end weights were within 1% of one another (i.e., for all practical purposes both wheel ends weighted the same) was selected. Table 18 shows the results of the statistical methodology applied this subset of data. As expected, the null hypothesis of equal left and right axle weights can only be rejected at a very low level of confidence (less than 75%), and therefore for this subset of data the wheel-end weights were the same for the left and right sides. On the other hand, the null hypothesis of equal brake efficiencies could be rejected with 99.53% confidence, thus strongly indicating that the right wheel ends show higher brake efficiencies than those on the left.

Table 18. Axle Weight and Brake Efficiency Statistical Comparison of Left vs. Right Wheel Ends (Left and Right Axle Weights within 1% Difference)

	Delta Weight (WtL – WtR)	Delta Brake Eff. (BEffR – BEffL)
Mean [lb]	-5.3333	0.0332
St Dev [lb]	43.9226	0.0630
No of Obs.	30	30
t paired Statistic	-0.6425	2.7836
Reject Ho at	73.72%	99.53%

These results suggest that there are asymmetries between the left and right side of a vehicle (at least, of those participating in this test) that produce larger brake lining wear and higher brake efficiencies on the right side than on the left side. Those differences could be the result of brake system design, power transfer from left to right, and braking patterns. For example, most off ramps are right turns, downhill (requiring hard application of brakes), and have super-elevations that may result in an uneven distribution of weight (with higher weights on the right side) which in turn could result in higher lining wear on the right wheel ends.

4. LEVEL-1/PBBT CORRELATION STUDY

4.1 LEVEL-1/PBBT ANALYSIS TOOL

The North American Standard Level-1 Inspection and Performance Based-Brake Test Analysis Tool (LPAT) was designed to aid in the analysis of data collected at the FMCSA's CMVRTC by ORNL researchers and interns located at the National Transportation Research Center in Knoxville, Tennessee. The data was originally collected to identify the correlation between the NAS Level-1 Inspection data and PBBT test data. The NAS Level-1 Inspection includes examination of the driver (hours of service, license, etc.), vehicle (brake systems, exhaust systems, fuel systems, etc.), and load requirements. The measurement results are compared to the minimum brake performance standards specified in the Federal Motor Carrier Safety Regulations (§393.52) which requires a 43.5% overall brake efficiency for most CMVs. In addition to this correlation, other analyses can be derived from this program. The LPAT allows the user to select a range of criteria to define data for analysis. The user can select the number of axles, brake efficiency, weight, violations, date range, and overall result of the inspection (pass or fail). The analysis returns the number of vehicles (or wheel ends, if applicable) and the percentage of the data that meets the criteria. Using the LPAT program for analysis, the correlation between NAS Level-1 Inspections and PBBTs was shown to be approximately 60%. Results from this correlation can be used to further support the use of PBBTs in the inspection of CMVs to ensure the safety of motorists on U.S. roads.

4.1.1 Introduction

The Level-1 and PBBT Analysis Tool (Figure 32) is a stand-alone web application designed to help identify trends in the data collected by researchers at the FMCSA CMVRTC. The data resides in a local database for the LPAT tool and there is built in data entry allowing for easy access and analysis. Additional features such as generating comma separated value (.csv) files and performing pre-defined analyses are included.

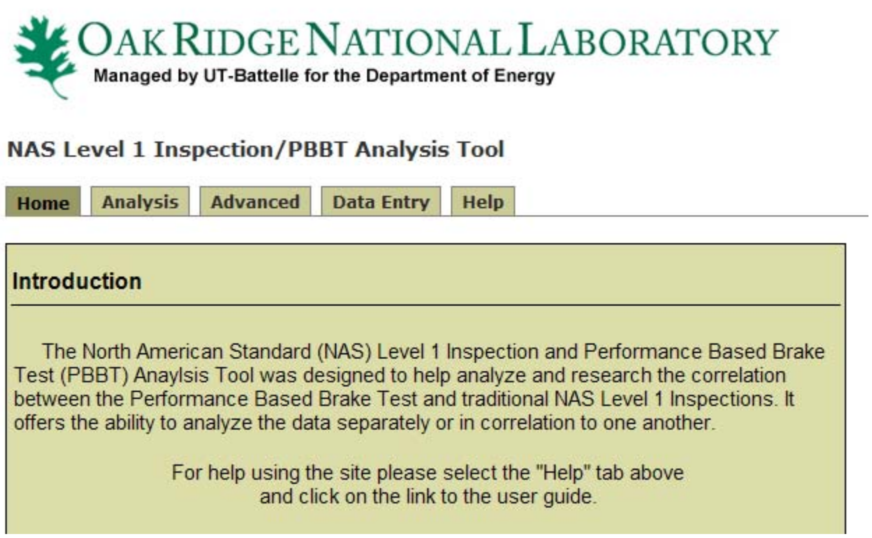

Figure 32. Introduction of Web Application

4.1.2 Analysis Tool

The Analysis Tool allows the user to select the data source and criteria for analysis. There are two types of inspections included in the database with multiple categories. These two inspections are the NAS Level-1 Inspection and the Performance-Based Brake Tester. There are options for each inspection. The analysis will return a pie chart and the number of vehicles matching the criteria chosen out of the number of vehicles analyzed. See Figure 33 below.

4.1.2.1 Categories

The pre-designated categories of data which can be analyzed are Typical, SIRIS, Random, PBBT Valuation Study, Other, Invalid, and BWPT. Categories can be chosen as criteria for the analysis.

Typical: Typical data represents the data collected in Greene County on vehicles chosen at the troopers' discretion.

SIRIS-1, 2, etc.: SIRIS data represents special test data collected in conjunction with the numbered interval of Smart Infrared Inspection System testing.

Random: Random data represents the randomly-selected vehicles chosen by ORNL researchers for the NAS Level-1 and PBBT Correlation Study.

PBBT Valuation Study: PBBT Valuation Study data represents the random vehicles chosen by ORNL researchers for the timed studies done for the PBBT Valuation Study.

Other: This data is not suitable for analysis. Data in this category may have been collected as part of equipment troubleshooting or verification.

Invalid: This data was the result of invalid PBBT tests. Reasons for invalid tests include indicated brake efficiency over 100%, lack of weight measurements, and slam braking.

BWPT: This data was collected from partner vehicles as part of the BWPT FOT.

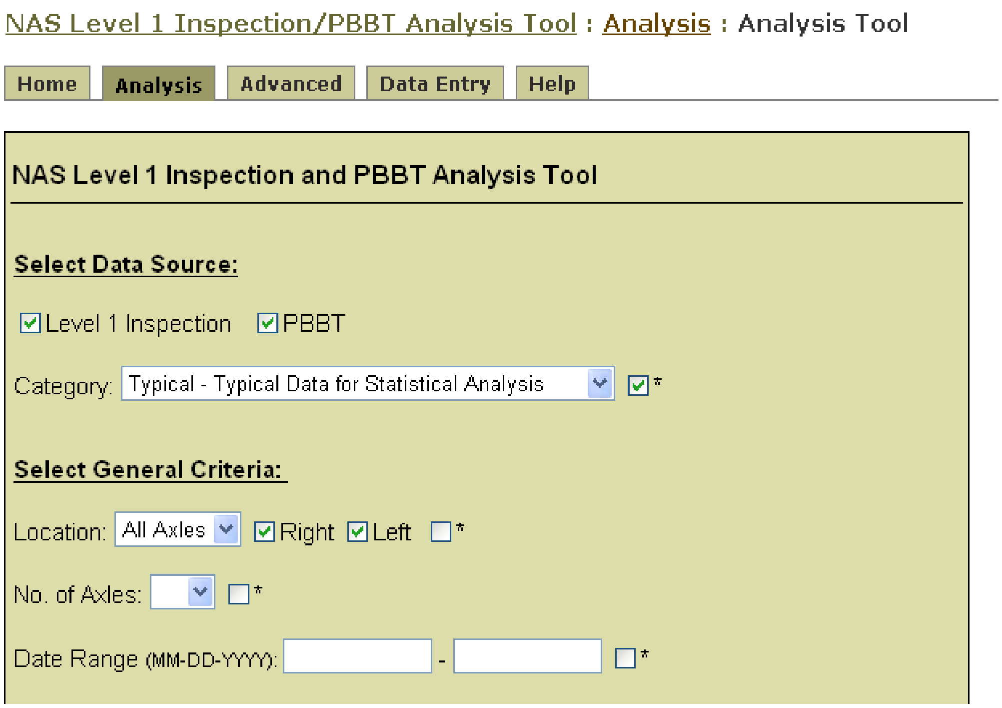

Figure 33. General Data Selection Options

4.1.2.2 NAS Level-1 Inspection

NAS Level-1 Inspections were performed by Tennessee State Troopers at the Greene Country CMV IS which serves as the eastern anchor for the CMVRTC. The NAS Level-1 Inspection includes examination of the driver (hours of service, license, etc.), vehicle (brake systems, exhaust systems, fuel systems, etc.), and load requirements. From this inspection, the following data was collected and made available as criteria for the analysis tool.

Date Range: The data to be analyzed can be screened for a date range (Figure 33). Any standard date format will work. For example, to select all tests after February 1, 2008, for analysis, a date range of 02/01/2008 – [current date] would be entered.

Number of Axles: The number of axles on a vehicle can be selected as an option (Figure 33). Data on vehicles with up to 11 axles is available. The majority of vehicles inspected were five-axle tractor-trailer trucks.

Violations: Violation detail is also available, including the FMCSA regulation code and the location of the violation on the vehicle. The violations are categorized as brake system, air supply and other or driver violations. The location, category or specific violation may be chosen as criteria (Figure 33 and Figure 34).

Overall Result: A violation can result in a vehicle being put (OOS. If a vehicle is put OOS, the vehicle is considered to have failed the inspection. The analysis may be done on either passing inspections or failing inspections (Figure 34). Passing and failing inspections will be included in the analysis if the option is left blank.

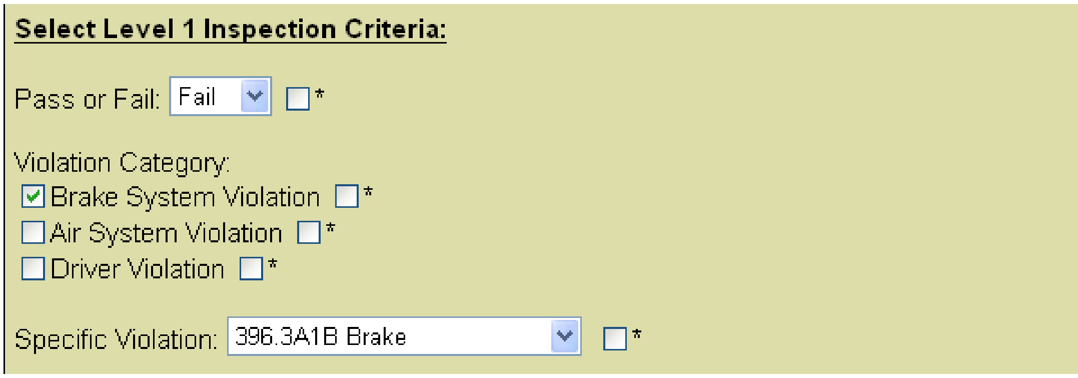

Figure 34. Level-1 Inspection Options

4.1.2.3 Performance-Based Brake Tester

PBBT Tests were also performed at the Greene County CMV IS. The PBBT is a device that measures brake forces at each wheel-end and for the vehicle as a whole to determine the current braking capability of a CMV. The measurement results are compared to the minimum brake performance standards specified in the Federal Motor Carrier Safety Regulation 393.52 which requires a 43.5% overall brake efficiency for most CMVs. From this test the following data was collected and made available as criteria for the analysis tool.

Brake Efficiency: The PBBT records the brake efficiency of the vehicle by measuring the brake force and vehicle's weight and then dividing the brake force by the weight. Operators are available to select a section or range of PBBT tests to analyze (Figure 35). Brake Efficiency must be given in decimal format. For example, .435 is a valid input. Using the greater than or equal to operator allows the selection of all tests with brake efficiencies greater than or equal to the input.

Age: The model year of the tractor is manually entered by the inspector. Using this information, the user can choose an approximate age of vehicles to analyze (Figure 35).

Weight: The weight is recorded as part of the PBBT test and reflects the load of the vehicle at the time of the inspection. The weight must be entered using numerical digits only. A range of weights may be selected by entering the lower and upper bounds in the required text boxes (Figure 35).

Overall Result: Brake efficiency below 43.5% can result in a vehicle being put out of service. If a vehicle's brake efficiency is below 43.5%, the test is considered to have failed the PBBT test. The analysis may be done on either passing tests or failing tests (Figure 35). Passing and failing tests will be included in the analysis if the option is left blank.

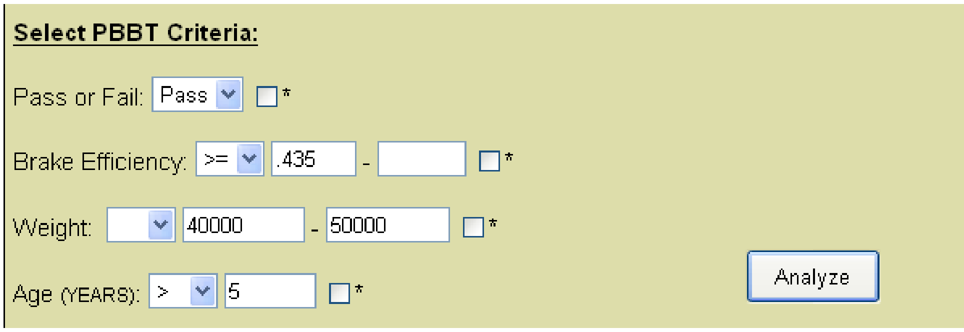

Figure 35. PBBT Options

4.1.2.4 Analysis Tool Results

Results from the analysis are returned with the number of vehicles meeting the selected criteria out of the number of vehicles analyzed. This percent is also represented in a pie chart. A summary of the criteria chosen is shown under the results. Results are created dynamically for every analysis (Figure 36).

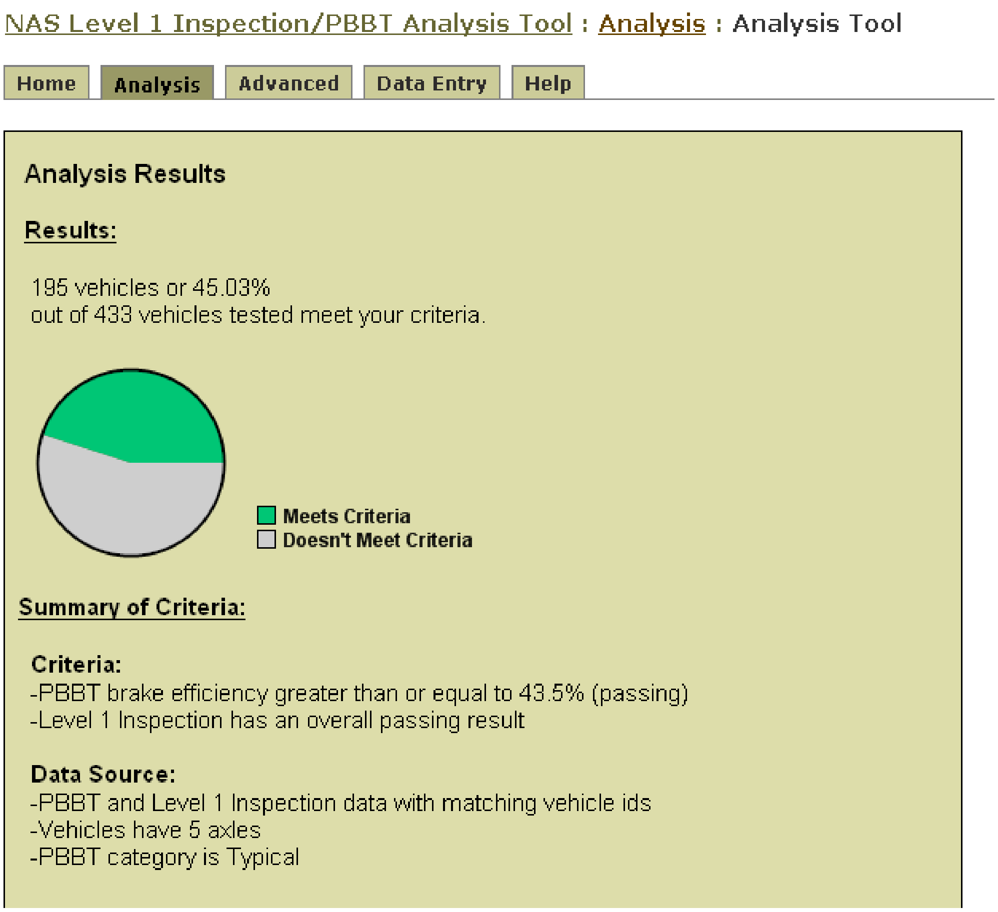

Figure 36. Sample Results of User-Defined Analysis

4.1.3 Data Entry

New NAS Level-1 Inspections and PBBT tests may be added using the data entry forms. NAS Level-1 Inspection data must be manually entered into the form and then submitted into the database. The PBBT test data can be loaded from files with the .vdf extension as shown in Figure 37.

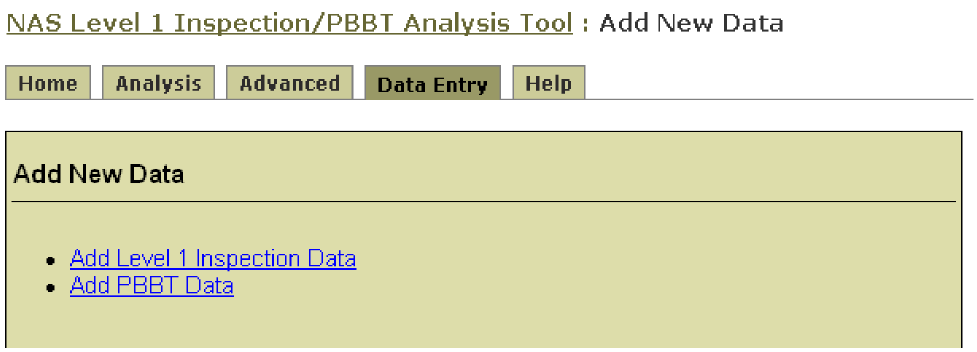

Figure 37. LPAT Data Entry

4.1.3.1 NAS Level-1 Inspection

Data from NAS Level-1 Inspections can be entered using the form in Figure 38. The category, test date, vehicle ID, and US DOT number are required. Right and left brake stroke measurements and the chamber type are required for the number of axles chosen. Any violations should be entered using the drop down boxes in the corresponding category. The overall result is calculated by the program by checking the violations for OOS criteria.

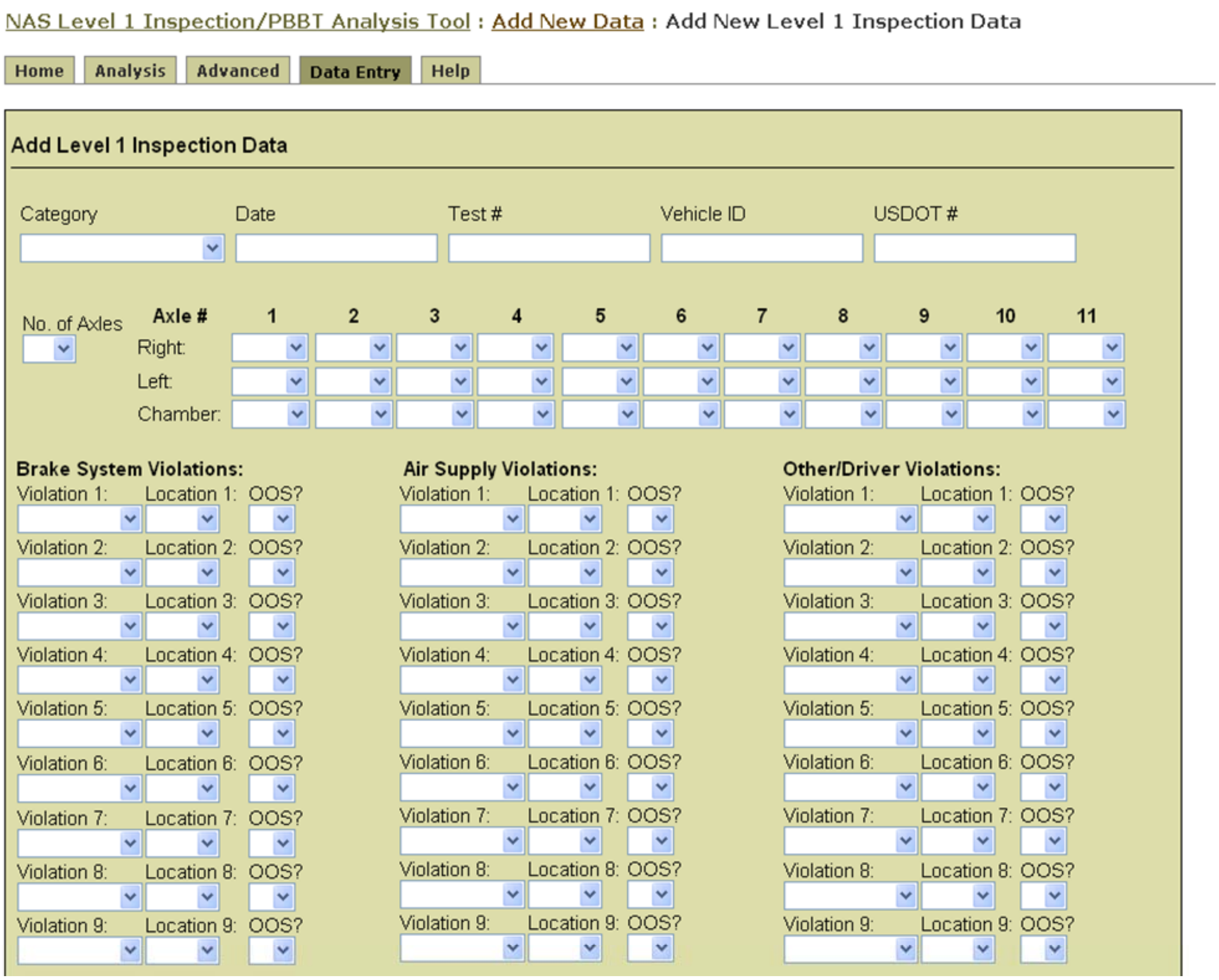

Figure 38. NAS Level-1 Data Entry

The PBBT files can be uploaded using the form in Figure 39. A folder path or a single file path may be chosen. All files with a .vdf extension will be uploaded using the given path. A folder path will overwrite the file path if two paths are given. The default category is typical. If any files are found to be invalid, their category will be reassigned before entry into the database.

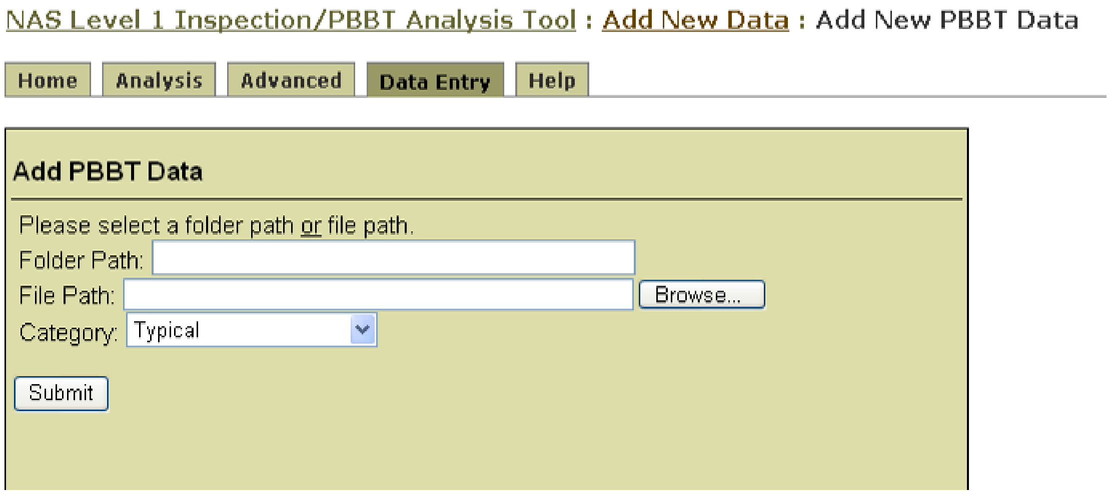

Figure 39. PBBT Data Entry

4.1.4 Additional Features

4.1.4.1 Pre-Defined Analyses

A collection of reports and analyses done on different variables of the data is located in the Analysis section of the program under Pre-Defined Analyses. These reports feature bar charts and pie charts with legends. All reports return the number of vehicles found to be in each category.

4.1.4.2 CSV-Format Downloads

Data in .csv format can be downloaded under the advanced section of the program (Figure 40). The user can limit the data returned in the download by selecting the type of inspection, category, date range, or vehicle ID.

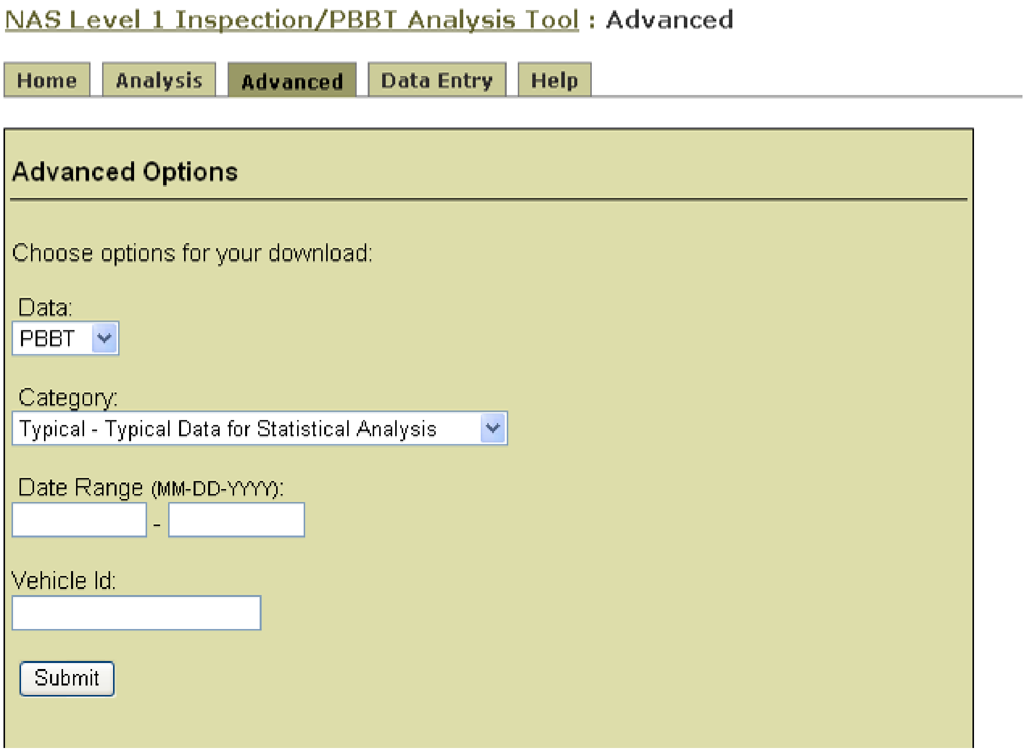

Figure 40. CSV Download Interface

4.1.4.3 User Guide

An "about" page and user guide are available under the help section of the program (Figure 41). The user guide covers the specifics of each option in the program.

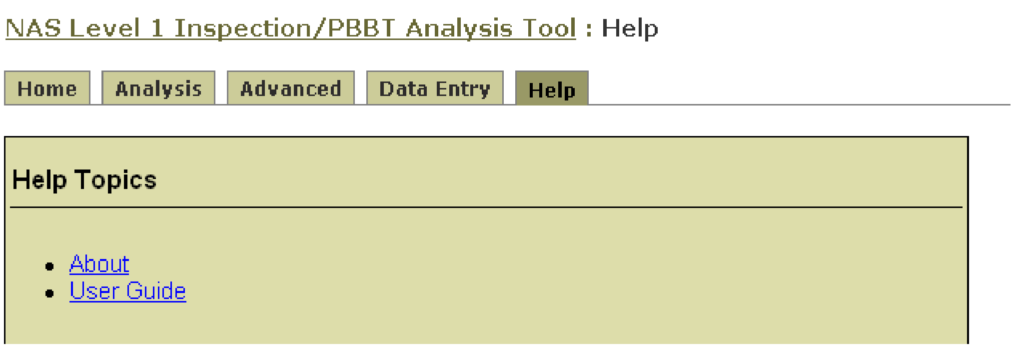

Figure 41. User Guide

4.1.5 Correlation Study

This program supports the correlation study with the Analysis Tool and Pre-Defined Analyses sections. A collection of graphs can be viewed by selecting Level-1/PBBT Correlation from the Pre-Defined Analyses drop-down list of options. In order to do analysis on the correlation using the Analysis Tool, the user must have both Level-1 and PBBT selected for the data source. This will match the two types of data based on the vehicle ID. A sample of such an analysis is shown in Figure 42 below.

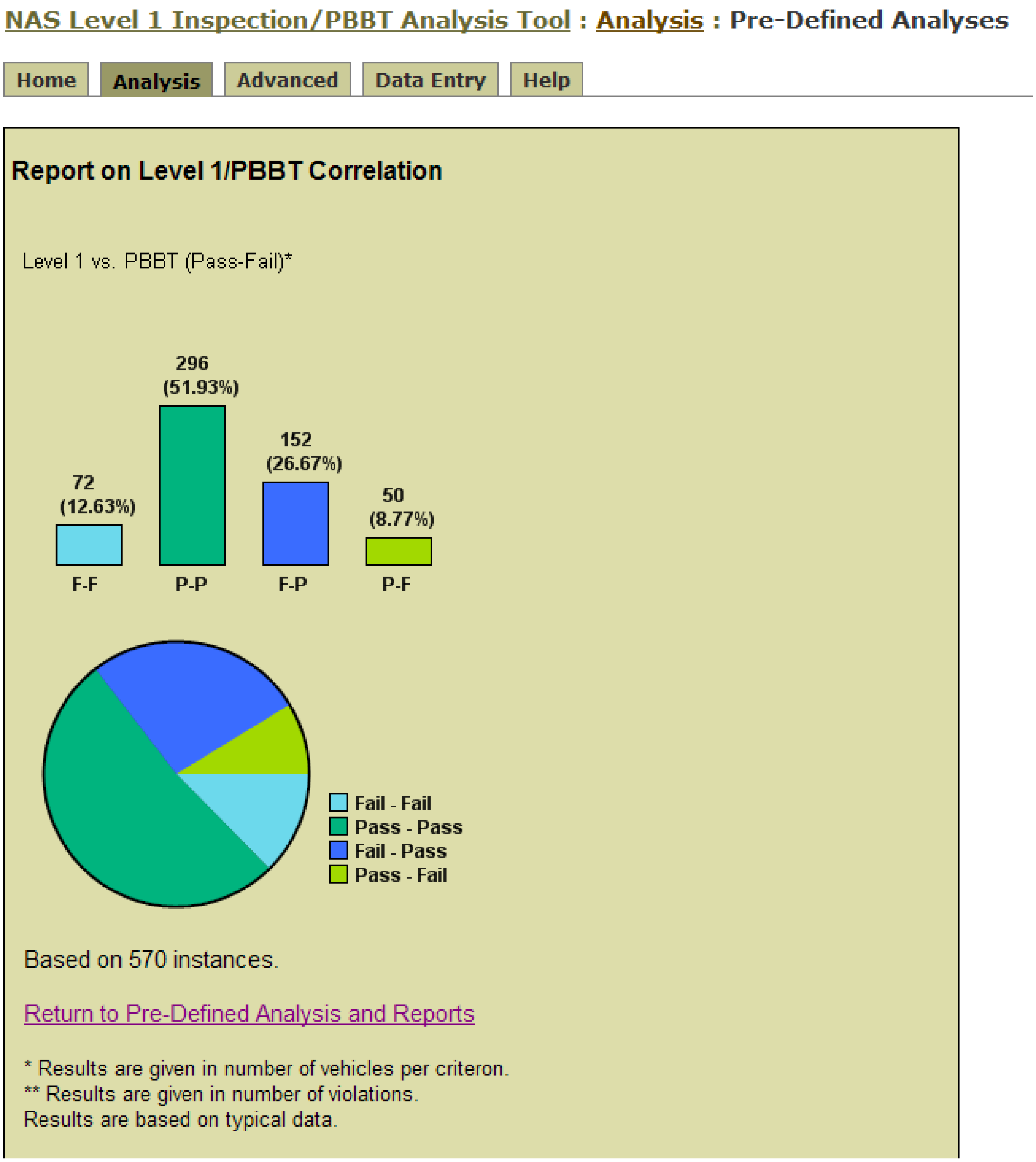

Figure 42. NAS Level-1/PBBT Correlation

4.2 OVERALL RESULTS

Using a pre-defined analysis in the LPAT, general statistics can be generated to describe the pass/fail rates for both Level-1 inspections and PBBT tests. This information for the 570 typical vehicles (selected for inspection using normal enforcement protocols) is summarized in Table 19.

Table 19. Level-1/PBBT Correlation for Typical Data

	Pass PBBT Test (%)	Fail PBBT Test (%)
Pass Level-1 Inspection	51.93	8.77
Fail Level-1 Inspection	26.67	12.63

This information indicates that the Level-1 OOS rate for the Greene County IS is approximately 39%; if the PBBT were used as a stand-alone inspection, the associated Level-4 (special inspection) OOS rate would be about 21%.

4.3 RANDOM SAMPLE CORRELATION

Because the Level-1 OOS rates determined in the correlation study were high compared to the national average, a concern was raised that the method of selecting vehicles to test may not lead to an accurate representation of the vehicle traffic found on I-81. Vehicles are selected by troopers, who are more likely to choose vehicles that they believe will be placed OOS. Because of this, the data analyzed may have a higher percentage of vehicles placed OOS than would be if vehicles are selected randomly from the traffic stream. For this reason, an assessment was performed by selecting random vehicles for testing and comparing the results to the overall study data. The objective of the assessment was to determine the presence and quantity of bias present in the study data.

4.3.1 Data Collection

For the random sample correlation, random vehicles were selected using a set procedure. First, the pre-selection program was set to require all CMVs to pass through the IS. Then the tenth vehicle in the sequence to pass through the station was stopped and tested using the same process as the general study data (Level-1 and accompanying PBBT test).

4.3.2 Results

For the mainline brake assessment, 24 vehicles were tested between October 6, 2008, and November 21, 2008. The results are summarized in Table 20.

Table 20. Level-1/PBBT Correlation for Random Sample

	Pass PBBT Test (%)	Fail PBBT Test (%)
Pass Level-1 Inspection	50.0	4.2
Fail Level-1 Inspection	37.5	8.3

4.3.3 Discussion and Conclusions

The Random Sample Correlation results are surprising, in that the random vehicles were only 1.93% less likely to “pass” both PBBT and Level-1 inspections. This seems to indicate that the current process of selecting vehicles for inspection leads to little difference in the OOS results than a "truly random" selection. This concept which runs counter to expectations because the current method of selecting vehicles is thought to significantly increase the percentage of inspected vehicles that are put OOS.

5. PBBT VALUATION STUDY

The purpose of this study was to determine the PBBT's ability to increase the number of contacts with CMVs and to explore how the PBBT affects the CMV OOS rate. Several test scenarios were employed using NAS Level-1, -2, and -3 CMV inspection criteria in conjunction with PBBT tests. Additionally, Level-1 inspections were performed with and without the use of an inspection pit to determine the time differences between the two methodologies.

5.1 PROJECT OVERVIEW

FMCSA requested ORNL and the THP to conduct a study regarding the use of a CMV inspection pit and PBBT). The purpose of this study was to determine the effects in regard to time savings and OOS rate for the implementation of the following scenarios: the use of a CMV inspection pit to conduct NAS Level-1 inspections, comparison of NAS Level-1, 2, and 3 inspections, and the use of a PBBT. Figure 43 shows a CMV being tested on the PBBT.

Figure 43. CMV Testing on the PBBT

5.1.1 NAS Inspections

The Level-3 inspection includes a check of the driver's credentials (including commercial driver's license and medical examiner's certificate) and hours-of-service information. The Level-2 includes an examination of the credentialing information included in the Level-3 as well as a check of vehicle systems which can be examined without getting under the vehicle (such as lighting devices and tires). The Level-1 inspection includes the elements of a Level-2 inspection in addition to items which require the inspector to go under the vehicle (such as the vehicle's braking system). Level-4 Inspections typically include one-time examinations of a particular item. In this study, the item of interest is the overall braking efficiency, as measured by a PBBT. The completion of a Level-4 Inspection requires the inspector to record the information in Aspen, as with other NAS inspections. A complete list of the components examined in these NAS inspections can be found on the CVSA website at http://www.cvsa.org/programs/nas_levels.aspx.

5.1.2 Test Scenarios

The PBBT Valuation Study involved a series of seven test scenarios performed between June 2, 2009, and July 13, 2009. All tests were conducted within an 8-hour shift during daylight hours. Each test was conducted at the Greene County CMV IS except for the inspection pit savings scenario, part of which was conducted at the Knox County CMV IS. THP provided commissioned officers (troopers) to conduct the study. ORNL randomly selected vehicles for testing by requesting that all vehicles be brought over the scales and choosing the tenth CMV for testing. The tests were conducted in the scenarios described below.

5.1.2.1 Inspection Pit Time Savings

This test was conducted between June 2, 2009, and June 5, 2009. The first two days of testing were conducted at the Knox County CMV IS, and the last two days were conducted at the Greene County CMV IS. ORNL secured two dedicated state troopers to conduct all four days of testing. The method used for testing was to time an entire NAS Level-1 inspection, making note of the time spent conducting the vehicle portion (manual inspection of the equipment). The purpose of this test was to compare the times required when using a mechanic's rolling inspection creeper versus the time needed when using an inspection pit to conduct the vehicle portion of the inspection.

5.1.2.2 NAS Level-1 Inspection Augmentation

This test was conducted between June 15, 2009, and June 16, 2009. The method of testing was to perform both a PBBT test and an NAS Level-1 inspection on each test vehicle. The time periods recorded were those to conduct the PBBT test and the entire Level-1, as well as the vehicle portion of the inspection and the brake stroke measurements within the Level-1.

5.1.2.3 NAS Level-2 Inspection Augmentation

This test was conducted on June 17, 2009, and June 18, 2009. The method of testing was to begin by performing a PBBT test. If the driver passed the PBBT, the trooper performed a NAS Level-2 inspection. If the driver failed the PBBT, the trooper performed an NAS Level-1 inspection. Times recorded for this test were those for the PBBT, and the Level-2 or Level-1. For vehicles which were given a Level-1 Inspection, the time required to complete the vehicle portion of Level-1 was also noted.

5.1.2.4 NAS Level-3 Inspection Augmentation

This test was conducted on June 19, 2009, and June 22, 2009. A PBBT test was performed and timed; if the driver passed the PBBT, an NAS Level-3 inspection was conducted and timed. Otherwise, an NAS Level-1 inspection was conducted, and this time (as well as the time for the vehicle portion) was recorded.

5.1.2.5 NAS Level-1 Replacement

The data for this test scenario was taken on June 26, 2009. The method of testing was to begin by performing a PBBT test and timing this test. If the driver passed the PBBT, the driver was released and no further inspection was performed. If the driver failed the PBBT, an NAS Level-1 inspection was performed; the total time to complete the entire inspection and the portion of time to complete the vehicle portion of the inspection were recorded.

5.1.2.6 PBBT with NAS Level-2

The next test scenario was conducted on June 29, 2009. The purpose of this test was to see how effective and time efficient it would be to merge the PBBT into the NAS Level-2 Inspection. Both of these were performed on each vehicle. The times collected were for the PBBT and the Level-2 Inspection.

5.1.2.7 Stand-Alone PBBT Test

This test was conducted on July 13 and involved running a stand-alone PBBT test on each vehicle. The PBBT times were recorded by task: gathering the drivers' information and running the PBBT.

5.2 PERFORMANCE-BASED BRAKE TESTER

By law, a failed PBBT test is a direct OOS violation, but the PBBT test cannot be used in lieu of the brake stroke measurements taken in a Level-1 inspection. Some potential causes for a vehicle to fail a PBBT test are excessively worn brake linings, excessively worn brake drums, cracked brake drums, air system leaks (including air suspension leaks), broken push rods, or other defects in the vehicle's foundation brake system.

5.3 DATA AND ANALYSIS

5.3.1 Inspection Pit Time Savings

The purpose of this specific study was to provide insight on how the use of an inspection pit compares to using the traditional method of a NAS Level-1 inspection, in which a creeper is used to crawl underneath the CMV. Figure 44 shows a trooper using an automotive mechanic's creeper to perform a brake stroke measurement.

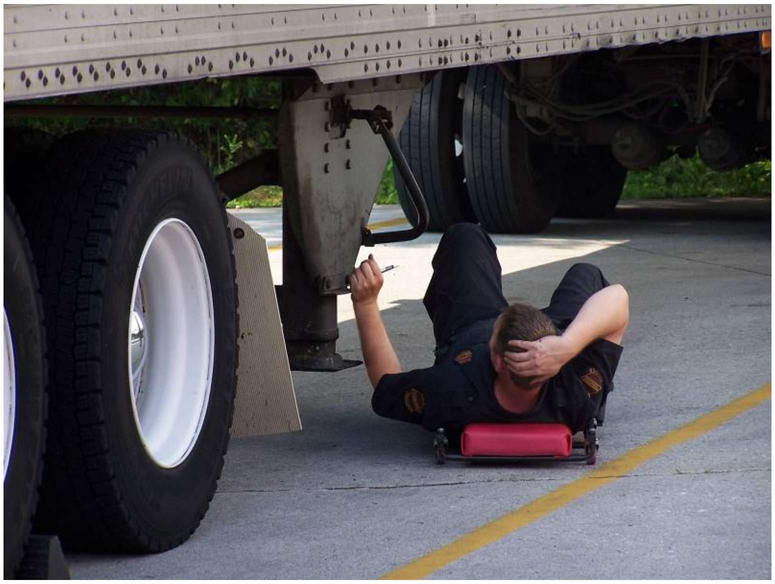

Figure 44. Trooper Performing an NAS Level-1 Inspection with an Automotive Type of Inspection Creeper

Figure 45 displays the inspection pit at the Greene County CMV IS. The variables for which data was collected were inspection times, OOS rate, and number of CMVs contacted within the test period.

