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Performance-Based Brake Testers Round Robin Final Report

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16. Abstract

This report documents the results of a series of tests in which several different types of performance-based brake testers (PBBTs) were compared side-by-side (i.e. a round robin test) in their ability to accurately measure brake forces (BFs) and wheel loads (WLs) of commercial vehicles (CVs), and to then predict the vehicle deceleration capability for a 32.2 km/hr on-road stopping test. The PBBTs consisted of five roller dynamometers (RD), two flat plate (FP) testers, and one breakaway torque tester (BTT). A PBBT that can also meet a set of functional specifications could be used for law enforcement by safety inspectors once performance-based criteria are codified. In the test program, specific ratios of BF to WL were imposed on both a 5-axle combination tractor semi-trailer and a two-axle straight truck, in both the fully laden and unladen conditions. In each loading condition, the overall vehicle braking capability was set to achieve a proposed minimum requirement of 0.4g, where g is the acceleration due to gravity. In addition, the brakes on specific individual wheels were set to provide a BF/WL of 0.25 and 0.35, for a steer and a non-steer wheel, respectively. The vehicles were also instrumented to record stopping distances and decelerations from on-road stopping tests performed from 32.2 km/hr. In general, nearly all of the PBBTs were able to accurately measure the CVs' brake forces. Only one of the FP-type testers experienced erratic performance during the round robin. In contrast, several of the PBBTs had difficulty in reporting the accurate gross vehicle weight. In some cases, particularly with the portable PBBTs, the reported wheel loads for axles 2 and 4 (the lead axle on the tandem set) of the 5-axle vehicle were very high, leading to an under-prediction of the vehicle deceleration capability. Calibration checks of the PBBT weighing mechanisms indicated that all could meet the functional specifications. As such, it was concluded that accounting for the redistribution of axle loads due to the vehicle suspension and the geometry of the PBBT ramp would require special test procedures or remote entry of vehicle or axle weights for use in law enforcement. The repeatability of all the PBBTs was good, meeting the acceptability criteria in more than 93 percent of the test cases.

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Abbreviations and Symbols

ARR	Acceptable Repeatability Range
BF	Brake Force
BF_{max}	Maximum Brake Force
BF_{min}	Minimum Brake Force
BF_{REF}	Reference Brake Force
BF_{TOT}	Total Brake Force
B&G	B&G Engineering
BTT	Breakaway Torque Tester
CFR	Code of Federal Regulations
COF	Coefficient Of Friction
CV	Commercial Vehicle
CVSA	Commercial Vehicle Safety Alliance
Decel	Deceleration
$Decel_{EQ}$	Equivalent Deceleration, BF_{TOT}/GVW
$Decel_{REF}$	Reference Deceleration
DOT	Department of Transportation
F	Friction Force
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMCSR	Federal Motor Carrier Safety Regulation
FMVSS	Federal Motor Vehicle Safety Standard
FP	Flat Plate Brake Tester
GAWR	Gross Axle Weight Rating
GVW	Gross Vehicle Weight
GVW_{REF}	Reference Gross Vehicle Weight
GVWR	Gross Vehicle Weight Rating
HEI	Hicklin Engineering, Inc.
MCSAP	Motor Carrier Safety Assistance Program
N	Normal Force
NHTSA	National Highway Traffic Safety Administration
OMCS	Office of Motor Carrier Safety
PB	Parking Brake
PBBT	Performance-Based Brake Tester
RAI	Radlinski and Associates, Inc.
RD	Roller Dynamometer
RR	Rolling Resistance
TRC	Transportation Research Center
VIS	Vehicle Inspection System
VRTC	Vehicle Research & Test Center
WL	Wheel Load
μ	Coefficient of Friction

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Executive Summary

Introduction

Based on a series of tests using performance-based brake testers (PBBTs), this report presents the results, conclusions and recommendations concerning the suitability of PBBTs to enforce prospective in-service commercial motor vehicle brake performance regulations.

A PBBT is a device that can assess the braking capabilities of a vehicle in its current condition. It measures either individual wheel brake forces, overall vehicle braking performance, or both. A PBBT is of benefit to both the law enforcement and the motor carrier communities because it can consistently provide an objective measure of the current braking performance of a vehicle. It does so irrespective of the brake type (disk or drum), the energy supply (air, hydraulic, electric, or spring), or the application method (s-cam, wedge, piston, spring, or lever and cable).

Several PBBTs were evaluated during a round robin[1] test series in order to assess their functional performance and potential for use in law enforcement. In addition, factors influencing the relationship between a vehicle's on-road stopping performance and that predicted by the PBBT were investigated. The tests were conducted in July of 1998 at the Vehicle Research and Test Center (VRTC) of the National Highway Traffic Safety Administration (NHTSA), United States Department of Transportation (USDOT). The project was sponsored by the USDOT, Office of Motor Carriers (OMC), now the Federal Motor Carrier Safety Administration (FMCSA).

[1] The term "round robin" describes a series of tests in which a single "standard" is used to evaluate the consistency of various test apparatus. In the round robin presented in this report, the "standard", a specific configuration of brake forces and wheel loads on a heavy-duty vehicle, was used to evaluate the candidate PBBTs and their operating protocols.

Background

Functional performance specifications for PBBTs have been developed and published for comment in the Federal Register[2].

For brake systems, current commercial vehicle safety enforcement is based on the results of a visual inspection designed to identify defective components. This technique cannot provide a measure of actual braking performance. New performance-based regulations are currently under consideration to permit the use of PBBT results for enforcement. A vehicle could be placed out of service (OOS) if it is found to have inadequate braking capability, or a citation could be issued if an individual brake is found to be weak.

For the use of recommended performance-based regulations, it is important that a vehicle's individual brakes or overall braking capability be judged accurately by a PBBT and consistently between different PBBTs. The purpose of the round robin was to evaluate the ability of the current generation of PBBTs to measure brake forces (BFs) and wheel loads (WLs) accurately and consistently, and to verify that these measurements could be used as an alternative to stopping distance tests or on-road deceleration tests.

Overview of the Test Plan

For the round robin, two types of commercial vehicles, with different braking and loading configurations, were instrumented: a combination three-axle tractor, two-axle semi-trailer (3-S2), and a two-axle straight truck. Each vehicle was tested fully laden and unladen. Both vehicles were set up with target low brake force to wheel load ratios (BF/WL) on selected wheels, keeping the braking capability of the vehicle consistent with the performance-based regulation under consideration at the time by the OMCS[3] (i.e. the ratio of the total brake force to the gross vehicle weight (BF_{TOT}/GVW) = 0.4).

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[2] "Development of Functional Specifications for Performance-Based Brake Testers Used To Inspect Commercial Motor Vehicles", FHWA-1998-3611-1, Federal Register, Vol. 63, No. 108 (June 1998).

[3] S. J. Shaffer and P. A. Gaydos, "Development, Evaluation and Application of Performance-Based Brake Testing Technologies", FHWA/MC-98/048 (April 1998). The executive summary is accessible at: http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/8mn01!.pdf

The eight PBBTs tested were three portable roller dynamometers (RD), two in-ground RDs, two flat plate brake testers (FP), and one portable breakaway torque tester (BTT). The testing program had two parts. In the first part of the testing program, the following evaluations were performed on weakly-braked vehicles:

1) The accuracy and applicability of BF measurements: For the accuracy, the PBBT-measured BFs per wheel were compared to the BFs measured using a calibrated torque wheel. For the applicability, the PBBT-measured total BFs (BF_{TOT}) were compared to BFs computed from the 32.2 km/hr (20 mph) on-road stops.
2) The accuracy and applicability of WL measurements: For the accuracy, sets of cement blocks of known weight were placed on the PBBT weighing mechanisms and the PBBT results were compared to the known weights. For the applicability, the PBBT-measured axle loads were compared to axles loads obtained using traditional in-ground or portable certified scales.
3) The applicability of the equivalent deceleration predicted using the PBBT measurements ($decel_{EQ} = BF_{TOT}/GVW$) for the vehicle: The PBBT results were compared to decelerations achieved during 32.2 km/hr (20 mph) road stops.
4) The repeatability of PBBT measurements (BFs, WLs and $decel_{EQ}$): PBBT results from three replicates were compared.

In the second part of the testing program, the brake forces of the two-axle truck were restored to their fully adjusted values and the vehicle load was changed. The brake forces were sufficient to lock the wheels in a high demand or panic stop. The following evaluations were performed on the strongly-braked 2-axle vehicle:

1) The applicability of the equivalent deceleration ($decel_{EQ}$): The equivalent deceleration predicted using the PBBT measurements was compared with the deceleration obtained during 32.2 km/hr (20 mph) road stops.
2) The repeatability of the BFs measurements: PBBT-reported BFs from three replicates were compared.
3) The effect of wet test surfaces on the PBBT-reported BFs was evaluated by comparing the maximum BFs reported under both wet and dry conditions.

Results

Part I: Vehicles with Weak Brakes

Brake Forces - Accuracy and Applicability of PBBT Results versus Reference BFs

The brake force reported by the PBBTs per wheel was compared to the brake force measured using a calibrated torque wheel. The torque wheel data were reduced to a single value using three different methods. Using the best match of the methods, agreement within the 2.5 percent accuracy requirement of the performance specifications was found for all of the RDs and for the BTT. However, for the HEKA FP, the BF data discrepancies were sometimes very large and appeared to be related to both the acquisition and the handling of dynamic data from the stop on the plates. As such, further demonstration of the HEKA accuracy in reporting BFs would be required. For the Hunter FP, the discrepancy in BF values were less than 10 percent, and appeared to be due solely to differences between the algorithm Hunter used and that used for the torque wheel data. Since the deceleration predicted by Hunter was subsequently found to match the on-road deceleration very well, the difference in BF was considered resolvable and not a potential safety concern.

The PBBT-measured BFs showed different degrees of applicability when compared to the BFs deduced from the 32.2 km/hr (20 mph) road stops. The Hunter test, which is conducted at 16 km/hr (10 mph), appeared most applicable. For the RDs, their applicability may have been affected by a sensitivity of brake torque output to speed. In general, slightly higher BFs were measured in the RD tests, in which the wheel is rotated at less than 2 km/hr (1.2 mph), compared with that deduced from the 32.2 km/hr (20 mph) on-road stopping test. Although the deviations were only on the order of ten percent, further investigation of the development of a scaling factor may be required to accurately predict on-road deceleration. The BTT also showed good applicability for the on-road stop in three of the four vehicle conditions. The applicability for the unladen 2-axle, however, may have been influenced by the higher measurable BF for the strong wheels using the BTT than that available due to traction with the ground during the on-road stop. As such, an upper limit cut-off (similar to the use of scaling factors for the RDs) would be required in such cases for improved accuracy in predicting on-road stopping performance.

Vehicle Weights - Accuracy and Applicability of PBBT Results versus Reference WLs

The weights reported by the PBBTs were found to be well within the 2.5 percent accuracy requirement during calibration tests using concrete blocks of known weight.

The reporting of axle loads from vehicles indicated that the loads obtained during the brake test were not always representative of those of the vehicle when flat on the ground. As such, for some PBBTs, the applicability of the weight measurements will require additional considerations for use in enforcement. The reporting of vehicle weight (total of axle loads) by PBBTs matched the reference values for 4 of the 8 PBBTs for the two-axle straight truck in both the laden and unladen conditions. For the 3-S2, the reported total vehicle weights adequately matched the reference value for only 2 of the 8 PBBTs (the Hunter FP and in-ground RAI RD) in both loading conditions. For the HEKA FP, RDs and the BTT, the differences in the axle-load measurements were due to load transfer between axles as the vehicle was braked into position on the PBBT. This load transfer was most significant with the particular vehicle characteristics (e.g. the 4-spring suspension and tandem axles) of the 3-S2. These effects were also more visible on the portable PBBTs because of the elevated test platforms. Improvement can be expected with implementation of different ramp configurations for these portable PBBTs. It was concluded from the axle load tests that special considerations or test procedures will be required for some vehicles.

Equivalent Decelerations - Comparison of PBBT results with Vehicle Deceleration

Using the equivalent deceleration (BF_{TOT}/WL_{TOT}, or BF_{TOT}/GVW) as the measure, 6 of the 8 PBBTs accurately predicted the vehicle's stopping capability for the laden and unladen 2-axle vehicle. For the laden 3-S2, 2 of 8 PBBTs accurately predicted the vehicle's stopping capability. For the unladen 3-S2, one of the 8 PBBTs accurately predicted the vehicle's stopping capability. Brake force measurements were accurate. The inaccurate predictions of deceleration stemmed primarily from weight measurements as some PBBTs reported high axle loads. Other factors included the coefficient of friction (COF) between the test surface and the

tire being different from the COF between the road and the tire or early test termination by the PBBT control mechanism or computer. Recommendations for correction were made at the time of the round robin, and these were being addressed by the PBBT manufacturers at the time of this report. Future work will focus on the resolution of these issues.

Repeatability

The ability of PBBTs to assess the overall vehicle stopping performance within an acceptable range of repeatability (ARR) was very good. Approximately 93 percent of all measurements, including BFs and WLs, were within the ARR.

Part II: Vehicles with Fully Adjusted, Strong Brakes

The ability of the PBBTs to measure the full braking capability of a strongly-braked vehicle was assessed. The traction which exists between the tires and the test surface (or the road) limits the maximum BF achieved by the vehicle either during a PBBT test or during a stopping test on the road. As such, variations reported between PBBTs in these tests were primarily a reflection of the different test surfaces used. PBBTs with higher traction between the test surface and the tire than that between the road and the tire tended to show a higher $decel_{EQ}$ than measured during the on-road stop, and vice-versa. No safety concern exists providing the differences in traction can be documented and accounted for. A summary of the findings of Part II follows:

- Most PBBTs predicted at least the on-road deceleration, which was approximately 0.6g[4] for the vehicle tested.
- The FPs showed higher variability testing the strongly-braked vehicle than the weakly-braked vehicles. This was likely due to variability in driver performance and possible wheel skidding[5].
- The VIS RD measured low BFs compared to the other PBBTs, apparently as a result of

[4] "g" represents the acceleration due to gravity.

[5] It should be noted that Hunter considers a test in which the vehicle is skidding to be invalid.

either premature test termination or a low traction roller surface.

- The BTT results were unaffected by either the vehicle's loading conditions or the presence of water on the test surface.
- For the VIS and standard HEI RDs, the presence of water on the test surface reduced the traction between the tire and the rollers, and greatly affected BF measurements.

Conclusions

The round robin was the first of its kind and constituted a significant milestone in the FMCSA's program to permit the use of PBBTs as a tool for law enforcement.