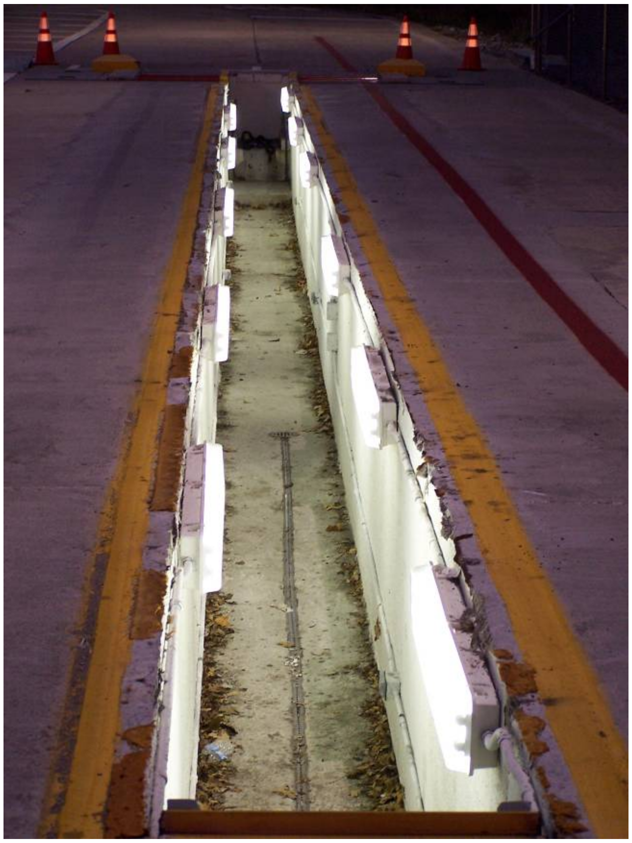

Figure 45. Greene County CMV IS Inspection Pit

Using an inspection pit saved 2.3 min in the vehicle portion of the inspection as opposed to an inspection performed without the benefit of a pit (Table 21).

Table 21. Average Times for Vehicle Portion of Level-1 Inspection with and without a Pit

Location	Vehicle Time (min)
Knox County – No Inspection Pit	21.0
Greene County – Using Inspection Pit	18.7

There were a total of 39 vehicles inspected in this test scenario. Although approximately the same number of vehicles was inspected at each location, there were approximately twice as many vehicles placed OOS using the inspection pit. Table 22 contains a summary of enforcement actions taken during this course of this testing.

Table 22. Overall Enforcement Statistics for Two Days of Testing at Each Location

Enforcement Action	Knox Co. (No Pit)	Greene Co. (With Pit)
Level-1 Inspections	20	19
Warnings	23	25
OOS Actions	4	9

The increased number of vehicles put OOS could be due to a more thorough inspection process for the Greene County inspections: both troopers indicated that they felt they were able to conduct a more thorough inspection with the inspection pit versus the creeper. The inspection pit allowed them to walk underneath the entire CMV so they could check bushings, air leaks, brake linings, and other components more easily. Additionally, the use of the inspection pit made possible the inspection of the tractor drive axles and trailers that could not otherwise have been inspected; some vehicles have obstructions that prevent an officer from crawling under the vehicle. Inspections performed at the Greene County IS involved less noise from the road due to the inspection pit's location away from other CMVs. The troopers could hear air leaks better and also had easier communication between the driver and trooper. The inspection pit was shown to be a more efficient and effective tool to conduct a Level-1 inspection.

5.3.2 NAS Level-1 Inspection Augmentation

The purpose of this test scenario was to compare the time required to conduct a PBBT test to the time needed to perform the brake stroke measurement portion of the Level-1 inspection. Figure 46 shows a trooper performing a brake stroke measurement.

Figure 46. Brake Stroke Being Measured

Other parameters of interest were the OOS rate and the overall time savings afforded to the Level-1 inspection by the use of the PBBT test in lieu of the brake stroke measurement. This test method was completed for 17 CMVs. Table 23 shows the average times for various components of the NAS Level-1 Inspection Augmentation.

Table 23. Average Times for NAS Level-1 Inspection Augmentation

Component	Time (min)
PBBT Test (for this scenario)*	10.8
Total Level-1 Inspection	32.2
Vehicle Portion of Level-1	13.1
Brake Stroke Portion of Level-1	5.4
*Excluding time to enter into Aspen	

The times shown in Table 23 reflect the average times for all vehicles tested in the three days that this scenario was used. The PBBT time included the time to explain the test to the driver, collect the driver's information, and complete the testing of the vehicle. The PBBT test took approximately twice as long as the brake stroke measurement. Out of these 17 inspections, there were a total of 9 CMVs put OOS. Out of these nine, only five vehicles failed the PBBT. The other four passed the PBBT but were put OOS on other criteria. Only one of these was placed OOS solely due to brake stroke lengths. In order to fail the brake stroke measurement, 20% of the vehicle's wheel-ends have to be out-of-adjustment. These OOS vehicles had problems including inoperative brakes, air leaks, or insufficient brake force.

5.3.3 NAS Level-2 and Level-3 Inspection Augmentations

The purpose of these two test scenarios was to quantify the time savings with the PBBT and to determine the resulting effect on the OOS rate. There were 12 CMVs inspected for the Level-2 inspection augmentation and 15 CMVs inspected for the Level-3 Inspection Augmentation. Table 24 shows the average times for these two test scenarios. Vehicles were first given a PBBT test. Vehicles which failed this test were given a Level-1 Inspection, and vehicles which passed were given a Level-2 or Level-3 Inspection according to the scenario being employed.

Table 24. Average Times for Components of the NAS Level-2 & 3 Inspection Augmentation Scenarios

Component	Time (min)
PBBT Test	9.4
Level-2 Inspection	23.7
Level-3 Inspection	14.9
Level-1 Inspection	33.4

Based on the difference between the Level-2 and Level-3 Inspections, it took an average of 5.6 min to perform the vehicle walk-around. On average, conducting a Level-2 Inspection in conjunction with a PBBT saved approximately 5.3 min over performing a Level-1 alone. Conducting a Level-3 Inspection with a PBBT resulted in a time savings of 10.9 min over a conducting a full Level-1 Inspection.

5.3.4 NAS Level-1 Replacement

The purpose of the NAS Level-1 replacement test scenario was to determine how using a PBBT test in lieu of a Level-1 Inspection would affect the number of CMVs contacted and the OOS rate. As shown in Table 25, in a given time period nearly three times the number of CMV contacts could be made with the PBBT as opposed to using a traditional Level-1 Inspection.

Table 25. Average Times for NAS Level-1 Replacement

Component	Time (min)
PBBT Test*	9.0
Level-1 Inspection	32.0
*Excluding time to enter into Aspen	

5.3.5 PBBT with Level-2 Inspection

The use of the PBBT with Level-2 Inspection was a new test scenario integrated into the PBBT Valuation Study after preliminary analyses. This test was performed because the initial analysis of data from the NAS Level-2 Inspection Augmentation (Section 5.3.3) indicated that this scenario might be the most efficient methodology to identify the maximum number of vehicles with OOS defects in a given amount of time. Table 26 summarizes the results of this scenario.

Table 26. Average Times for PBBT and Level-2

Component	Time (min)
PBBT Test*	8.0
Level-2 Inspection	17.7
*Excluding time to enter into Aspen	

5.3.6 Stand-Alone PBBT

In the stand-alone PBBT test scenario, a PBBT test was performed for each vehicle to determine how much time it takes to run a PBBT test, excluding the time it takes to gather the driver's information and to enter it into the computer. This test involved 15 CMVs. Table 27 displays the average times for each portion of this test and compares these times to the time needed to measure the brake stroke.

Table 27. Average Times for PBBT and Brake Stroke Measurement

Component	Time (min)
Total PBBT time*	7.1
Running PBBT	5.1
Driver info collected	2.0
Brake Stroke Measurement**	5.8
*Excluding time to enter into Aspen **Estimate from other test scenarios	

The data collected shows that it takes approximately 5.1 min to run only the PBBT test and approximately 2.0 min to collect the driver information. The brake stroke measurement data shown in Table 27 is an average of data collected in other scenarios. From this test scenario, the vehicle portion of the PBBT test was found to be slightly faster that the brake stroke measurement conducted in the Level-1 inspection.

5.3.7 Overall Data Collection and Analysis

A total of 132 CMVs were contacted during the PBBT Valuation Study. Within the data collected, analyses were performed to quantify time savings with the PBBT and determine differences in the OOS rates between the various test scenarios in an effort to determine the number of various types of inspections which could be conducted during a given time period. Table 28 summarizes the enforcement actions performed during the course of this testing.

Table 28. Summary of Enforcement Activity during Testing

Date (s)	Test Scenario	Number of CMVs				
		Total Contacted	Passed PBBT	Failed PBBT	Invalid PBBT	Placed OOS
June 2-5	Inspection Pit Time Savings	39	N/A	N/A	N/A	13
June 15-16,26	Level-1 Inspection Augmentation	19	12	5	2	10
June 17,18	Level-2 Inspection Augmentation	12	7	5	0	4
June 19,22	Level-3 Inspection Augmentation	15	9	3	3	4
June 23,24	Level-1 Replacement	22	17	4	1	5

		Number of CMVs				
June 29	Level-2 with PBBT	10	8	1	1	1
July 13	Stand-Alone PBBT	15	9	5	1	0*
TOTAL		132	62	23	9	37
* PBBT results were not entered into Aspen for this scenario, therefore no vehicles were placed OOS.						

The information collected in this test was used to generate a worksheet to compare the estimated number of CMV contacts and OOS orders for various types of inspections. A sample worksheet for a 4-hour time period is shown in Table 29.

Table 29. CMV Enforcement Resource Evaluation Worksheet

Category	Inspection Type	Summary Statistics		Estimate for Inspection Period	
		Average time (min)	OOS Rate (%)	CMV Contacts	CMVs/Drivers OOS
Existing Inspections	Level-1 Inspection	45	26.6	5	1
	Level-2 Inspection	20	22.4	12	3
	Level-3 Inspection	15	9.2	16	1
	Level-4 Special Inspection: PBBT Test	16	24.4	15	4
Hybrid Inspections	Level-2 Inspection + PBBT Test	31	34.5	7	2
	Level-3 Inspection + PBBT Test	26	29.5	9	3
Other	PBBT Test to replace Brake Stroke in Level-1 Inspection	48	23.6	5	1
*Estimates shown are based on a 4-hr inspection period using estimated times for Level-1, -2, and -3 inspections provided by CVSA. OOS rates are from the 2009 Safety Check where available and experimentally-determined values from this study were used where national data were not available.					

Another goal of this study was to see how the time to conduct a PBBT compared to equivalent times for NAS Level-1, -2, and -3 inspections. Table 30 displays the average time results for all test data with the exception of data collected as part of the inspection pit comparison study.

Table 30. Overall Average Times

Component	Time (min)
Total Level-1 Inspection	32.5
Vehicle Portion	13.1
Brake Stroke	5.9
Level-2 Inspection	19.8

Component	Time (min)
Level-3 Inspection	14.9
Level-4 Special Inspection: PBBT Test	16.0
Conduct Test	9.0
Complete Aspen report*	7.0
*Estimate from trooper feedback (~5 min for identifying information and ~2 min for PBBT results)	

5.4 SUMMARY OF RESULTS AND CONCLUSIONS

While the data from the pit comparison study does not seem to indicate a significant time savings associated with the use of an inspection pit, it does appear that using a pit allows the inspector to find more defects. For this short-term test, the NAS Level-1 scenario resulted in the highest OOS rate compared to the other scenarios. Based on the testing times, the use of the Level-3 inspection would result in the highest number of CMV contacts in a given period of time. In most cases, the NAS Level-4 special inspection using the PBBT screening test was found to be the least time-consuming; however, this inspection does not involve a check of the driver's credentials or equipment. The data collected in this study was used to develop a worksheet to help determine the most effective use of personnel in a given time period based on typical inspection times and OOS rates.

In conclusion, the PBBT Valuation Study provided valuable information regarding time savings, OOS rates, and the number of vehicles which could be contacted using various inspection methods. The inspection pit was shown to be beneficial because its use doubled the OOS rate in the small sample of vehicles tested, although it did not appear to increase the number of vehicles contacted. This is explained by the better access to the underside of the vehicle, allowing the officer to conduct a more thorough inspection.

Referring to Table 29, the Level-4 Special (PBBT) Inspection has the best OOS rate and provides nearly the best CMV contact rate, but does not provide any check of the driver or carrier. For this testing, the Level-1 inspection had the lowest contact rate and OOS rate of all existing inspections and potential hybrid inspections studied. By substituting the PBBT test for the brake stroke measurement portion of the Level-1 very little time was saved and there was no change in the OOS rate.

The best inspection methodology would seem to be through the combination of the PBBT test with the Level-2 or Level-3 Inspection to optimize the number of CMVs contacted and placed OOS for a given time period.

6. ADDITIONAL TESTING TASKS

A number of additional brake or PBBT-related testing tasks were completed under the Brake Wear and Performance Test. A summary of these efforts is provided below. In most cases, stand-alone reports were also issued at the completion of each task.

6.1 INDEPENDENT TESTING OF THE EWJ PBBT MACHINE

6.1.1 Objective

The main objective of the tests was to determine the accuracy of the EWJ PBBT machine in measuring axle weight and artificial axle load. The PBBT tested is currently in use at the I-81 CMV IS in Greene County Tennessee. The tests were also designed to establish if there were any discrepancies between the data collected by the PBBT machine and the data reported by the WinBrake software used to conduct a PBBT test.

6.1.2 Introduction

This testing was conducted on November 28, 2007. The test was divided into two parts. In the first part, portable scales (PS), which are regularly used by the THP, served as instruments to gather "ground truth" weight and axle load data. In this part of the test, only the PBBT weighing capabilities were used and no brake performance tests were conducted. Note: the roller portion of the PBBT machine could not be operated while the PS devices were being used. The second part of the tests focused on brake performance testing, involving exclusively the PBBT machine. In both parts, independent voltage signals for the brake force, weight and AAL transducers were collected directly from the EWJ control box, prior to manipulation by any software algorithm.

A GMC C5500 (21-ft steel AATAC rollback body, wheel lift) truck was used as the test vehicle (TV) for both sessions. The TV was weighed at the Greene County IS on a certified scale prior to the start of the tests. The weight ticket indicted 7,420 lb for the steer axle and 8,140 lb for the drive axle of the TV, with a total weight of 15,550 lb. WinBrake software version 1.29 was used in conjunction with the PBBT machine EPROM version 1.29.

6.1.3 Test Protocols

6.1.3.1 Part A

The test consisted of placing portable scales on top of the PBBT rollers and then placing the wheels of the axle to be tested on top of the portable scales (see Figure 47).

Figure 47. Test Setup (Steer Axle)

For the tests involving the steer axle, two portable scales were used, one for each wheel, while four scales were used when the drive axle was tested (see Figure 48).

Figure 48. Test Setup (Drive Axle)

The test started by measuring the weight of each wheel end of the steer axle without AAL using both the scales and the PBBT machine. The readings of the scales were rounded to 50 lb (each interval between consecutive tick marks represented 100 lb). To collect the data generated by the PBBT machine, a data acquisition system (DAS) was connected to different PBBT circuit boards tapping into five channels: Left and Right Wheel Brake Force (not used for Part A of the tests), Left and Right Wheel Weight, and AAL. The gain for each of these raw data signals was provided by EWJ, and these, along with the offsets used in the data reduction, are shown in Table 31. The data collection frequency was set at 10 Hz. See Figure 49 for the location of the circuit boards.

Table 31. Factors Used for DAS Signal Voltage Reduction

	Left BF	Right BF	Left Weight	Right Weight	AAL
Nom. Offset	2.5 volts		2.5 volts		1.0 volts
Offset Used	2.542	2.5208	2.5014	2.5173	0.9963
Gain	4,000 lb/volt		9,000 lb/volt		4,329 lb/volt

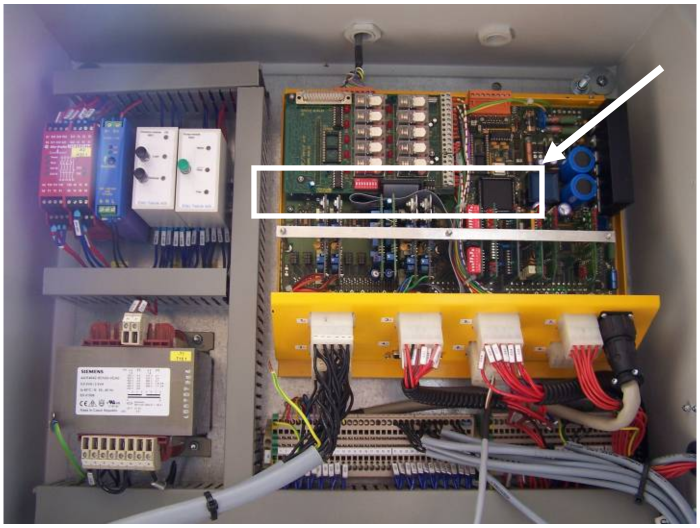

Figure 49. Printed Circuit Board

Following the first test, the AAL was engaged and artificial axle load increments of 500 lb were used up to an AAL of 6,000 lb. For each one of the tests, the scale readings and PBBT display readings were noted and the corresponding file using the DAS was generated.

The same procedure was used for the drive axle tests, except that in this case the maximum AAL was 11,000 lb. The drive axle tests were repeated, but on this occasion using AAL increments of 2,000 lb/3,000 lb instead of 500 lb. The results of this second battery of tests (i.e., AAL increments of 2,000 lb/3,000 lb) was similar to those of the first one (i.e., AAL increments of 500 lb) and are not reported in this document.

6.1.3.2 Part B

In the second part of the tests, regular brake performance tests were conducted on the drive axle of the vehicle using AALs of 0 lb, 3,000 lb, 5,000 lb, 7,000 lb, 9,000 lb, and 11,000 lb. The PBBT display readings were noted and DAS and WinBrake files were generated for these tests.

6.1.4 Test Results

6.1.4.1 Part A

Table 2 shows the results of the steering axle weight tests using the portable scales. Those results are then compared in Table 32 against the PBBT display readings and in Table 4 against those obtained using the DAS. In Table 32, columns 2 and 3 (left and right axle weights) show only one value. This is the axle weight when no AAL was applied. The next column (column 4) indicates the AAL that was specified by the PBBT operator. When applying a given AAL, the PBBT should display the sum of the axle load with no AAL (row 1) plus the specified AAL; since this was not the case, a fifth column was added to Table 33. This column (Round Factor) includes a correction factor such that for any given row in the table, the sum of the axle weight without AAL (row 1) and the AAL of that row equals the total load displayed by the PBBT display.

Table 32. Steer Axle Weight Tests: Portable Scale Readings

Run No.	AAL Called for by Operator [lb]	Portable Scales Readings		
		Left Wheel Weight [lb]	Right Wheel Weight [lb]	Total Axle Weight [lb]
1	0	3,650	3,650	7,300
2	500	3,850	3,800	7,650
3	1,500	4,350	4,350	8,700
4	2,000	4,600	4,550	9,150
5	2,500	4,850	4,800	9,650
6	3,000	5,050	5,000	10,050
7	3,500	5,300	5,200	10,500
8	4,000	5,500	5,450	10,950
9	4,500	5,700	5,650	11,350
10	5,000	5,950	5,850	11,800
11	5,500	6,150	6,100	12,250
12	6,000	6,350	6,300	12,650

Table 33. Steer Axle Weight Tests: Portable Scale Readings vs. PBBT Display Readings

Run No.	PBBT Display					Portable Scale	% Error
	Left Wheel Weight [lb]	Right Wheel Weight [lb]	AAL Called for by Operator [lb]	AAL Round Factor [lb]	Total Axle Weight [lb]	Total Axle Weight [lb]	
1	3,680	3,720	0	0	7,400	7,300	1.37
2	3,680	3,720	500	-100	7,800	7,650	1.96
3	3,680	3,720	1,500	-100	8,800	8,700	1.15
4	3,680	3,720	2,000	-100	9,300	9,150	1.64
5	3,680	3,720	2,500	-100	9,800	9,650	1.55
6	3,680	3,720	3,000	-100	10,300	10,050	2.49
7	3,680	3,720	3,500	-100	10,800	10,500	2.86
8	3,680	3,720	4,000	-100	11,300	10,950	3.20
9	3,680	3,720	4,500	-100	11,800	11,350	3.96
10	3,680	3,720	5,000	-100	12,300	11,800	4.24
11	3,680	3,720	5,500	-100	12,800	12,250	4.49
12	3,680	3,720	6,000	-100	13,300	12,650	5.14

The information shown in Table 34 was collected using the DAS which was connected to the PBBT circuitry. The DAS was set to run for 30 sec starting from the moment the PBBT operator pressed the “Start” button and collected data at 10 Hz. The values displayed in columns 2 and 3 of Table 34 were generated by averaging the last 50 readings (i.e., the last 5 sec of the 30-sec data collection period) of the DAS left and right axle weight channel data stream. A visual inspection of the data indicated that the applied AAL became stable at about 10-15 sec into the data collection, so it was judged that the interval 25-30 sec from the time the rollers begin to move was representative of the axle weight. The same procedure was used to determine the AAL values. The AAL was computed using the signal from the pressure and a calibration factor provided by EWJ (see Table 31).

Notice that the DAS left and right weight channels provided the weight of the axle plus the AAL (so the total axle weight, column 7 in Table 33, is the sum of the values provided in columns 2 and 3). The DAS-collected AAL channel is shown in column 4 of Table 34, while the subsequent column presents the actual AAL. For any given run in Table 34, the actual AAL was computed as the difference between the sum of the left and right wheel weight for that run (column 7) minus the sum of the left and right wheel weight for run 1.

Table 34. Steer Axle Weight Tests: Portable Scale Readings vs. PBBT DAS Readings

Run No.	PBBT DAS						Portable Scale	% Error
	Left Wheel Weight [lb]	Right Wheel Weight [lb]	DAS AAL [lb]	Actual AAL [lb]	AAL Called for by Operator [lb]	Total Axle Weight [lb]	Total Axle Weight [lb]]	
1	3,641	3,721	2	0	0	7,361	7,300	0.84%
2	3,646	3,725	433	9	500	7,370	7,650	-3.66%
3	4,119	4,198	918	956	1,500	8,317	8,700	-4.40%
4	4,469	4,549	1,748	1,657	2,000	9,018	9,150	-1.44%
5	4,697	4,785	2,076	2,121	2,500	9,482	9,650	-1.74%
6	4,953	5,071	2,792	2,662	3,000	10,023	10,050	-0.27%
7	5,247	5,287	3,200	3,173	3,500	10,534	10,500	0.32%
8	5,371	5,487	3,418	3,496	4,000	10,857	10,950	-0.85%
9	5,639	5,722	4,069	3,999	4,500	11,360	11,350	0.09%
10	5,800	5,948	4,601	4,387	5,000	11,749	11,800	-0.44%
11	6,032	6,177	5,168	4,848	5,500	12,209	12,250	-0.33%
12	6,223	6,359	5,230	5,221	6,000	12,582	12,650	-0.53%

The last column of Table 33 shows the error between the portable scale measurements and the readings presented by the PBBT display. The results indicate that when using the PBBT display readings, there is an overestimation of the total load and this error increases with load, up to a maximum of about five percent at 6,000 lb of AAL.

In Table 34, the errors are shown between the portable scale measurements and those computed using the DAS. When the DAS information is used, the errors become very small (except for a several cases at low AAL loads) and can be considered negligible. That is, they are within the margin of error that can be expected by an operator reading an analog portable scale with tick marks at 100-lb intervals and using equipment that is not completely error free. For example, notice that when comparing the portable scale readings for the case with no AAL (i.e., 7,300 lbs; see row 1, column 5 in Table 32) against the Green County IS weight ticket (i.e., 7,410 lbs), the portable scales show an error of -1.62% (i.e., a weight measurement underestimation). The trooper helping with the tests pointed out to the researchers that in general, the portable scales were less accurate when measuring low weights than at higher weights. This was later confirmed when the drive axle tests were conducted (see Table 5, first row in which the portable scales showed a weight underestimation of only 0.5% when compared with the Greene County IS weight ticket; that is, 8,100 lbs vs. 8,140 lbs, respectively).

Discussions with the manufacturer of the PBBT machine indicated that the weight figures shown in the PBBT display are computed by adding the AAL specified by the operator to the initial axle weight. Those displayed figures may not coincide (and in fact they did not coincide for these tests) with the actual load measurements (i.e. axle weight and AAL) provided by the PBBT, thus explaining the larger errors in Table 33 when compared with those of Table 34.

Similarly to the three previous tables, Table 35, Table 36, and Table 37 show the results of the drive axle tests.

Table 35. Drive Axle Weight Tests: Portable Scale Readings

Run No.	AAL Called for by Operator [lb]	Portable Scales Readings				
		Left Wheel 1 Weight [lb]	Left Wheel 2 Weight [lb]	Right Wheel 1 Weight [lb]	Right Wheel 2 Weight [lb]	Total Axle Weight [lb]
1	0	2,350	1,650	2,250	1,950	8,200
2	3,000	2,900	2,400	2,950	2,350	10,600
3	3,500	3,050	2,500	3,000	2,500	11,050
4	4,000	3,200	2,600	3,050	2,600	11,450
5	4,500	3,400	2,950	3,350	2,750	12,450
6	5,000	3,650	3,050	3,500	3,000	13,200
7	5,500	3,650	3,000	3,500	3,000	13,150
8	6,000	3,950	3,350	3,650	3,200	14,150
9	6,500	3,900	3,450	3,700	3,150	14,200
10	7,000	3,900	3,350	3,650	3,150	14,050
11	7,500	4,150	3,550	3,950	3,350	15,000
12	8,000	4,250	3,600	3,950	3,350	15,150
13	8,500	4,300	3,650	4,150	3,500	15,600
14	9,000	4,450	3,700	4,150	3,550	15,850
15	9,500	4,550	3,950	4,350	3,650	16,500
16	10,000	4,700	4,150	4,450	3,750	17,050
17	10,500	4,850	4,300	4,650	3,950	17,750
18	11,000	4,900	4,450	4,700	4,000	18,050

Table 36. Drive Axle Weight Tests: Portable Scale Readings vs. PBBT Display Readings

Run No.	PBBT Display					Portable Scales	% Error
	Left Wheel Weight [lb]	Right Wheel Weight [lb]	AAL Called for by Operator [lb]	AAL Round Factor [lb]	Total Axle Weight [lb]	Total Axle Weight [lb]	
1	4,040	4,220	0	40	8,300	8,200	1.22
2	4,040	4,220	3,000	0	11,300	10,600	6.60
3	4,040	4,220	3,500	0	11,800	11,050	6.79
4	4,040	4,220	4,000	0	12,300	11,450	7.42
5	4,040	4,220	4,500	0	12,800	12,450	2.81
6	4,040	4,220	5,000	0	13,300	13,200	0.76
7	4,040	4,220	5,500	0	13,800	13,150	4.94
8	4,040	4,220	6,000	0	14,300	14,150	1.06
9	4,040	4,220	6,500	0	14,800	14,200	4.23
10	4,040	4,220	7,000	0	15,300	14,050	8.90
11	4,040	4,220	7,500	0	15,800	15,000	5.33
12	4,040	4,220	8,000	0	16,300	15,150	7.59
13	4,040	4,220	8,500	0	16,800	15,600	7.69
14	4,040	4,220	9,000	0	17,300	15,850	9.15
15	4,040	4,220	9,500	0	17,800	16,500	7.88
16	4,040	4,220	10,000	0	18,300	17,050	7.33
17	4,040	4,220	10,500	0	18,800	17,750	5.92
18	4,040	4,220	11,000	0	19,300	18,050	6.93

Table 37. Drive Axle Weight Tests: Portable Scale Readings vs. PBBT DAS Readings

Run No.	PBBT DAS						Portable Scales	% Error
	Left Wheel Weight [lb]	Right Wheel Weight [lb]	DAS AAL [lb]	Actual AAL [lb]	AAL Called for by Operator [lb]	Total Axle Weight [lb]	Total Axle Weight [lb]	
1	4,020	4,227	-35	0	0	8,247	8,200	0.57
2	5,344	5,407	2,571	2,505	3,000	10,751	10,600	1.43
3	5,614	5,647	3,083	3,014	3,500	11,261	11,050	1.91
4	5,791	5,805	3,300	3,349	4,000	11,596	11,450	1.27
5	6,155	6,133	3,995	4,042	4,500	12,289	12,450	-1.30
6	6,613	6,550	4,567	4,916	5,000	13,163	13,200	-0.28
7	6,623	6,556	4,940	4,933	5,500	13,179	13,150	0.22
8	7,133	6,999	5,517	5,885	6,000	14,131	14,150	-0.13
9	7,147	7,016	5,919	5,916	6,500	14,163	14,200	-0.26
10	7,097	6,996	5,870	5,847	7,000	14,093	14,050	0.31
11	7,634	7,479	6,882	6,866	7,500	15,113	15,000	0.75
12	7,611	7,443	6,864	6,808	8,000	15,054	15,150	-0.63
13	8,002	7,779	7,675	7,534	8,500	15,781	15,600	1.16
14	8,169	7,918	7,770	7,840	9,000	16,087	15,850	1.49
15	8,527	8,195	8,592	8,476	9,500	16,722	16,500	1.35
16	8,803	8,426	9,105	8,982	10,000	17,229	17,050	1.05
17	9,126	8,737	9,635	9,616	10,500	17,863	17,750	0.63
18	9,270	8,857	10,033	9,881	11,000	18,127	18,050	0.43

As in the case of the steer axle tests, the DAS left and right weight channels provided the weight of the axle plus the AAL (so the total axle weight, column 7 in Table 37, is the sum of the values provided in columns 2 and 3). The DAS-collected AAL channel is shown in column 4 of Table 37, while the subsequent column presents the actual AAL. For any given run in Table 37, the actual AAL was computed as the difference between the sum of the left and right wheel weight for that run minus the sum of the left and right wheel weight for run 1 in Table 37.

Again, the results show that when actual measurements are used, as opposed to the values shown in the PBBT display, the PBBT machine is very accurate in determining the axle weight and the added AAL.

6.1.4.2 Part B

The second part of the tests consisted of performing regular brake performance tests on the drive axle of the vehicle. Two rounds of six PBBT tests were conducted using artificial loads of 0 lb, 5,000 lb, 7,000 lb, 9,000 lb, and 11,000 lb (first trial); and 0 lb, 3,000 lb, 5,000 lb, 7,000 lb, 9,000 lb, and 11,000 lb (second trial), respectively. To simplify the test procedure, instead of running six separate PBBT tests for each round, a six axle vehicle was specified in WinBrake thus generating only two files (AAL TEST_071128_150503.VDF and AAL TEST_071128_155356.VDF). The results of these tests are shown in the following tables.

Table 38. Drive Axle PBBT: PBBT Display/WinBrake Screen Data (First Trial)

ID in WB File	Left Wheel Weight [lb]	Right Wheel Weight [lb]	AAL Called for by Operator [lb]	Total Axle Weight [lb]	Left Wheel Brake Efficiency [%]	Right Wheel Brake Efficiency [%]
Axle 1	4,140	4,040	0	8,100	61.6	59.9
Axle 2*	4,140	4,040	0	8,100	62.9	54.0
Axle 3*	4,140	4,040	5,000	13,100	68.0	62.3
Axle 4*	4,140	4,040	7,000	15,100	63.7	53.5
Axle 5*	4,140	4,040	9,000	17,100	62.8	51.5
Axle 6*	4,140	4,040	11,000	19,100	61.3	49.2

* To simplify the test procedure, instead of running six separate PBBT tests for each round, a six axle vehicle was specified in WinBrake. That is, Axle 1 was tested six times with different AAL (0 lbs for round 2; 5,000 lbs for round 3, etc.)

Table 39. Drive Axle PBBT: DAS Data (First Trial)

ID in WB File	Left Wheel Brake Force [lb]	Right Wheel Brake Force [lb]	Left Wheel Weight [lb]	Right Wheel Weight [lb]	Left Wheel Brake Efficiency [%]	Right Wheel Brake Efficiency [%]
Axle 1	2,663	2,551	4,154	4,036	64.1	63.2
Axle 2	2,544	2,802	3,858	4,046	65.9	69.2
Axle 3	4,634	4,150	6,601	6,477	70.2	64.1
Axle 4	4,900	4,112	7,307	7,157	67.1	57.5
Axle 5	5,420	4,599	8,177	7,974	66.3	57.7
Axle 6	5,857	5,097	9,246	8,828	63.3	57.7

Table 40. Drive Axle PBBT: PBBT Display/WinBrake Screen (Second Trial)

ID in WB File	Left Wheel Weight [lb]	Right Wheel Weight [lb]	AAL Called for by Operator [lb]	Total Axle Weight [lb]	Left Wheel Brake Efficiency [%]	Right Wheel Brake Efficiency [%]
Axle 1	3,740	4,160	0	8,000	61.9	62.1
Axle 2*	3,740	4,160	3,000	11,000	63.9	61.3
Axle 3*	3,740	4,160	5,000	13,000	66.8	54.9
Axle 4*	3,740	4,160	7,000	15,000	65.1	52.7
Axle 5*	3,740	4,160	9,000	17,100	60.8	53.9
Axle 6*	3,740	4,160	11,000	19,000	61.9	53.0

* To simplify the test procedure, instead of running six separate PBBT tests for each round, a six axle vehicle was specified in WinBrake. That is, Axle 1 was tested six times with different AAL (3,000 lbs for round 2; 5,000 lbs for round 3, etc.)

Table 41. Drive Axle PBBT: DAS Data (Second Trial)

ID in WB File	Left Wheel Brake Force [lb]]	Right Wheel Brake Force [lb]]	Left Wheel Weight [lb]	Right Wheel Weight [lb]	Left Wheel Brake Efficiency [%]	Right Wheel Brake Efficiency [%]
Axle 1	2,496	3,070	3,949	4,178	63.2	73.5
Axle 2	3,895	3,304	5,404	5,380	72.1	61.4
Axle 3	4,364	4,143	6,414	6,287	68.0	65.9
Axle 4	4,866	4,501	7,480	7,330	65.0	61.4
Axle 5	5,292	4,724	8,135	7,826	65.0	60.4
Axle 6	5,882	5,171	9,261	8,906	63.5	58.1

The results show that in all the cases except one (i.e., left efficiency with specified AAL = 7,000 lb, second trial) the brake efficiencies are always smaller when using the PBBT display (or WinBrake dialog box) data than when using the DAS collected data (or the data included in the native WinBrake files[3]). The previous findings show that the PBBT display almost always overestimated the applied load (see Table 33, Table 36, and Table 37). As discussed previously, the manufacturer indicated that for the weight computations, the AAL level selected by the user is directly added to the axle weight and that result is used in the calculations instead of the measured axle weight plus the AAL load.

6.1.5 Conclusions

The results of the weight tests conducted on November 28th, 2007 at the Greene County IS strongly suggest that the PBBT is very accurate at measuring actual (i.e., axle weight) and artificial loads. However, the load information portrayed on the PBBT display and used in the calculations performed by WinBrake is not a measured load except for the case in which no AAL is used. This calculated load, which results from adding the AAL called for by the operator to the measured axle weight, could impact the determination of the brake efficiencies. It is therefore advisable that a real axle load (taken from the sum of the AAL and individual WL signals) be used in computing the brake efficiencies rather than the additive quantity that is currently utilized.

At present, the brake performance criterion found in FMCSR 393.52 specifies that the vehicle be tested in the "as-is" condition of loading. As such, the use of AAL does not come into play. However, for research purposes, or in the event that braking efficiency is used as a criterion in conjunction with AAL, an alternate method of computing wheel loads to be used in the calculation will be necessary. Note that the maximum difference observed was only 5 percent.

[3] During the analysis, it was noticed that the axle-weight information included in the WinBrake file double counted the AAL specified by the operator. Discussions with the manufacturer indicated that this problem has been solved for version 1.31 of the software, which was installed at the PBBT after the tests described in this report were performed.

6.2 WEIGHT COMPARISON STUDY AND SITE ANALYSIS

6.2.1 Comparison of Brake Efficiency Calculation Methods

In order to resolve the perceived discrepancy of the right side brake efficiency (BE) compared to that of the left side, two potential solutions were explored. The first was to delay reading the weight until after the rollers had begun moving in the expectation that any significant weight transfers which occur during the test would have already taken place; this is the software change proposed by the PBBT manufacturer, EWJ. The second possible solution involved taking the weight readings at the time the brake force reading used in the BE calculation was taken. This would take place either around the time of lockup or at the end of the test (as determined by the software, based on the test outcome). This second solution would be equivalent to the "dynamic" weight setting in the PBBT software.

The first eight tests conducted on February 7, 2008 were used to provide data for a comparison of each of these potential solutions to the current calculation method. Because all three methods of calculating the BE used the same braking force (BF), the appropriate weights were identified in each data file, entered into a spreadsheet, and used to calculate the BF. The overall BE values for each method and test vehicle are shown below in Figure 50.

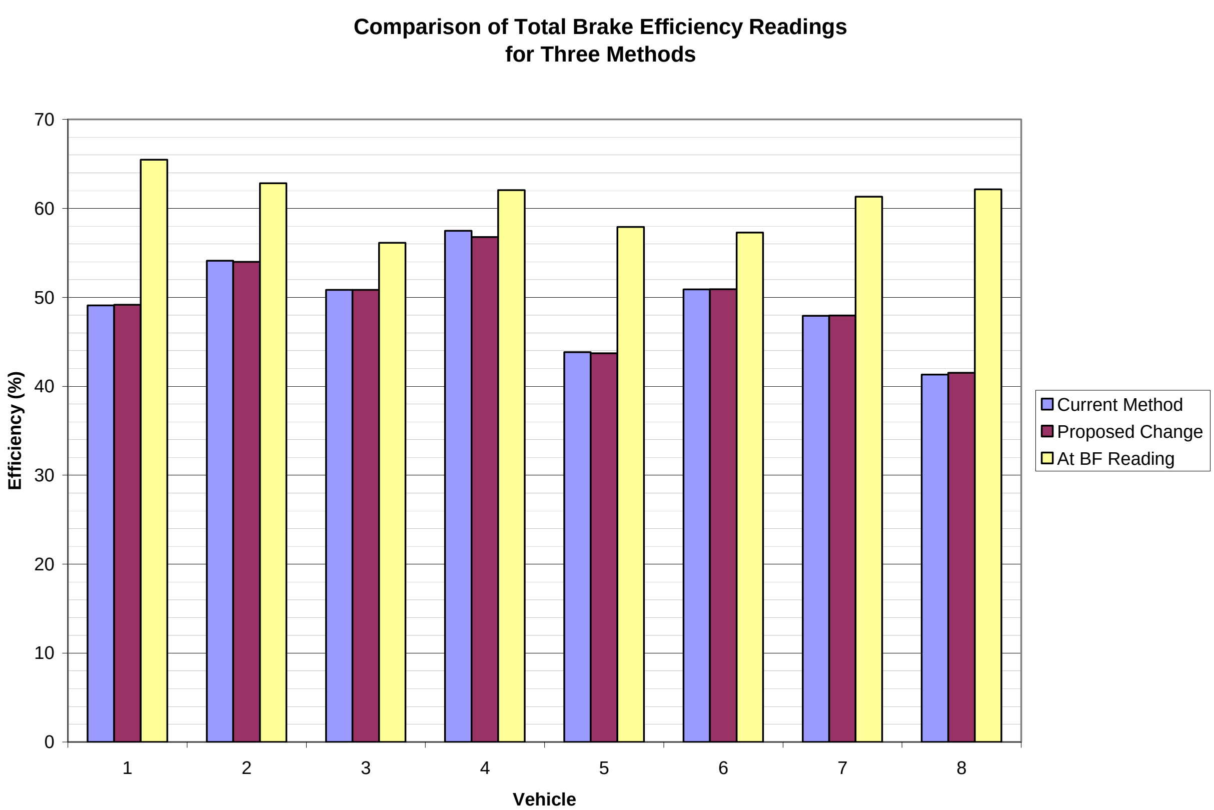

Figure 50. Total Brake Efficiency

It is apparent that the BE calculated using the weight at the time the BF reading was taken is significantly higher than either of the other two methods. While the current method and the

EWJ-proposed change in method yield very similar results, the "dynamic" reading is much higher than both—yet not by a proportional amount. This difference in method could affect whether a vehicle's brakes pass or fail the PBBT test. Vehicle 8, for example (Figure 50), would be put out of service using the current BE calculation method. However, if the weights used in the calculation were obtained at the same instant the BF readings were obtained, this vehicle would pass by a wide margin.

A 1-sec delay was suggested to solve the perceived right and left side values for BE. To quantify this observation, the right BE was subtracted from the left BE and the results shown in Figure 51.

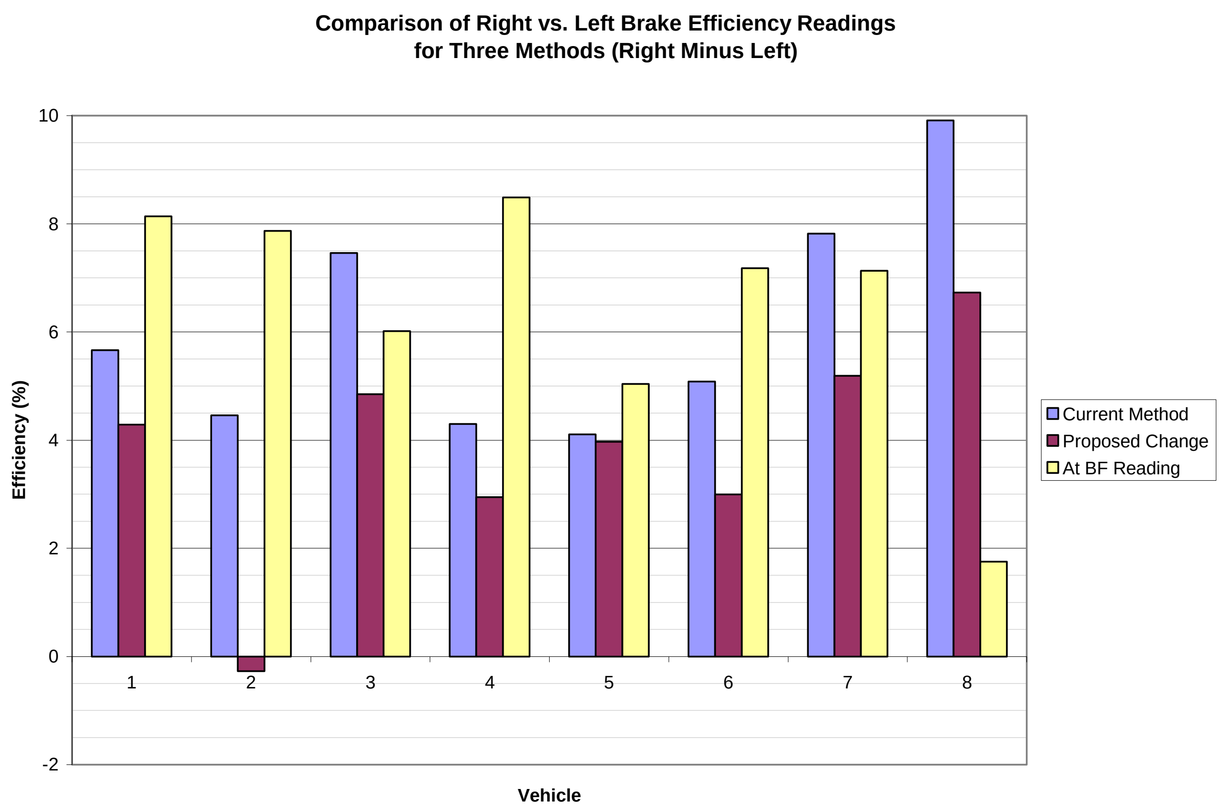

Figure 51. Difference Between Right and Left BE Values

As illustrated in this figure, the proposed change does seem to lessen the discrepancy, but does not solve the problem. All else being equal, it is expected that the right side BE values would be higher than the left approximately half the time. (That is, the difference graphed in Figure 51 would be positive for about half of the tests.) Figure 51 shows that the proposed software change does not solve this discrepancy.

A first-order approximation of a correction for a discrepancy which might be introduced due to the grade was performed by dividing the total weight for each axle evenly between the wheel ends before calculating the brake force. The differences between the right and left BE values after this correction are shown in Figure 52.

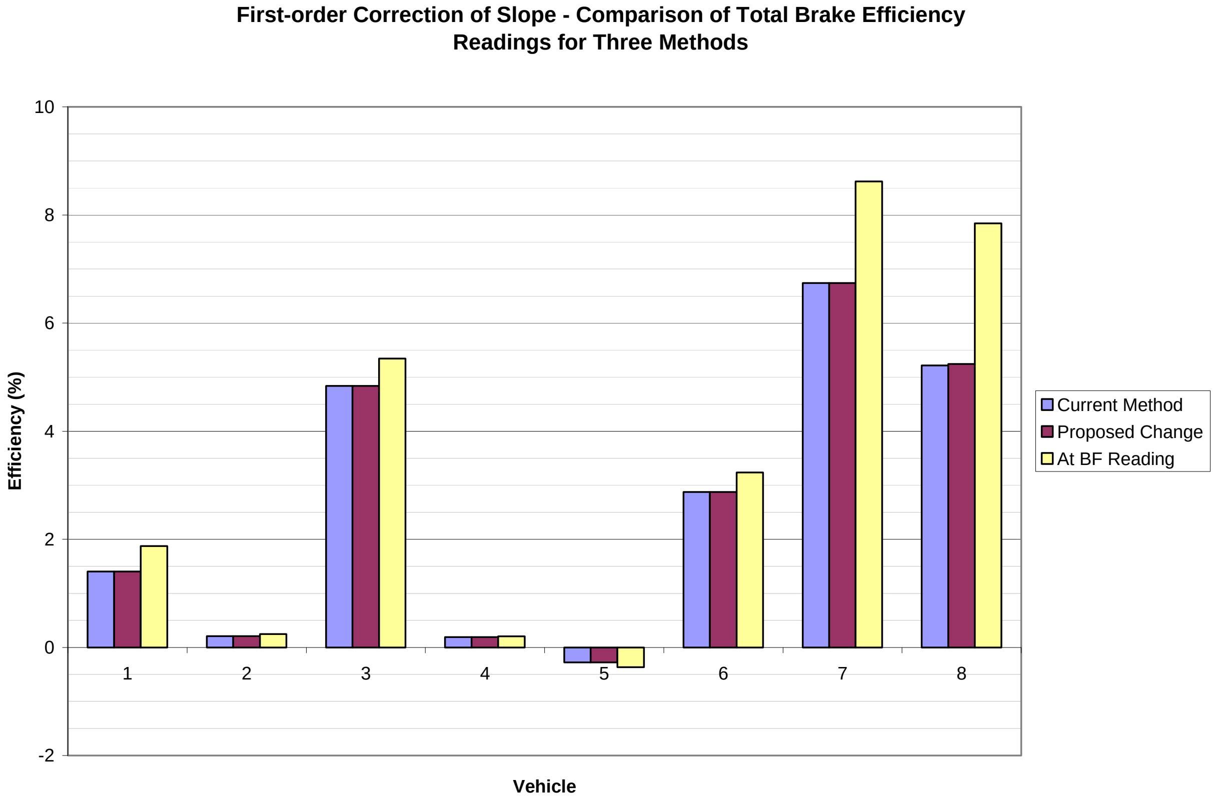

Figure 52. Difference between Right and Left BE Values after First-Order Slope Correction

This simple correction factor reduces the difference between the current method for calculating the BE and the proposed change in method to zero for this small sample. Here again, a successful correction would be marked by an equal number of positive and negative values. However, this is not the case; it seems that a further offset of about 3% would be required to result in a "corrected" set of data. This seems to indicate that there is another factor influencing the right vs. left imbalance other than only the grade of the site.

6.2.2 Site Analysis

Recent analyses focused on the discrepancy between the right and left readings. In addition, the various methods for calculating BE, which were based on weight readings taken at different times during the PBBT test, yielded results with significant disparities, warranting further investigation. In order to quantify the slope of the PBBT site, detailed grade data was taken. Furthermore, the weighing of individual wheel ends for a few vehicles prior to PBBT testing provided necessary "ground-truth" information crucial to the study of both the slope and static-vs.-dynamic weighing methods.

6.2.2.1 Site Grade

Measurement of the grade at the PBBT site revealed two facts about the site not previously realized. First, the difference in height between the right and left sides (measured at the center of each wheel end) is only approximately 1-2 inches along the truck path (approaching and exiting the PBBT). Second, there is an upward slope along the truck's path approaching and exiting the PBBT which translates to an average grade of approximately 0.7%.

The grade data for the PBBT site is graphed in Figure 53. Measurements were taken every 2 ft along the truck path, 100 ft before and after the PBBT.

Figure 53. PBBT Site Elevation Plot

Based on the grade depicted in Figure 53, it would be expected that the weight readings reported by the PBBT would be slightly lower for the steer and/or drive axles and slightly higher for the trailer axles. However, the grade is small enough that this shift is expected to be small (i.e., under 100 lb).

The small difference in height between the right and left sides (approximately 1.5 inches) translates to a lateral slope of only about 1.12 deg. This means that for a standard homogeneously-loaded dry-box van, the weight shift (from the right to the left) would rarely be more than approximately 300 lb. A shift by more than this amount from the actual weight (determined as described in the next section) would seem to be a result of factors independent of the left-to-right slope.

6.2.2.2 Detailed Weights

Individual wheel-end weights were obtained as follows (other than for the first vehicle, in which the process was still being fine-tuned). The information obtained from each reading is shown above each scale position. Figures are not to scale.

1) Weigh the entire vehicle as is done in normal operations (Figure 54).

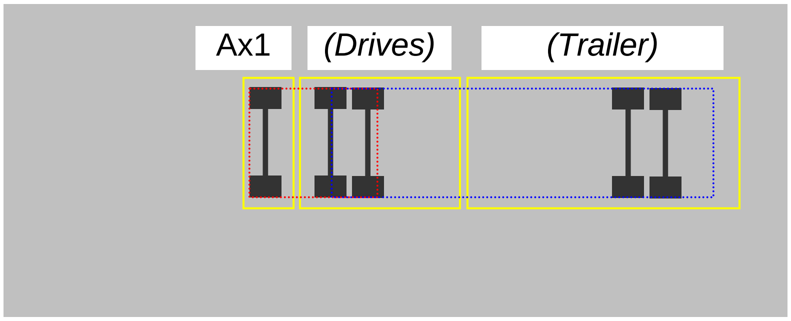

Figure 54. Obtaining Axle-1 Weight

2) Weigh the drive axles separately (Figure 55).

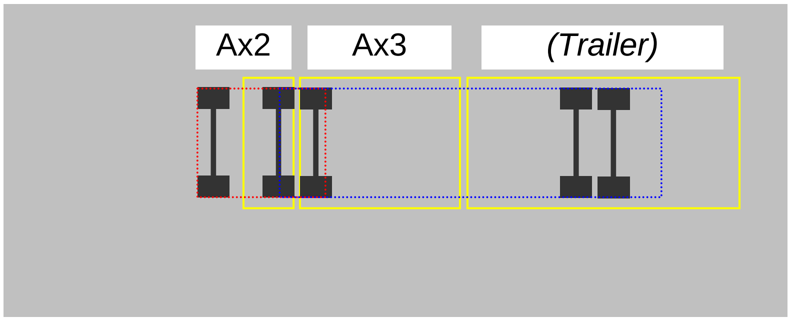

Figure 55. Obtaining Weights for Axles 2 and 3

3) Weigh the trailer axles separately (Figure 56).

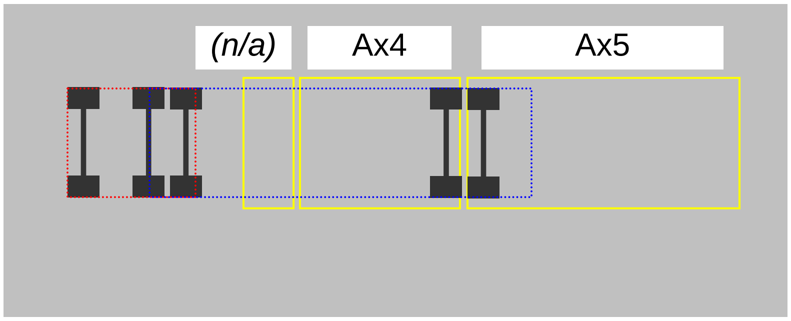

Figure 56. Obtaining Weights for Axles 4 and 5

4) Weigh the entire right side (Figure 57).

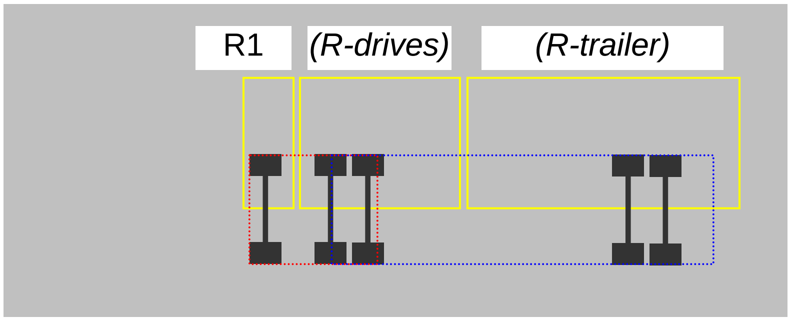

Figure 57. Obtaining Right-Side (R) Weight for Axle 1

5) Weigh the right side of the drive axles (Figure 58).

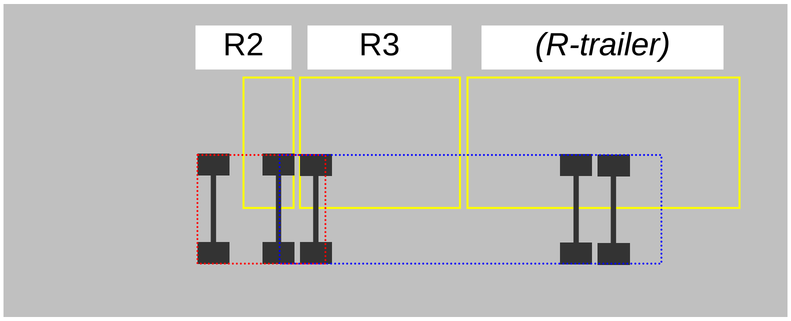

Figure 58. Obtaining Right-Side Weights for Axles 2 and 3

6) Weigh the right-side trailer axles (Figure 59)

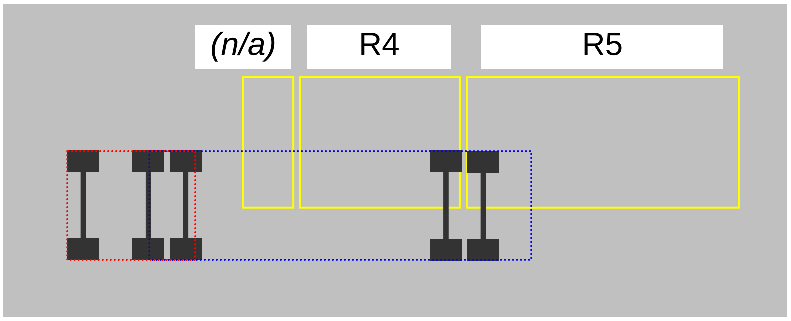

Figure 59. Obtaining Right-Side Weights for Axles 4 and 5

7) Calculate all of the left-side weights.

L1 = Ax1 – R1
L2 = Ax2 – R2, etc.

Due to the nature of the pit scales and type of weigh configurations used, this so-called "ground-truth" approach in some cases yields individual wheel-end weights which, when summed, do not equal the total vehicle weight obtained in Step 1. This error was generally found to be low, the worst-case scenario involving an error of under 6% of the axle group weight (under 2% of the total vehicle weight).

6.2.2.3 *"Ground-Truth" Brake Efficiency Calculations*

The actual weights for each wheel end (obtained from the scales as described in the previous section) were used to calculate the "ground-truth" BE using the braking force measured by the PBBT. The results for total vehicle BE are compared to the three other methods in Figure 60.

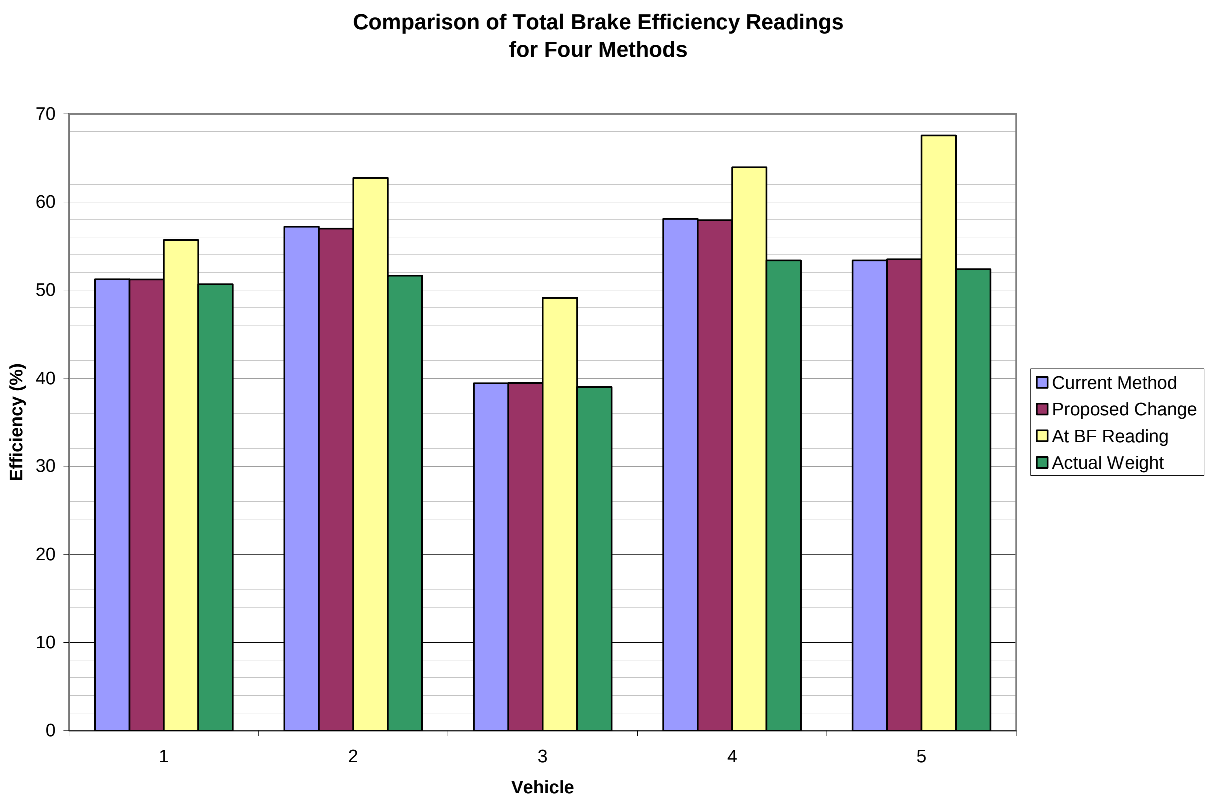

Figure 60. Comparison of the Total BE Calculation Methods for Five-Truck Sample

This figure shows that both the current and proposed "static" methods yield results closer to the actual BE. In contrast, the "dynamic" method (described in Section 6.2.1) yields values much farther from the true BE (based on actual weight), indicating that this "dynamic" method is likely inaccurate. The BE calculated using actual wheel-end weights is lower than any other PBBT-calculated method presented here for this small five-truck sample (although in some of the cases it is quite close to either "static" method).

The right and left BEs were also calculated using this "ground-truth" method. The differences between the right and left BE values were plotted and compared to results of other calculation methods. The results are shown in Figure 61. Note that with this plot, the green "Actual Weight" reading is assumed to be the true difference in BE between the right and left sides. (This analysis is based on the assumption that the brake force measured by the PBBT is correct.)

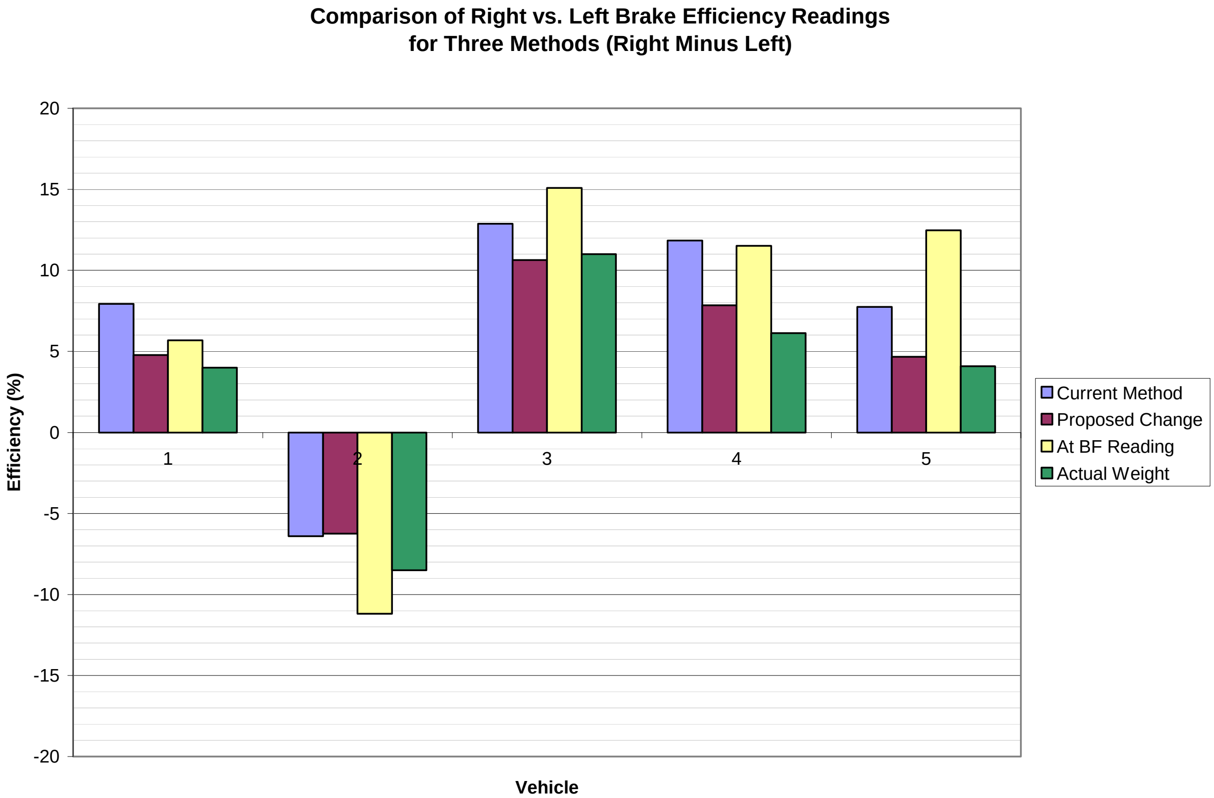

Figure 61. Right Minus Left BE Values

From the small sample shown in Figure 61, it seems that the proposed change (1-sec delay "static" weight) more closely follows the actual BE for most observations. This would also be the conclusion based on Figure 60, which compares total BE calculation methods.

When the right-vs.-left phenomenon of the individual axles themselves was studied (Figure 62), the "ground-truth" method resulted in less of a disparity between the right and left sides. The right side was only higher for 64% of the 25 axles measured (compared to over 75% for all of the other methods). Ideally, given a very large sample size, this ratio is expected to be approximately 50%. For this comparison, the proposed 1-sec delay weight measurement method was closest to the ground-truth value approximately half of the time.

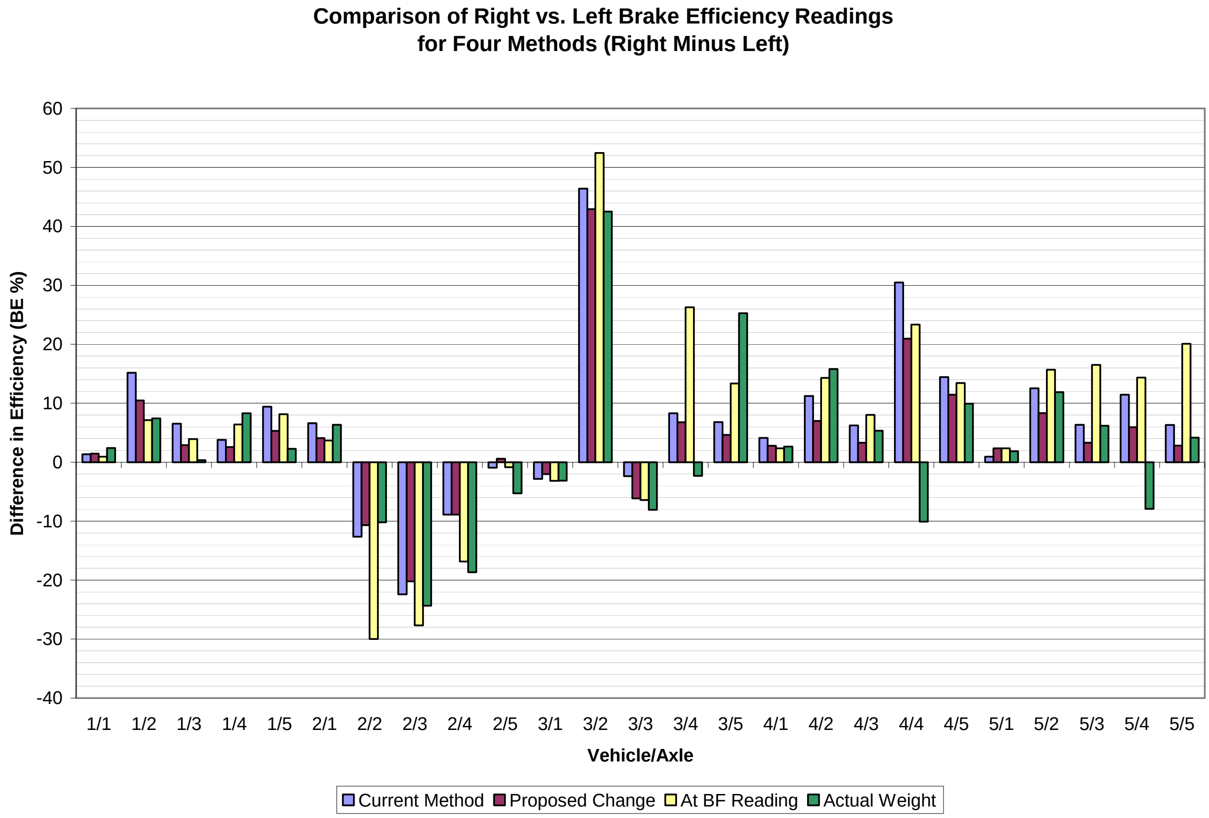

Figure 62. Comparison of Right Minus Left Readings for Each Axle Tested

6.2.2.4 PBBT Weight Measurements during Testing

Figure 63 illustrates the weight gain/loss detected by the PBBT throughout the steer axle tests of the first four test vehicles. Similar plots were prepared for each axle. The ordinate scale is kept consistent for each plot to permit more accurate comparisons.

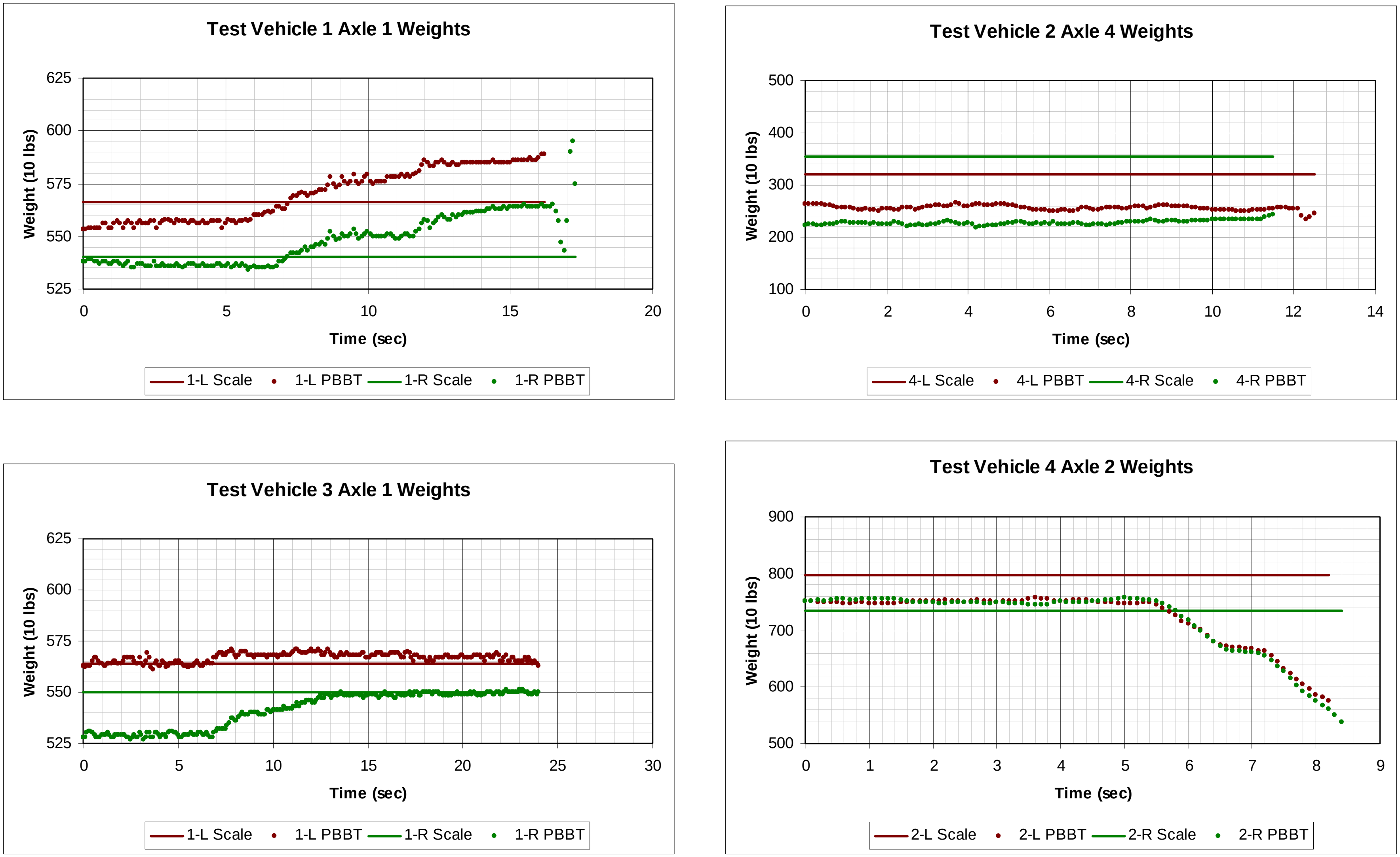

Figure 63. Steer-Axle Weight Plots for the First Four Test Vehicles

In this test, the weight readings begin too low compared to the "ground-truth" measurements (with the exception of the left wheel end trace for Vehicle 3, which is fairly accurate) and then increased before leveling out at the end of the test. For the case of axle 3, the right-side weight levels out at the correct weight, but for the other vehicles it levels out above the correct weight (as would be expected due to the grade). The initial “static” weight for either axle is not off by more than about 200 lb.

6.2.3 Conclusions

Based on the detailed wheel-end weights, the BE calculation method involving proposed 1-sec delay before measuring axle weights seems to be the most accurate of the three PBBT methods explored. Although this 1-sec delay reading method does not line up with the actual weight, it is observed that in each case for this small sample, this would not result in putting a good vehicle out of service (but rather it gives the vehicle the "benefit of the doubt").

The PBBT site elevation measurements were performed in an attempt to provide an algorithm to compensate for the site particulars and to yield accurate results. However, simple predictions based on site elevation do not seem to hold true in actual PBBT testing. Instead, the weight time-history plots from the testing do not seem to give any indication of how to determine actual weight; there are no identifiable trends, even when restricting observations to a particular wheel position. The PBBT weight readings are therefore highly sensitive to some other external factor(s) besides grade. For example, there is likely a significant amount of "weight trading" within each axle group as well as between axle groups as the vehicle's brakes are applied and the ride-height control valves seek to maintain the proper height. Thus, unless another influential, easily-characterized external factor is identified, it appears that the system may be too complicated to provide an increased level of precision in vehicle weight (and therefore BE).

6.3 TESTING OF OVALITY AND ECCENTRICITY

6.3.1 Background

The goal of the ovality study was to explore the effect of wear on ovality and eccentricity, and also the effect of this runout on brake performance. This study is based on the assumption that a new, near-perfect drum is close to perfectly round. Eccentricity (off-centeredness) may be introduced as the drum is mounted on the vehicle. It is commonly believed that ovality (out-of-round) is introduced as the drums heat up in use and the parking brake is set, causing the circular drums to take a set in an oval shape.

It is of interest to determine if and how much this out-of-round characteristic impacts the braking performance of a vehicle. Certain PBBT tests seem to indicate ovality could be an appreciable factor in performance on the PBBT, characterized by a sinusoidal shape superposed on the regular brake curve, such as shown in Figure 64.

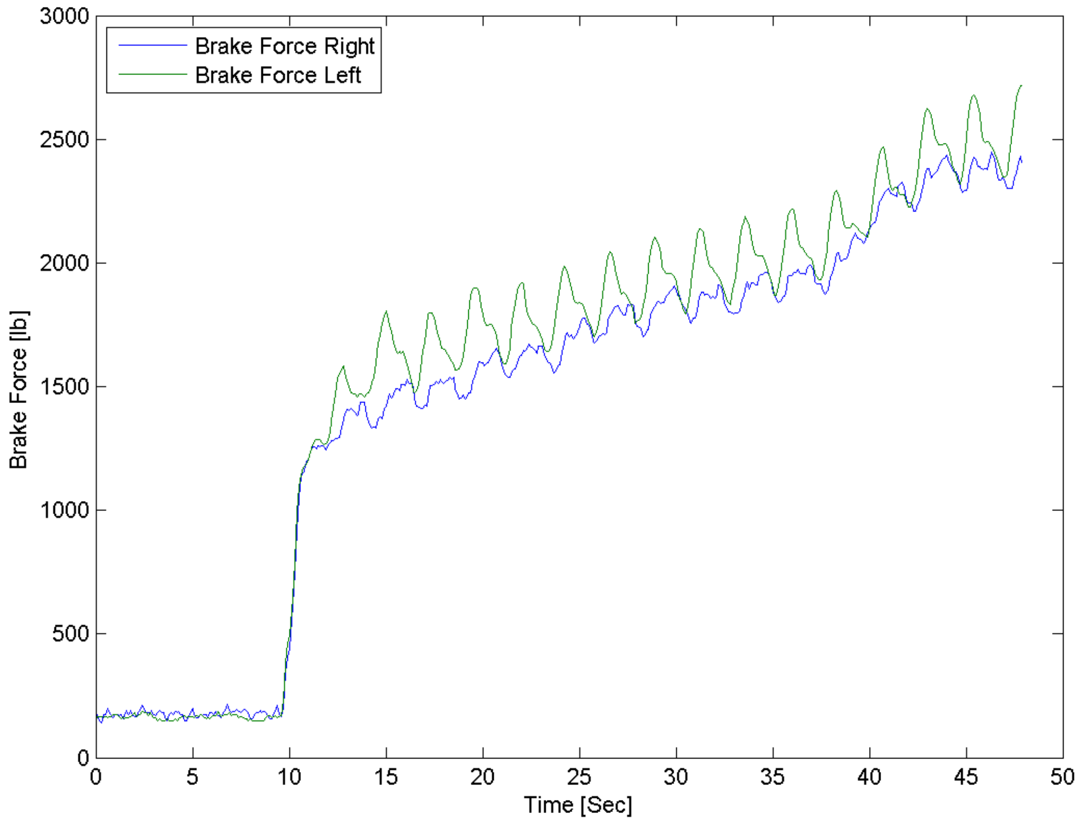

Figure 64. Illustration of Perceived Ovality or Eccentricity in a Brake Force Curve

6.3.2 Methods for Measuring Ovality

6.3.2.1 Dial Indicator

The circular runout was measured with the drum both on and off the vehicle by rotating the drum about a stationary dial indicator. Measurements were taken 1 in from the edge of the drum, because initial tests with a new drum indicated that the drum irregularities are more pronounced toward the drum's edge.

A graphical user interface (GUI) was developed in Matlab to make it possible for the dial indicator to be mounted where it was not visible to the user without perturbing the system by pressing any button on the indicator. The GUI and a sample file are shown in Figure 65.

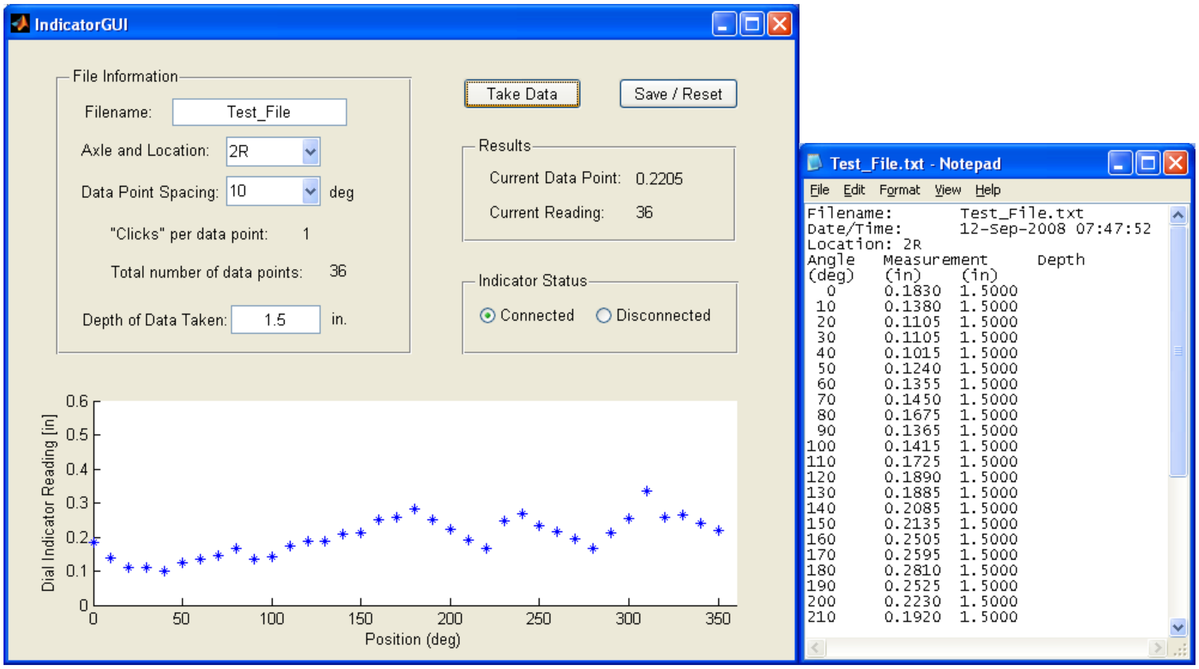

Figure 65. Circular Runout Data Collection GUI and Data File

In order to collect this data while the drums were still on the test vehicle, equally-spaced points had to be marked on the tire and then transferred to the drum so the device operator could take the measurements at the proper locations. The axle was raised slightly so the wheel-end could be rotated into position. A magnetic base was used to fix the dial indicator to the axle so the drum could be freely rotated to the marked positions (Figure 66). The on-vehicle tests revealed that typical circular runouts are likely very low (less than 0.015 in for all of the tested drums).

Figure 66. Collecting Eccentricity and Ovality Data while the Drum is Still Mounted on the Vehicle (RD 379)

Off-vehicle measurements were taken in an effort to decouple the mounting eccentricity from the ovality. This was done with the stand-alone device shown in Figure 67. This device contains a mechanism which ensures that drum is measured in a discrete number of equally-spaced positions (up to 36).

Figure 67. Drum Ovality Data Collection Using Apparatus (RD 379)

Results of the off-vehicle measurements proved inconclusive. For drums measured using both the on- and off-vehicle methods, the circular runout (difference between the maximum and minimum dial indicator readings) measured on the vehicle was in general less than or equal to the circular runout measured on the tester. This indicates that the mounting device did not eliminate the eccentricity, but actually appeared to introduce a significant amount of eccentricity. This arises from the difficulty in working within manufacturing tolerances of both the tester and the drum to construct a device which properly centers the drum on the ovality device and holds it in place without binding.

6.3.2.2 Ovality feature of the PBBT

Currently, an ovality test can be run using the PBBT machine; however, this is a different test from the normal brake efficiency tests. The methodology described here uses the information collected during a regular PBBT test to attempt to measure ovality, thus eliminating the need of extra tests.

During PBBT tests, drivers apply the brakes with increasing pressure as the PBBT rollers maintain constant wheel speed. In most cases, the brake force measured by the machine varies (increases) linearly with time. However, in some instances, roughly sinusoidal disturbances are present in this straight-line plot, possibly indicating brake drum ovality or out-of-roundness. The methodology proposed here isolates these disturbances and measures the amplitude of the quasi-sinusoidal resulting function as a proxy for measuring drum ovality.

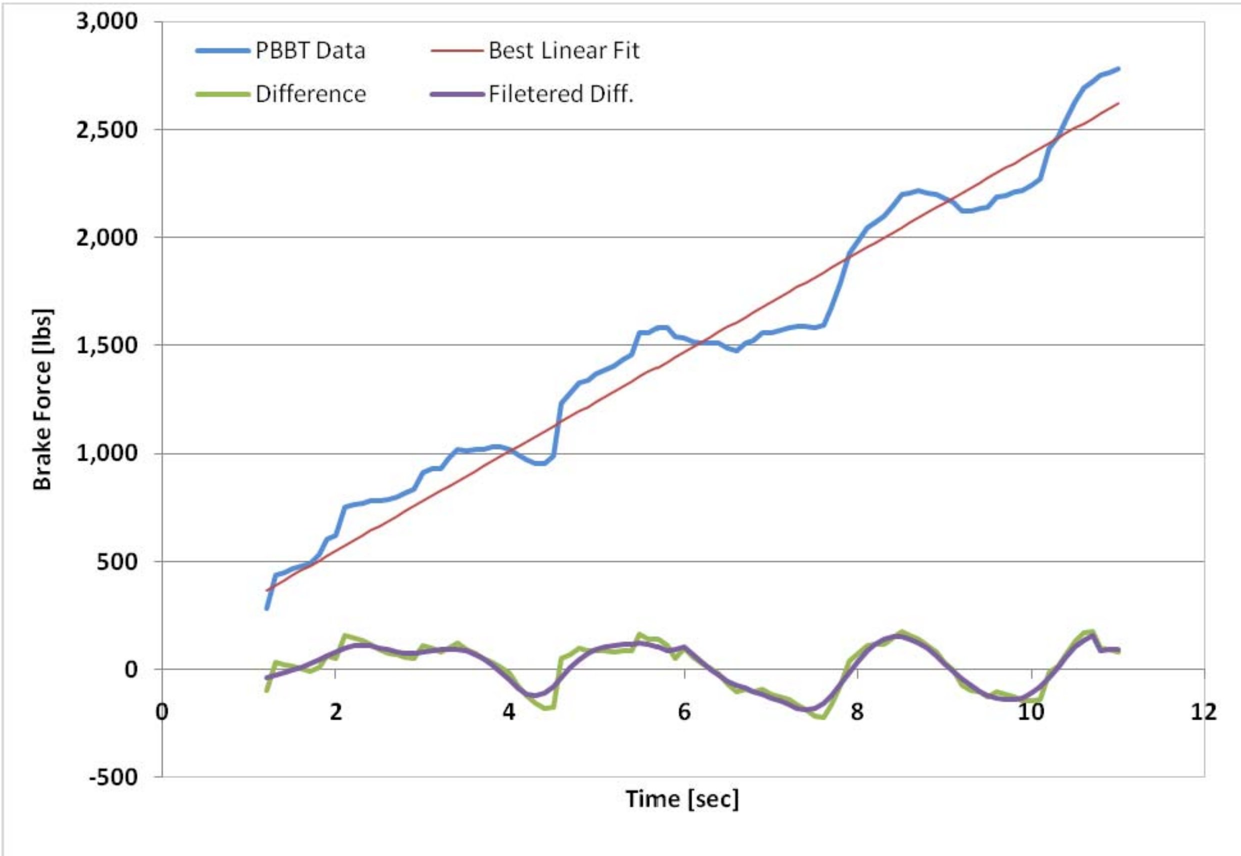

Figure 68. Portion of Brake Force vs. Time Curve (Filtered and Unfiltered)

Figure 68 shows data collected in one of the PBBT tests –right steer axle of a tested vehicle– where only the central part of the test, in which the brake force increases with time, is represented. This middle section of the test contains information that can be used to assess ovality, although in some cases sinusoidal disturbances have been observed in the last part of the test, when the brake force has achieved its maximum value.

Focusing on the data collected in the central part of the test, the methodology to assess ovality consists first in determining the best linear fit to the data collected. In normal tests –i.e., test without ovality– this central part is characterized by linearly increasing brake forces as time elapses. The best linear fit tries to recover the underlying linear relationship between brake force and time. The best linear fit is then subtracted from the collected data; the result is shown as the "Difference" curve in Figure 1, which is filtered using a Butterworth filter to eliminate high frequency disturbances (noise). The latter, shown as the "Filtered Diff." in Figure 68, is the used to compute the amplitude of the disturbances which is used as a (proxy) measure of ovality.

6.4 SYNTHETIC STOPPING DISTANCE EXPLORATORY STUDY

The 20-mph stopping distance test has long been used to determine the effectiveness of CMV braking systems. However, this test is very resource-intensive and is also difficult to perform, relying heavily on operator skill. The PBBT test determines a similar measure of brake effectiveness much more efficiently and there is physical and mathematical support for the concept of a synthetic stopping distance test using the type of data collected in a PBBT brake test where air pressure is monitored.

The goal of this study was to explore the use of a simplified model based on data from a PBBT test and to infer the results of a stopping distance test. Ultimately, it is hoped that an algorithm could be developed to allow a form of the much more efficient PBBT test to be used as a substitute for a stopping distance test. For this study, a simplified model was developed for such a synthetic stopping distance test, taking into account the operator's behavior. This was done by using the pressure curve of the actual stopping distance test and mapping the pressure to a brake force using the PBBT test results. This brake force information was used to estimate a deceleration and corresponding stopping distance.