- Under most test conditions, the accuracy and repeatability of most of the participating PBBTs, regardless of the principle of operation, were acceptable for meeting the functional specifications, and therefore for use in law enforcement.
- The Hunter FP and the RAI in-ground RD showed the most immediate potential for use in law enforcement on weakly-braked vehicles based on repeatability and accuracy results when compared to measured vehicle decelerations in a 32.2 km/hr (20 mph) road stop.
- Where needed, factors or modifications to obtain acceptable PBBT performance for use in enforcement fell into one of two categories:
    1) Modifications consistent with the PBBT functional specifications that had been developed for eligibility for funding through the Motor Carrier Safety Assistance Program (MCSAP).
    2) Procedural modifications to improve the applicability of the PBBT results to on-road stopping results.
- Weight measurements were found to be affected by specific characteristics of the vehicles or by the elevation and ramp configurations of the portable PBBTs.
- Consideration should be given to additional criteria for judging brake effectiveness in cases where weights are unavailable or cannot be measured in a representative manner due to vehicle configuration. For example, when wheel lock up occurs, if the traction

between the tire and the test surface is at least equal to 0.6 (as required in the PBBT functional specifications), the braking capability of the wheel would be considered adequate, regardless of the weight measurements. When the brakes are too weak to lock up the wheels, the weight measurements are critical, and alternative procedures and/or criteria would be required.

- The PBBT-measured BFs were in good agreement with the BFs measured with the torque wheel. Deviations were attributed to one of two causes:
  - The algorithm used by PBBT manufacturers to acquire and manipulate the raw data and report a single BF value.
  - In the case of the flat plate testers, the effect of dynamic loading.
- The roller dynamometers, as a class, reported slightly higher BFs for weakly-braked vehicle on dry pavement than the corresponding reference values derived from road stops. It was suspected that this was a result of either geometry of the wheel/roller contact patch or changes in brake torque output as a function of speed: the portable RDs operate at less than 2 km/hr (1.2 mph), while the road stops were performed at 32.2 km/hr (20 mph). Additional data are required in this area.
- Finally, the following recommendations were made to the PBBT manufacturers to assist them in meeting the functional specifications:
  - Alter the test surface to meet minimum COF requirements.
  - Standardize test protocols, including data analysis and reporting procedures.
  - Develop appropriate calibration procedures.
- Some PBBTs showed that their BF results were unaffected by the condition of the test surfaces. Although the COF in wet conditions is not part of the proposed PBBT functional specifications at this time, PBBTs for which BF measurements were affected by the test surface conditions should address this problem.

Remaining Challenges

Remaining challenges for use of PBBTs in law enforcement include:

- Establishing appropriate test termination, data reduction and reporting algorithms for the PBBTs such that consistent results are obtained from machine to machine for a given vehicle.
- Developing standard test procedures for each type of PBBT.
- Developing training requirements for inspectors to use PBBTs for enforcement, including calibration and operating protocols.
- Establishing a list of special considerations for certain vehicle configurations (e.g. axle load or BF measurement applicability limitations). When applicable, modified testing procedures should be implemented.
- Developing regulations for individual brake pass/fail evaluation that are independent of WL, when WL measurements are either unavailable or significantly altered by the vehicle configuration.
- Establishing a policy or procedure for compliance testing, including documentation of calibration requirements necessary to meet potential legal challenges.

For a fundamental understanding of the relationship between PBBT testing and vehicle on-road performance, the following challenges are posed:

- Characterizing and understanding the sensitivity of brake force to velocity, static versus dynamic testing, wheel contact geometry or COF limitations as they are needed to establish the correlation between PBBT measurements and 32.2 km/hr (20 mph) road stops.

1. Introduction

1.1 Background

In an effort to improve highway safety, the US Department of Transportation, Federal Motor Carrier Safety Administration (FMCSA) is supporting a program for the development, evaluation, and application of Performance-Based Brake Testers (PBBTs) for use on commercial vehicles. A PBBT is a device that can evaluate the braking capabilities of a vehicle in its current condition through a quantitative assessment (i.e. measurement) of brake forces. Some PBBTs can also evaluate the fully laden braking capabilities of an unladen vehicle. A PBBT is of benefit to both the law enforcement and the motor carrier communities because it provides an objective measure of the braking performance of a vehicle. It does so irrespective of the brake type (disk or drum), the energy supply (air, hydraulic, electric, or spring), or the application method (s-cam, wedge, piston, spring, or lever and cable). Examples of PBBTs include roller dynamometers (RDs), flat plate brake testers (FPs), and breakaway torque brake testers (BTTs).

PBBTs have been in common use in Europe for more than 20 years for periodic safety inspections of commercial vehicles (CVs). The PBBTs used in Europe are almost exclusively in-ground RDs, and the European regulations have been developed accordingly. Additionally, European vehicle design regulations require access to certain diagnostic signals that are not available on North American fleets. As a result, European criteria are not generally applicable to the fleet of vehicles operating in North America. The FMCSA-sponsored program has been examining additional types of PBBTs, with a focus on portable models. As such, there is no precedent for guidance on regulations applicable for use of PBBTs in North American law enforcement activities.

New performance-based regulations may be developed which define the criteria by which underbraked vehicles as well as individual weak brakes can be identified using a PBBT. Prior field testing of PBBTs indicated that the applicability of criteria based on agreement with CVSA[1] inspection results was limited. As such, a universally applicable set of criteria was presented as part of the recent field evaluation research[2]. Any new regulations must be consistent with current performance-based braking safety criteria, i.e. measures of vehicle deceleration, stopping distance, or both. The current criteria[3] are codified in Title 49 of the Code of Federal Regulations, Section 393.52 (49 CFR 393.52).

The PBBT performance-based criterion recommended in the earlier field evaluation research for identification of an underbraked vehicle is based on the ratio of all brake forces available at the wheels (BF_{TOT}) to the GVW. This ratio is referred to as the "equivalent deceleration", $decel_{EQ}$. The recommended performance-based criteria for identification of weak brakes included a single low BF with respect to the wheel load (WL) as well as a BF imbalance across a given axle. The performance-based criteria from the earlier field research are reviewed in Table 1.

Table 1. Recommended criteria for identification of an unsafe vehicle due to insufficient braking capacity or weak brakes.

Assessment for	Minimum criterion	Result when criterion is not met
Underbraked vehicle	Underbraked if $BF_{TOT} / GVW < 0.4$	Out Of Service
Imbalanced braking on power-unit steer axle	Out of balance if $BF_{min} / BF_{max} < 0.55$	Out Of Service
Defective brake on steer axle wheels	Defective if $BF / WL < 0.25$	Citation
Defective brake on non-steer axle wheels	Defective if $BF / WL < 0.35$	Citation

BF - brake force; BF_{TOT} - total BF; GVW - gross vehicle weight; WL - wheel load

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[1] The Commercial Safety Alliance (CVSA) is the organization responsible for the development and maintenance of the North America Uniform Out-of-Service criteria for heavy trucks and buses: critera include vehicles, drivers and transport of hazardous materials. Information about the CVSA can be found at (301) 564-1623 or at http://www.cvsa/org.

[2] S. J. Shaffer and P. A. Gaydos, "Development, Evaluation and Application of Performance-Based Brake Testing Technologies", FHWA/MC-98/048, April, 1998. The executive summary can be accessed at the following address: http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/8mn01!.pdf

[3] For vehicles over 10,000 lbs. or combination vehicles, a braking force (BF) as a percentage of gross vehicle or combination weight (GVW) of at least 43.5 must be achieved during a stop from 32.2 km/hr (20 mph) on dry pavement. Alternatively, a combination vehicle must be able to stop within 12.2 meters from 32.2 km/hr, or 40 feet from 20 mph.