Data used in this exploratory study was collected for the U-14: Field Testing and Analysis of Braking Performance of In-Service Trucks and included information from both the PBBT and 20-mph stopping-distance tests. Using a sample of approximately 30 tests, it was discovered with 99.99% certainty that these simplified synthetic test results have a linear relationship with the actual test results. A plot of the synthetic and actual results for these tests is shown in Figure 69.

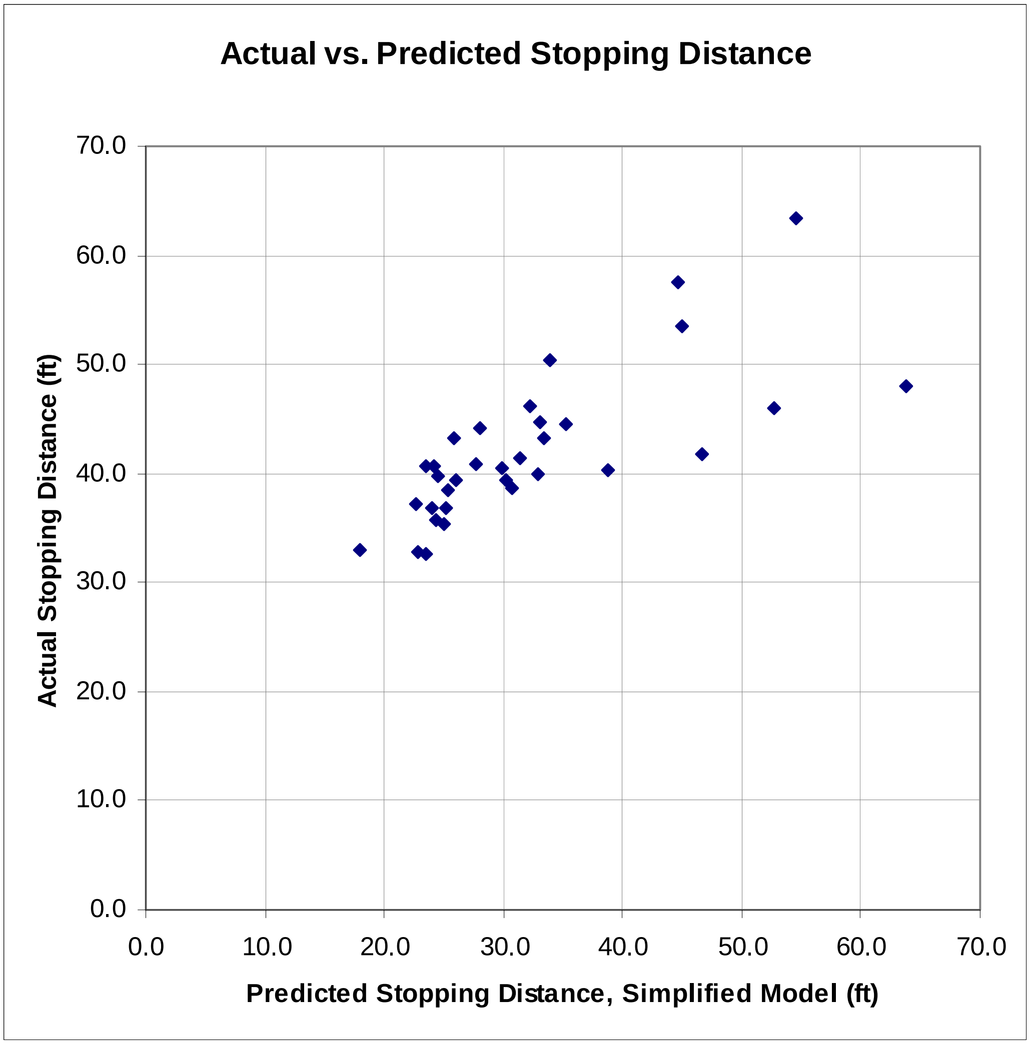

Figure 69. Scatter Plot of Simplified Stopping Distance Test Results

The null hypothesis that the actual stopping distance test results are not linearly related to the synthetic test was rejected at the 99.99% confidence level in favor of the research hypothesis that such a linear relationship does exist. However, the low percent of variability explained by the linear model (R-squared) indicates that further development of the model is necessary for any practical implementation. The results also indicate that the final model will likely include one or more variables which represent the various time regions of the stopping distance curve. More detailed examination of the stopping distance test data is required to determine the major sources of error in this simplified model. It is not expected that the next step in refinement of this model would require additional testing; the existing data would likely be sufficient for further analysis.

7. LESSONS LEARNED

7.1 BRAKE WEAR AND PERFORMANCE TEST

7.1.1 Partnerships

7.1.1.1 Semi-Gratis Partnerships

ORNL used project funds to provide the brake components and in some cases reimbursed the partner for the labor costs to install the components. Establishing these semi-gratis partnerships proved to be a tremendous cost savings mechanism as well as providing “real-world” data in harsh environments such as experienced by the dump trucks.

7.1.1.2 Partner Installation of Components

Having each partner purchase and install the brake components for their respective vehicles and then reimbursing them via a heavy vehicle research support contractor was a very effective and efficient method of getting the brake components purchased and installed. This method allowed each partner to determine the brake components that they wanted for their vehicles, allowed them to take advantage of quantity price agreements that they had in with their suppliers, allowed them to have total control over the installation process, and removed liability for the brake materials or installation from ORNL.

7.1.1.3 Working with TDOS

As is typical, TDOS proved to be a great CMV safety research partner. Using THP officers to operate the PBBT via the MCSAP CMVRTC grant saved research dollars and provided valuable insight during the data collection.

7.1.2 Testing

7.1.2.1 Availability of Test Vehicles

As with any FOT in which active fleets are utilized, issues arose concerning the test vehicle’s availability for testing. There were many times that the test vehicles were simply not available due to scheduling or because of a partner’s inability to remove the vehicle from service due to workload. This caused data collection to be missed for that vehicle for a given month or in some cases two or three continuous months. Better understanding of the fleets' scheduling constraints on the part of ORNL and better understanding of the critical need to collect data (on a regular basis) on the part of the partners might have led to the selection of different partners and/or more diligence in making the vehicles available on the part of the partner(s). In principle, having fixed dates and times each month would mitigate this problem, but in practice this was not practical for this set of partners. In real-world data collection, scheduling is typically a major factor in missed data collection.

7.1.2.2 Brake Stroke Measurement

ORNL did not make plans to incorporate the measurement of each test vehicle’s wheel-end brake stroke until about half way through the FOT. Unfortunately, by this time the troopers conducting the tests had already become accustomed to the original protocol, and although the data collection check sheets were modified to include the measurement of the brake stroke, this data was not collected. This data would have been useful in helping understanding the variation in brake force seen in the PBBT data. Periodic lower brake force readings might have been explained by longer brake stroke readings due to lining and drum wear. Periodic higher readings might have been explained by shorter brake stoke readings due to recent slack adjuster indexing. The manual reading of the brake stroke adds additional time to the testing with takes away from the vehicle and driver productivity for a given day. While an electronic brake stroke measurement system may be feasible solution in the future, currently-available sensors for brake stroke measurements do not provide the needed resolution.

7.1.2.3 Vehicle Loading

Vehicle loading for some fleets was inconsistent or not possible due to routing. In some cases, only empty test vehicles were southbound on I-81. This required the use of AAL to offset the lack of vehicle weight. To simplify the instructions for TDOS staff, AAL was only used on empty vehicles and was not used for partially loaded vehicles. Thus, loading was not consistent for some of the vehicles during the testing. AAL was not used during some discrete testing events because it was not understood by some of the troopers that this information was needed. Future data collection might be better served by selecting vehicles that do not require AAL. This would simplify the process and assure more consistent vehicle loading.

7.1.2.4 Communication with Testers

From time-to-time some data (AAL, brake pressure transducer, vehicle mileage) was not collected by TDOS staff due to misunderstanding of data requirements. Additional training should be conducted and test data collection should be limited to those with full understanding of data collection requirements and procedures.

7.1.2.5 Staffing Limitations

Due to the limited enforcement staff and their need to conduct normal enforcement actions, TDOS staff was not always available to collect PBBT data during the FOT. Again, this is not abnormal for FOTs using real (active) enforcement staff. Emergencies, enforcement priorities, and staff not available for overtime duty were all legitimate reasons for staff unavailability. Having fixed dates and times each month would mitigate this problem to some degree, but in practice this was not practical for this set of partners as mentioned previously.

7.1.2.6 Component Life

As was learned in previous brake wear testing conducted by ORNL, drums and linings last much longer that expected if: 1) they are of good quality, and 2) they are installed on vehicles that have had their foundation brake system repaired to as-new or good condition. This was again the case for this testing. The overall wear of the majority of the vehicle's lining and drums was far less than to "end-of-life." This did not allow the testing to answer the question of brake performance at near end-of-life, nor did it allow a good picture of total life as a function of mileage. This could have been mitigated by conducting a longer FOT. Periods of two years for the FOT would yield a more complete data set than the 12-month testing period of this FOT.

7.1.2.7 PBBT Machine

The PBBT machine itself presented operational problems. Some of these problems were explained as failures of the machine (tachometer sensor failure, pressure sensor cable reel failure). Also, the machine was damaged by being struck by a low-hanging vehicle. In another instance, the calibration of the machine was done improperly. These failures, damage, and improper calibration incidents led to interruptions in data collection. Diagnosis and repair takes time. It is difficult to determine a mitigation plan for all these circumstances, but better training would help to some degree as would a maintenance contract for the PBBT machine. TDOS now has a maintenance contract in place.

7.1.2.8 Partner Records

One important set of data for correlation with the brake performance was the detailed brake maintenance records, including information about when slack adjustments were made. Although the importance of keeping these records for the project team was communicated to the partners at the start of the FOT, this information was not recorded. This situation illustrates that when testing involves real-world fleets, researchers must plan to work within the bounds of their industry partners' standard operating procedures. In certain cases, the importance of collecting a certain type of information may make it necessary to select partners based on the standard set of information the partners collect. In other cases, it may be possible to collect the information with a method that does not require partner involvement; in this case, it may have been possible to collect much of the required data from brake stroke measurements taken after each PBBT test.

7.2 PBBT VALUATION STUDY

The PBBT Valuation Study results show empirically how the PBBT and inspection pit can be useful. As described in the following sections, a number of lessons were learned throughout the period of testing.

7.2.1 Thoroughness of Inspection Efforts Using a Pit

The use of an inspection pit allowed the trooper to complete a more thorough inspection due to a variety of factors. At the Greene County CMV IS, the trooper could see better with the lights on in the pit instead of having to use a flash light. The increased visibility made it possible to check the vehicles more thoroughly. Air leaks could be heard more easily for inspections done at the pit because there were no trucks running in the immediate vicinity of the inspection area, unlike the inspection area at Knox County. At the Greene County CMV IS, the troopers were able to mark all of the brakes at one time, thereby completing the brake stroke measurements more efficiently. At the Knox County CMV IS, brake stroke measurements had to be taken one axle at a time due to the time required for the trooper to get into position with the creeper.

7.2.2 Use of the PBBT

7.2.2.1 Additional Vehicle Condition Indicators

In some cases, the use of the PBBT allowed air supply issues to be noticed immediately because the tractor was not able to maintain the required 90-100 psi for a proper PBBT test. Low scores on the PBBT (under 10) for the wheel-end served as an indicator of braking problems, such as a severe air system leak, bad air distribution valve, bad S-cam bushings, or a grease/oil leak within the braking system.

7.2.2.2 Concerns Regarding PBBT Usage

A PBBT test may take longer than usual at times because some axles do not test as well or drivers are not accustomed to the test. For example, in some cases if the driver slams on the brakes it will lock his brakes; in this case, the axle would need to be re-tested. Trailers carrying lightweight items do not work well with the PBBT and often have tested efficiencies in excess of 100. In this case, the test results usually come up invalid due to the lightly-laden trailer axle. Lastly, if the driver could not get the CMV's differential to release, the test result was not valid due to the inability to test the locked differential. While the PBBT provides information about the condition of a vehicle's brakes beyond what could be determined from visual inspection methods, some troopers are hesitant to use the PBBT because they cannot always pinpoint the cause for a failed PBBT test. Perhaps a more significant reason for slow adoption of the PBBT by the troopers into their regular enforcement protocols is the fact that currently the state of Tennessee does not get credit within the CVSP for this type of inspection.

8. SUMMARY OF RESULTS AND CONCLUSIONS

8.1 SUMMARY OF RESULTS

Eight vehicles participated in the 20-month test during which time 90 PBBT tests were conducted resulting in 367 axle evaluations. In 73 of the 90 PBBT tests, brake-line air pressure data was also collected in real time. Previous to the first PBBT test, all of the participant vehicles were equipped with new brakes and drums, and a thorough maintenance of the entire brake system was conducted.

8.1.1 Brake Efficiency Analysis

In 86 out of the 90 tests conducted (95.5% of the cases) the vehicles passed the PBBT test (i.e., the vehicle's overall brake efficiency was larger than 0.435). Considering the 90 tests, the average vehicle brake efficiency ranged from 0.490 (RD 375) to 0.570 (ST 2226), and for single tests the minimum and maximum were 0.366 and 0.706, respectively (both for PP 2).

The single wheel-end tests permitted the study of brake efficiency variations along the life cycle of the brakes. In most cases, the second and, sometimes, the third PBBT test was conducted within a few days of the first test, with subsequent tests performed at varying intervals which, depending on the vehicle, ranged from one to several months. The data showed that for the cases in which a second (or third) PBBT test was conducted within 5,000 miles of the initial test, there was almost always an increase in the brake efficiency with respect to the first test. That is, 36 out of 38 wheel-end brake efficiency measurements were larger in the second (or third) test than in the first test, in some cases by a substantial amount (e.g., 49% for ST 2235 Axle 4 Right). For the two cases in which the brake efficiency actually decreased in the second test, the percentage changes were very small (0.4% and 1.9%). The likelihood of observing 36 instances of brake efficiency increases out of 38 cases just by chance was computed at 2.6E-09, a very rare event. Therefore, this result suggests that brakes become better (i.e., brake efficiency increases) during the first period of their life cycle (i.e., 5,000 miles in the tests conducted in this project).

The wheel-end brake data collected during this project was also used to analyze whether there was a loss of brake efficiency during the test period. Linear regression analyses were performed on the wheel-end brake efficiencies as a function of the vehicle mileage. The results of the statistical tests showed that the null hypothesis stating that the slopes of these regression lines were equal to zero could only be rejected at a very low confidence level (i.e., less than 75%), thus indicating that the vehicle mileage did not have an effect on the measured brake efficiencies. This result suggests that there was not a statistically significant degradation of the brakes during the length of the test conducted in this project. This in turn shows that the automatic slack adjusters, which all the participant vehicles had, performed well. Notice also that all of the participant companies indicated that they conducted regular brake maintenance, and one of them (RD) pointed out that their vehicle brakes were always checked and, if needed, adjusted, before the PBBT tests. This result was therefore not unexpected. However, it confirmed that careful maintenance of the brake system results in consistently high performing brakes, even after a considerably large number of miles (more than 170,000 miles for RD 375).

8.1.2 Brake Force and Air Pressure Relationship

Information collected in the 73 tests in which the brake-line air pressure was measured at the same time that the PBBT tests were performed was used to investigate the relationship between brake force and air pressure. A machine vision algorithm was used to isolate data corresponding to the proportionality region of the brake force-air pressure relationship, and the slope "s" of this linear region (change of lb/psi) was computed using regression analysis techniques. The distribution of slope "s" had a mean equal to 77 lb/psi, and ranged from 13 lb/psi to 160 lb/psi. For each type of vehicle and axle, the slopes were similar for the left and right ends, but were different for different axles in the same vehicle. This simply reflects the fact that different axles carry different weight and therefore the brakes have to provide, at any given time, a larger brake force for those axles that support higher weights. Since the air pressure is the same for any wheel end (under normal conditions), then those axles carrying a heavier weight showed a steeper slope than those supporting less weight.

8.1.3 Brake Lining Wear and Drum Diameter Elongation

As part of the research conducted under this project, measurements of brake pads and drums were made at the beginning and at the end of the tests to study the wear of these components and to determine how fast (in terms of miles logged) different type of brakes wear . The results of the brake lining wear analysis showed that on average, the left and right end of any given axle presented similar wear of the brake linings. However, there was a slight tendency in the data towards a faster wear of the linings of the right wheel brakes (this observation was further investigated and is discussed below). In 86% of the cases in which the brake shoes are arranged in a top-bottom layout, the linings of the bottom shoe wears at a fast rate than that of the top shoe. The remaining 14% of the cases include the tag axles of the ST 2226 and ST 2235, which are rarely used.

The wear analysis results showed that the smallest lining wear per 1,000 miles traveled was registered by the RD vehicles, which were equipped with OEM linings (Meritor). When the RD's wear rates were compared against those of other vehicles, the brake linings of the latter were found to wear between 2 and 4 times faster. This difference in lining wear rates not only depends on the quality of the brake linings, but also on the way that the vehicles operate in terms of braking patterns. For example, it is expected that RD vehicles would brake less often than the ST vehicles, and therefore the latter would show a faster wear of the linings. Nevertheless, even taking into account the braking patterns, the differences in wear rates by 1,000 miles between the RD vehicles and the other vehicles were significant.

The results of the wear analysis also showed that, in general, the axles that support less weight presented a smaller change of the diameter of the drums over the test period. For PP 2, the two RD vehicles, and the two ST vehicles, the steer axle drum (left and right sides) presented less deformation than any of the other axle drums. This was also the case for axles 2 and 3 of PP 1, and the left drive drum of vehicle GC 194. Regarding the average drum wear per 1,000 miles traveled, vehicle RD 379 presented the smallest drum diameter change rate for both the left and right sides. When this drum diameter change rate was compared to that of the other vehicles, it was found that GC 194, PP 1, PP 2, and RD 375 presented wear rates that were, in the majority of the cases, less than 1.5 (1.7 for PP 1 left side) that of RD 379. However, when compared to the ST vehicles, the latter showed a rate of drum diameter wear per 1,000 traveled that was between 2.6 and 3.8 times that of vehicle RD 379.

Statistical tests were also performed to determine if there was a difference between the wear of brake linings on the left and right wheel ends. The results of these tests showed that the null hypothesis of equal wear rates could be rejected with more than 98% confidence, thus indicating that there was strong evidence in the data that the brake linings on the right side of the vehicle wear faster than those on the left side.

Similar statistical tests were performed to investigate any differences in brake efficiencies between the left and right wheel ends. Since differences in weight between the left and right side could affect brake efficiencies, a subset of the data was selected in which the left and right wheel-end weights were within 1% of one another (i.e., for all practical purposes both wheel ends weighted the same). The results of the statistical methodology showed that the null hypothesis of equal brake efficiencies could be rejected with 99.5% confidence, thus strongly indicating that even with equal wheel-end weights, the right wheel ends show higher brake efficiencies than those on the left.

8.2 CONCLUSIONS

The main conclusion from the data collected in the FOT is that well maintained brakes result in consistently high performing brakes, even after a considerably large number of miles logged (the result of the analysis suggested that there was not a statistically significant degradation of the brakes during the length of the test conducted in this project). The data also showed that brakes improve over time (burnishing period) and that this period could be as long as 5,000 miles or longer (depending on the frequency of brake application). The length of this break-in or burnishing period is an approximation since the PBBT tests conducted in this project were not aimed at investigating this particular brake characteristic, and therefore the data was not collected consistently in terms of miles traveled.

The wear analysis indicated that the brake lining of the bottom shoe (for the cases in which the brake shoes are arranged in a top-bottom layout) wears at a faster rate than that of the top shoe. The data also showed that the brake linings on the right side of the vehicle wear faster than those on the left side and that brake efficiencies were higher on the right side than on the left, even when controlling for wheel-end weight (i.e., same weight on both axles). These results suggest that there may be asymmetries between the left and right side a vehicle (at least, of those participating in this test) that produce larger brake lining wear and higher brake efficiencies on the right side than on the left side. Those differences could be the result of brake system design, power transfer from left to right, and braking patterns. For example, most off ramps are right turns, downhill (requiring hard application of brakes), and have super-elevations that may result in an uneven distribution of weight (with higher weights on the right side) which in turn could result in higher lining wear on the right wheel ends.

9. SUGGESTED FUTURE RESEARCH

The research within the BWPT covered the study of vehicle safety performance parameters, brake component wear, enforcement tools, enforcement methodologies, and infrastructure and operation issues. This wide array of topics present many potential areas of future research, however, three areas were selected for further discussion due to their importance to public safety and lack of existing data in the particular area. They are: 1) Quantifying the Effectiveness of the PBBT Machine as a Mainstream Enforcement Tool; 2) Contrasting the Typical Brake Component Replacement Methodology with a "Total Foundation Brake" Approach; 3) Understanding Brake Performance at the Lining End-of-life; and 4) Assessing the Brake Condition of the General CMV Population.

9.1 QUANTIFYING THE EFFECTIVENESS OF THE PBBT MACHINE AS A MAINSTREAM ENFORCEMENT TOOL

From the small study reported in Section 5.0 it was determined that the use of a PBBT machine can positively impact the number of CMV contacts and the OOS rate within a given period of time. However, changes will need to be made to the NAS guidelines in order to give weight to the PBBT inspection, making it on par with the current Level-1 and Level-2 vehicle inspections. Also, changes will be needed in the MCSAP CVSP that will accept a PBBT inspection as part of the performance-based criteria in lieu or in support of NAS Level-1 and -2 inspections.

In order to foster support for these needed changes to the NAS guidelines and the MCSAP CVSPs for states, additional data will be required that can substantiate the findings from this initial study. One approach to gaining this data would be to implement the recommendations from this study for a given amount of time with the CMVRTC. It is suggested that a research project be conducted that utilized the PBBT machine in a primary way in conjunction with the NAS Level-2 inspection for a one-year period to determine this combination's effectiveness in increasing CMV contacts and corresponding OOS rate as compared with conventional inspection methods. A four-faceted rotating FOT is proposed that would contrast the NAS Level-1, the NAS Level-2/PBBT combination, the NAS Level-3/combination, and the NAS Level-4 PBBT inspection. These four inspection methods would be rotated in a Monday through Sunday cycle for one year giving each method statistical significant exposure to day of the week, month, and season. The number of CMV contacts, OOS rate, and vehicle and driver violations would be recorded and analyzed. The findings would be compared across the inspection methods and also to data from past years of traditional inspections within the CMVRTC.

The data from such an extensive effort should be sufficient to substantiate or refute the viability of the PBBT as a mainstream CMV enforcement tool.

9.2 CONTRASTING THE TYPICAL BRAKE COMPONENT REPLACEMENT METHODOLOGY WITH A "TOTAL FOUNDATION BRAKE MAINTENANCE" APPROACH

As with the Heavy Single-Unit Truck Original Equipment and Aftermarket Brake Performance Characterization in Field, Test-Track and Laboratory Environments (NHTSA Brake Study) conducted in 2006 by ORNL via the National Transportation Research Center, Inc. for the National Highway Traffic Safety Administration, this study found that for vehicles with good foundation brakes, longer brake lining and drum life can be expected as well as stable performance over the life of the components if properly maintained. What was not determined by these two studies was the overall economic impact (positive or negative) to carriers for maintaining good foundation brakes. Is there a cost saving in premature component failures, fines, vehicle downtime, and accidents from going beyond simply installing linings and drums as they reach the end of their life as opposed to taking a "total foundation brake maintenance" approach? This total foundation brake maintenance approach includes the inspection and replacement (as needed) of all foundation brake components (by a certified brake mechanic) including: foot valve, air distribution valves, air lines, brake chambers, slack adjusters, s-cam shafts, s-cam bushings, brake shoe pivot pins, and brake shoe springs.

A study is proposed that would contrast simple lining and drum replacement with the total foundation brake maintenance approach. A candidate vocational fleet would be chosen whose maintenance practice does not currently include a total foundation brake maintenance approach. Vehicles would be chosen from this fleet whose mileage and age are progressed to the point of previously needing new linings and drums, and whose mileage, condition, and service duty cycle are similar. Half of these vehicles would receive new linings or linings and drums commensurate with the fleet's current practice, and the other half of these vehicles would receive a thorough inspection of the entire foundation brake system and all components not in good serviceable condition would be replaced. The components replaced and the total cost would be tracked for all vehicles. Further, the wear, performance, maintenance cost, brake related downtime, brake related violations, OOS orders, citations, and accidents would be tracked for each vehicle.

An analysis would be conducted to determine the safety impact of the total foundation brake maintenance approach (performance, accidents, and OOS orders) as well as the total cost per operating vehicle (component cost, accidents, and citations). This data could then be used to reinforce or refute the need for total foundation brake maintenance.

9.3 UNDERSTANDING BRAKE PERFORMANCE AT LINING END-OF-LIFE

Again, as with the NHTSA Brake Study, the FOT in this study did not operate for a sufficiently long period of time to see the VUTs come to the end of their brake component life; thus, the brake efficiency in this region is still unknown. There is a safety concern here in that many fleets do take linings and drums to the end of their life (lining wears to the manufacturer-indicated wear bars or 0.25 in, drums to 125 thousandths of diameter wear) and in many cases beyond these wear limiters. The performance of vehicles with linings and drums in this state of wear has not been statistically quantified using a PBBT and it is not known if performance degrades significantly in this region. Further, we have learned from the NHTSA Brake Study and this research that it is very difficult to determine when a vehicle's brakes will be at the end of their life. In most cases in these two tests, the linings and drums lasted far longer that the carriers expected.

In order to gain a better understanding of end-of-life brake component efficiency, ORNL proposes to reconnect with the carriers of this study and continue to monitor these vehicles with the PBBT on a less than monthly (perhaps quarterly) basis until they reach the end of their life. At that time, wear measurements on the linings, drums, and rotors would once again be taken. This extended or additional testing would give a better picture of performance as a function of mileage as well as wear as a function of mileage. Additionally, it would answer this critical performance question without the cost of a completely new research project, and the data collected would be directly related to the current BWPT data.

9.4 ASSESSING THE BRAKE CONDITIONS OF THE GENERAL CMV POPULATION

The random sample correlation study (Section 4) gave an indication that the brake conditions of the CMV general population appears to be worse than expected. The results of this very limited sample showed that there were no significant differences in test results (PBBT and Level-1) when the vehicles were selected at random or when a more traditional selection methodology was used. In general, the latter focuses on a subset of the CMV population, and implicitly assumes that the rest of that population has good brakes and does not need to be inspected. The random sampling, on the other hand, focuses on the entire population and if the findings of the small study hold, then the percentage of CMVs with brakes in poor condition could be much higher than normally assumed.

ORNL proposes to expand the random sample study to better understand the status of the brakes of the general CMV population. The information collected in these random samples will also be combined with the information collected from the vehicles participating in this project and in the ones proposed in sections 9.2 and 9.3 above (i.e., control vehicles) to estimate the distribution of the age of brakes in the general population. That is, the random sample data will be used to generate probability distributions of the brake efficiencies provided by the PBBT for both the overall measurement of the braking system of each truck and each of its wheel-end performances. These probability distributions will be used in conjunction with the information gathered through the control vehicles to make inferences about the age (in terms of miles traveled) of brakes in the general CMV population. That is, the brake performance index of the control vehicles will be mapped on top of the general population probability distributions to investigate how the performance of these brakes, over time (miles traveled), "moves" within that general population distribution. This is shown graphically in Figure 70, where the bell-shaped curve represents the probability distribution (or histogram) of the brake efficiency index for the general population that will be collected through random sampling. The performance, again in terms of the brake efficiency index, of the control vehicles is overlaid over that general population distribution and shown in the grayed areas. Three different brake ages are shown: new brake conditions (right shaded area), after being used for M1 miles (center shaded area) and after M2 >M1 miles (right shaded area). Using this type of analysis it would be possible to determine the percentage of the trucks in the general population that behave as having brakes that have traveled over M2 miles.

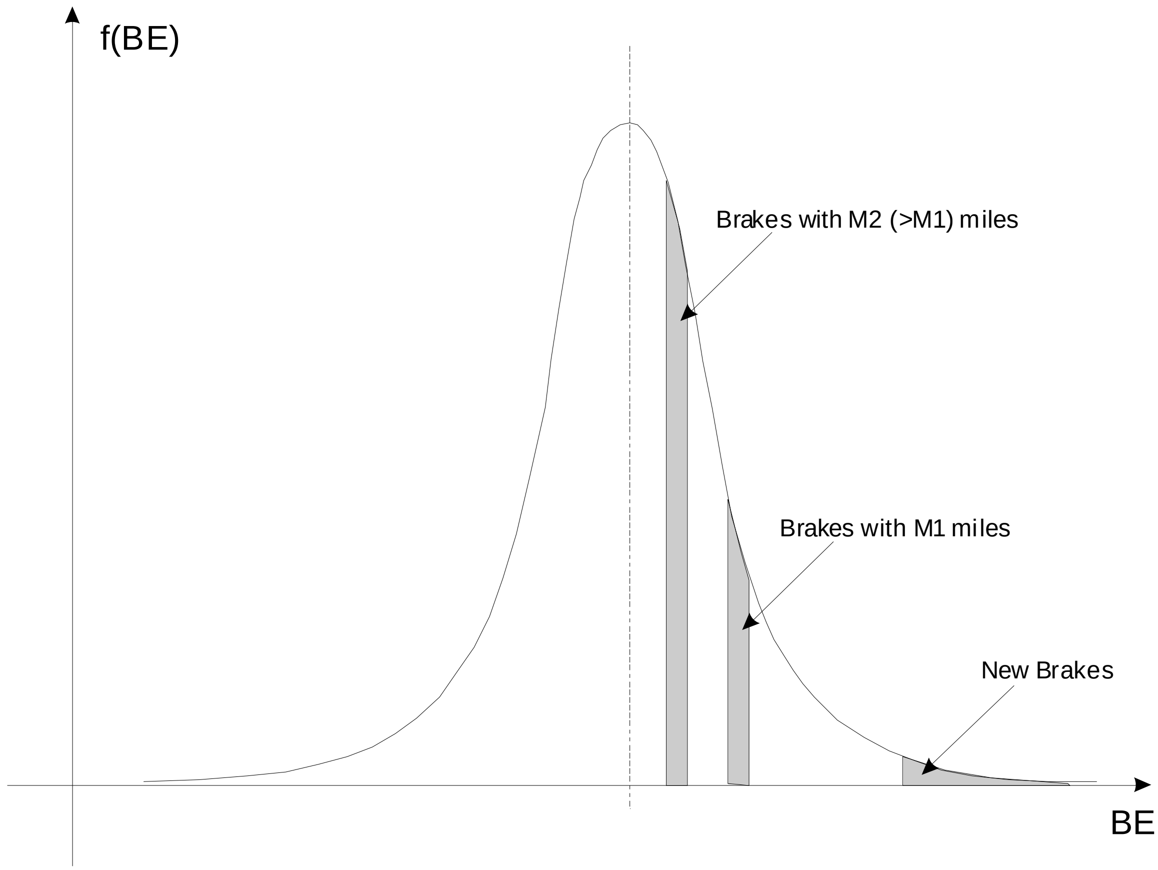

Figure 70. Probability Distribution of Brake Efficiency (BE) Index

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APPENDIX A: MEMORANDUM OF UNDERSTANDING FOR PARTICIPATION

in the

Commercial Motor Vehicle Field Based Brake Wear and Performance Test

Rev 0.0 18Sep07

The purpose of this Memorandum of Understanding (MOU) is to define the roles and responsibilities of the Oak Ridge National Laboratory (ORNL) and XXXXXX (Partner) in their partnership to support of the U.S. Department of Transportation (DOT) Federal Motor Carrier Safety Administration's Commercial Motor Vehicle Field Based Brake Wear and Performance Test (CMV FBBWPT). This project hereafter in this agreement will be referred to as Brake Wear and Performance Test (BWPT).

BACKGROUND

The BWPT will be conducted using a Performance-Based Brake Tester (PBBT) to measure the brake performance of selected vehicles. PBBTs are devices that can evaluate the current braking capabilities of a vehicle through the measurement of brake forces developed as a vehicle engages in a braking event while on a PBBT. PBBT devices are typically in-ground, but can also be in portable configurations. The common types of PBBTs include roller dynamometers, flat-plate testers and breakaway torque testers. Some PBBTs are equipped with the capability for artificial axle loading (AAL). This capability can assure constant wheel loadings and repeatable testing despite the actual load of the vehicle.

Motor carrier communities and law enforcement can benefit from PBBT technologies because they can reduce overall inspection times, and can provide a consistent and objective measure of the braking performance of a vehicle.

Although PBBTs have been in general use in Europe and Australia for over 25 years, the experience has not been the same in the US. This may be due however to the short amount of time since FMCSA issued its final rule establishing performance criteria for use with PBBTs (effective February 5, 2003 and is applicable to all commercial motor vehicles and commercial vehicle combinations weighing over 10,000 pounds).

Because of the significant benefits of utilizing PBBT technologies (time/labor savings, error reduction, objective measures, consistency, enhanced fleet safety), FMCSA has an interest in assessing a vehicle's long-term brake performance using PBBT technology over time in a real-world testing environment. That is, there is interest on the part of FMCSA in studying PBBT performance in conjunction with volunteer fleets over a sufficiently long period of time, to measure (for each vehicle in the test fleet) the brake force for the overall vehicle, and for each individual wheel-end. Such an effort would provide experiential data, and would quantitatively assess benefits from long-term brake performance data.

REQUIREMENTS

The Partner will make available on a gratuitous basis (for no remuneration) two class-8, XXXXXX (test vehicles) to be used in the BWPT. ORNL will provide for the cost of the necessary brake components to bring the foundation brake system of the two test vehicles to "new condition." ORNL will provide the cost for new brake lining, drums/rotor, and other foundational brake components as need. The costs for the brake components must be itemized and submitted to ORNL for approval prior to the actual purchasing of the components.

Each participating test vehicle's braking system should be inspected by a certified mechanic to be sure that other foundation brake components (beyond linings, drum/rotors) are good serviceable condition (i.e. air lines, brake cambers, slack adjusters, pushrod, camshaft, camshaft bushings, s-cams, wheel seals, etc.). These components should also be replaced if they are found not to be serviceable.

In the event that a test vehicle needs a brake component(s) replaced due to wear during the course of the testing (i.e. linings wear out in the first eight months of the testing), ORNL may elect to replace these components and continue the test until the end of the 18 months. However, depending on the timing, cost, and amount of data already collected up to that point, ORNL may elect to end the testing for that specific vehicle.

The brake application pressure of the test vehicle will need to be monitored during the PBBT testing. If the test vehicle does not have a glad-hand connection on the service brakes, a pressure port will need to be installed to allow the pressure to be monitored. ORNL will reimburse the Partner for the cost of installing this pressure port (if it is needed). If the vehicle has a glad-hand connection, ORNL has a pressure port that can be installed at the glad-hand during PBBT testing.

The PBBT used for BWPT will be a roller-based PBBT and is shown in Figure 1. The PBBT has ALL capability which will be used during the BWPT for any vehicles that are unladen.

Figure 1 – Roller-Based PBBT and Inspection Pit at the Greene County Inspection Station

Partners are cautioned to have there driver's complete pre-trip inspections on the test vehicles prior to arriving at the inspection station to participate in the PBBT testing. Also, logbooks should be up to date and drives should have needed hours to complete the testing and return to Partners facility.

Any repairs or adjustments made to the test vehicle's brake or braking system during the 18 month test period should be noted by the Partner as to the date, mileage, and type of work done and then reported to ORNL.

TIMELINE

For the purpose of this agreement, the BWPT will begin in September 2007 and will conclude in April 2009. Key events in the schedule are as follows:

- September 2007 – Partners identify test vehicles
- September 2007 – Partners identify brake components and submit cost estimate to ORNL for approval

- September 2007 - Partner purchases brake components
- September 2007 - ORNL makes initial measurements on brake linings, drums/rotors
- October 2007 - Partner brings test vehicles to the Greene County Commercial Motor Vehicle Inspection Station (inspection station) for baseline PBBT testing
- October 2007 – Partner Installs new brake components
- October 2007 – Partner brings test vehicles to inspection station for initial brake burnishing testing
- October 2007 – 18-Month field test begins
- April 2009 – 18-month field test ends

Table 1 shows the testing frequency from each of the two test vehicles.

Table 1 - Testing Frequency

Vehicle		Laden	AAL	Laden	AAL	Laden	AAL	Laden	AAL	Laden	AAL
		Initial Test/Old Brakes	Initial Test/Old Brakes	Initial Test/New Brakes	Initial Test/New Brakes	Weekly Burnish Testing	Weekly Burnish Testing	Bi-Monthly Testing	Bi-Monthly Testing	Monthly Testing	Monthly Testing
VUT	1	1		1		1	2	17	17		
	2		1		1	2	1	17	17		

The test vehicles can be brought to the inspection station for PBBT testing 24-hours-a-day and seven-days-a-week. 24-hour advance notice is required so that ORNL can coordinate with TDOS personnel to be sure that a PBBT trained trooper will be available to perform the testing. ORNL will work with each partner and TDOS to coordinate this testing.

TESTING STEPS

Once the brake linings and drums/rotors have been purchase and received by the Partner, the Partner will notify ORNL and set up a time for ORNL staff to come to the Partners facility and take initial measurements from the components for the wear portion of the testing. This will consist of drum diameters, rotor thicknesses (if applicable), and lining thicknesses. The measurements will take approximately three hours to collect.

Prior to the start of the field test (the actual collection of wear and performance data), the Partners will bring the test vehicles to the inspection station located at mile-marker 21 on I-81 southbound. Each test vehicle will be tested on the PBBT with the vehicle's current brakes to establish the vehicle's pre-brake up fit baseline.

Next, the Partner will install the new brake components and return the test vehicles to the inspection station for the first PBBT test with the new brake components. This will be the brake burnishing phase and will require the test vehicles to come to the inspection station each week for a total of four weeks. It is very important that the test vehicle be brought to the inspection station immediately after the new brake components are installed so that a PBBT reading can be obtained before the burnishing period has advance.

Once, the burnishing period is completed (~3 to 4 weeks) the test vehicles will need to be returned to the inspection station each month for 17 months. It is not critical that the vehicle be tested exactly every 30 days. Monthly testing is indicated to access trends in the braking performance. Testing can vary 5 to 7 days without affecting the overall test.

At the end of the BWPT field test or the end of the normal life of the brake linings, ORNL will need to collect total wear data. In order to do this the wheels or wheels and drums will need to be removed from each wheel position. The brake lining will not need to be removed.

ROLES AND RESPONSIBILITIES.

ORNL will be responsible for all phases of the BWPT (test design, test conducting, data collection, and data analysis). Specifically, ORNL will:

- Design and specify the testing to be conducted
- Reimburse the Partner for the cost of brake components for the BWPT
- Coordinate with the Partner and TDOS for each PBBT test
- Collect test data
- Analyze test data
- Draft and maintain this MOU

The Partner will:

- Provide two each class-8 XXXX to participate in the BWPT for a period of 18 months
- Select the brake components to be used in the BWPT
- Notify ORNL once the brake components arrive and make time available for ORNL time take the initial measurements
- Arrange for the installation of the brake components
- Provide the test vehicles and drives to meet the testing schedule. Approximately 22 visits to the inspection station for each test vehicle for the 18 month field test.
- Notify ORNL of any brake systems adjustments or repairs and note the date, mileage, and action taken
- Remove wheels/wheels and drums at the end of the testing to allow ORNL to make its final measurements

REIMBURSEMENT

Once the Partner has decided on the components that will be used on the test vehicles, an estimate of total cost should be provide to ORNL for approval. Once ORNL has approved the cost, the Partner can procure the materials and request re-imbursement by submitting a detailed cost invoice to:

Commercial Carrier Consultants
C/O Wilber Thomas
45 Robertson Rd
Pueblo Co. 81001
Phone: 719 545 7843
Fax: 719 545 7844

POINTS-OF-CONTACT

Each Party will designate a Point-of-Contact for implementation of this MOU. The designated Points-of-Contact are:

ORNL
NAME: Gary Capps
TITLE: Technical Director CMVRTC
PHONE: 865 946 1285

XXX XXX COMPANY, INC.
NAME: XXX
TITLE: XXX
PHONE: XXX

AMENDMENTS

This MOU may be amended in writing, requiring agreement by both parties.

APPENDIX B:
FOT RAW DATA

This appendix presents the raw data collected in the project as well as some processed information used in the data analysis chapter. In the tables that follow, the highlighted cells indicate PBBT tests that were conducted without artificial axle load.