In addition, functional specifications for PBBTs (e.g. calibration documentation requirements and the minimum required accuracy for PBBTs purchased with funds from the FMCSA's Motor Carrier Safety Assistance Program (MCSAP)) are being developed[4].

A round robin[5] was conducted in July 1998 at the Vehicle Research and Test Center (VRTC) of the National Highway Traffic Safety Administration (NHTSA).

1.2 Objectives

The objective of the round robin was to determine whether or not the current generation of PBBTs could be used for enforcement, i.e. whether or not a vehicle's individual brakes or overall braking capability could be judged accurately and repeatably from one PBBT to another, and whether the results were representative of a vehicle's on-road braking capability (applicability).

1.3 Method of Evaluation

The tests were designed to allow the evaluation of the accuracy, the applicability and the repeatability of the measurements of the current generation of PBBTs under variable conditions (e.g. vehicle types, vehicle load, vehicle braking capacity or test surface conditions).

<u>Accuracy</u> addresses the question: "Does the PBBT report the actual forces (e.g. BFs and WLs) being applied within an acceptable tolerance?"

<u>Applicability</u> addresses the question: "Are the forces being applied by the vehicle during the PBBT test representative of those applied during on-road braking from 32.2 km/hr (20 mph)?"

<u>Repeatability</u> addresses the question: "Does the PBBT report the same forces under repeated identical conditions?"

The PBBT results were compared to reference values as shown in Table 2.

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[4] "Development of Functional Specifications for Performance-Based Brake Testers Used To Inspect Commercial Motor Vehicles", FHWA-1998-3611-1, Federal Register, Vol. 63, No. 108 (June, 1998).

[5] The term "round robin" describes a series of tests in which a single "standard" is used to evaluate the consistency of various test apparatus. In the round robin presented in this report, the "standard", a specific configuration of brake forces and wheel loads on a heavy-duty vehicle, was used to evaluate the candidate PBBTs and their operating protocols.

Table 2. References used to determine the accuracy, the applicability and the repeatability of PBBTs

	Measurement	Reference
Accuracy	WL	Calibration using traceable dead weights
	BF	Calibration using traceable loads applied via fixture
		Calibrated torque wheel
Applicability	$Decel_{EQ}$	Average deceleration measured from a 32.2 km/hr (20 mph) road stop
	GVW	Sum of pre-measured axle loads using certified scales
	WL	Pre-measured axle or wheel load using certified scales
	BF_{TOT}	Total BFs computed from GVW (certified scales) and average deceleration (on-road stops).
Repeatability	$Decel_{EQ}$	Replicate values reported from repeat tests of same conditions
	GVW	
	WL	
	BF_{TOT}	

2. Experimental Details

2.1 Test Stations

The round robin included nine stations as listed in Table 3. The stations included three portable RDs, two in-ground RDs, one in-ground FP, one portable FP, one portable BTT, and a 32.2 km/hr (20 mph) road stop. The principles of operation of RDs, FPs and BTT are detailed elsewhere[6]. An additional portable RD, which was equipped with some experimental hardware and software, was included in a selected number of tests. The order of the testing was the same as the station number, and was determined by site logistics at the VRTC. Photographs of each of the PBBTs are presented in Appendix A.

Table 3. List of test stations

Station No.	Manufacturer/Vendor	Type	Method
1	Hunter	In-Ground	Flat Plate
2	BM/RAI	Portable	Roller Dynamometer
3	VIS	Portable	Roller Dynamometer
4	BM/VRTC	In-Ground	Roller Dynamometer
5a	HEI	Portable	Roller Dynamometer
6	B&G	Portable	Breakaway Torque Tester
7	HEKA	Portable	Flat Plate
8	-	On-Road	32.2 km/hr (20 mph) Road Stop
9	BM/RAI	In-Ground	Roller Dynamometer
5b*	HEI	Portable	Roller Dynamometer

* Included in selected tests, as time allowed.

2.2 Vehicle Description

Two types of commercial vehicles, with different braking and loading configurations, were prepared. A combination three-axle tractor, two-axle flatbed semi-trailer (3-S2) and a

[6] S.J. Shaffer, & G.H. Alexander, "Evaluation of Performance-Based Brake Testing Technologies", FHWA-MC-96-004, December, 1995.

two-axle flatbed straight truck (2) were selected for the tests as they represent the majority of the axle configurations of commercial vehicles on the road. Each vehicle was tested fully laden and unladen. Both vehicles were initially set up with target brake force to wheel load ratios (BF/WL) on selected wheels, keeping the braking capability of the vehicle as a whole consistent with the performance-based regulation under consideration by the OMCS at the time of the round robin. Additional testing was performed on the 2-axle vehicle in a weakly-braked condition.

The convention used in this report to identify vehicle wheels is shown in Figure 1.

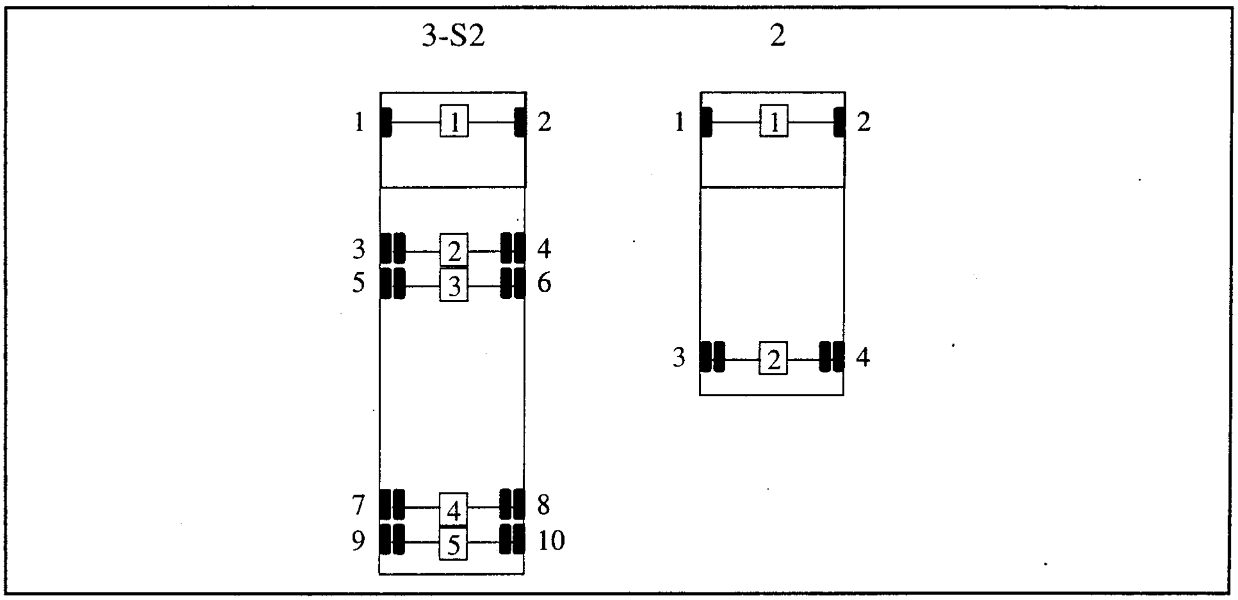

Figure 1. Identification of wheel numbers on the two test vehicles.

Both vehicles were instrumented and data were collected at 100 Hz. A fifth-wheel speed sensor was installed on each vehicle, and was used to derive stopping distances and decelerations. In addition, a Labeco on-board computer tied to a switch on the brake pedal was installed on both vehicles to compute stopping distances[7]. An instrumented torque wheel was fitted to wheel number 5 on the 3-S2. Air pressure was monitored on the 3-S2, using transducers at each of the six tractor wheel air chambers and upstream of the trailer distribution valve. The air pressure was controlled on the two-axle vehicle, but not monitored during testing.

[7] The two-axle vehicle experienced some instrumentation difficulties, so data were not always available from both systems.

2.3 Test Matrix

The test matrix for the round robin is shown in Table 4. A total of 9 test conditions were run. The testing program had two parts, which are described in more detail below.

Table 4. Test matrix of vehicle conditions for PBBT round robin

Part 1: Vehicles with Weak Brakes Dry conditions only - 3 replicate tests (separate)				
Test No.	**1**	**2**	**3**	**4**
Vehicle Type and Loading	3-S2	2-Axle	3-S2	2-Axle
	Laden		Unladen	
Condition	Dry	Dry	Dry	Dry

Part 2: Vehicles with Fully-Adjusted Strong Brakes Dry and wet conditions, 2-axle truck only - 3 replicate tests (consecutive)					
Test No.	**5**	**6**	**7**	**8**	**9**
Vehicle Loading	2-Axle	2-Axle	2-Axle	2-Axle	2-Axle
	Unladen	1/3 laden	2/3 laden	2/3 laden	Unladen
Condition	Dry	Dry	Dry	Wet	Wet

2.3.1 PART 1 – VEHICLES WITH WEAK BRAKES

In the first part of the testing program (Tests 1-4), three rounds were conducted for each test condition such that, in each round, the vehicles traveled from test station to test station, resulting in three separate replicate test [8]. In Tests 1-4, the following evaluations were performed on weakly-braked vehicles, under laden and unladen conditions:

1) The accuracy and applicability of BF measurements: For the accuracy, the PBBT-measured BFs per wheel were compared to the BFs measured using a calibrated torque wheel. For the applicability, the PBBT-measured total BFs (BF_{TOT}) were compared to BFs computed from the 32.2 km/hr (20 mph) on-road stops.

[8] The 3-S2 combination vehicle with weak brakes under empty conditions (Test 3) was not properly set up for the first replication of this test. Recognizing the improper set-up after the first round, several brakes were readjusted. As a consequence, only results from the second and third rounds are utilized for analysis of this condition.

2) The accuracy and applicability of WL measurements: For the accuracy, sets of cement blocks of known weight were placed on the PBBT weighing mechanisms and the PBBT results were compared to the known weights. For the applicability, the PBBT-measured axle loads were compared to axles loads obtained using traditional in-ground or portable certified scales.
3) The applicability of the equivalent deceleration ($decel_{EQ}$): The PBBT measurements were compared to the deceleration achieved during 32.2 km/hr (20 mph) road stops.
4) The repeatability of the PBBT measurements: PBBT results from three replicates were compared.

2.3.2 PART 2 – VEHICLES WITH FULLY-ADJUSTED STRONG BRAKES

In the second part of the testing program (Tests 5-9), the brake forces of the two-axle truck were restored to their fully adjusted values, providing braking forces sufficient to lock the wheels in a high demand or panic stop[9]. In this condition, the testing focused on additional factors that could affect the results of the PBBTs, such as the vehicle load (empty or partially laden) or the condition of the PBBT test surface (wet or dry). The accuracy, repeatability and applicability of the WL measurements are not expected to be affected by the level of braking capability or the test surface conditions. Since WL variations are not expected to differ from those discussed in Part 1, the $decel_{EQ}$ and the BFs variations are assumed proportional. Therefore, in Part 2, the following evaluations were conducted on the weakly-braked, 2-axle vehicle:

1) The applicability of the equivalent deceleration ($decel_{EQ}$): The equivalent deceleration predicted using the PBBT measurements was compared with the deceleration from 32.2 km/hr (20 mph) road stops.
2) The repeatability of the BF measurements: PBBT-reported BFs from three replicates were compared.
3) The effect of wet test surfaces on the PBBT-reported BFs was evaluated by comparing the maximum BFs reported under both wet and dry conditions.

[9] The tests on lightly loaded vehicles were designed to subject the wheels to lockup. If BF/WL > COF (road or PBBT test surface), then the braking force will prevent rolling of the wheel (i.e. the wheel locks up) and skidding will occur.

In Tests 5-9, the three replicate tests were conducted consecutively on each test station, i.e. after the first or second replicate test was completed, the vehicle was backed off the PBBT and subsequently repositioned for further replicate testing[10].

As an added, but previously unplanned part of the evaluation, calibrations of the PBBTs, both for BF and WL measurements, were carried out for some of the PBBTs as time allowed. Calibration procedures, when available, were also reviewed. These reviews were performed for the benefit of the PBBT participants and the results are not included in this report.

2.4 Target Vehicle Set-up

2.4.1 BRAKE FORCES

The VRTC in-ground RD was used to set up target brake forces on the two test vehicles. The target brake forces were selected in accordance with the tentative criteria for identification of weak brakes (Table 1). As shown in Figure 2, the target BF/WL ratio for one of the steer axle wheels was 0.25. The target BF/WL ratio for one of the non-steer axle wheels was 0.35. The overall vehicle BF_{TOT}/GVW (equivalent deceleration) target was 0.4. BFs at each wheel were controlled by limiting the control line air pressure with regulators and proportioning valves[11] while the driver imparted full pedal application.

Due to the nature of friction in a sliding contact, a minimum of ten percent variation in brake force is to be expected from one application to another for nominally identical conditions. This fact was used in establishing both the accuracy and the acceptable range of repeatability for PBBT BF measurements.

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[10] In the second part of testing, to prevent rearward movement of the vehicle, the third replicate test on the RDs was to be performed with the front wheels chocked while testing the vehicle's rear wheels. However, due to the slippery epoxy-painted concrete floor and to the steep angle of the chock block, rearward movement of the vehicle at test termination could not be completely prevented on the RDs.

[11] On the 3-S2, regulators were fitted to the tractor wheel air chambers as well as upstream of the trailer distribution valve. On the two-axle vehicle, a single regulator was used to limit the overall pressure, and proportioning valves on each axle controlled the side-to-side BF imbalance.

2.4.2 WEIGHTS

For the fully laden cases, the vehicles were loaded with concrete blocks near the legal road limit[12]. The axle load measurements, shown in Table B3 (Appendix B), were used as reference loads to evaluate the applicability of the PBBTs axle load measurements, i.e. to evaluate whether or not the PBBT-reported WLs are representative of the vehicle's WLs when on the ground. Axle and/or wheel loads were measured using certified in-ground platform scales at the Transportation Research Center (TRC) as well as individual certified portable scales provided by the Ohio State Highway Patrol.