Table B1. Vehicle Mileage, Weight, and Brake Efficiency by Axle - GC 190

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.
1	367,473	49,800	0.4822	0.4210	0.4770	0.4669	0.5224	0.4834	0.5191
2	368,402	50,360	0.4914	0.4685	0.4752	0.5185	0.5638	0.4650	0.4253
3	369,969	50,490	0.5216	0.4715	0.5322	0.4649	0.5469	0.5771	0.5492
4	376,922	50,420	0.5372	0.5484	0.5402	0.5118	0.5237	0.4865	0.6317
5	385,253	50,400	0.5317	0.5811	0.5960	0.5292	0.5820	0.4878	0.3986
6	396,569	37,770	0.6123	0.6595	0.6228	0.5353	0.6824	0.5457	0.6451
7	410,155	45,540	0.5665	0.5750	0.5750	0.4864	0.6349	0.5140	0.6307
8	412,813	46,030	0.5736	0.5208	0.5247	0.5455	0.6498	0.5403	0.6712
9	415,571	45,670	0.5450	0.5155	0.4602	0.5477	0.6293	0.4456	0.6649
10	420,188	45,480	0.5569	0.4543	0.5478	0.5161	0.6483	0.5301	0.6632
11	423,093	45,600	0.5779	0.5328	0.5179	0.5542	0.6215	0.5762	0.6967
12	425,861	45,510	0.6241	0.5191	0.5449	0.6103	0.8008	0.5403	0.6883
13	428,446	49,440	0.5547	0.5509	0.5395	0.5396	0.6546	0.5009	0.5214
14	432,143	49,510	0.5331	0.4980	0.5214	0.5156	0.6099	0.4784	0.5646
15	432,659	42,630	0.6436	0.6854	0.7005	0.5326	0.6660	0.6104	0.7413
16	436,322	45,760	0.5973	0.5747	0.5718	0.5688	0.6100	0.5752	0.7245
17	445,244	45,560	0.5266	0.5107	0.5404	0.4715	0.5280	0.5329	0.6302

Table B2. Vehicle Mileage, Total Weight, and Weight by Axle - GC 190

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt
1	367,473	49,800	7,760	7,290	9,990	9,760	7,840	7,160
2	368,402	50,360	7,830	7,370	10,040	9,910	7,940	7,270
3	369,969	50,490	7,820	7,370	10,210	9,860	7,990	7,240
4	376,922	50,420	7,810	7,630	10,020	9,830	7,940	7,190
5	385,253	50,400	7,690	7,490	10,180	9,760	7,940	7,340
6	396,569	37,770	5,650	5,450	8,140	7,500	5,890	5,140
7	410,155	45,540	7,610	7,280	10,020	9,570	5,910	5,150
8	412,813	46,030	7,690	7,400	10,090	9,710	5,930	5,210
9	415,571	45,670	7,570	7,460	10,050	9,500	5,940	5,150
10	420,188	45,480	7,590	7,400	10,040	9,500	5,840	5,110
11	423,093	45,600	7,580	7,450	9,940	9,610	5,840	5,180
12	425,861	45,510	7,660	7,350	10,020	9,520	5,830	5,130
13	428,446	49,440	7,580	7,370	10,020	9,520	7,860	7,090
14	432,143	49,510	7,580	7,400	10,040	9,530	7,840	7,120
15	432,659	42,630	5,900	6,220	10,050	9,490	5,890	5,080
16	436,322	45,760	7,640	7,380	10,140	9,600	5,850	5,150
17	445,244	45,560	7,660	7,330	10,090	9,500	5,920	5,060

Table B3. Vehicle Mileage, Weight, and Brake Efficiency by Axle - GC 194

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.
1	169,418	50,510	0.4697	0.4562	0.4302	0.5325	0.5600	0.4097	0.3871
2	171,493	50,850	0.5443	0.5100	0.5051	0.5498	0.6558	0.5156	0.4995
3	180,947	50,580	0.5558	0.5349	0.5526	0.5957	0.5721	0.5124	0.5515
4	189,255	50,540	0.5459	0.5625	0.5371	0.5366	0.6129	0.4914	0.5253
5	194,126	50,500	0.5560	0.5428	0.5394	0.5806	0.5706	0.4955	0.6010
6	199,340	50,620	0.5450	0.6115	0.6545	0.5013	0.4854	0.5047	0.5478
7	205,562	49,510	0.5170	0.5256	0.5584	0.5061	0.4624	0.5118	0.5580
8	207,551	50,010	0.4788	0.4903	0.5083	0.4458	0.4399	0.4690	0.5434
9	209,711	50,030	0.5130	0.5645	0.5561	0.4746	0.4559	0.4860	0.5724
10	209,893	38,610	0.5793	0.6115	0.5713	0.5075	0.6715	0.5138	0.6143
11	211,431	50,830	0.4681	0.4550	0.4858	0.4273	0.4480	0.4787	0.5340
12	226,516	50,280	0.4956	0.5007	0.5359	0.4657	0.4947	0.4638	0.5269

Table B4. Vehicle Mileage, Total Weight, and Weight by Axle - GC 194

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt
1	169,418	50,510	7,580	7,550	10,310	9,490	8,060	7,520
2	171,493	50,850	7,680	7,610	10,270	9,660	8,100	7,530
3	180,947	50,580	7,570	7,610	10,510	9,280	8,170	7,440
4	189,255	50,540	7,580	7,530	10,330	9,450	8,100	7,550
5	194,126	50,500	7,460	7,660	10,550	9,270	8,230	7,330
6	199,340	50,620	7,740	7,410	10,220	9,650	8,110	7,490
7	205,562	49,510	7,630	7,190	10,220	9,200	8,120	7,150
8	207,551	50,010	7,620	7,390	10,090	9,460	8,070	7,380
9	209,711	50,030	7,500	7,500	10,260	9,320	8,130	7,320
10	209,893	38,610	5,550	5,540	8,450	7,440	6,160	5,470
11	211,431	50,830	7,760	7,670	10,380	9,450	8,070	7,500
12	226,516	50,280	7,570	7,610	10,320	9,280	8,140	7,360

Table B5. Vehicle Mileage, Weight, and Brake Efficiency by Axle - PP 1

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.	A5L Eff.	A5R Eff.
1	40,812	70,660	0.5161	0.6581	0.6718	0.3722	0.4577	0.4239	0.4612	0.4472	0.5984	0.6044	0.5734
2	42,500	70,660	0.5070	0.6190	0.6301	0.3932	0.5332	0.3664	0.4681	0.4605	0.5156	0.5982	0.5761
3	45,400	70,240	0.5883	0.7528	0.6971	0.4248	0.5345	0.4733	0.5997	0.5443	0.6233	0.6730	0.6621
4	65,625	70,700	0.4815	0.5648	0.5704	0.3826	0.3475	0.3771	0.4033	0.5289	0.4767	0.6196	0.6390
5	98,734	70,970	0.5654	0.6730	0.6551	0.4280	0.6749	0.3780	0.5263	0.4856	0.6360	0.5388	0.7493
6	120,627	70,720	0.4858	0.6626	0.6640	0.3599	0.3826	0.3413	0.4723	0.4284	0.5150	0.5614	0.6030
7	134,315	70,050	0.4853	0.7064	0.7282	0.3293	0.5367	0.1699	0.2724	0.4806	0.5671	0.5678	0.6943
8	183,657	74,260	0.5652	0.6768	0.7835	0.4257	0.5849	0.4264	0.6238	0.4806	0.5671	0.5678	0.6943
9	195,066	71,080	0.4536	0.5830	0.6319	0.3828	0.3007	0.2246	0.2791	0.5580	0.5558	0.5541	0.6117

Table B6. Vehicle Mileage, Total Weight, and Weight by Axle - PP 1

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt	A5L Wt	A5R Wt
1	40,812	70,660	5,900	5,540	8,280	7,800	8,170	7,730	6,520	6,840	6,990	6,890
2	42,500	70,660	5,800	5,480	8,210	7,740	8,250	7,680	6,630	6,990	7,030	6,850
3	45,400	70,240	5,800	5,430	8,140	7,730	8,140	7,680	6,550	6,920	6,960	6,890
4	65,625	70,700	5,820	5,480	8,260	7,690	8,210	7,630	6,640	7,090	7,000	6,880
5	98,734	70,970	5,820	5,480	8,330	7,700	8,230	7,730	7,010	6,750	6,880	7,040
6	120,627	70,720	5,830	5,590	8,320	7,800	8,370	7,580	6,830	6,590	6,820	6,990
7	134,315	70,050	5,780	5,500	8,350	7,570	8,250	7,510	6,860	6,570	6,830	6,830
8	183,657	74,260	5,680	5,380	10,040	8,000	9,920	8,150	6,860	6,570	6,830	6,830
9	195,066	71,080	5,940	5,550	8,510	7,570	8,240	7,700	6,740	6,590	6,910	7,330

Table B7. Vehicle Mileage, Weight, and Brake Efficiency by Axle - PP 2

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.	A5L Eff.	A5R Eff.
1	185,600	25,950	0.7058	0.7586	0.7620	0.4537	0.5329	0.4812	0.9809	0.8190	0.7901	0.7090	0.8689
2	187,288	71,140	0.4695	0.6836	0.6497	0.2917	0.3160	0.4541	0.4713	0.5849	0.4926	0.3245	0.5490
3	208,428	72,010	0.4906	0.6027	0.6377	0.3726	0.3887	0.3493	0.4139	0.5753	0.5897	0.4877	0.5994
4	212,443	71,130	0.5061	0.6865	0.5809	0.3597	0.4493	0.4084	0.3495	0.5962	0.5518	0.5424	0.6326
5	227,067	71,390	0.3658	0.4819	0.5039	0.2658	0.3099	0.2557	0.2789	0.4416	0.4423	0.2840	0.4983
6	266,890	71,460	0.5321	0.6223	0.8054	0.4129	0.4429	0.4792	0.4049	0.5791	0.5679	0.5369	0.5911
7	285,538	71,350	0.4089	0.5478	0.6332	0.2128	0.2068	0.4571	0.3169	0.3240	0.3619	0.5236	0.6421
8	304,299	71,260	0.4718	0.7125	0.6429	0.3606	0.3658	0.3445	0.3278	0.4665	0.5491	0.5145	0.5939
9	319,992	71,030	0.4693	0.6400	0.6250	0.3426	0.3694	0.4168	0.3505	0.4819	0.5549	0.4850	0.5501

Table B8. Vehicle Mileage, Total Weight, and Weight by Axle - PP 2

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt	A5L Wt	A5R Wt
1	185,600	25,950	5,150	4,660	2,960	2,190	2,660	2,460	1,580	1,520	1,550	1,220
2	187,288	71,140	5,980	5,630	8,290	7,680	7,970	8,020	6,830	7,010	7,030	6,700
3	208,428	72,010	5,900	5,790	8,180	7,930	7,970	8,060	6,970	6,990	7,400	6,820
4	212,443	71,130	6,090	5,970	7,740	7,350	7,940	8,120	6,840	7,010	7,330	6,740
5	227,067	71,390	5,970	5,640	8,360	7,770	8,100	7,930	6,880	6,780	7,050	6,910
6	266,890	71,460	5,910	5,730	8,150	7,830	8,040	7,960	7,050	6,880	7,160	6,750
7	285,538	71,350	6,010	5,700	8,260	7,700	7,950	8,000	7,130	6,990	6,940	6,670
8	304,299	71,260	5,690	5,500	8,140	7,930	7,940	8,120	7,140	6,930	7,300	6,570
9	319,992	71,030	5,930	5,690	8,140	7,920	7,850	8,180	6,860	6,760	7,130	6,570

Table B9. Vehicle Mileage, Weight, and Brake Efficiency by Axle – RD 375

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.	A5L Eff.	A5R Eff.
1	351,322	65,650	0.5009	0.6130	0.6209	0.4087	0.5356	0.4156	0.5016	0.4965	0.4583	0.4502	0.5437
2	356,200	79,700	0.4822	0.6521	0.6809	0.4440	0.4623	0.5252	0.5285	0.3695	0.4350	0.4005	0.4638
3	387,184	74,660	0.4701	0.6177	0.6266	0.3866	0.5572	0.4639	0.5284	0.3638	0.4190	0.3875	0.4506
4	398,157	61,920	0.5011	0.5651	0.6560	0.4598	0.5636	0.4782	0.4529	0.4253	0.4656	0.4657	0.5221
5	409,058	68,370	0.4934	0.6355	0.6306	0.4532	0.4856	0.4299	0.5134	0.3915	0.4933	0.4144	0.5607
6	420,592	78,220	0.4173	0.4825	0.5335	0.3879	0.4692	0.4133	0.4729	0.3856	0.3743	0.3564	0.3771
7	426,044	79,420	0.4971	0.6310	0.6241	0.4811	0.5440	0.5302	0.5352	0.4350	0.4285	0.3889	0.4629
8	431,443	78,980	0.4788	0.6009	0.6765	0.4716	0.5099	0.4911	0.5191	0.3607	0.4283	0.3891	0.4688
9	460,743	78,420	0.5377	0.6996	0.6982	0.5119	0.5789	0.5091	0.5756	0.4696	0.4387	0.5291	0.4836
10	481,672	73,220	0.5301	0.6665	0.6542	0.6001	0.5145	0.5510	0.5371	0.4163	0.4400	0.4928	0.4775
11	500,212	58,640	0.5222	0.5197	0.6186	0.4818	0.6088	0.5157	0.6280	0.4569	0.4925	0.3995	0.5035
12	525,776	79,530	0.4509	0.5323	0.4731	0.4336	0.5123	0.4739	0.5121	0.3296	0.4484	0.3928	0.4556

Table B10. Vehicle Mileage, Total Weight, and Weight by Axle – RD 375

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt	A5L Wt	A5R Wt
1	351,322	65,650	5,760	5,600	6,750	7,130	6,910	6,270	7,180	6,470	6,790	6,790
2	356,200	79,700	5,970	5,760	8,810	8,590	8,360	7,430	9,690	7,770	9,170	8,150
3	387,184	74,660	5,700	5,370	8,780	8,440	8,770	7,080	8,430	6,900	7,940	7,250
4	398,157	61,920	5,610	5,300	5,800	5,850	7,170	6,470	6,880	5,990	6,480	6,370
5	409,058	68,370	5,780	5,460	6,950	7,020	7,180	6,270	7,860	7,030	7,520	7,300
6	420,592	78,220	5,700	5,320	8,700	8,160	8,330	7,230	9,460	8,040	8,810	8,470
7	426,044	79,420	6,030	5,760	8,700	8,620	8,400	7,410	9,340	7,990	8,740	8,430
8	431,443	78,980	5,860	5,660	8,730	8,410	8,890	7,000	9,640	7,710	9,140	7,940
9	460,743	78,420	5,640	5,450	8,730	8,370	8,490	7,220	9,600	7,770	8,990	8,160
10	481,672	73,220	5,730	5,480	8,660	8,390	8,580	7,110	8,270	6,450	7,800	6,750
11	500,212	58,640	5,940	5,590	6,640	6,490	6,640	5,390	6,220	4,820	5,710	5,200
12	525,776	79,530	6,010	5,760	8,650	8,360	8,440	7,610	9,440	7,930	8,830	8,500

Table B11. Vehicle Mileage, Weight, and Brake Efficiency by Axle – RD 379

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.	A5L Eff.	A5R Eff.
1	279,163	62,990	0.5314	0.5960	0.7313	0.5432	0.5315	0.4996	0.6231	0.4530	0.4689	0.4121	0.4823
2	301,642	78,840	0.4887	0.6014	0.6054	0.6278	0.5187	0.4988	0.5127	0.3718	0.4192	0.4125	0.4094
3	323,793	76,830	0.4560	0.4411	0.4747	0.4546	0.5385	0.4634	0.5603	0.4103	0.4398	0.4078	0.3910
4	348,569	74,330	0.5440	0.5744	0.6984	0.4916	0.5607	0.5548	0.6653	0.4370	0.4829	0.4309	0.6181
5	381,012	79,090	0.5127	0.6605	0.7169	0.4889	0.5639	0.5420	0.5840	0.3843	0.4681	0.4120	0.4492
6	410,971	74,160	0.4970	0.5176	0.6327	0.5036	0.5365	0.4902	0.5646	0.3770	0.4647	0.4060	0.5465

Table B12. Vehicle Mileage, Total Weight, and Weight by Axle – RD 379

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt	A5L Wt	A5R Wt
1	279,163	62,990	5,540	5,430	7,220	7,020	7,410	6,490	6,740	5,270	6,340	5,530
2	301,642	78,840	5,840	5,760	8,370	8,230	8,470	7,630	9,880	7,550	8,950	8,160
3	323,793	76,830	5,870	5,730	8,670	7,790	8,760	7,200	9,560	6,930	8,850	7,470
4	348,569	74,330	5,850	5,580	7,740	7,770	7,790	7,430	8,930	7,200	8,240	7,800
5	381,012	79,090	5,930	5,620	8,490	8,150	8,470	7,820	9,900	7,470	9,270	7,970
6	410,971	74,160	5,840	5,620	8,030	7,720	7,950	7,430	9,070	6,790	8,230	7,480

Table B13. Vehicle Mileage, Weight, and Brake Efficiency by Axle – ST 2226

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.
1	282,513	47,260	0.5884	0.5352	0.5292	0.5120	0.5411	0.6256	0.6814	0.5976	0.6049
2	283,580	53,750	0.4859	0.4609	0.4373	0.4605	0.4575	0.4848	0.5421	0.5145	0.5178
3	284,180	53,670	0.6039	0.5738	0.5683	0.5356	0.5720	0.6195	0.6330	0.5968	0.7055
4	286,246	53,850	0.6158	0.5340	0.5568	0.5397	0.6309	0.5967	0.6415	0.6642	0.7700
5	286,739	54,370	0.5877	0.5570	0.5737	0.4533	0.6227	0.5280	0.6764	0.5076	0.7767
6	287,103	54,270	0.6114	0.6072	0.4743	0.5041	0.6846	0.6319	0.6492	0.6420	0.7205
7	290,835	55,100	0.6091	0.6004	0.5420	0.4657	0.6533	0.6187	0.6322	0.6741	0.6890
8	295,767	52,770	0.5861	0.4182	0.5672	0.6397	0.5419	0.6524	0.6240	0.6191	0.6535
9	298,197	52,950	0.4765	0.4058	0.4145	0.5468	0.5313	0.4334	0.5106	0.5062	0.5307
10	303,458	53,600	0.4118	0.1833	0.5338	0.3941	0.3924	0.4060	0.4392	0.4829	0.4690
11	309,280	53,580	0.6037	0.1084	0.7350	0.5776	0.5580	0.6694	0.6724	0.7417	0.8086
12	311,972	48,600	0.6515	0.6490	0.7259	0.6684	0.5691	0.6444	0.6968	0.6172	0.6190
13	316,307	53,830	0.5788	0.6002	0.6917	0.4610	0.5009	0.5123	0.6158	0.5694	0.6007

Table B14. Vehicle Mileage, Total Weight, and Weight by Axle – ST 2226

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt
1	282,513	47,260	5,110	4,180	5,160	4,260	7,190	7,160	7,070	7,130
2	283,580	53,750	8,180	8,040	4,880	4,090	6,990	7,370	7,080	7,120
3	284,180	53,670	8,290	7,950	4,970	3,860	7,080	7,330	7,080	7,110
4	286,246	53,850	8,240	8,000	5,140	4,010	7,030	7,270	7,170	6,990
5	286,739	54,370	8,270	7,900	5,570	4,150	7,150	7,170	7,130	7,030
6	287,103	54,270	8,060	7,970	5,600	4,480	6,840	7,320	6,930	7,070
7	290,835	55,100	8,240	7,840	6,010	4,650	7,010	7,230	7,130	6,990
8	295,767	52,770	8,350	7,810	4,680	3,560	7,060	7,200	6,950	7,160
9	298,197	52,950	8,220	7,930	4,760	3,640	7,010	7,240	7,120	7,030
10	303,458	53,600	8,180	7,960	5,080	3,970	7,120	7,140	7,120	7,030
11	309,280	53,580	8,250	7,880	4,990	4,140	7,150	7,110	7,000	7,060
12	311,972	48,600	6,260	5,900	4,530	3,630	7,080	7,080	6,900	7,220
13	316,307	53,830	8,250	7,830	5,160	4,260	7,130	7,090	6,930	7,180

Table B15. Vehicle Mileage, Weight, and Brake Efficiency by Axle – ST 2235

Test	Mileage	Total Weight	Vehicle Eff.	A1L Eff.	A1R Eff.	A2L Eff.	A2R Eff.	A3L Eff.	A3R Eff.	A4L Eff.	A4R Eff.
1	97,968	55,380	0.4984	0.5185	0.5770	0.4363	0.5034	0.3923	0.4134	0.5820	0.5600
2	99,001	54,310	0.5789	0.5811	0.6240	0.3954	0.5030	0.6009	0.6640	0.6203	0.6399
3	99,785	54,550	0.5783	0.5329	0.5661	0.5061	0.5216	0.5678	0.6919	0.6175	0.6338
4	102,760	54,540	0.5234	0.5253	0.5829	0.4683	0.4592	0.4906	0.5610	0.5192	0.5723
5	104,604	54,030	0.5415	0.4662	0.6363	0.4517	0.4814	0.5748	0.5858	0.6015	0.5290
6	104,921	54,130	0.6060	0.5503	0.6758	0.5540	0.5036	0.6267	0.6622	0.6259	0.6443
7	106,261	54,600	0.5721	0.6124	0.5738	0.4671	0.4770	0.5889	0.6241	0.6187	0.6086
8	113,950	53,920	0.5452	0.4454	0.5212	0.4576	0.5329	0.5357	0.6766	0.5556	0.6678
9	116,924	52,920	0.4499	0.4188	0.4038	0.4387	0.4668	0.4326	0.4732	0.4803	0.5036
10	122,409	54,500	0.4381	0.4275	0.5108	0.3714	0.4118	0.4935	0.4861	0.3935	0.4022
11	126,501	41,880	0.6240	0.6102	0.6374	N/A	N/A	0.5759	0.6759	0.5422	0.7078
12	137,141	53,540	0.5117	0.5065	0.5707	0.5426	0.5314	0.5030	0.4944	0.4644	0.4773

Table B16. Vehicle Mileage, Total Weight, and Weight by Axle – ST 2235

Test	Mileage	Total Weight	A1L Wt	A1R Wt	A2L Wt	A2R Wt	A3L Wt	A3R Wt	A4L Wt	A4R Wt
1	97,968	55,380	7,950	7,440	7,500	6,160	6,660	6,570	6,620	6,480
2	99,001	54,310	7,950	7,390	7,250	5,360	6,600	6,700	6,550	6,510
3	99,785	54,550	8,020	7,410	7,190	5,610	6,710	6,550	6,580	6,480
4	102,760	54,540	7,930	7,390	7,040	5,860	6,720	6,520	6,680	6,400
5	104,604	54,030	7,940	7,430	6,670	5,650	6,670	6,570	6,610	6,490
6	104,921	54,130	7,890	7,350	7,000	5,760	6,640	6,490	6,610	6,390
7	106,261	54,600	8,000	7,320	7,120	6,050	6,660	6,510	6,520	6,420
8	113,950	53,920	7,950	7,450	6,680	5,600	6,800	6,380	6,690	6,370
9	116,924	52,920	7,990	7,440	6,300	4,970	6,740	6,410	6,600	6,470
10	122,409	54,500	7,950	7,430	6,930	5,740	6,730	6,570	6,640	6,510
11	126,501	41,880	8,020	7,410	N/A	N/A	6,810	6,510	6,630	6,500
12	137,141	53,540	7,840	7,300	6,670	5,450	6,660	6,550	6,510	6,560

Table B17. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle - GC 190

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope
1	367,473	49,800	N/A	N/A	N/A	N/A	N/A	N/A
2	368,402	50,360	N/A	N/A	N/A	N/A	N/A	N/A
3	369,969	50,490	58.9280	65.3820	93.6968	108.9937	55.0175	47.6636
4	376,922	50,420	72.0396	73.0652	108.9905	93.9650	75.3185	60.1647
5	385,253	50,400	N/A	N/A	N/A	N/A	N/A	N/A
6	396,569	37,770	N/A	N/A	N/A	N/A	N/A	N/A
7	410,155	45,540	59.7443	51.8580	103.0664	123.4140	64.4300	57.5646
8	412,813	46,030	51.4472	52.0426	90.2377	108.0153	67.2897	64.1756
9	415,571	45,670	54.4562	48.1339	86.6416	99.5229	64.0383	65.9068
10	420,188	45,480	51.1147	57.4230	80.4907	96.6669	60.5786	63.0915
11	423,093	45,600	50.3233	47.9259	83.9102	99.8573	66.5826	60.1757
12	425,861	45,510	58.4596	61.1758	84.6951	110.9833	68.4916	64.3692
13	428,446	49,440	N/A	N/A	N/A	N/A	N/A	N/A
14	432,143	49,510	55.8866	56.4556	89.6452	95.8252	56.3139	67.6824
15	432,659	42,630	45.9298	49.7283	76.3202	74.0049	48.4634	55.9817
16	436,322	45,760	53.8884	51.0565	78.7975	76.4395	51.4795	61.5874
17	445,244	45,560	58.6027	57.7584	79.2371	75.2124	45.5029	59.2152

Table B18. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle - GC 194

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope
1	169,418	50,510	44.7994	43.0483	69.1516	67.6534	35.3605	30.3679
2	171,493	50,850	83.8580	79.4079	130.9229	118.8554	53.7749	49.6899
3	180,947	50,580	N/A	N/A	N/A	N/A	N/A	N/A
4	189,255	50,540	78.3818	73.6444	99.2991	98.5487	58.9427	58.5640
5	194,126	50,500	73.6686	77.1558	77.6298	73.7312	52.6659	50.3524
6	199,340	50,620	57.7670	58.5128	72.4154	70.4905	47.7909	46.8431
7	205,562	49,510	71.8808	81.0037	88.1149	73.1529	57.3222	59.1139
8	207,551	50,010	60.1904	60.0806	75.3507	88.2392	49.6979	50.3334
9	209,711	50,030	71.3592	71.4864	77.7414	67.1661	71.8312	67.3039
10	209,893	38,610	68.8470	72.7068	82.0147	59.2938	60.3257	62.6868
11	211,431	50,830	56.2850	58.8723	59.9802	61.5614	40.8255	41.0706
12	226,516	50,280	71.9038	68.3680	76.3422	74.6397	46.6736	47.7868

Table B19. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle - PP 1

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope	A5L Slope	A5R Slope
1	40,812	70,660	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	42,500	70,660	46.3107	44.0099	67.3082	70.4169	92.7948	60.9553	75.4807	95.4542	71.1283	61.9602
3	45,400	70,240	48.6354	39.4723	75.6108	71.3295	97.9956	51.2968	84.7228	105.9926	74.5064	70.8550
4	65,625	70,700	50.4929	47.0314	77.8536	73.0385	90.8435	76.6087	112.6514	61.1729	109.1187	80.1449
5	98,734	70,970	54.5372	51.0581	85.1866	86.9472	102.7329	99.3566	80.4593	104.0958	107.0233	127.7663
6	120,627	70,720	50.0339	43.1035	72.4127	72.0395	86.9454	70.8507	86.4501	76.5597	72.9407	77.4357
7	134,315	70,050	48.5634	48.6455	61.6203	64.5120	77.6928	75.6077	97.4596	100.0379	73.5229	93.6024
8	183,657	74,260	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
9	195,066	71,080	43.3259	44.1450	71.6359	63.7175	86.6974	72.2422	87.2982	81.8848	78.2340	90.0611

Table B20. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle - PP 2

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope	A5L Slope	A5R Slope
1	185,600	25,950	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	187,288	71,140	44.1822	46.1991	92.9422	95.4493	83.9940	72.8161	121.8635	103.2797	84.0461	90.9717
3	208,428	72,010	59.4089	62.3207	88.8112	99.6097	99.3115	98.7677	N/A	N/A	N/A	N/A
4	212,443	71,130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	227,067	71,390	95.1469	95.0492	74.4592	73.5538	109.8441	72.5317	N/A	N/A	N/A	N/A
6	266,890	71,460	52.2124	55.0729	70.1688	72.8444	86.9207	67.6969	118.0071	147.1091	133.9149	132.6431
7	285,538	71,350	46.9287	46.2204	61.6152	67.8201	80.4772	66.2074	112.7083	136.1193	108.0501	114.1559
8	304,299	71,260	47.3084	43.8605	63.7337	62.7855	71.6459	58.0178	109.7229	115.4860	114.6573	115.9208
9	319,992	71,030	47.8648	48.8986	68.0514	63.7372	84.8616	56.0177	105.9391	118.2698	104.7875	104.0474

Table B21. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle – RD 375

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope	A5L Slope	A5R Slope
1	351,322	65,650	35.1975	34.3577	64.4692	71.3104	69.4271	73.5461	63.2303	65.1779	66.5363	68.8946
2	356,200	79,700	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	387,184	74,660	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	398,157	61,920	38.2917	35.8072	73.6375	72.7630	89.8692	97.4908	67.2233	70.1563	78.5928	89.2363
5	409,058	68,370	28.6611	29.9424	58.1942	62.0903	64.9370	68.3713	64.2478	71.8677	72.3825	76.6408
6	420,592	78,220	38.5485	39.7799	94.8705	70.5085	74.8451	62.1669	84.3184	82.4170	86.2605	94.2814
7	426,044	79,420	43.8967	39.6464	84.8850	81.4101	86.2958	90.2522	89.4268	110.0215	89.7701	109.7993
8	431,443	78,980	39.2960	40.6044	103.9711	90.4877	94.9947	90.9082	86.8510	89.0011	81.1051	88.9356
9	460,743	78,420	40.7341	39.3991	94.5556	72.3014	97.0662	76.5262	108.4398	116.3381	103.4801	124.8700
10	481,672	73,220	43.5129	37.0089	69.5411	76.8576	80.8831	83.8201	75.4586	80.0946	79.5278	93.3025
11	500,212	58,640	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	525,776	79,530	37.0265	29.5653	62.8471	70.2379	75.8168	79.7082	84.9447	96.4368	101.9212	119.3029

Table B22. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle – RD 379

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope	A5L Slope	A5R Slope
1	279,163	62,990	34.3500	41.4738	49.2507	58.7988	57.0564	55.6016	54.3864	55.8005	49.6630	53.6890
2	301,642	78,840	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	323,793	76,830	39.9704	38.0934	65.4499	67.8903	71.0917	64.1613	55.8998	44.1251	105.5349	78.6929
4	348,569	74,330	31.5194	43.9017	58.0032	63.6467	87.7589	N/A	71.4007	88.5177	95.1600	73.7195
5	381,012	79,090	40.1497	42.6599	71.4087	68.3871	72.9068	76.4768	72.7447	72.7814	81.5647	65.2408
6	410,971	74,160	44.0197	42.4941	77.1667	79.4827	84.1829	81.0168	63.6899	73.3421	89.4239	63.2124

Table B23. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle – ST 2226

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope
1	282,513	47,260	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	283,580	53,750	64.0683	56.1673	43.6338	70.3092	89.6645	98.6688	102.3340	91.4970
3	284,180	53,670	53.8679	57.2462	43.1616	62.7753	86.1156	93.4582	96.8324	99.8307
4	286,246	53,850	53.8221	66.3115	47.5538	70.3013	94.6585	99.0523	99.6120	112.2050
5	286,739	54,370	50.1741	66.0952	61.9835	162.7296	95.5171	90.7630	105.8686	120.1226
6	287,103	54,270	49.3417	63.5833	85.6394	85.6044	86.9867	88.3565	91.0286	98.0996
7	290,835	55,100	49.9061	86.4314	118.8261	107.1948	78.8381	90.8336	128.2805	136.0116
8	295,767	52,770	53.7758	84.6859	71.7383	75.0880	111.0737	116.9820	136.0322	136.7831
9	298,197	52,950	68.4420	72.6819	N/A	N/A	105.1181	127.6302	160.0164	161.1557
10	303,458	53,600	32.0435	115.1376	83.4818	104.8173	111.9939	104.0161	131.0833	140.9274
11	309,280	53,580	13.4200	73.1756	52.7327	51.6982	92.7532	127.3224	166.5461	154.9239
12	311,972	48,600	44.8811	55.0608	95.0019	81.9406	104.2060	110.0198	107.7796	121.7009
13	316,307	53,830	86.3229	64.0896	67.9523	98.4416	92.7520	117.9208	111.8432	115.6677

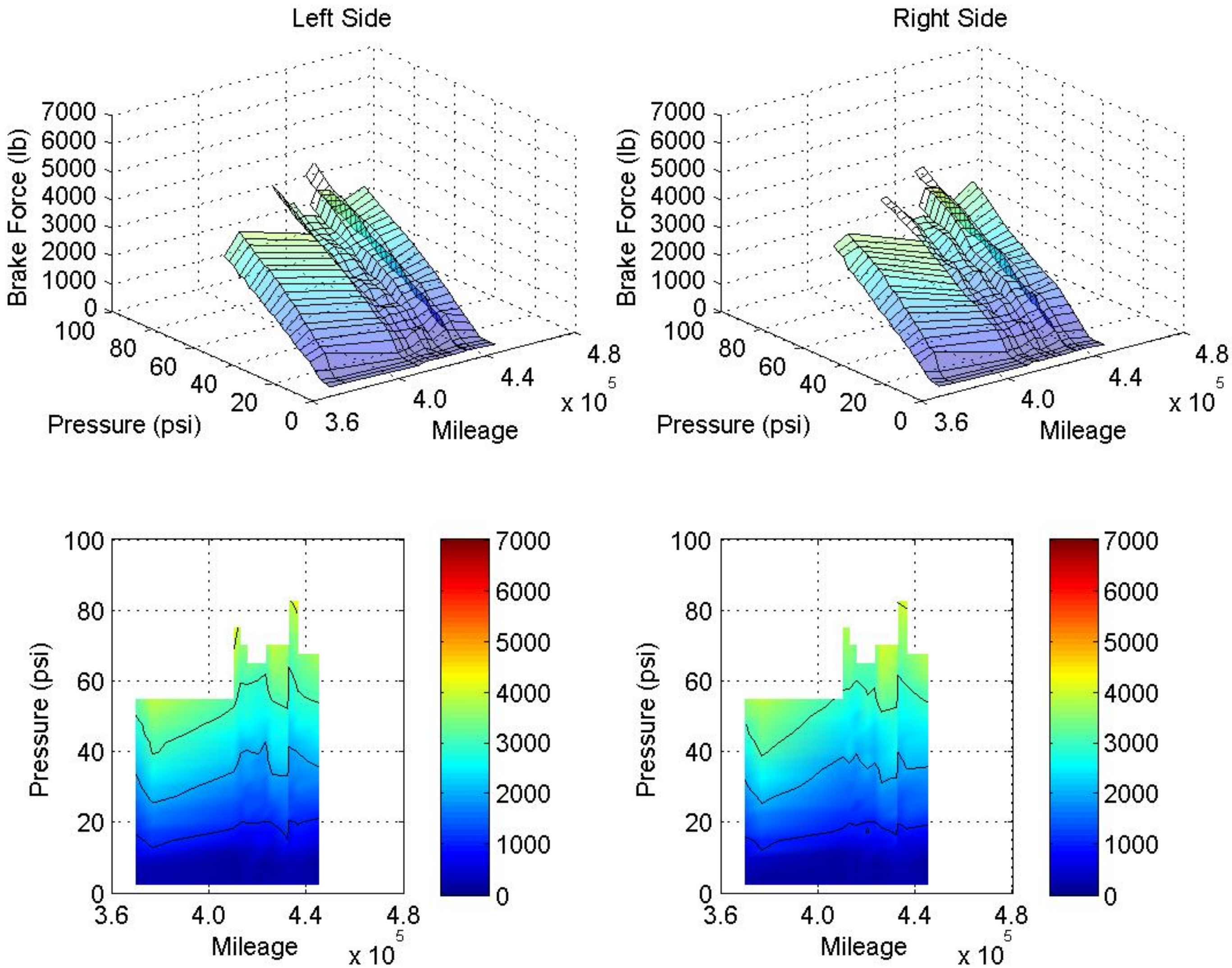
Table B24. Vehicle Mileage, Weight, and Brake Force-Air Pressure Slope in the Proportionality Region by Axle – ST 2235

Test	Mileage	Total Weight	A1L Slope	A1R Slope	A2L Slope	A2R Slope	A3L Slope	A3R Slope	A4L Slope	A4R Slope
1	97,968	55,380	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	99,001	54,310	49.3417	51.7816	70.7448	60.2617	66.9628	72.3750	69.8508	76.9183
3	99,785	54,550	45.3000	46.4460	57.8410	71.7527	83.5436	83.2738	68.7186	71.4873
4	102,760	54,540	63.8217	68.6837	55.9856	56.1404	104.8244	110.4589	127.5950	140.0507
5	104,604	54,030	56.1105	51.4381	88.1780	102.3791	84.5404	92.3097	103.3688	83.1351
6	104,921	54,130	52.3694	49.5611	55.1194	77.4569	104.7252	105.2871	100.5914	99.8996
7	106,261	54,600	58.1492	51.8786	94.8683	90.5259	95.8926	91.2580	103.3813	97.3922
8	113,950	53,920	70.5248	58.7904	93.4629	108.4039	86.9907	82.8396	93.4214	97.7740
9	116,924	52,920	49.8128	60.6069	68.7763	78.7344	92.8893	100.4796	96.5265	101.7833
10	122,409	54,500	57.3771	79.1974	60.6605	81.2849	133.8199	136.2657	95.7371	106.5032
11	126,501	41,880	53.9517	57.6390	N/A	N/A	80.4249	88.4691	84.6180	94.0287
12	137,141	53,540	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

APPENDIX C:
THREE-DIMENSIONAL PLOTS OF BRAKE FORCE

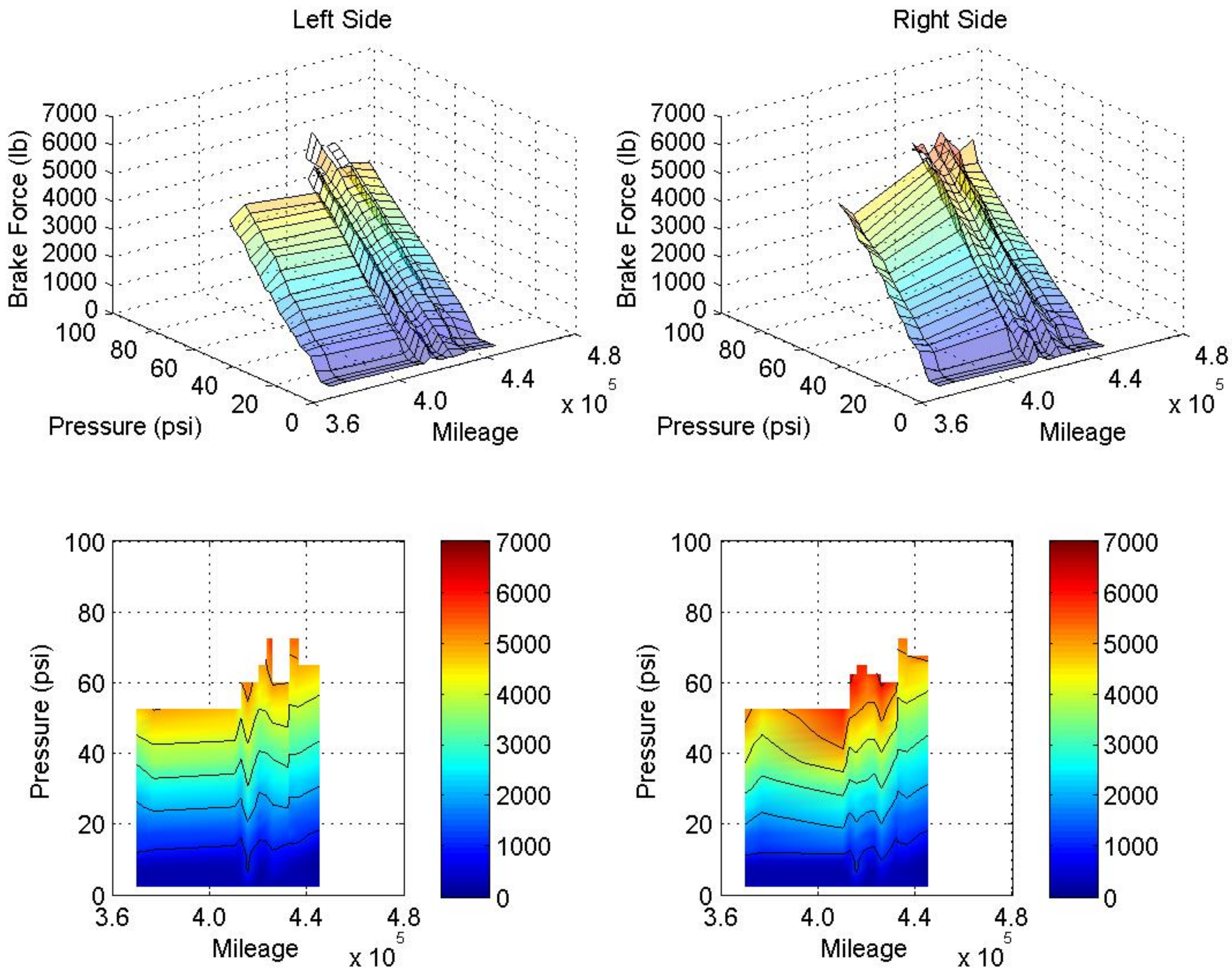
The following pages contain plots of brake force as a function of pressure and mileage for each wheel-end of each test vehicle. These plots represent the unfiltered data collected via PBBT tests.