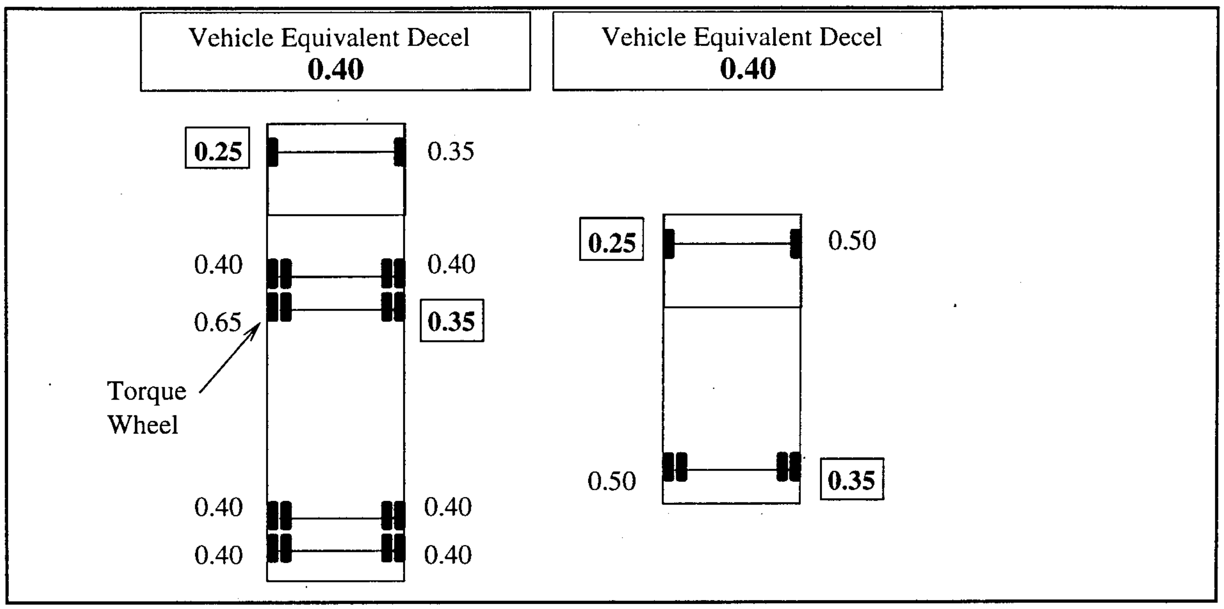

Figure 2. Target brake-force-to-wheel-load ratios for each wheel and for the overall test vehicles for Tests 1-4.

The actual weight of a vehicle is not expected to vary to the same extent as the brake forces in repeated measurements. However, load distribution on the individual wheels can vary as a result of friction in the suspension components when a vehicle is stopped in position on a platform scale. Variations on the order of 50 to 150 lbs. in the wheel/axle

[12] For the 3-S2, the steer axle was near 12,000 pounds and the drive and trailer axles were near 17,000 pounds each. For the two-axle truck, the steer axle was near 11,500 pounds and the drive axle was 21,000 pounds, resulting in the vehicle's weight slightly exceeding the GVWR. Federal limits on axle weights are codified under Title 23 CFR Part 658.17.

weight measurements of multi-unit or tandem-axle vehicles were observed using certified in-ground scales, resulting in a variation up to 5% for each wheel of a 6,000-lb axle.

The use of portable scales resulted in smaller variations in WL measurements because all wheel loads were measured simultaneously. When available, portable scale weight measurements were used rather than in-ground platform scale weight measurements.

3. Results

3.1 Vehicles with Weak Brakes (Tests 1-4)

This section investigates the ability of PBBTs to identify weak brakes and underbraked vehicles. All BF and WL data from each test can be found in Appendix C.

The key requirement for use of PBBTs in enforcement is accuracy. Acceptable accuracy of the PBBT results can be documented through a calibration check of the PBBT transducer outputs, compared with known standards. The functional specifications list the required accuracy (± 2.5 percent). This method uses direct calibration standards, such as dead weights applied through lever arms of know geometry (for BF calibration) or concrete blocks of known weight (for WL calibration). For accuracy checks using forces and loads applied by the vehicle (i.e. indirect standards), additional factors must be considered. Table 5 lists the acceptable accuracy range when direct and indirect standards are used. When indirect standards are used, a measurement uncertainty or real-life variation is added to the direct standard uncertainty. For example, for the brake force measured using known lever arms and weights (direct standard), the acceptable accuracy range is ± 2.5 percent. But when a vehicle is used to apply the loads (indirect standard), the geometry of the contact between the wheel and the test surface must be considered. Therefore, the acceptable accuracy ranges using indirect standards are larger than those using direct standards.

Table 5. Acceptable ranges of accuracy for PBBTs. Acceptable range of applicability and repeatability are also indicated in bold characters.

Measurement	**Direct Standards (%)**	**Measurement Uncertainty* or Expected Real Life Variations, (%)**	**Indirect Standards (%)**
Brake Force (from Torque Wheel)	± 2.5	FPs: ± 1.8 BTT: ± 3.1 RDs: ± 4.6	FPs: ± 4.3 BTT: ± 5.6 RDs: ± 6.9
Brake Force (from Road Stop)	± 2.5	± 5.0	**± 7.5****
Wheel Load or GVW	± 2.5	± 0.5	**± 3.0****
BF/WL or BF_{tot}/GVW	± 5.0	± 5.0	**± 10.0****

* Differences in torque wheel measurements are due to a "geometry factor" which incorporates the different tire/test surface contact conditions (See Appendix B, page 6).
** Acceptable ranges of applicability are shown in bold.

To use PBBTs to predict braking capabilities of a vehicle on the road, the applicability of PBBT-reported values must be considered in addition to accuracy. Acceptable ranges of applicability are assumed equal to those of accuracy when indirect standards are used (Table 5). However, in some cases, the significance of the deviations between the PBBT-reported value and that of a reference value was assessed using engineering judgement of their safety criticality. Additionally, it is expected that deviations between the predicted $decel_{EQ}$ and the on-road deceleration can be accounted for through physical or procedural modifications to the PBBT test and/or through development of appropriate scaling factors.

3.1.1 Brake Forces – Individual Brake Force Evaluation - Accuracy

On the 3-S2 vehicle, brake torque data were collected during Tests 1 and 3 by a torque wheel installed on wheel number 5. The BFs achieved during the test were calculated by dividing the measured torque by the tire radius.

Over the duration of a PBBT test, the BF at a wheel varies with time. The BF value reported by the PBBT depends not only on the proper calibration and accuracy of the PBBT force sensor, but also on the processing of the data collected by the sensor as a function of time. Since the details of data processing used by each PBBT vendor were not known to the report authors, three distinct methods were used to calculate reference BFs from the torque wheel data. The best match of the three methods was used in the accuracy analysis. In summary, Method 1 reported the maximum BF measured at any time during the test. Method 2 computed and reported the average of the data falling within a given percentage of the maximum. Method 3 reported the BF at the time of test termination. Details are included in Appendix B.

The results for each replicate test of the laden and unladen conditions are tabulated in Appendix B (Table B2). Also, the brake forces measured by the torque wheel are plotted as a function of time in parallel with BFs (where available) measured by PBBTs (Appendix D). These plots are referred to as "time history" plots.

Figure 3 illustrates the percent deviation of PBBT reported BF from the BF computed with the torque wheel data (using the best match from the three methods) for the laden and unladen conditions, respectively. These data are the average from three repeat tests on a single wheel. The proposed FMCSA functional specifications for PBBTs call for ±2.5 percent accuracy of BFs for the PBBTs. The total accuracy range incorporates the torque wheel transducer accuracy, the tire radius measurement accuracy, and the error induced on the radius measurement by the varying contact geometries (dependent on the PBBT type), as detailed in Appendix B. The total acceptable range varies from 4.3 to ± 6.9 percent.

As can be seen in Figure 3, all PBBTs except the flat plates had less than a 3 percent deviation from the torque wheel results, and therefore their accuracy was considered acceptable without further consideration.

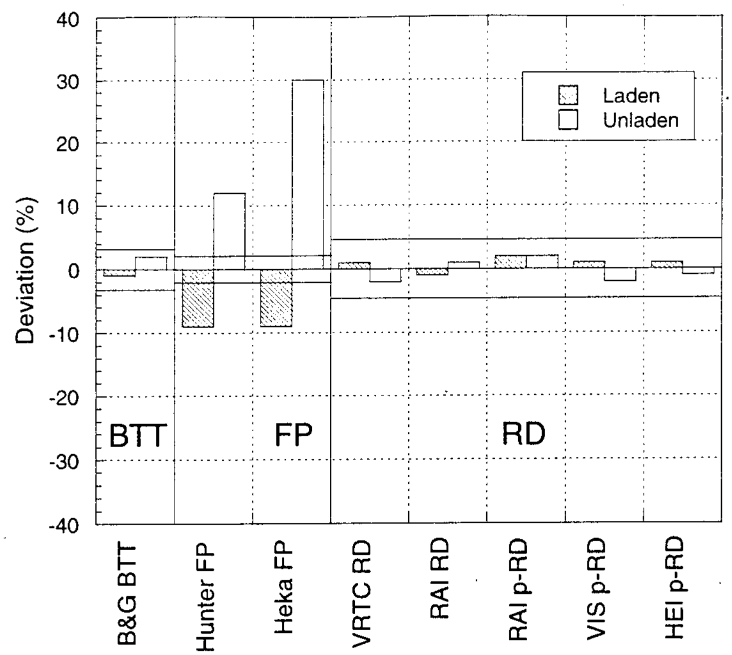

Figure 3. Average deviation of PBBT-reported BF from BF computed from the torque wheel data from wheel 5 of the 3-S2 in the laden and unladen conditions. The algorithm to compute BF from the torque wheel data which gave best fit was used to plot these data. The solid horizontal lines indicate the acceptable ranges for accuracy as listed in Table 5 for indirect standards.

For the FPs, low BFs were reported in the laden condition and high BFs were reported in the unladen condition. It should be noted that low reported brake forces do not necessarily lead to a safety concern. The deviations in the FP data must result from the effects of dynamic loading, data manipulation and/or algorithm for reporting BFs. Since the algorithm used by Hunter was unknown, but their FP demonstrated good prediction of $decel_{EQ}$ (Section 3.1.3), the significance of the 10 percent deviation from the reference BF values is not considered to be a safety issue or of critical significance. No time history data was available from the HEKA FP unit. As such, since deviations up to 30% were observed, this unit would not be considered acceptable for use in enforcement and further evaluation is warranted after appropriate modifications are made by the vendor.

The shape of the time history plots reported by the PBBT vendors appeared to match the data obtained from the torque wheel (Appendix D). The slight variations between the PBBT-reported brake forces and those calculated from the torque wheel data must result from differing algorithms. As such, it is recommended that for each type of PBBT, a common procedure be developed, adopted and documented. The algorithm for reporting the BF should include filtering to avoid any problems resulting from anomalous spikes. In doing so, assuming the unit is correctly calibrated, the reported BF should be PBBT-vendor independent.

3.1.2 Brake Forces – Overall Vehicle Brake Force Evaluation - Applicability

In this section, we examine the applicability of the PBBT-reported BFs through comparison with the total BF produced by the vehicle during a 32.2 km/hr (20 mph) on-road stop. For the weakly braked vehicles, it was assumed that no wheels were skidding[13] during the stops and thus that the maximum available brake forces were transmitted to the ground during the stop. As such, the total brake forces were computed using the equation:

$$F = Ma,$$

where F is the overall vehicle brake force, M is the vehicle mass (in this case, GVW was used), and a is the average deceleration over the course of the stop. The GVW was measured with certified scales prior to the test and the average deceleration was computed using a linear regression of the slope of the velocity versus time data from the 5th wheel data. (See Appendix B for details.) These values were considered the reference for applicability. The BF_{TOT} for the PBBT was simply the sum of the individual BFs measured on an axle-by-axle basis.

Figure 4 shows the PBBT-reported BF_{TOT} for each of the replicate tests for the weakly braked vehicles. The total vehicle BF deduced from the 32.2 km/hr (20 mph) stops is shown, along with the acceptable range of applicability (Table 5).

[13] There may have been some skidding of the most strongly braked wheel (number 5 on the 3-S2 and number 2 on the 2-axle), but this could not be confirmed. Individual wheel speed data were not available from the tests.