GC 190 Axle 1

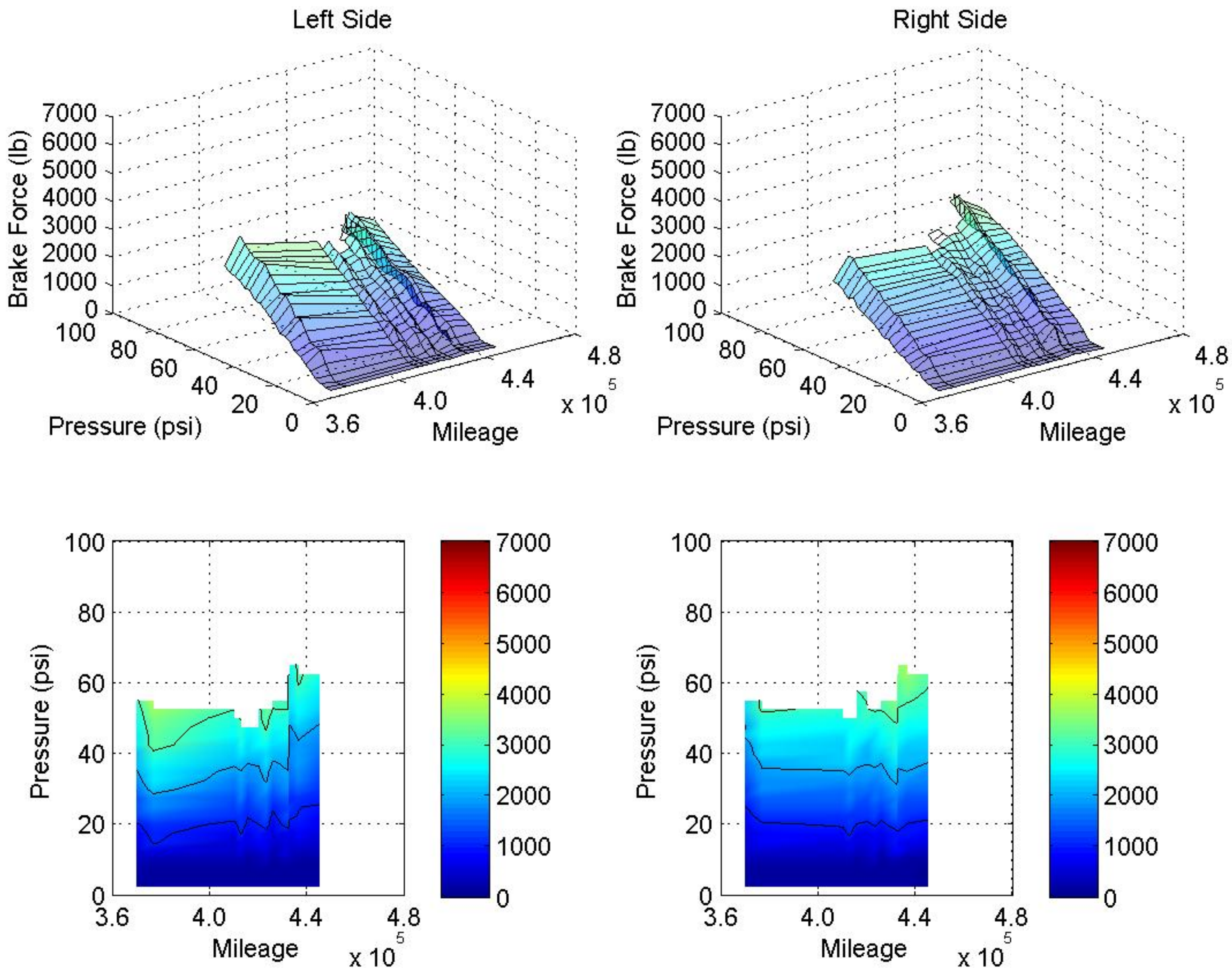


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
3.6
4.0
4.4
4.8
x 10^5
Mileage

GC 190 Axle 2

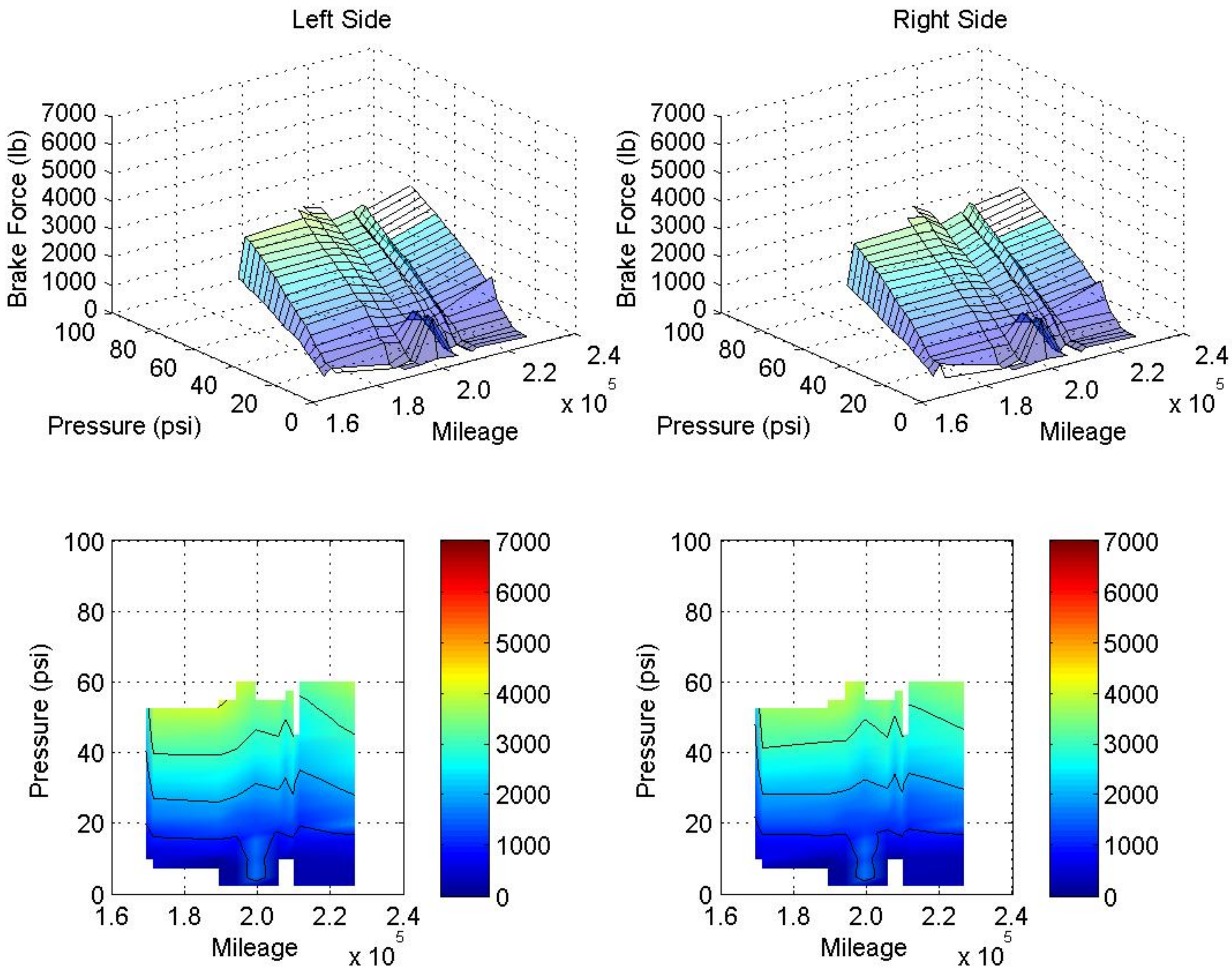

Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
3.6
4.0
4.4
4.8
Mileage
x 10^5
Pressure (psi)
Mileage
x 10^5

GC 190 Axle 3

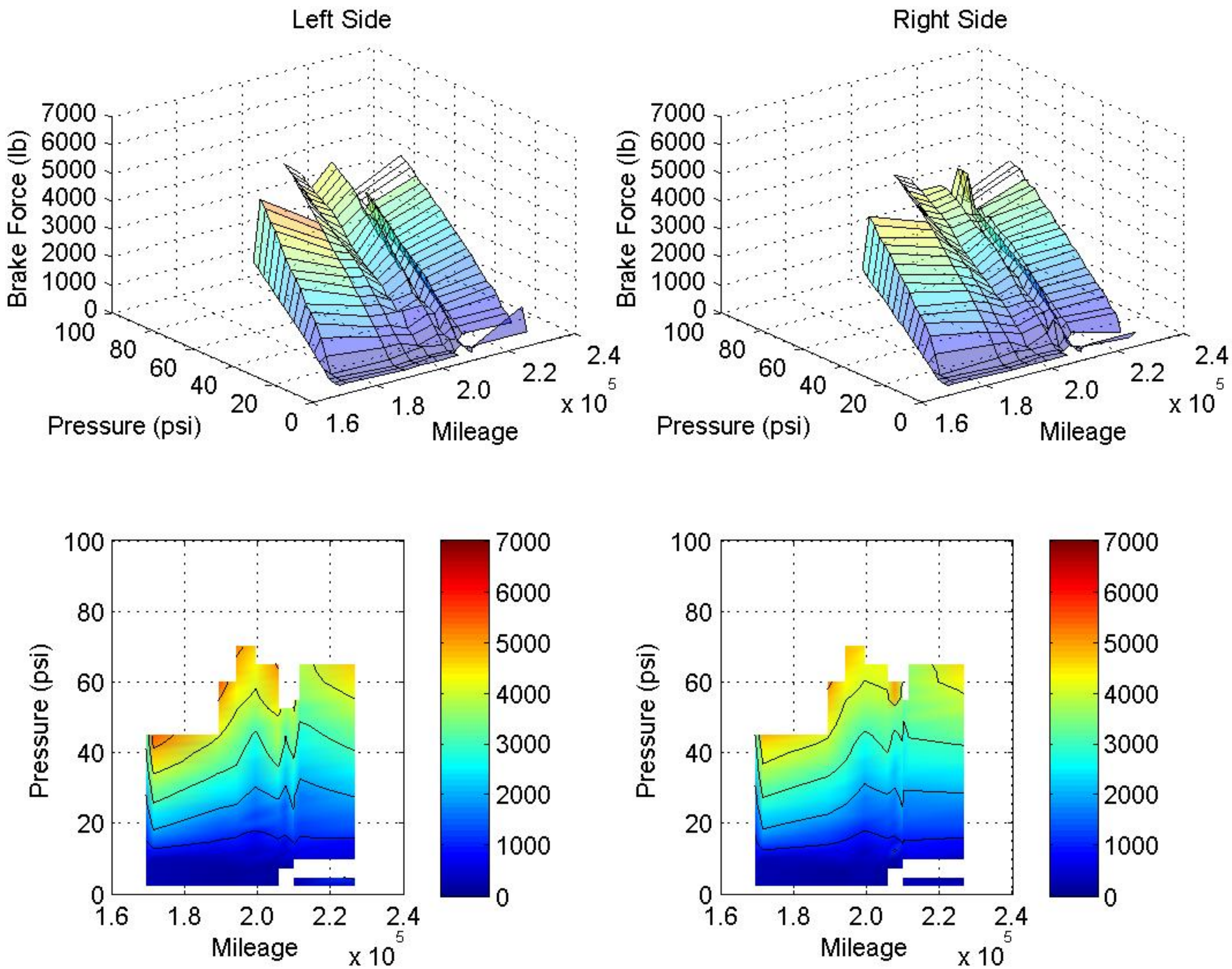


Left Side
Right Side
Brake Force (lb)
Pressure (psi)
Mileage
x 10^5

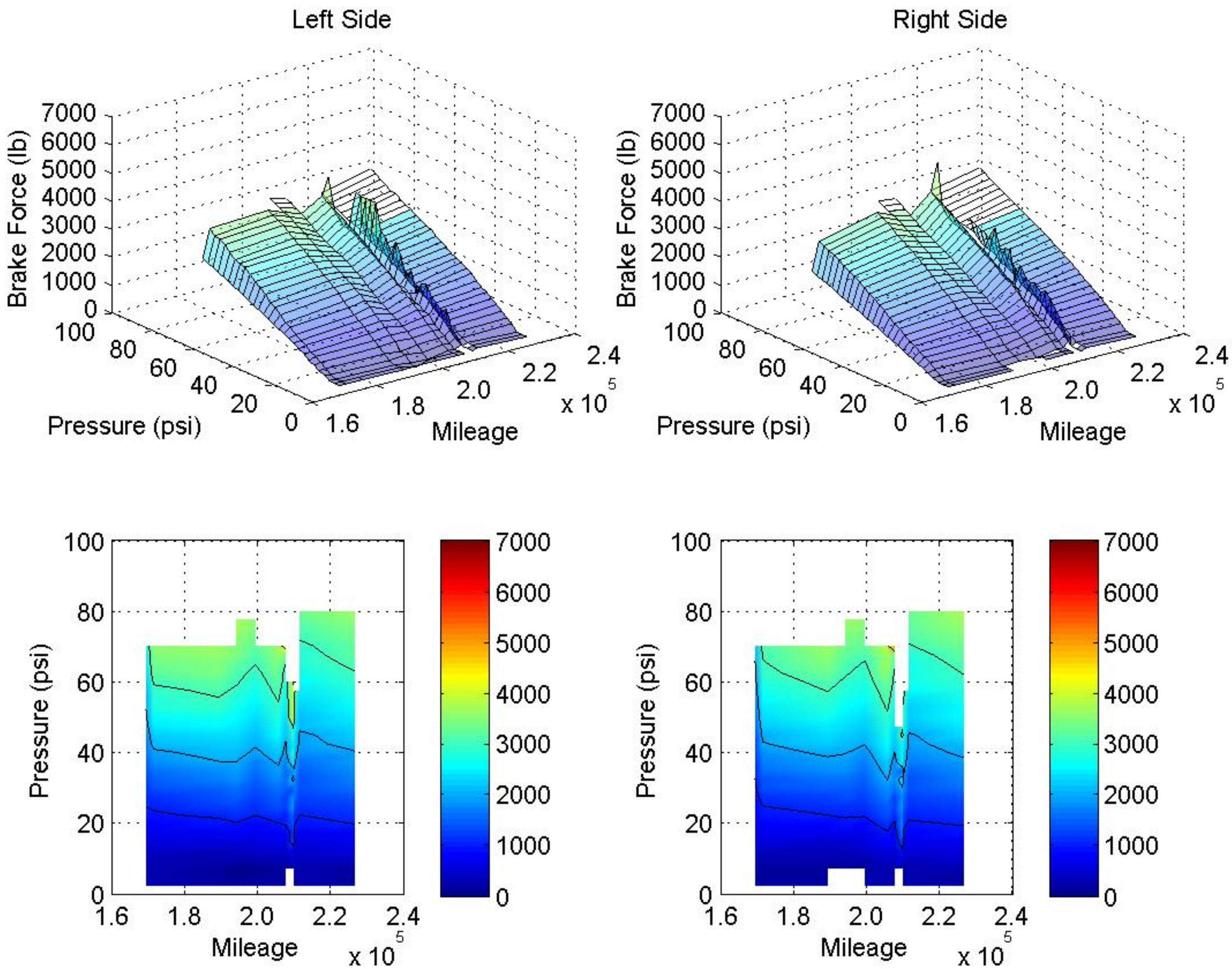
GC 194 Axle 1


Left Side
Right Side
Brake Force (lb)
Pressure (psi)
Mileage
x 10^5
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
1.6
1.8
2.0
2.2
2.4

GC 194 Axle 2

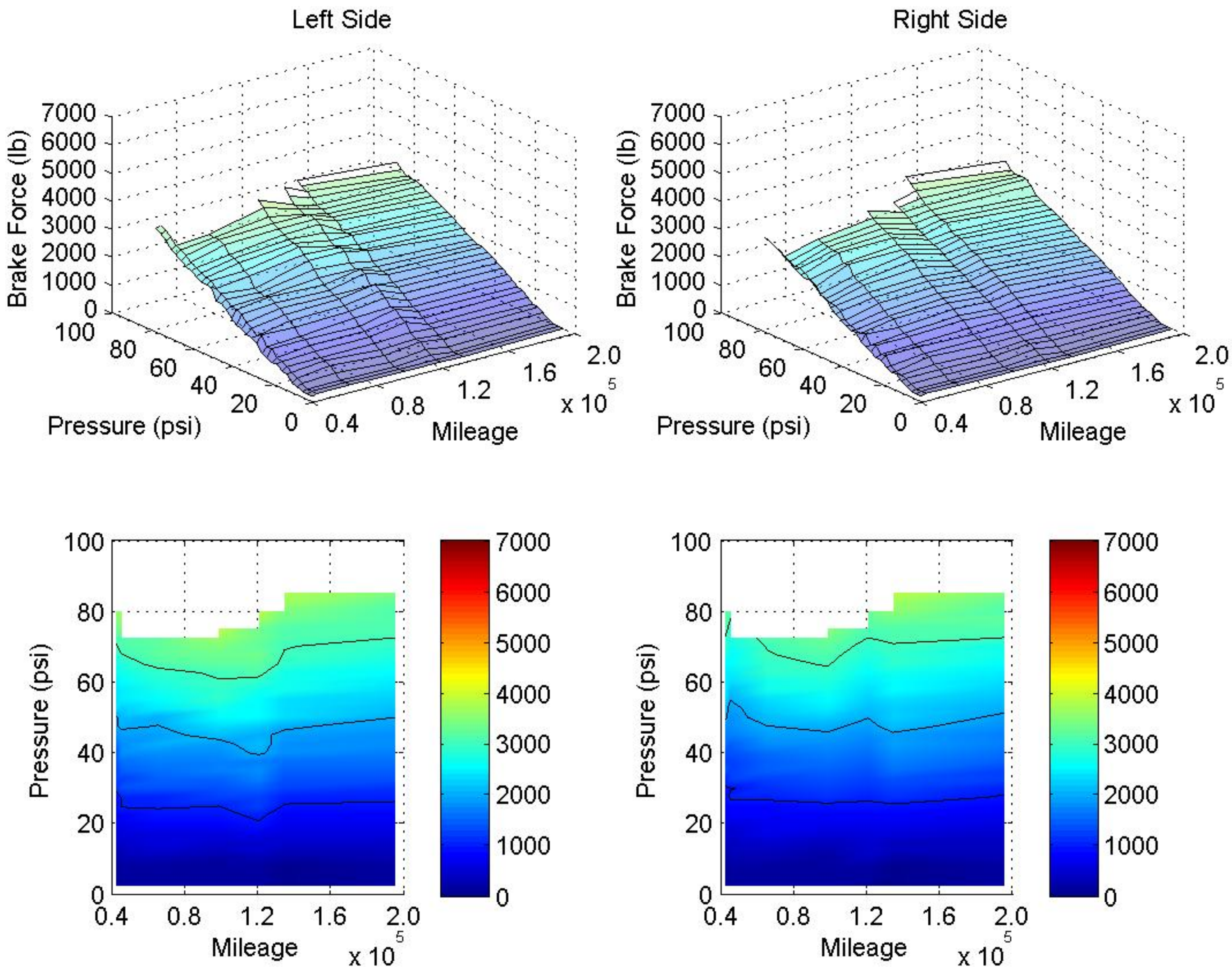

Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
1.8
2.0
2.2
2.4
x 10^5
Mileage
Pressure (psi)
Mileage

GC 194 Axle 3

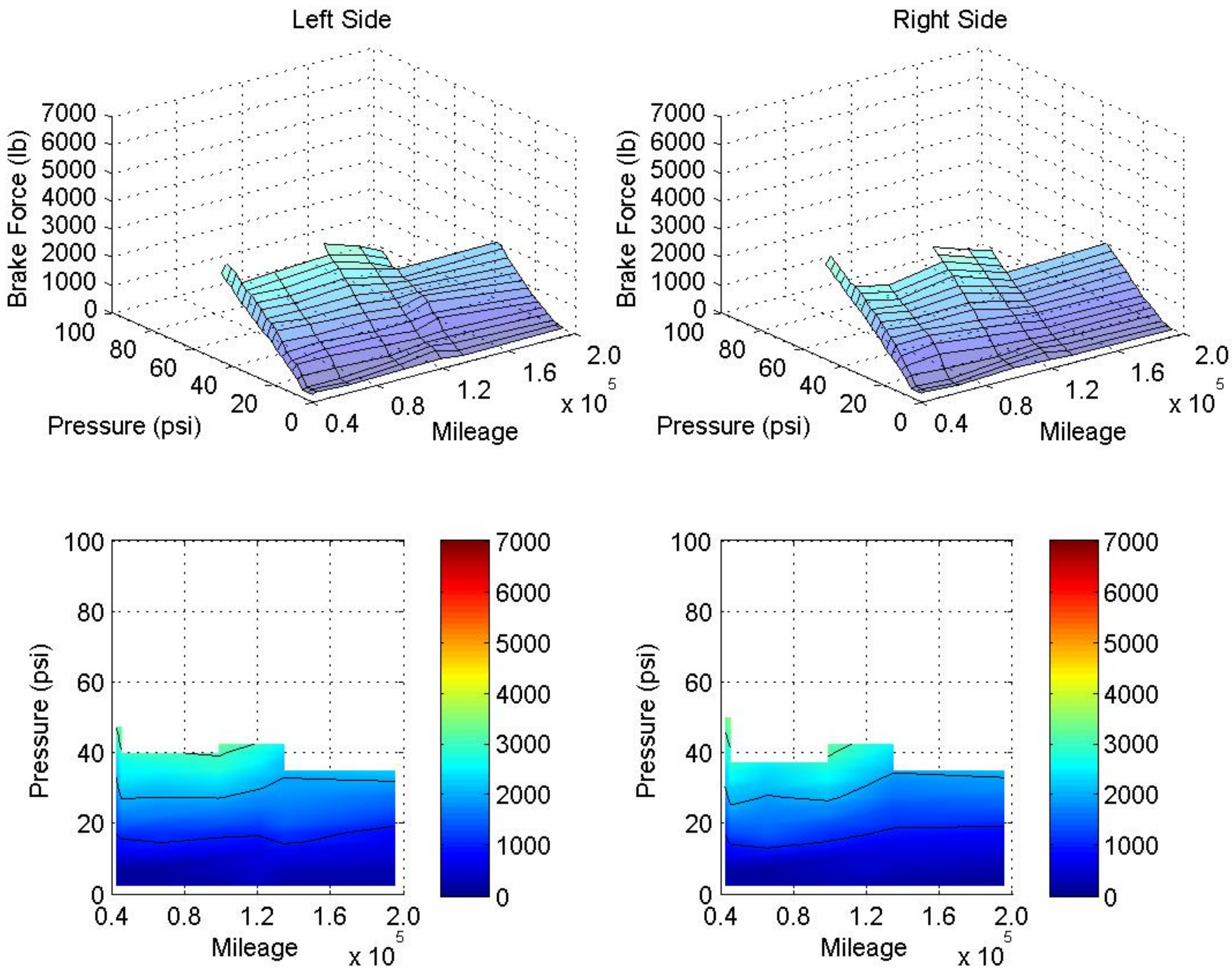


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
1.8
2.0
2.2
2.4
x 10^5
Mileage
Pressure (psi)
7000
6000
5000
4000
3000
2000
1000
0

PP 1 Axle 1

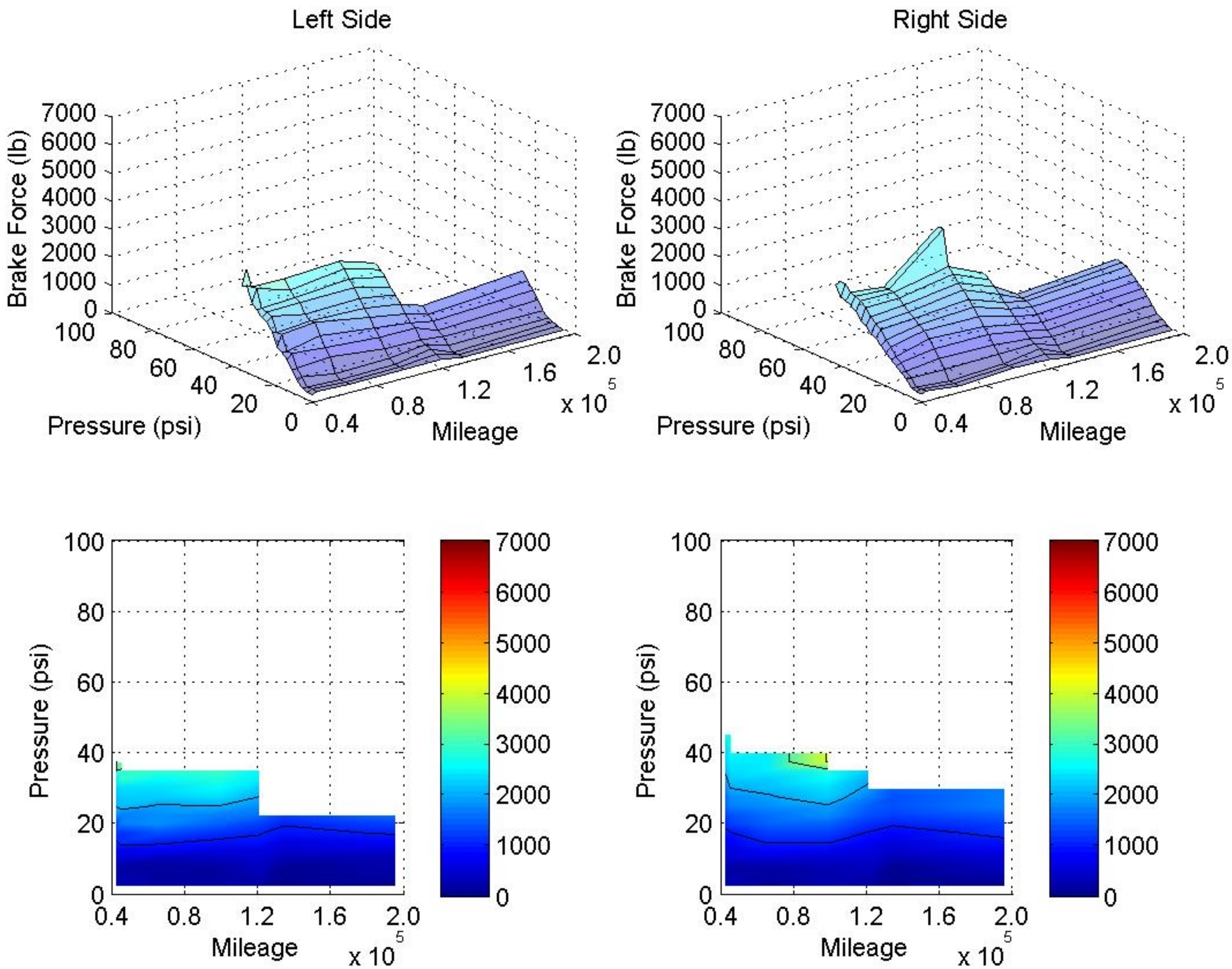

Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
0.4
0.8
1.2
1.6
2.0
x 10^5
Mileage
Pressure (psi)
Mileage
x 10^5
7000
6000
5000
4000
3000
2000
1000
0

PP 1 Axle 2



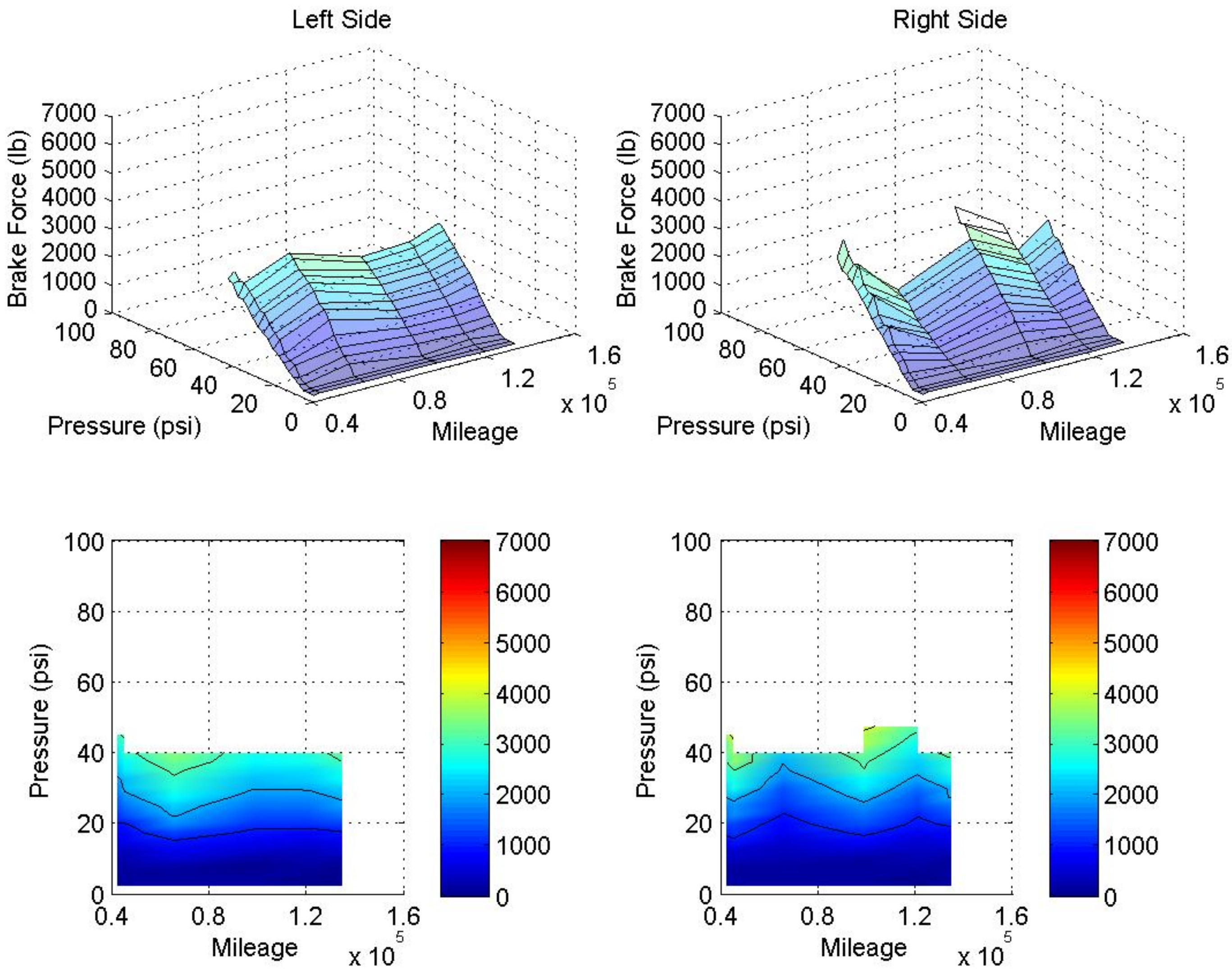
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
0.4
0.8
1.2
1.6
2.0
x 10^5
Mileage

PP 1 Axle 3

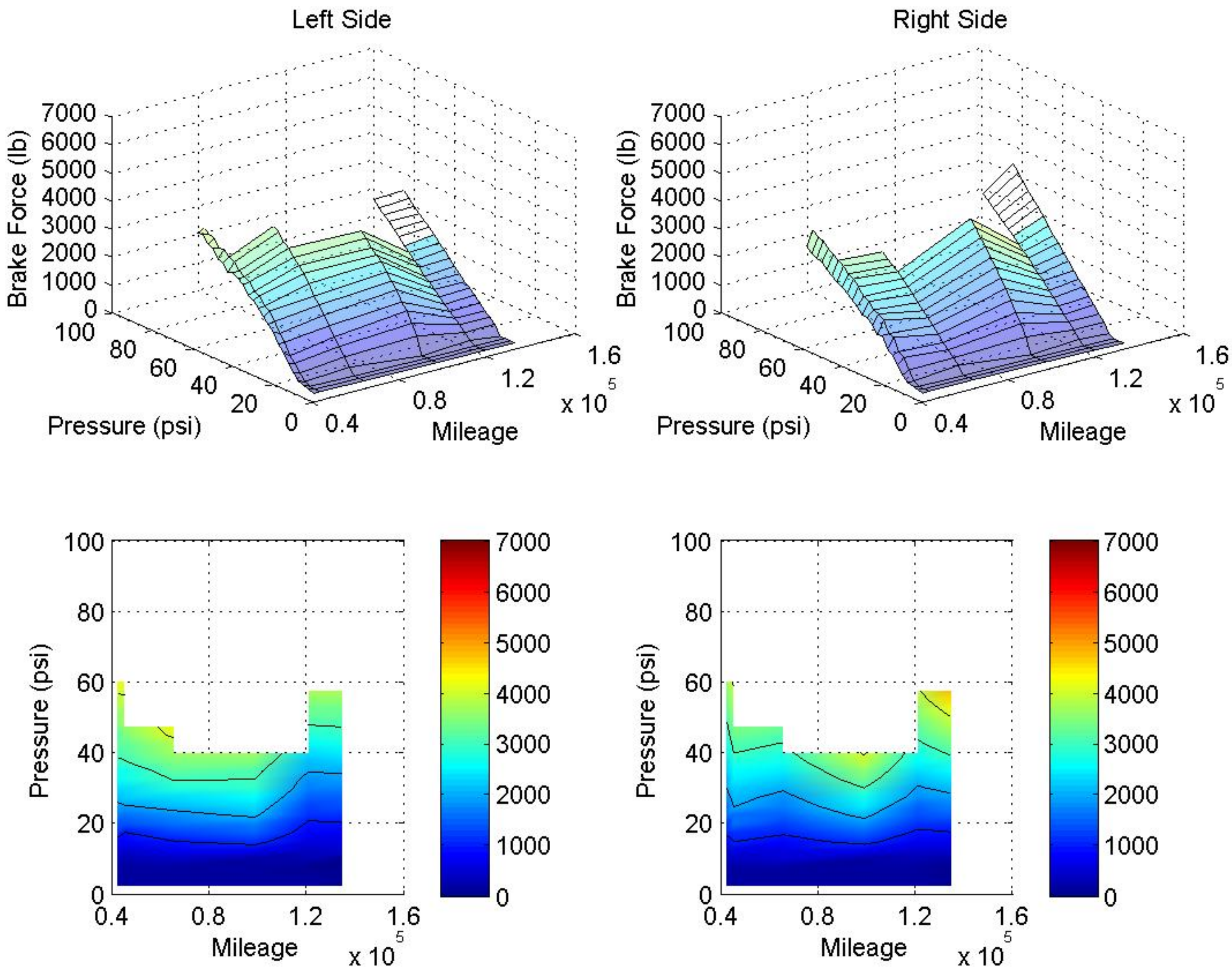


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
0.4
0.8
1.2
1.6
2.0
x 10^5
Mileage

PP 1 Axle 4

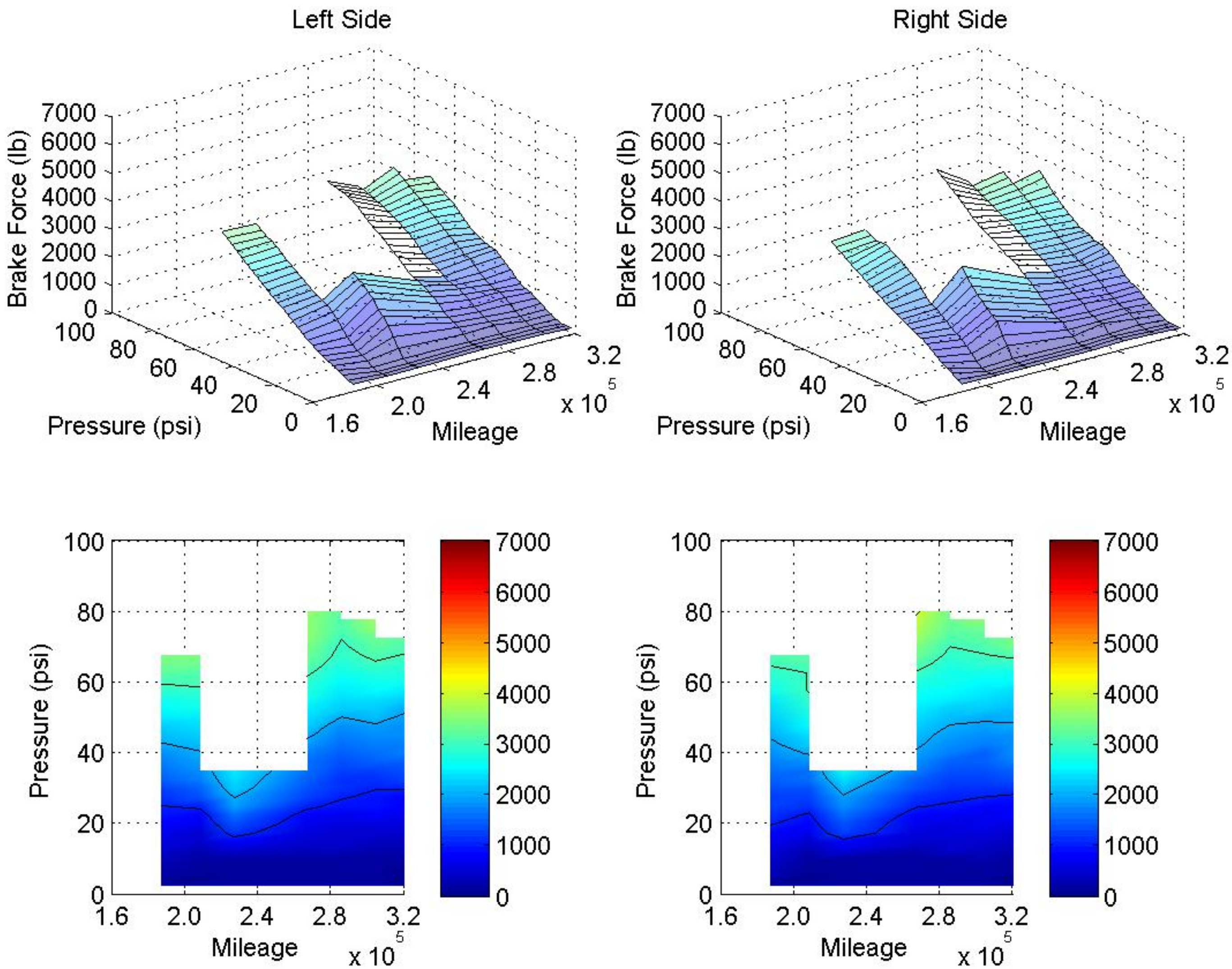

Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
0.4
0.8
1.2
1.6
x 10^5

PP 1 Axle 5



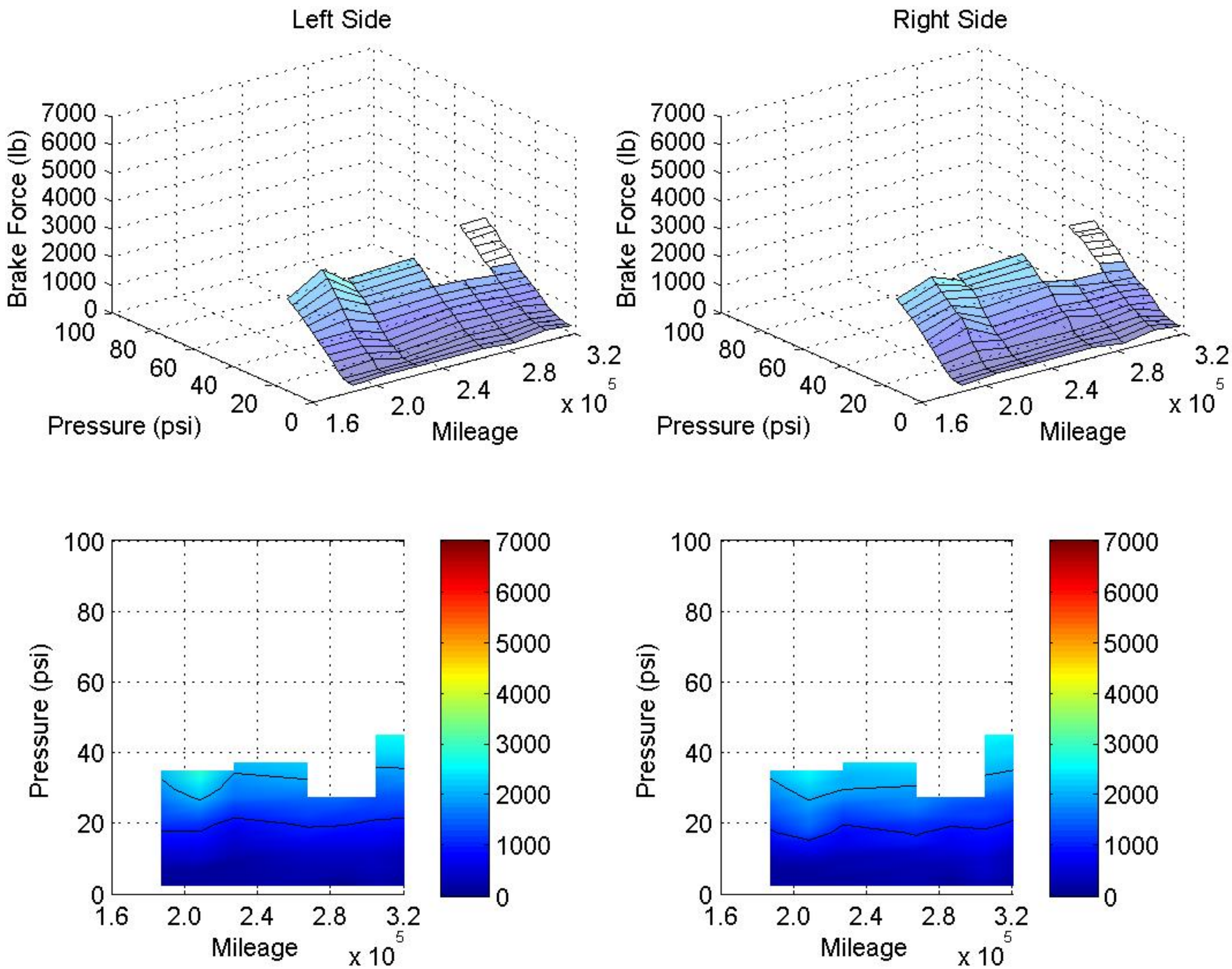
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
0.4
0.8
1.2
1.6
x 10^5

PP 2 Axle 1



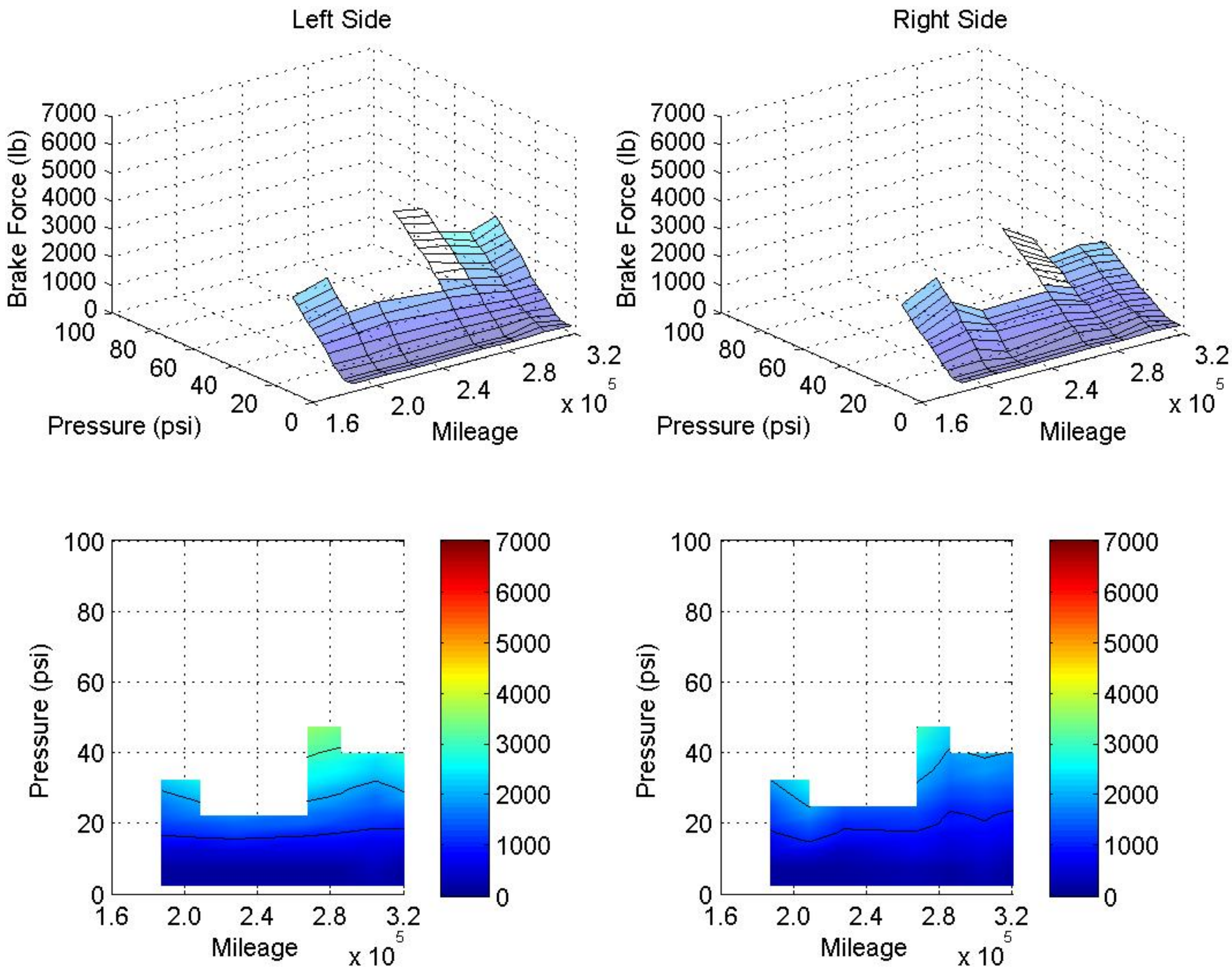
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
2.0
2.4
2.8
3.2
x 10^5
Mileage

PP 2 Axle 2



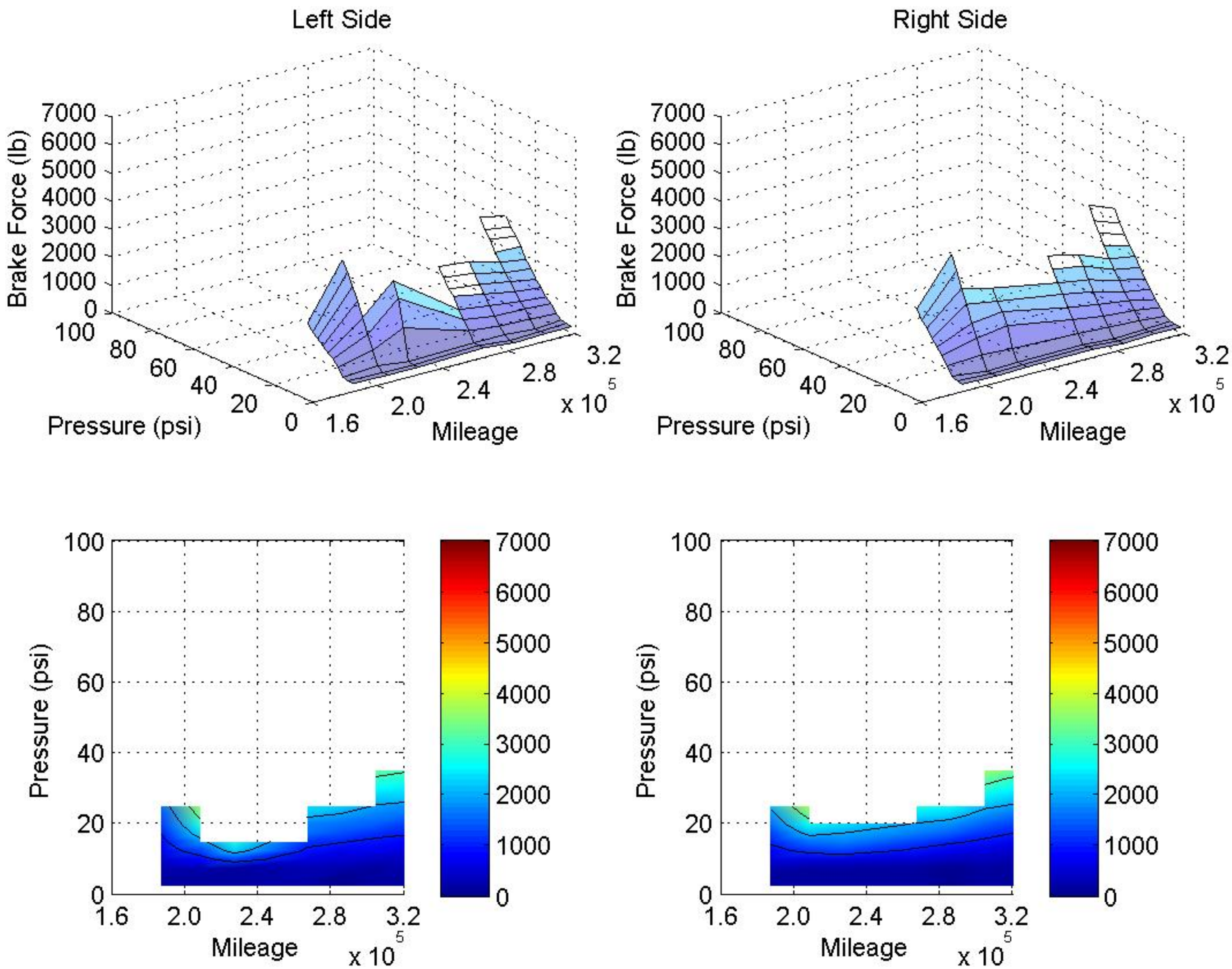
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
1.6
2.0
2.4
2.8
3.2
x 10^5

PP 2 Axle 3



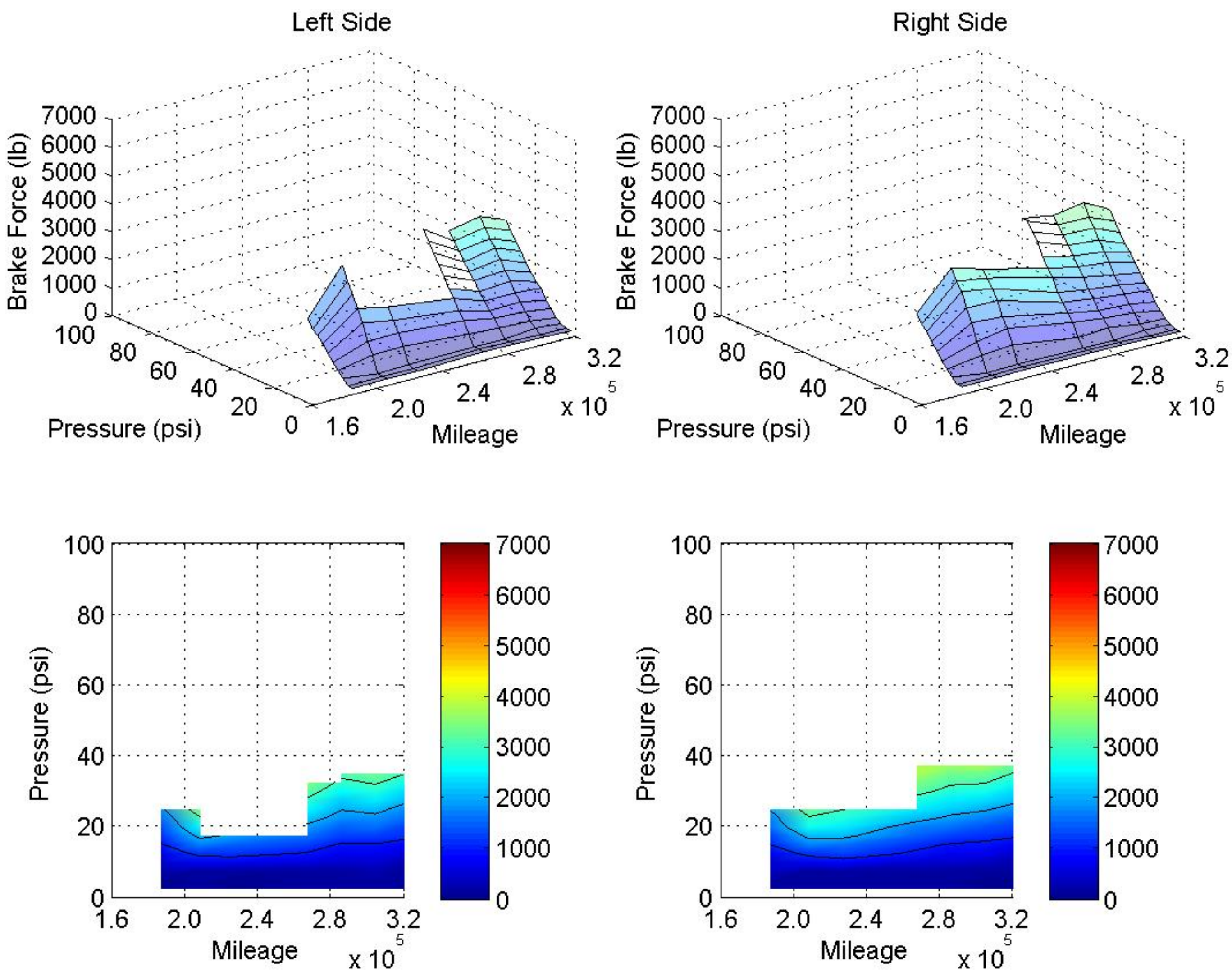
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
2.0
2.4
2.8
3.2
x 10^5
Mileage
Pressure (psi)
Mileage
x 10^5

PP 2 Axle 4



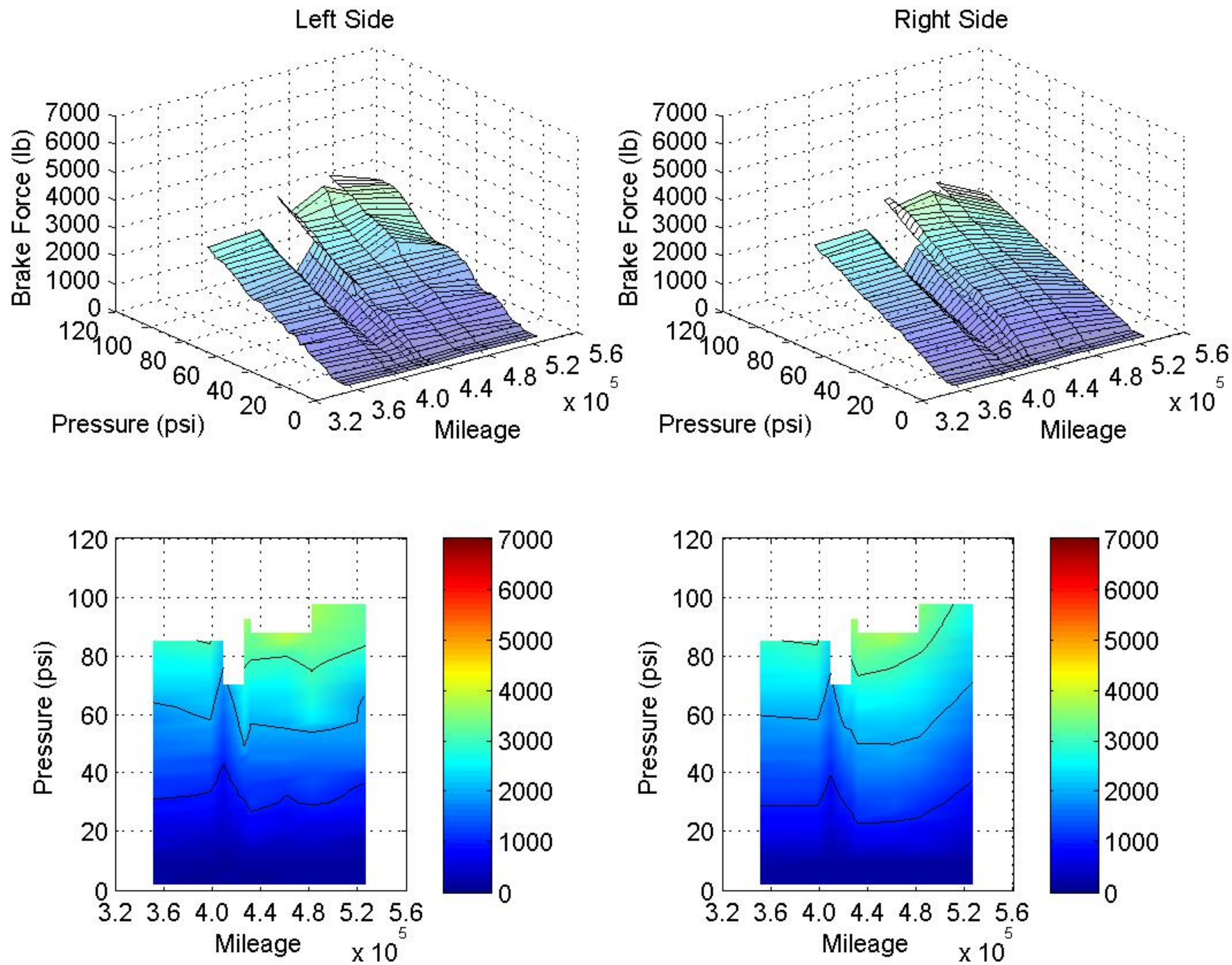
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
2.0
2.4
2.8
3.2
x 10^5
Mileage

PP 2 Axle 5

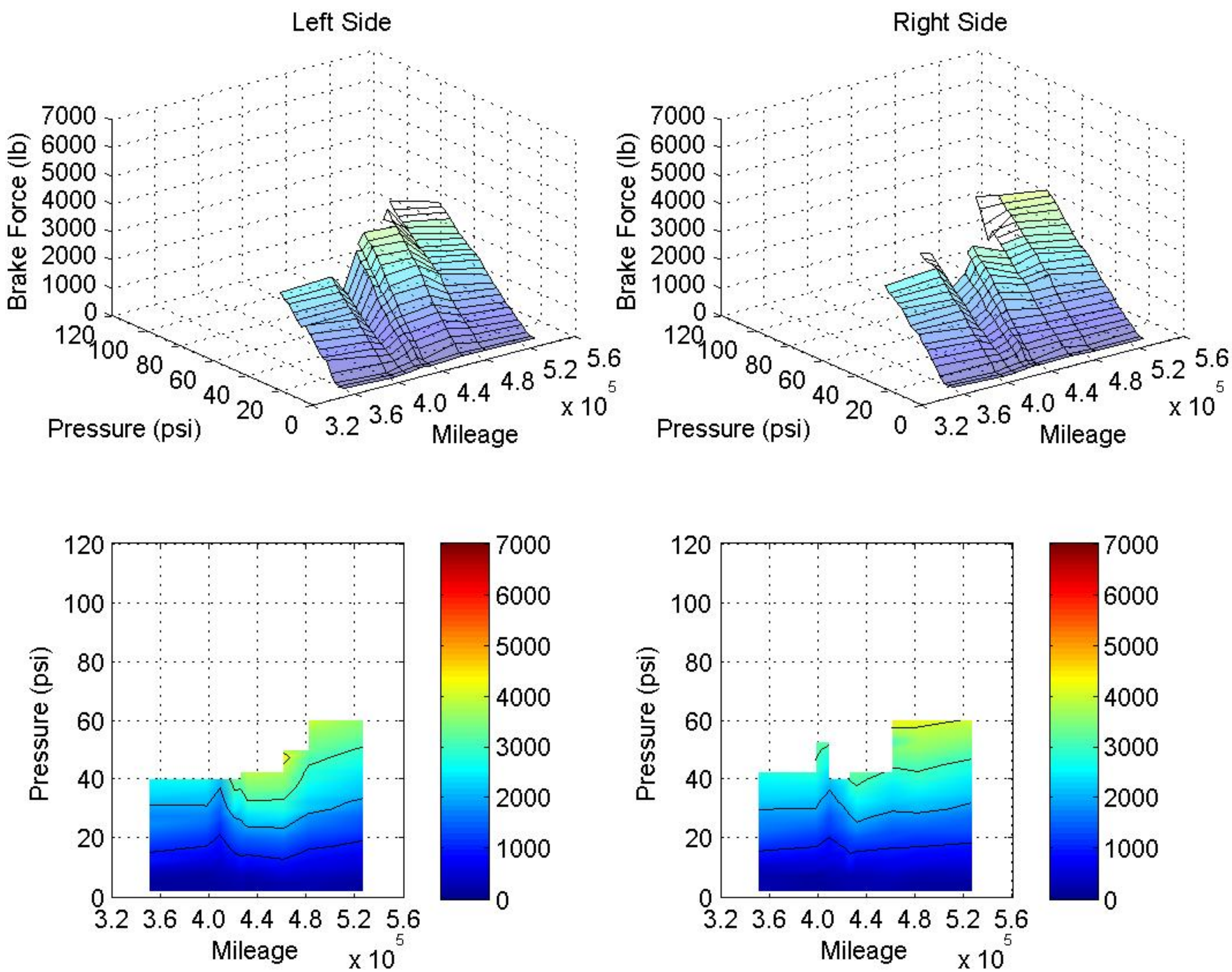


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
1.6
2.0
2.4
2.8
3.2
x 10^5
Mileage

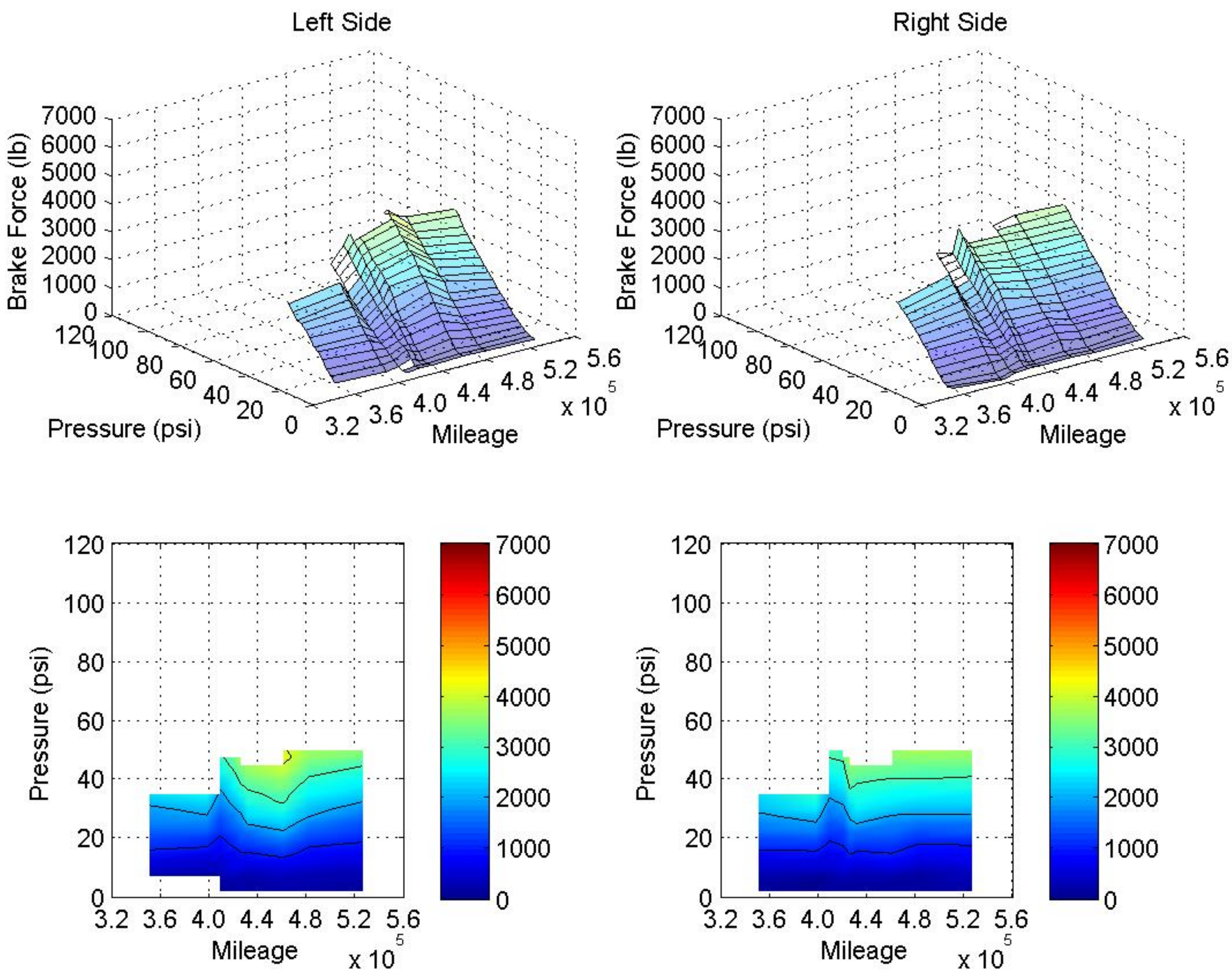
RD 375 Axle 1


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
0
Pressure (psi)
3.2
3.6
4.0
4.4
4.8
5.2
5.6
Mileage
x 10^5
Pressure (psi)
Mileage
x 10^5
7000
6000
5000
4000
3000
2000
1000
0

RD 375 Axle 2

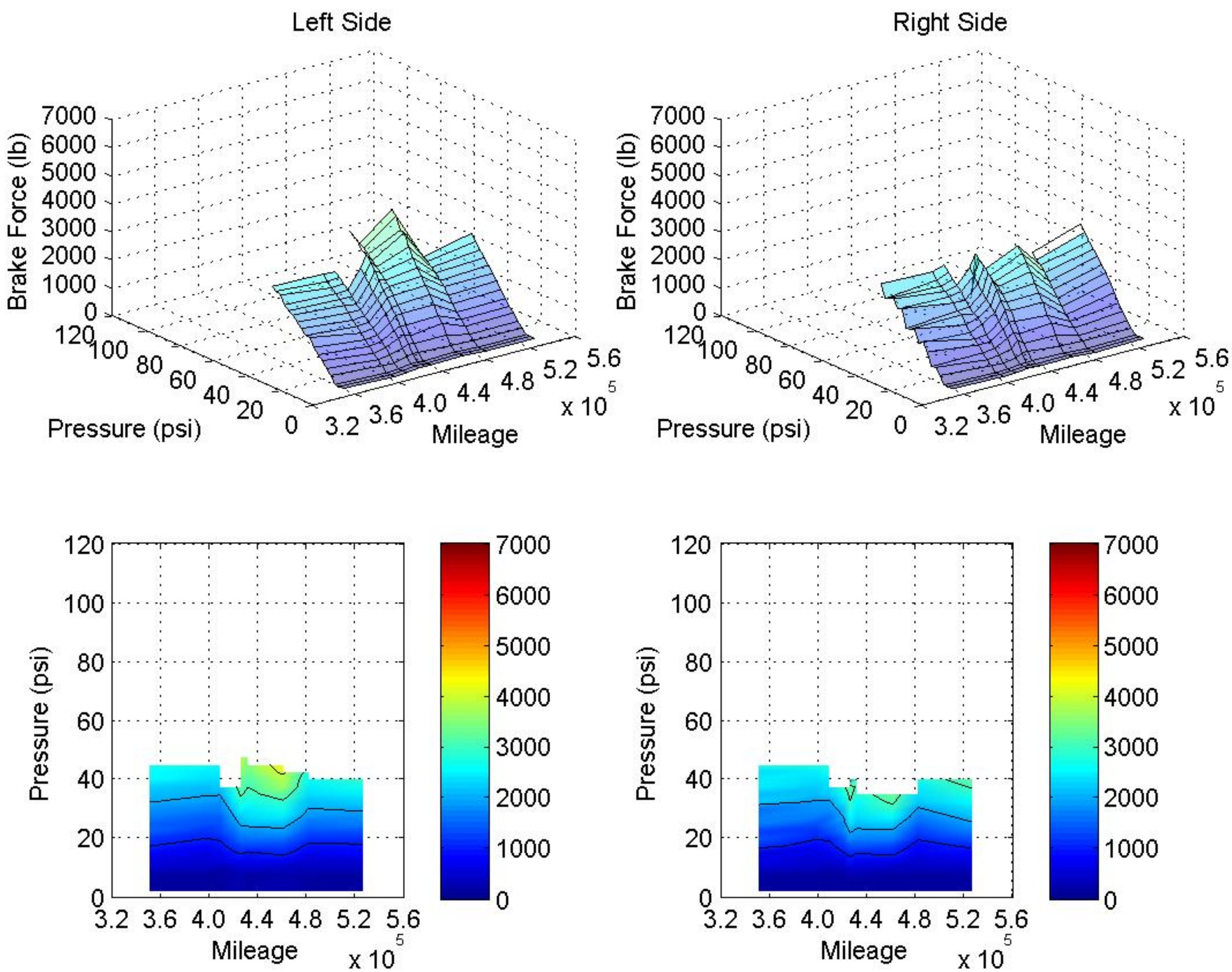

Left Side
Right Side
Brake Force (lb)
Pressure (psi)
Mileage
x 10^5
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
3.2
3.6
4.0
4.4
4.8
5.2
5.6

RD 375 Axle 3

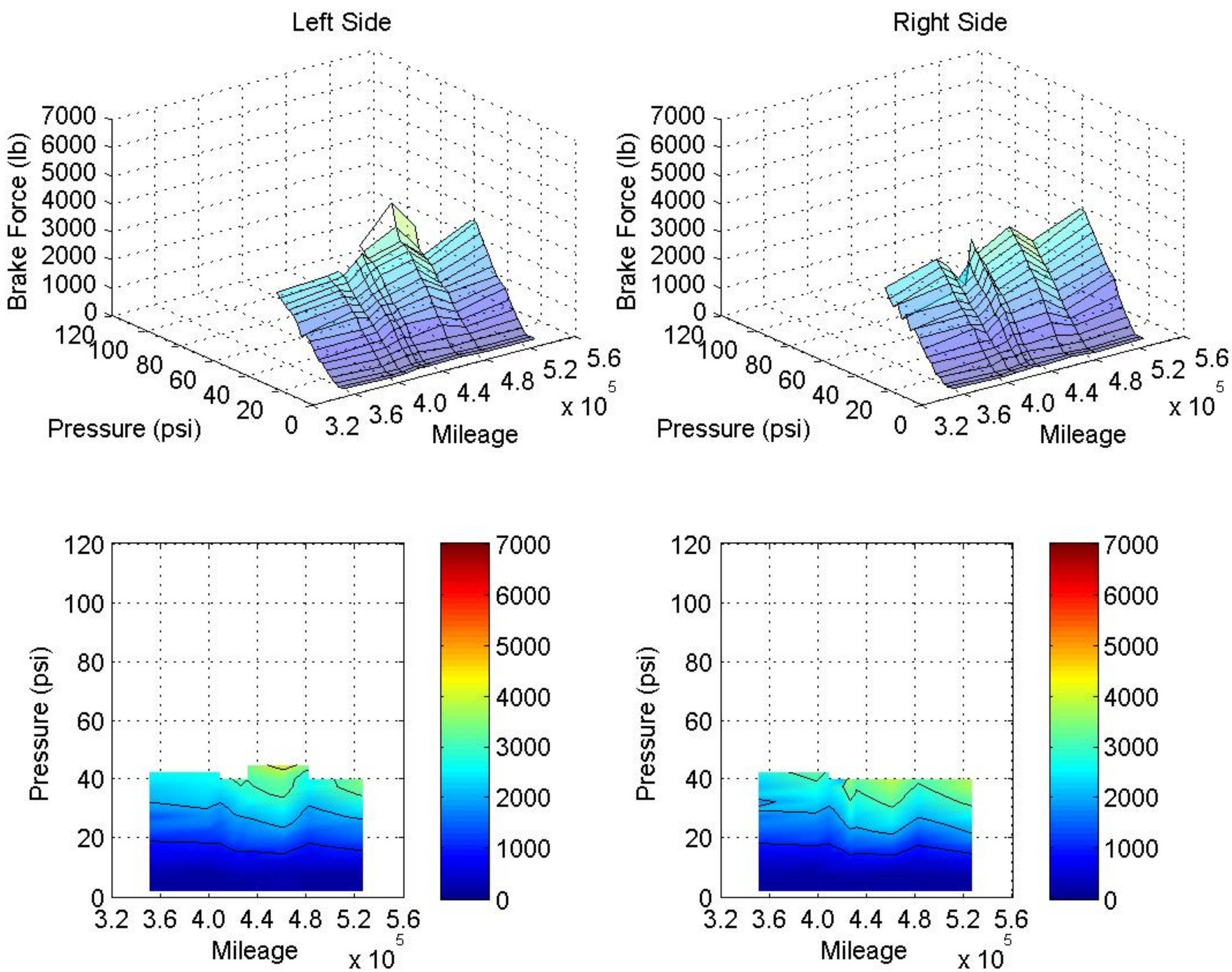


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
0
Pressure (psi)
3.2
3.6
4.0
4.4
4.8
5.2
5.6
Mileage
x 10^5

RD 375 Axle 4

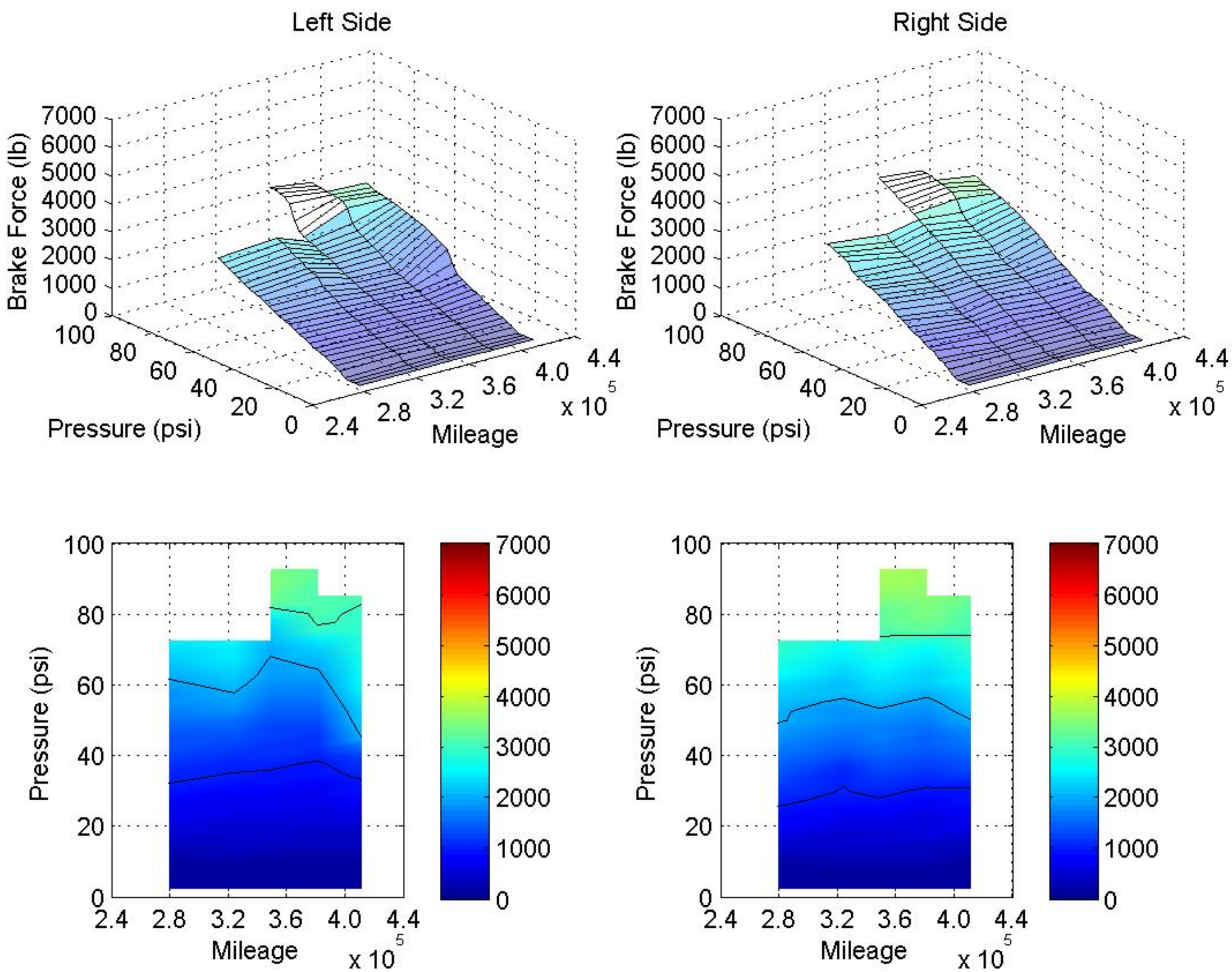

Left Side
Right Side
Brake Force (lb)
Pressure (psi)
Mileage
x 10^5
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
3.2
3.6
4.0
4.4
4.8
5.2
5.6

RD 375 Axle 5



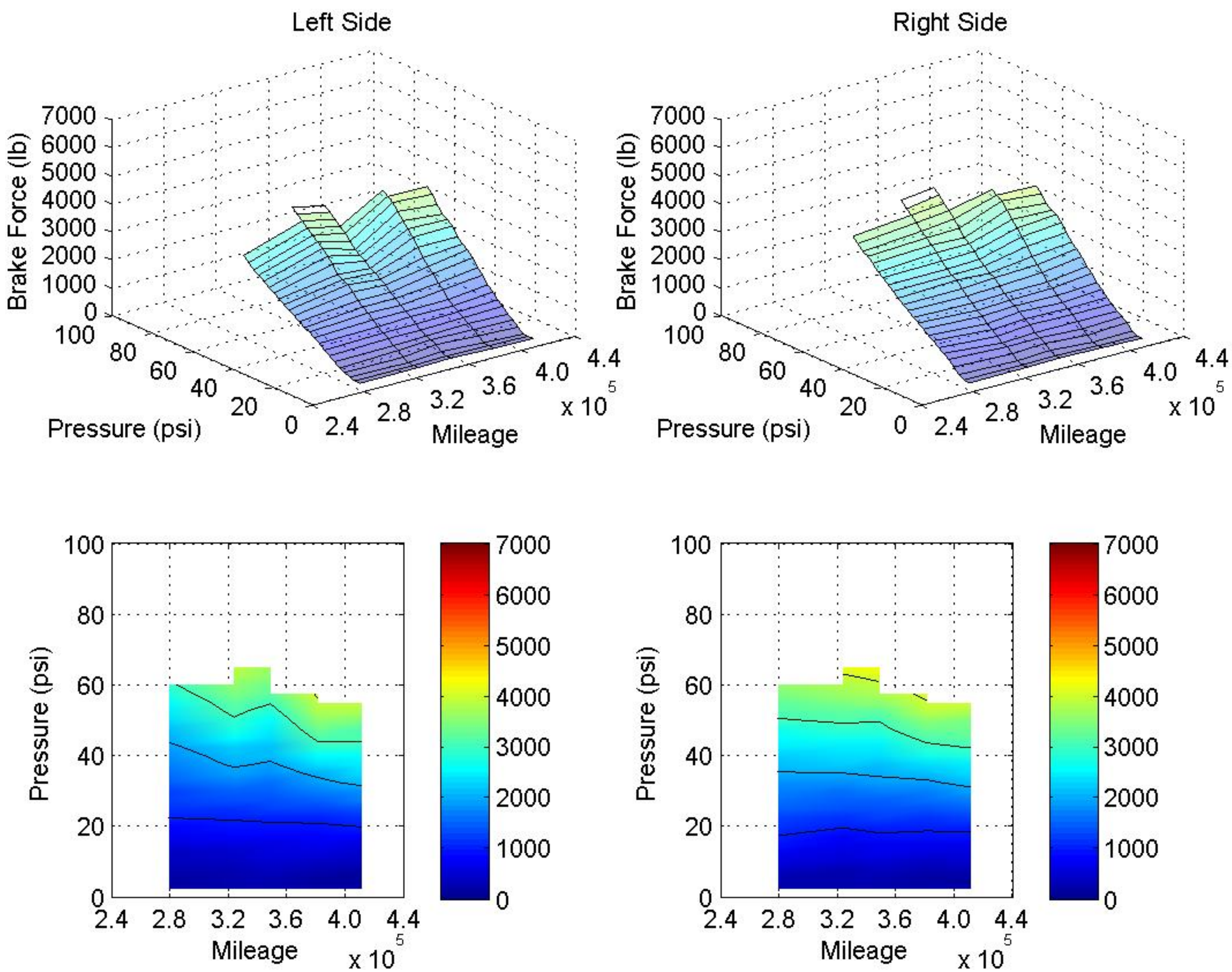
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
120
100
80
60
40
20
0
Pressure (psi)
3.2
3.6
4.0
4.4
4.8
5.2
5.6
x 10^5
Mileage

RD 379 Axle 1



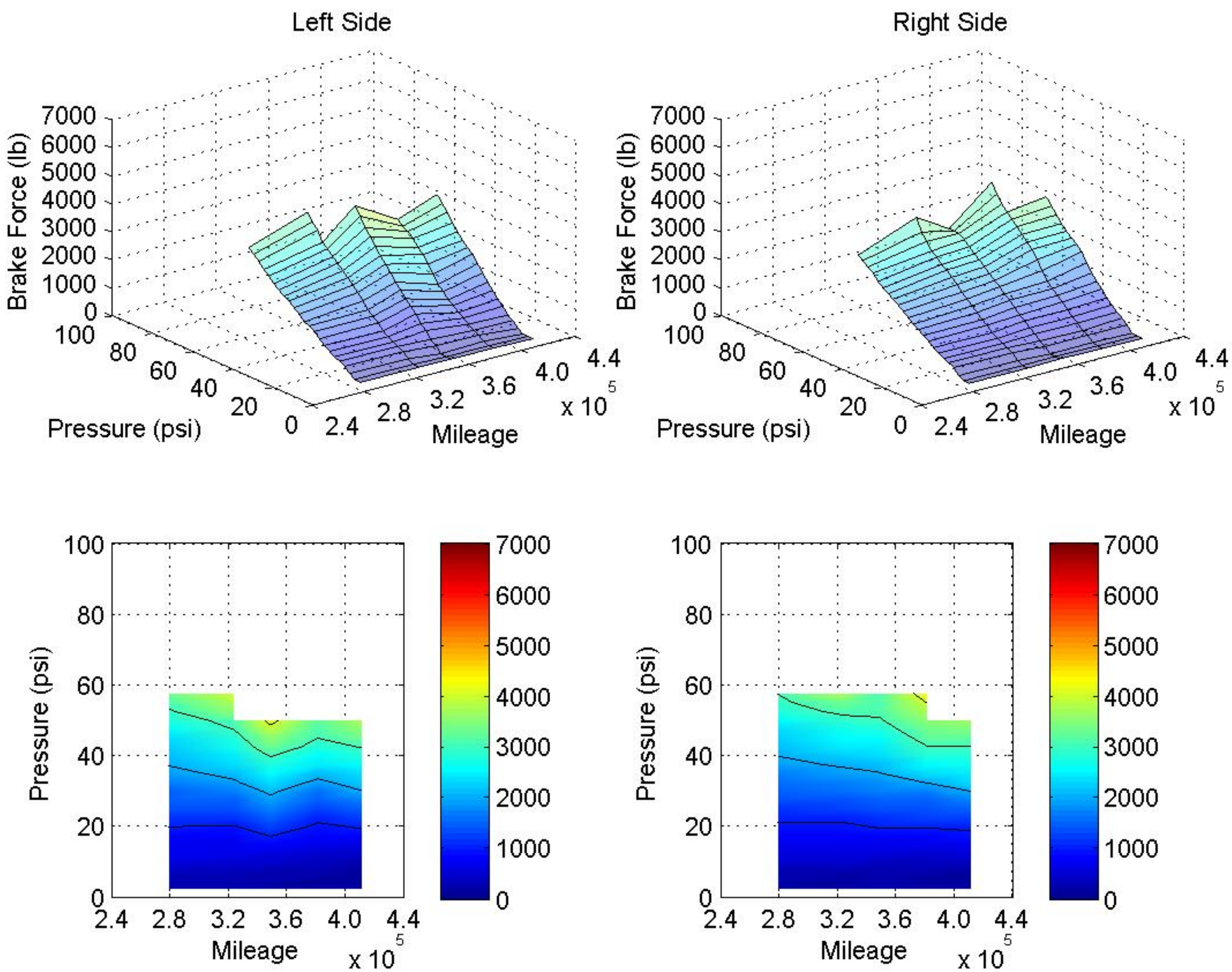
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
100
80
60
40
20
0
Pressure (psi)
2.4
2.8
3.2
3.6
4.0
4.4
x 10^5
Mileage

RD 379 Axle 2

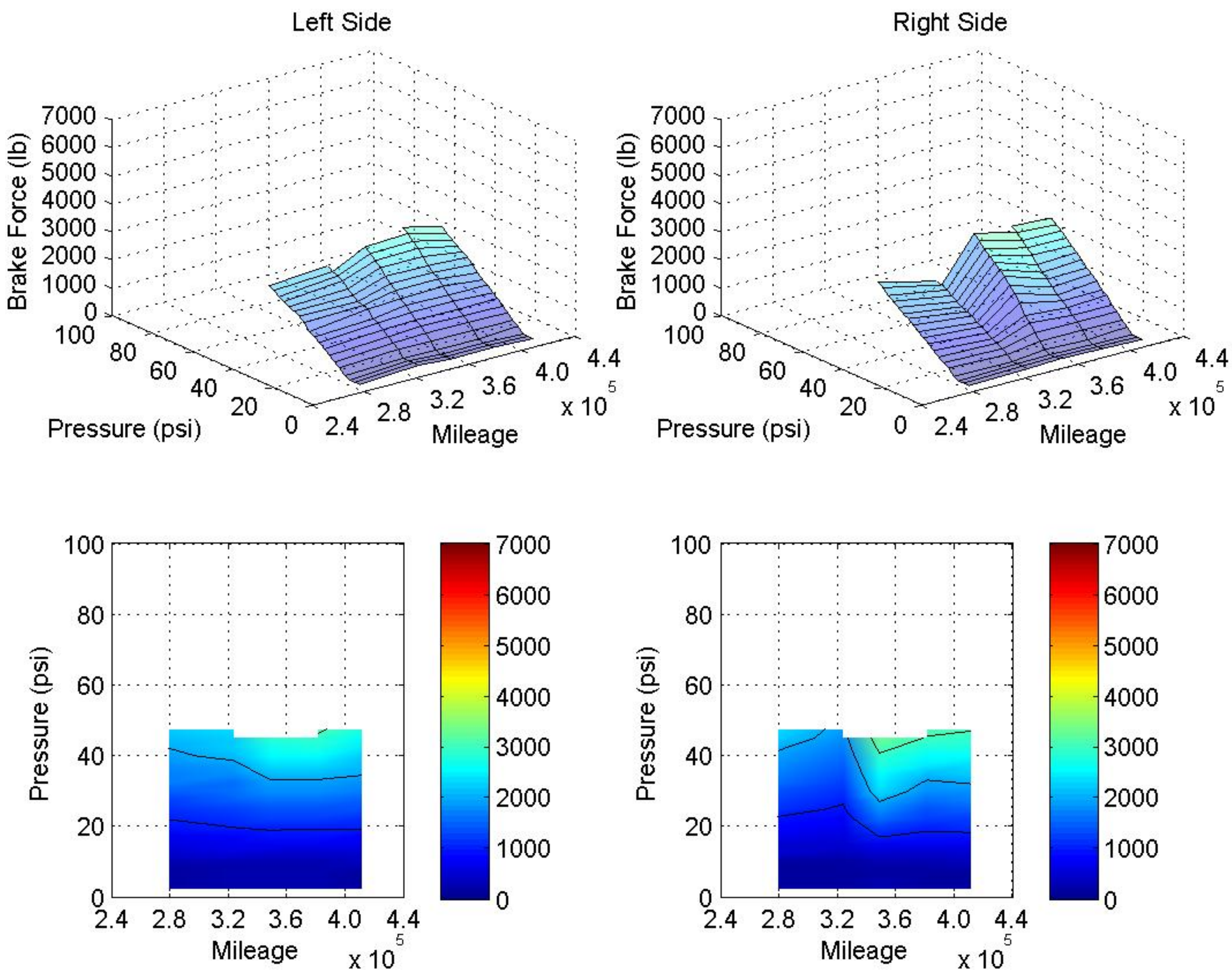


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
2.4
2.8
3.2
3.6
4.0
4.4
x 10^5

RD 375 Axle 3

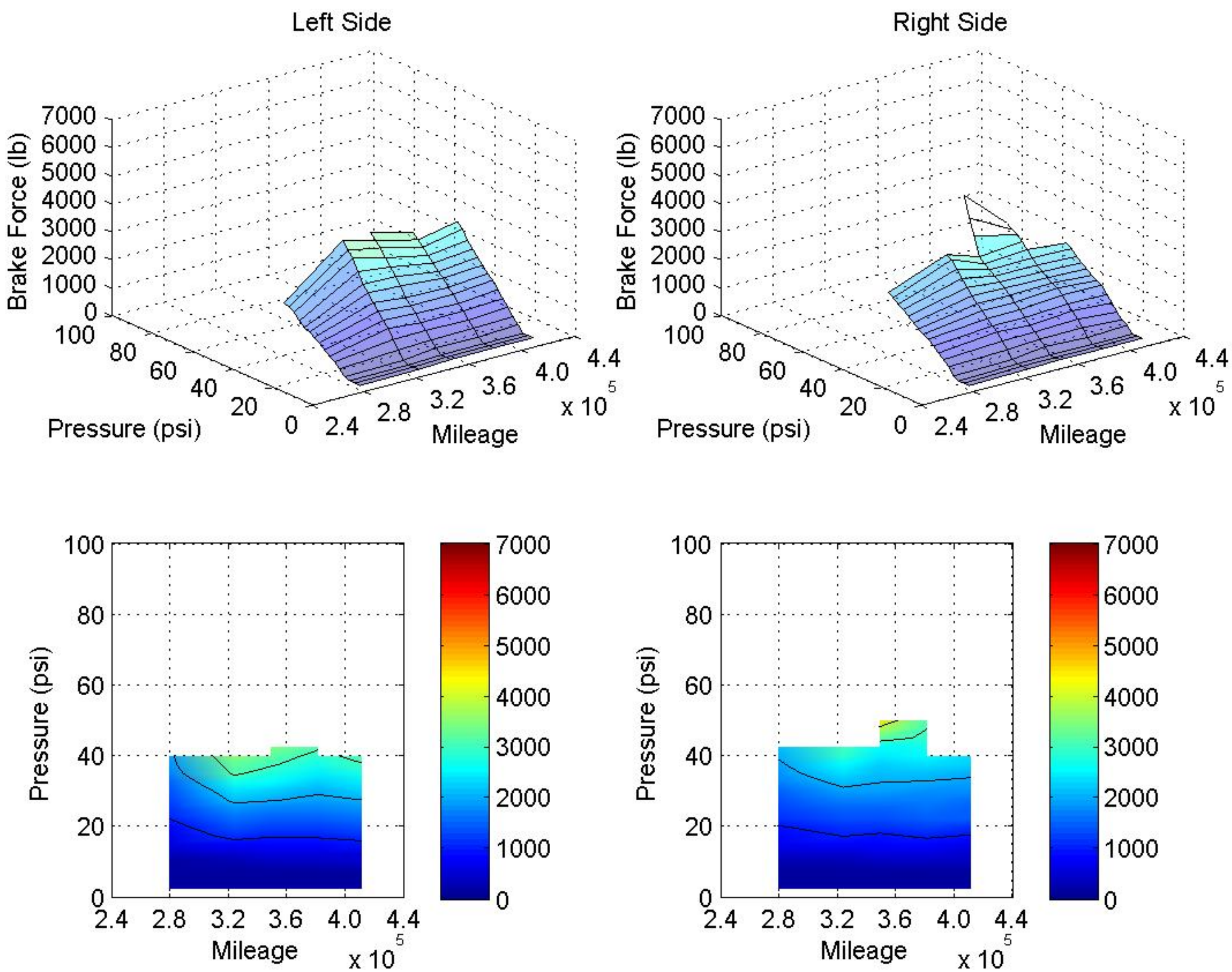

Left Side
Right Side
Brake Force (lb)
Pressure (psi)
Mileage
x 10^5
0
1000
2000
3000
4000
5000
6000
7000
0
20
40
60
80
100
2.4
2.8
3.2
3.6
4.0
4.4

RD 375 Axle 4



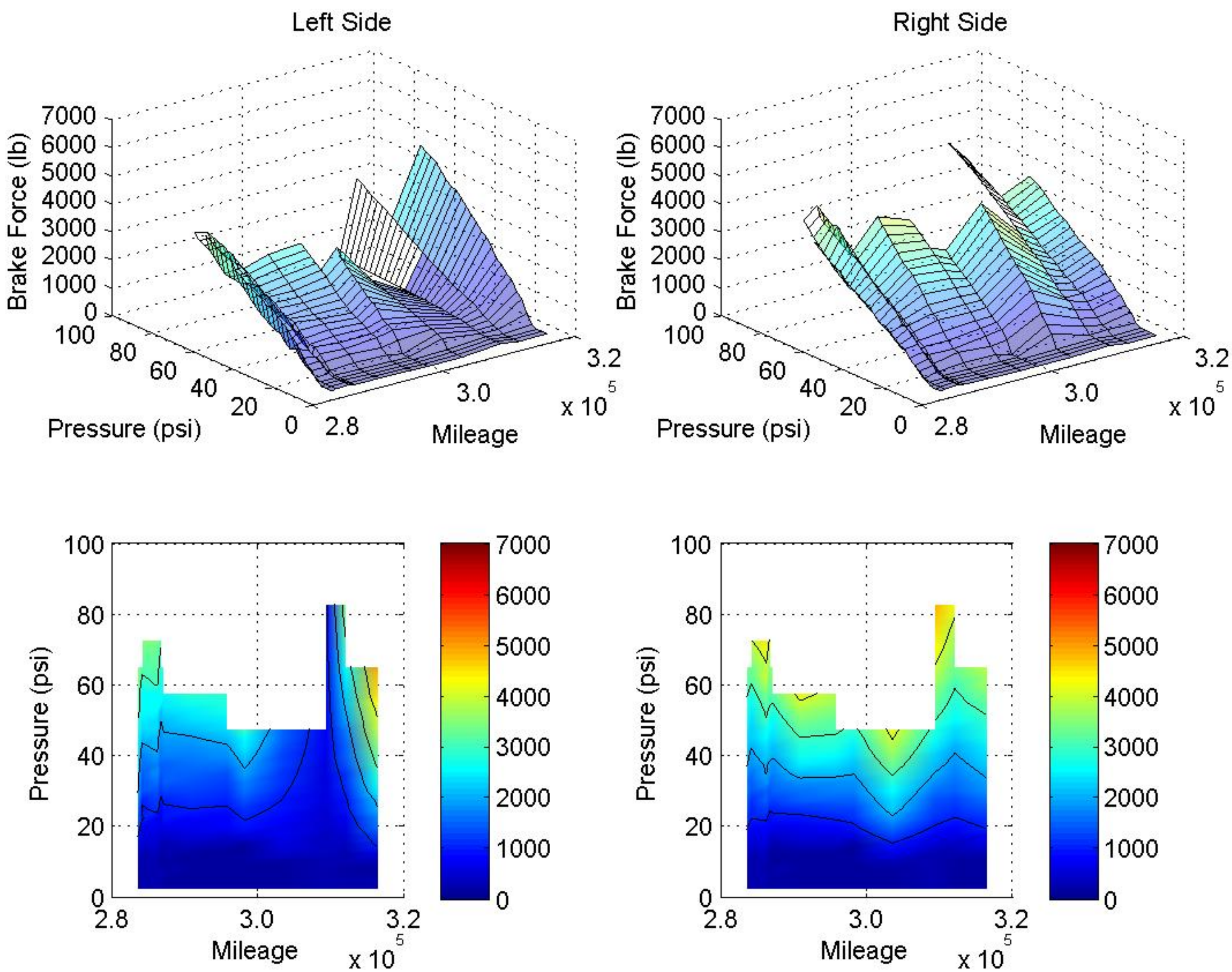
Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
2.4
2.8
3.2
3.6
4.0
4.4
x 10^5

RD 375 Axle 5

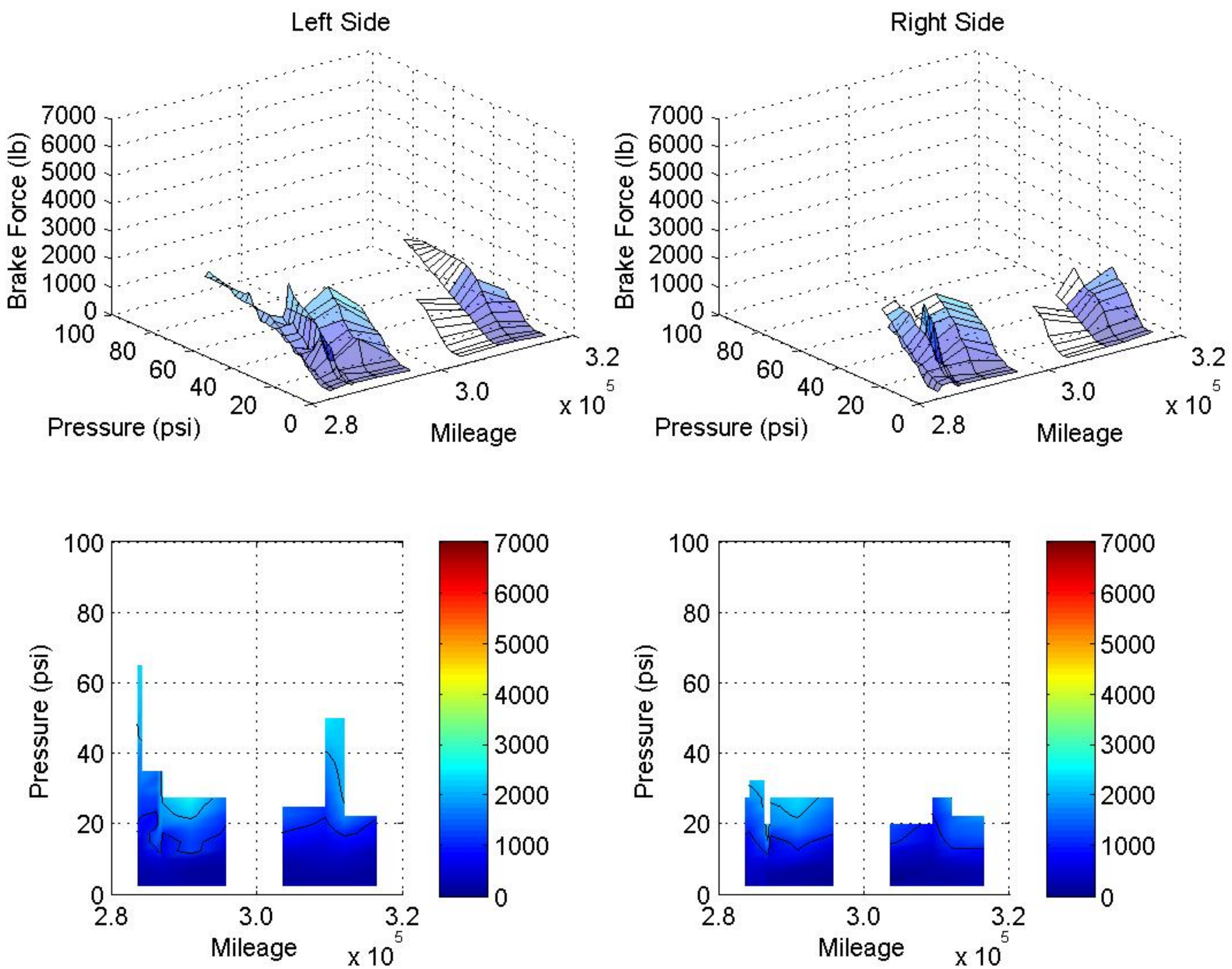


Left Side
Right Side
Brake Force (lb)
7000
6000
5000
4000
3000
2000
1000
0
Pressure (psi)
100
80
60
40
20
0
Mileage
2.4
2.8
3.2
3.6
4.0
4.4
x 10^5

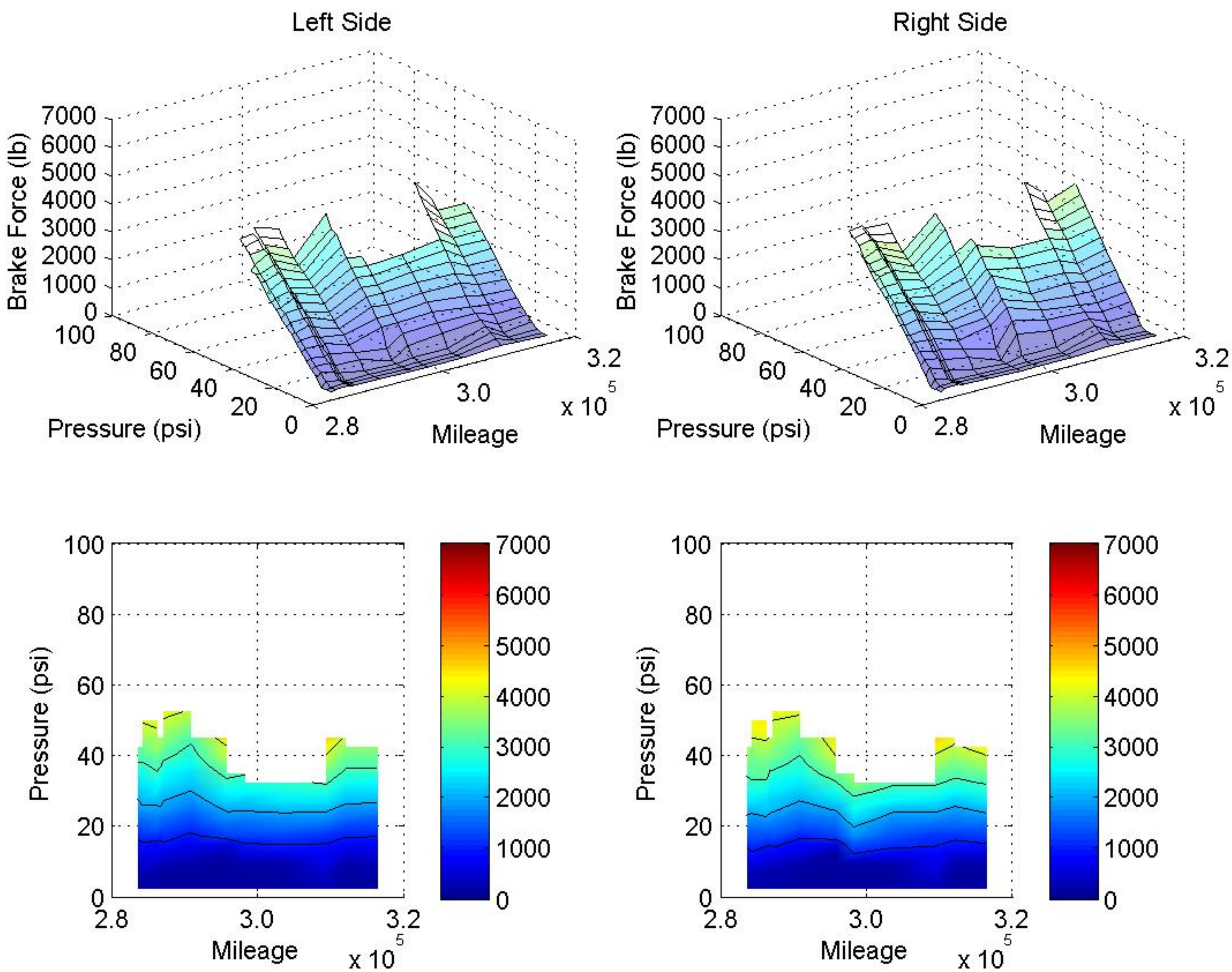
ST 2226 Axle 1



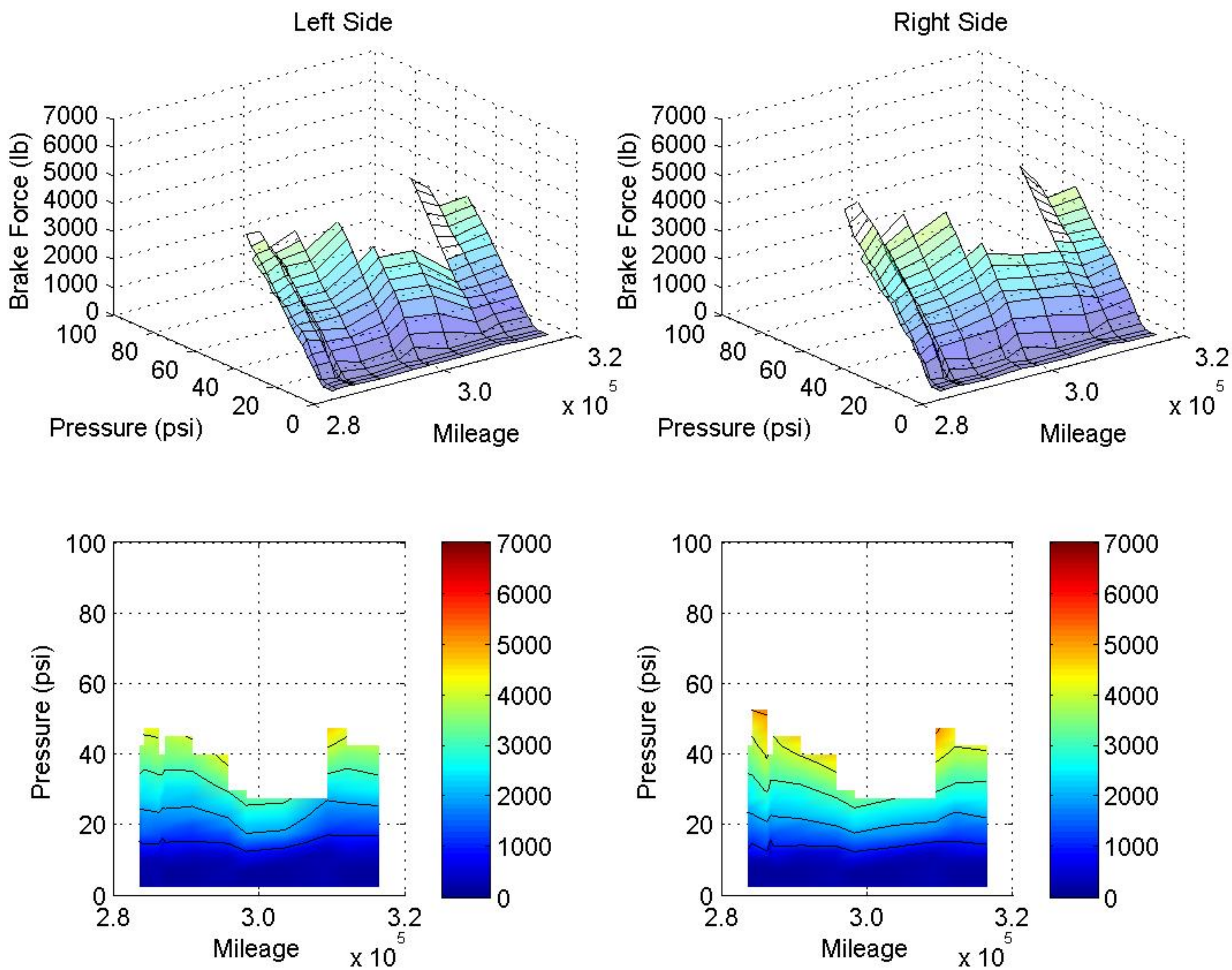
ST 2226 Axle 2



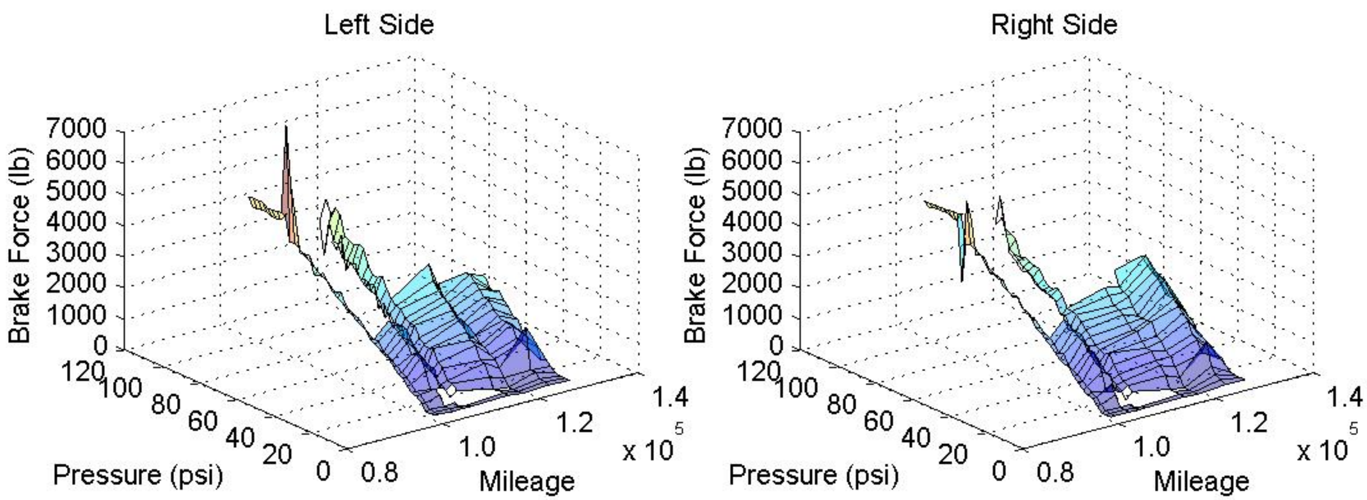
ST 2226 Axle 3

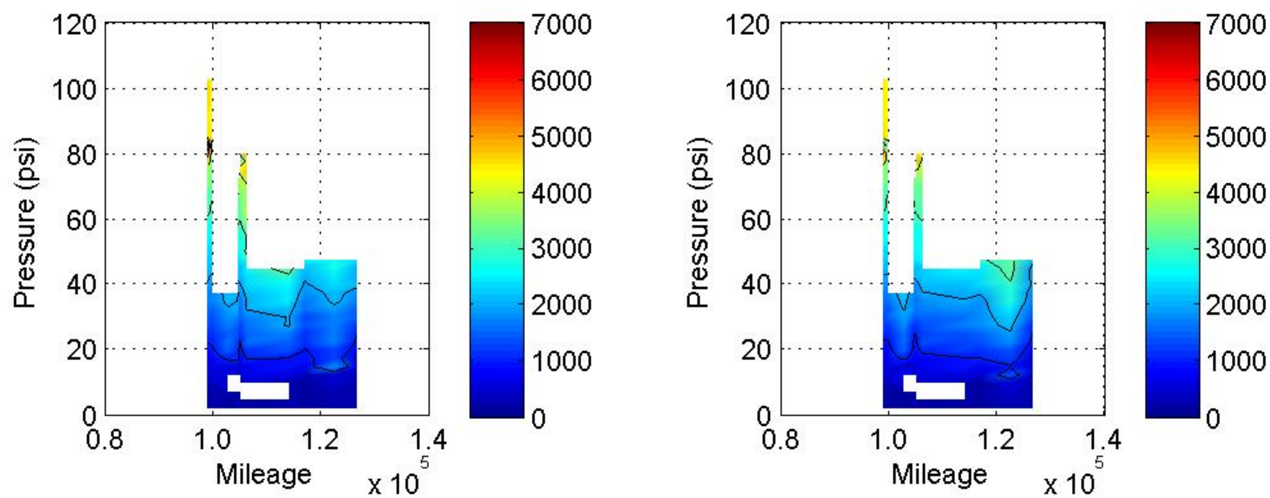


ST 2226 Axle 4

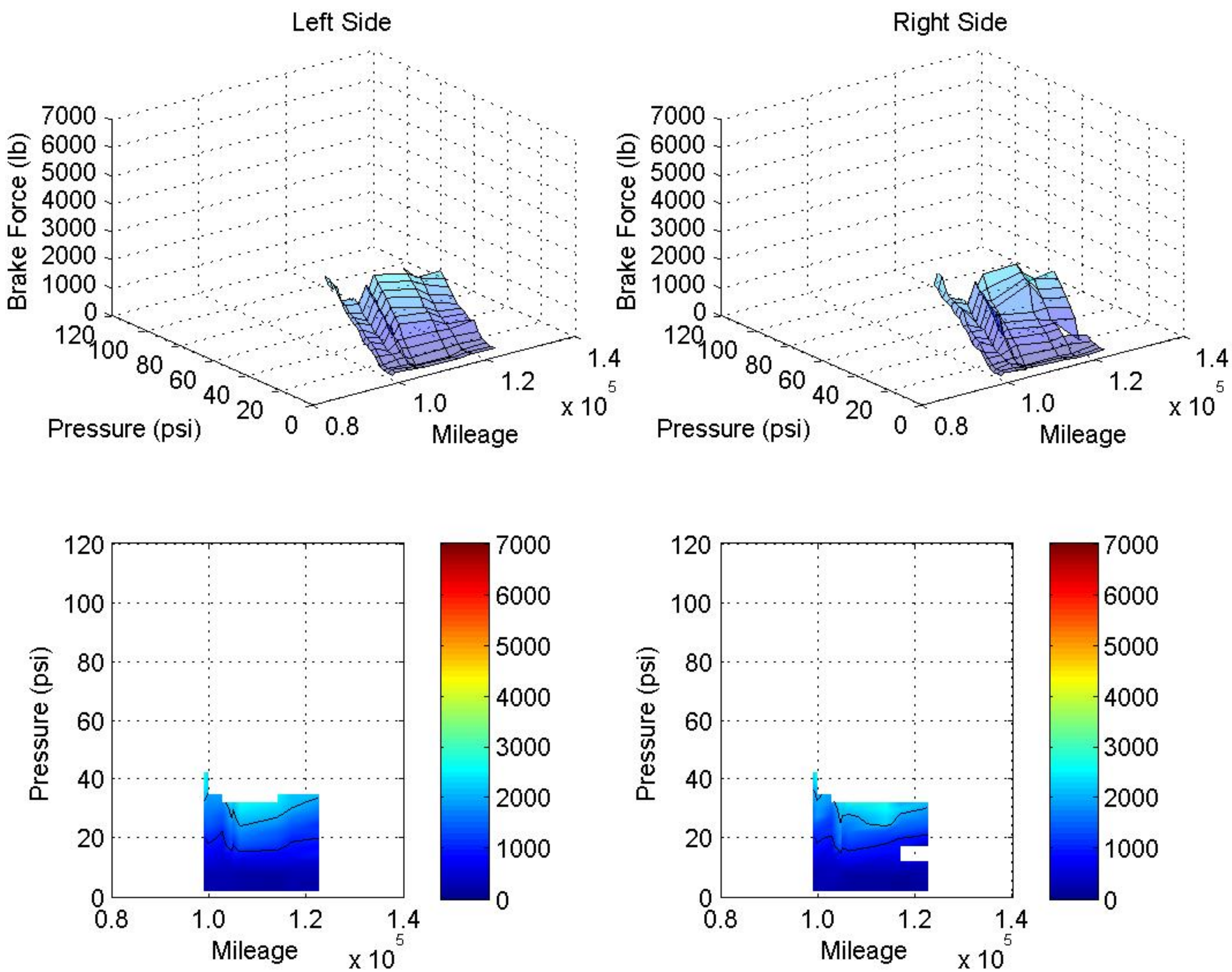


ST 2235 Axle 1

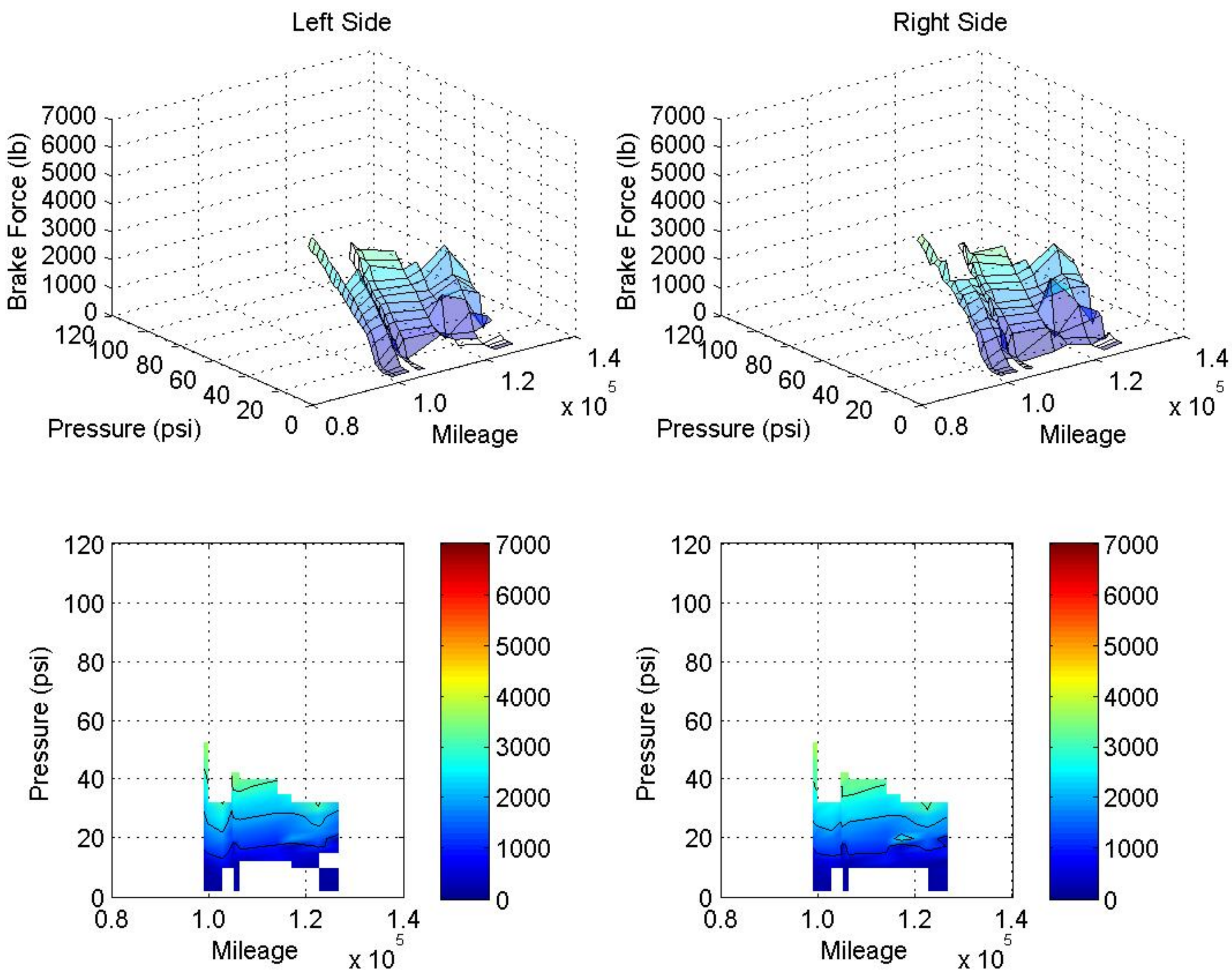




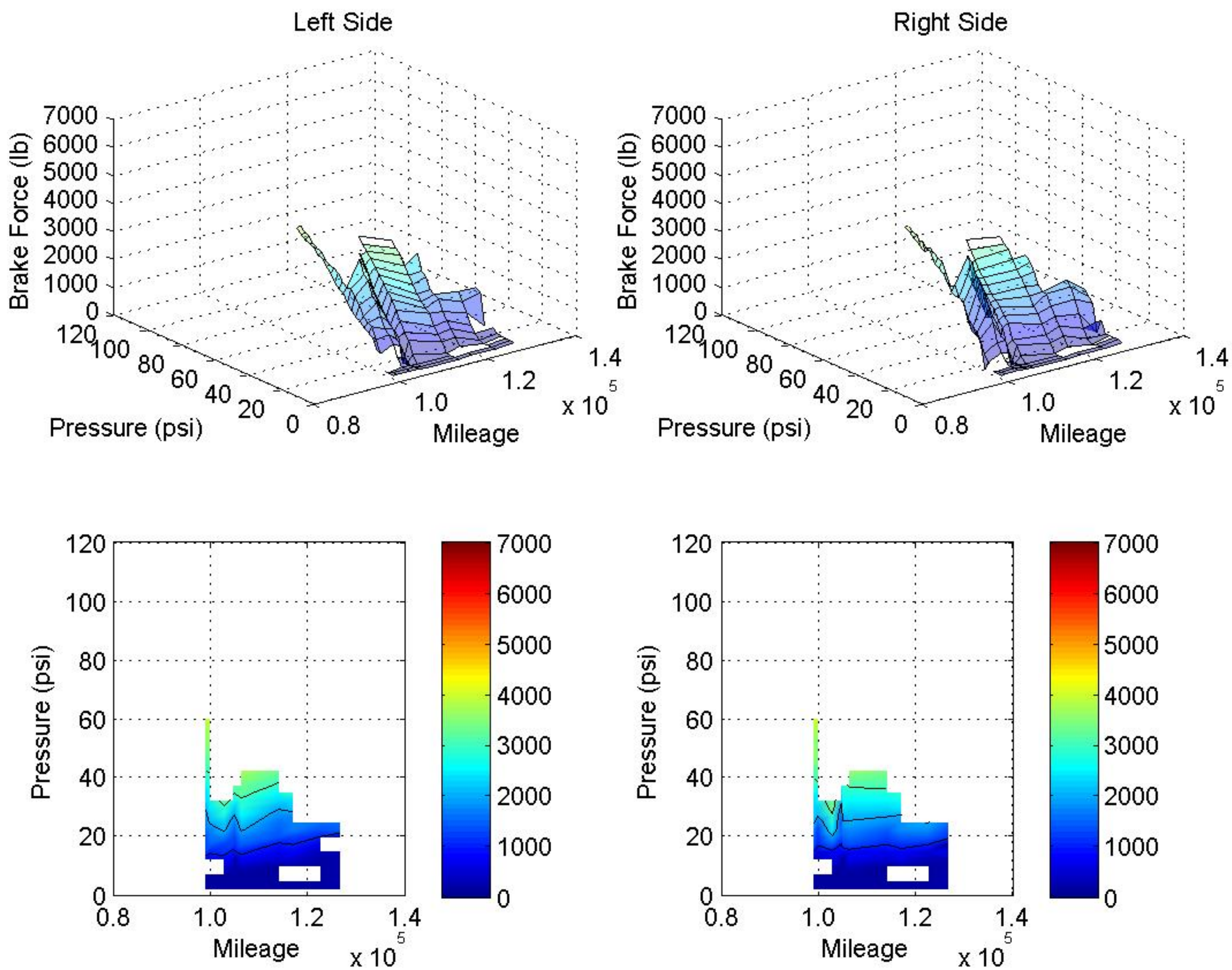
ST 2235 Axle 2



ST 2235 Axle 3



ST 2235 Axle 4



APPENDIX D: VIOLATIONS INCORPORATED INTO LPAT DATABASE

Regulation Code	Description	Violation Category
172.200(a)	Desc. of Hazardous Materials Req.	Other - Paperwork
172.506(a)(1)	Placards Not Affixed to Vehicle	Other
177.817(e)	Shipping Paper Accessibility	Other - Paperwork
374.201(a)	No Smoking on Interstate Passenger Carrier Vehicles	Other - Driver
383.23(a)(2)	Operating a CMV without a CDL	Other - Driver
387.301(a)	No Evidence of Liability Insurance	Other - Driver
390.21(a)	No DOT # marking and/or name/city/state	Other
390.21(b)	All Other Equipment Defects	Other - Vehicle
391.11(b)(4)	Operating Commercial Vehicle without Corrective Lenses	Other - Driver
391.41(a)	No Medical Certificate in Driver's Possession	Other - Driver
391.43(h)	Incorrect Form of Medical Examiner's Certificate	Other - Driver
391.45(b)	Expired Medical Examiner's Certificate	Other - Driver
391.49(j)	No Valid Medical Waiver in Driver's Possession	Other - Driver
392.16	Failing to Use Seat Belt while Operating CMV	Other - Driver
392.2	Local Laws (General)	Other - Local Laws
392.2C	Local Laws (Failure to Obey Traffic Control Device)	Other - Driver
392.2W	Local Laws (Overweight/height)	Other - Load
392.71(a)	Using or Equipping a CMV with Radar Detector	Other - Driver
392.9	Failure to Secure Driver Load	Other - Load
392.9(a)	Failure to Secure Load	Other - Load
392.9(a)(2)	Failure to Secure Vehicle Equipment	Other - Load
392.9a(a)(2)	Operating Beyond Scope of Operating Authority	Other - Driver
393.100(a)	Lack of/Improper Load Securement	Other - Load
393.102(a)	Improper Securement System	Other - Load

Regulation Code	Description	Violation Category
393.104(b)	Improper Blocking and/or Bracing-Lateral	Other - Load
393.104(d)	Cargo Securement	Other - Load
393.104(f)(3)	Improper Blocking and/or Bracing	Other - Load
393.11	Defective Lighting Devices	Other - Lighting
393.11RT	Defective Lighting Devices	Other - Lighting
393.201(a)	Cracked/Bent/Broken/Loose Frame	Other - Vehicle
393.201(d)	Frame Accessories Not Bolted/Riveted Securely	Other - Vehicle
393.203(c)	Cab Door Missing/Broken	Other - Vehicle
393.205(a)	Cracked and/or Broken Wheel/Rim	Other - Wheel
393.205(b)	Wheel Stud or Bolt Hole Shape	Other - Wheel
393.205(c)	Loose and/or Missing Wheel Nut or Bolt	Other - Wheel
393.207(a)	Axle Positioning Parts Defective/Missing	Other - Axle
393.207(b)	Axle Locking Parts Defective/Missing	Brake - Wheel
393.207(c)	Leaf Spring Assembly Defective/Missing	Air - Wheel
393.207(e)	Torsion Bar Cracked and/or Broken	Other - Wheel
393.207(f)	Air Suspension Pressure Loss	Air - Wheel
393.209(b)	Excessive Steering Wheel Lash	Other - Vehicle
393.209(d)	Steering System Components Worn/Welded/Missing	Other - Vehicle
393.209(e)	Power Steering Violations	Other - Vehicle
393.24(a)	Head Lamps Not Operative on Low Beam	Other - Lighting
393.24(b)	Non Compliance with Head Lamp Requirements	Other - Lighting
393.25(f)	Stop Lamp Violations	Other - Lighting
393.28	Improper or No Wiring Protection as Required	Other - Vehicle
393.40	Inadequate Brake System on a CMV	Brake
393.43	No/Improper Breakaway or Emergency Braking	Brake
393.43(a)	Emergency Brake Requirements, Vacuum Brakes	Brake
393.43(d)	Automatic Trailer Brake Violations	Other
393.45	Brake Tubing and Hose Adequacy	Air

Regulation Code	Description	Violation Category
393.45(b)(2)	Brake Tubing and Hose Mechanical Damage	Air
393.45(d)	Brake Tubing and Hose Connections	Air
393.47(a)	Brake Components Avoid Excessive Fading and Grabbing	Brake
393.47(d)	Brake Lining and Pad Thickness	Brake
393.47(e)	Clamp and Roto-chamber Brake Actuator Readjustment Limits	Brake
393.47(g)	Brake drum and rotor thickness	Brake
393.48(a)	Brakes Must Be Capable of Operating at All Times	Brake
393.50	Brake Reservoir Requirements	Brake
393.51	No or Defective Brake Warning System	Other
393.52(a)(1)	Failed PBBT	Brake
393.53(b)	Automatic Brake Adjusters (Air Brake System)	Air, Brake
393.60	Window Glazing in Specified Openings	Other - Vehicle
393.60(c)	Windshield Condition	Other - Vehicle
393.65	Fuel System Requirements	Other - Vehicle
393.67	Fuel Tank Requirement Violations	Other - Vehicle
393.70	Coupling Devices and Towing Methods	Other - Vehicle
393.70(b)	Defective/Improper Fifth Wheel Assemblies	Other
393.71(h)(10)	No/Improper Safety Chains/Cables for Tow bar	Other - Vehicle
393.75(a)	Flat Tire or Fabric Exposed	Other - Wheel
393.75(a)(1)	Tire-Ply or Belt Material Exposed	Other - Wheel
393.75(a)(2)	Tire-Tread and/or Sidewall Separation	Other - Wheel
393.75(a)(3)	Tire-Flat and/or Audible Air Leak	Other - Wheel
393.75(a)(4)	Tire-Cut Exposing Ply and/or Belt Material	Other - Wheel
393.75(b)	Tire-Front Tread Depth Less Than 4/32 of Inch	Other - Wheel
393.75(c)	Tire-Other Tread Depth Less Than 2/32 of Inch	Other - Wheel
393.75(f)	Tire Loading Restrictions	Other - Wheel
393.75(h)	Tire Inflation Pressure	Other - Wheel

Regulation Code	Description	Violation Category
393.78	Windshield Wipers Inoperative/Defective	Other - Vehicle
393.81	Horn Inoperative	Other - Vehicle
393.83(a)	Exhaust System Location	Other - Vehicle
393.83(g)	Exhaust Leak Under Truck Cab and/or Sleeper	Other - Vehicle
393.87(a)	No Warning Flag on Projecting Load	Other - Load
393.9(a)	Required Lamps Incapable of Operation	Other - Lighting
393.95(a)	No/Discharged/Unsecured Fire Extinguisher	Other - Vehicle
393.95(f)	Emergency Warning Devices Not As Required	Other - Vehicle
393.9H	Inoperable Head Lamps	Other - Lighting
393.9T	Inoperable Tail Lamps	Other - Lighting
393.9TS	Turn Signals Inoperable or Obscured	Other - Lighting
395.3(a)(1)	10 Hr Rule Violation	Other - Driver
395.3(a)(2)	15 Hr Rule Violation	Other - Driver
395.3(b)	60/70 Hr Rule Violation	Other - Driver
395.8	Log Violation (General/Form and Manner)	Other - Driver
395.8(a)	No Drivers Record of Duty Status	Other - Driver
395.8(e)	False Report of Drivers Record of Duty Status	Other - Driver
395.8(f)(1)	Driver's Record of Duty Status Not Current	Other - Driver
395.8(k)(2)	Driver Failing to Retain Previous 7 Days Logs	Other - Driver
396.11	Driver Vehicle Inspection Report	Other - Driver
396.17(c)	Periodic Inspection and Documentation	Other - Driver
396.3(a)(1)	Inspection/Repair and Maintenance	Brake, Air
396.3A1B	Brakes (General)	Brake
396.3A1BA	Brakes Out of Adjustment	Brake
396.3A1BC	Brake-Air Compressor Violation	Air
396.3A1BL	Brake-Reserve System Pressure Loss	Air
396.3A1T	Tires (General)	Other - Wheel
396.5	Excessive Oil Leaks	Other - Vehicle

Regulation Code	Description	Violation Category
396.5(b)	Oil and/or Grease Leak	Other - Vehicle
396.7	Unsafe Operations Forbidden	Other - Vehicle
396.83(g)	Inspection/Repair and Maintenance	Other
396.9(c)(2)	Operating OOS Vehicle	Other - Driver

BWPT Final Report Revision History			
Revision	Document ID	Description of Change	Change Effective Date
0	Rev 0	Incomplete draft	13Jul09
1	Rev 1	Draft update - added partnerships	13Jul09
2	Rev 1.1	Draft update - added sub-sections regarding correlation study, lessons learned, and appendices A and B	03Sep09
3	Rev 2	Reorganized sections, added valuation study	04Sep09
4	Rev2.1	Added forward; various edits	08Sep09
5	Rev2.2	Added weight/site survey section; various edits	09Sep09
6	Rev2.3	Added ovality, stopping distance sections; various edits	10Sep09
7	Rev2.4	Minor edits, compress images to make document easier to manage	10Sep09
8	Rev 2.5	Added 3D BF plots; minor edits	11Sep09
9	Rev 2.6	Added Chapters 3, 8, and Appendix B	14Sep09
10	Rev 2.7	Minor edits before internal review	14Sep09
11	Rev 2.8	Correction to first internal review	06Oct09
12	Rev 2.9	Corrections from partial second internal review	07Oct09
13	Rev 3.0	Corrections from internal review (MBL)	13Oct09
14	Rev 3.1	Corrections from internal review (OF)	13Oct09
15	Rev 3.2	Figure corrections (MBL)	15Oct09
16	Rev 3.3	Final internal revisions	21Oct09
17	Rev 3.4	Incorporate comments by LL	25Nov09
18	Rev 4.0	Final version	02Dec09