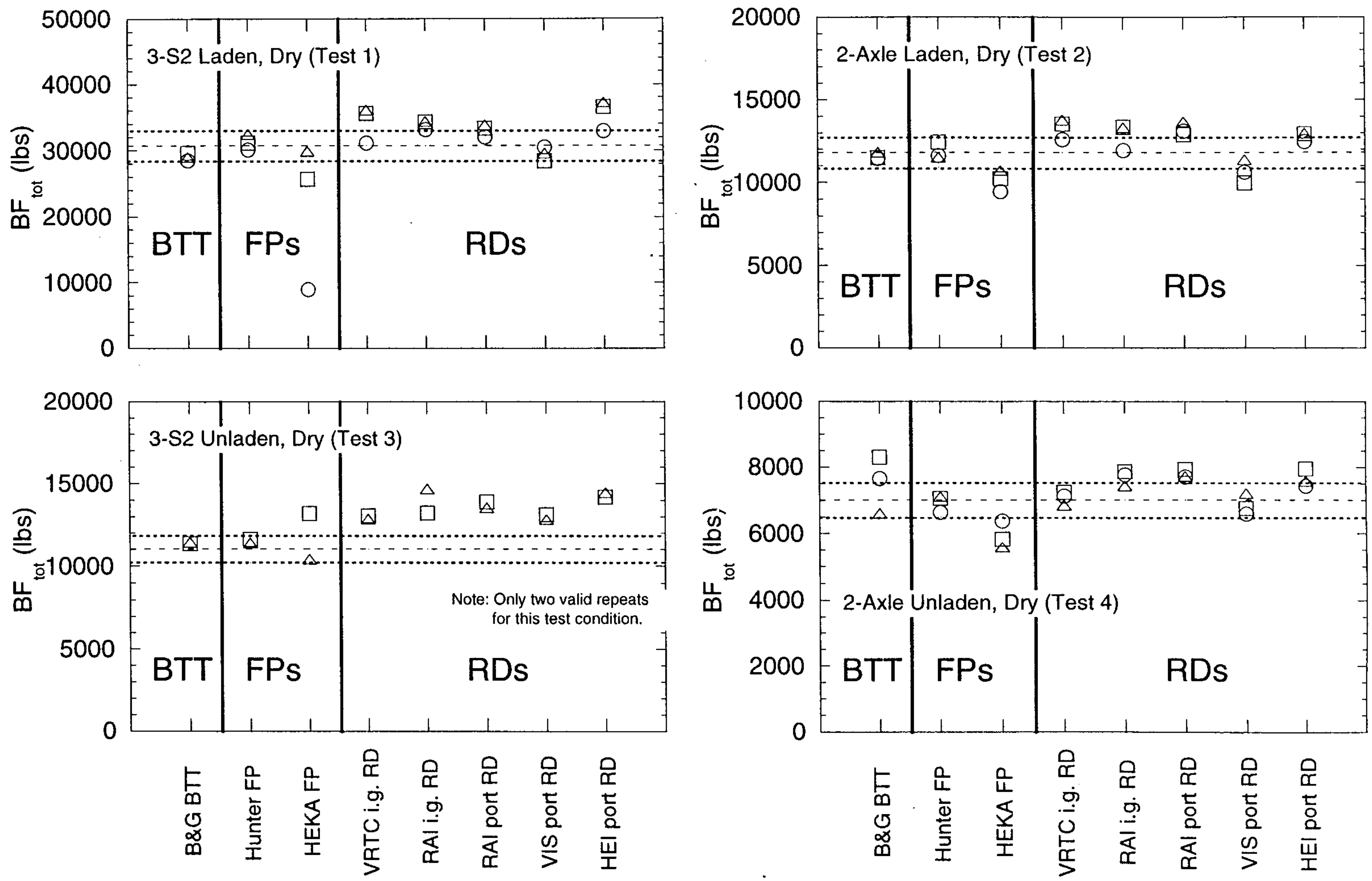

Figure 4. **BF_{TOT} for weakly braked vehicles (Tests 1 - 4).**
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The upper and lower dashed lines in the plots show the acceptable range of applicability (± 7.5 %, as listed in Table 5). The middle line represents the reference BF computed fro the reference GVW (measured with certified scales) and the average deceleration from 32.2 km/hr (20 mph) on-road stops. If PBBT transducers have acceptable accuracy, PBBT or procedural modifications will be required to account for deviations beyond the acceptable range of applicability.

The breakaway torque brake tester (BTT) had acceptable applicability in reporting BF_{TOT} for weakly braked vehicles for all tests except Test 4, the empty 2-axle, in which two of the three measurements were higher than those computed from on-road stop. As shown in Appendix Table C4, the measured BFs for the strongly braked wheels (numbers 2 and 3) were high. These wheels may have been locked during the road stop, thus limiting the ratio of BF to WL to the road COF. In contrast, the BTT does not have a COF limit since the wheel can not slip in the grips. Torque wheel or wheel speed data were not available to confirm whether or not wheel lock-up occurred. A procedural modification, in which the maximum BF/WL ratio for strong brakes is limited to an assumed maximum road COF value, may have to be invoked in some cases for use in enforcement, so that the BTT does not report BFs higher than those which can be achieved on the road.

The flat plate brake testers (FPs) were split in their applicability in reporting BF_{TOT} for weakly braked vehicles. The applicability of the Hunter FP was acceptable in all cases. The HEKA exhibited erratic behavior, with only one repeat from each test near the acceptable range. The other repeats showed wide scatter, mostly due to low reported BF_{TOT}. Since the deviations were not systematic, it was not possible to isolate the cause, nor make recommendations for correction. It was most likely due to the handling of the dynamic data and the algorithms used to compute BFs.

Four of the five roller dynamometers (RDs) showed either acceptable applicability for reporting BF_{TOT}, or slightly higher values than those measured during road stops. This was clearly seen in Test 3 (unladen 3-S2). Since none of the roller surfaces had a COF higher than that expected for the road, the discrepancy was likely due to either geometric effects from the tire/roller contact patch, or to low speed of the rollers (<2 km/hr or <1.2 mph, for portable RDs) compared to 32.2 km/hr (20 mph) for the vehicle stops. The brake force generated can be higher at low speeds. The development of a scaling factor to account for the speed or geometry dependence may be required for use in enforcement. In contrast, the VIS RD showed somewhat lower BF_{TOT} than the other RDs. Since the individual torque wheel calibration check did not indicate this systematic difference (Fig. 3), it is suspected that a possible early test termination caused by the stronger brake, or a lower, and thus limiting, roller COF may have been the cause. Meeting the functional performance specifications and use of common test termination and data reduction procedures should adequately address these issues in the future.

3.1.3 WHEEL LOADS – INDIVIDUAL WHEEL LOAD EVALUATION - ACCURACY

As shown in Figure 5, acceptable accuracy of the wheel load measurements was observed for all PBBTs for which data were available. Data are included in Appendices B and C. The calibration was performed for the HEKA FP, but the data were not provided for publication. However, it is recollected that the weight calibration was acceptable. Weight calibration of the BTT was not performed due to minor damage to the hydraulic system as the PBBT was moved to get access to the concrete blocks. Similarly, the concrete blocks could not be transported to the off-site RAI in-ground RD, so an electronic shunt-calibration was performed instead, and results were accurate within 2.5%. Acceptable calibrations and documentation of the ability to meet the functional specifications for weighing accuracy will be required as part of compliance testing for use of all PBBTs for enforcement.

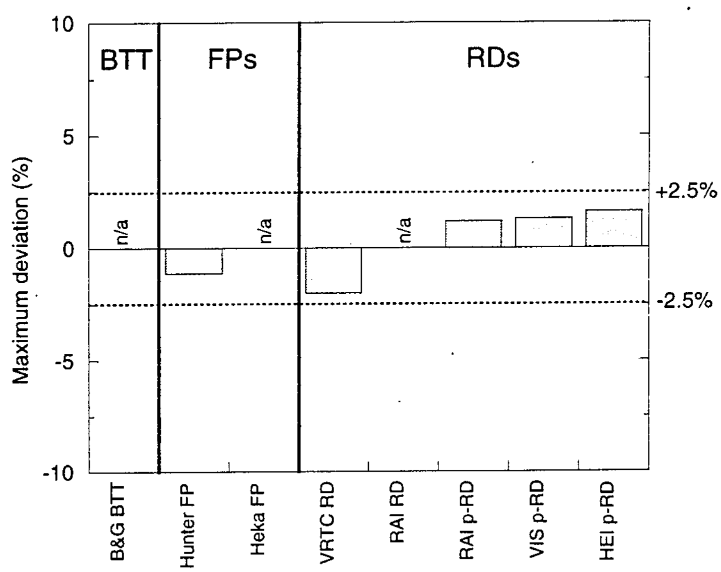

Figure 5. Maximum deviation of PBBT reported WL from series of applied loads using concrete blocks of known weight. The dashed lines show the acceptable range of accuracy as listed in the PBBT functional specifications and in Table 5.

3.1.4 WHEEL LOADS – OVERALL VEHICLE (GVW) EVALUATION - APPLICABILITY

The applicability of the PBBT-reported GVW measurements was assessed by comparing the GVW obtained using certified portable scales (in which the entire vehicle weight was measured at once) to the sum of the wheel (or axle) weights reported by the PBBTs. Results are shown in Figure 6 and revealed that, prior to the use of PBBTs for enforcement, procedural or physical modifications will be required, because only the Hunter FP and the RAI in-ground RD had acceptable deviations (Table 5) from the known GVW for all four test conditions. In general, GVW results were more acceptable for the 2-axle vehicle than for the 3-S2 vehicle. Systematic deviations were only observed for the VIS portable RD, which reported low GVWs in each test and the HEKA FP, which reported high GVWs except for Test 2. In Test 2, software problems for the HEKA lead to zero values for some of the axles. As such, the applicability for these two PBBTs was expected to be correctable through appropriate modifications by the PBBT manufacturers.

As shown in Tests 1 and 3, the overall applicability of PBBT-reported GVW for the 3-S2 was questionable. With the exceptions of the Hunter FP and RAI in-ground RD listed above, some PBBTs reported GVWs which were up to 40 percent higher than the reference vehicle weight. Appendix Figure E2 shows that the weight of axles 2 and 4, the leading axles for the tandem set were measured high. Specific procedures will be required when using PBBT-measured GVWs for enforcement. For example, use of modified ramps is expected to resolve this problem. Alternatively, the entry of remotely measured axle weights or criteria for brake forces which do not depend on weight may be required.

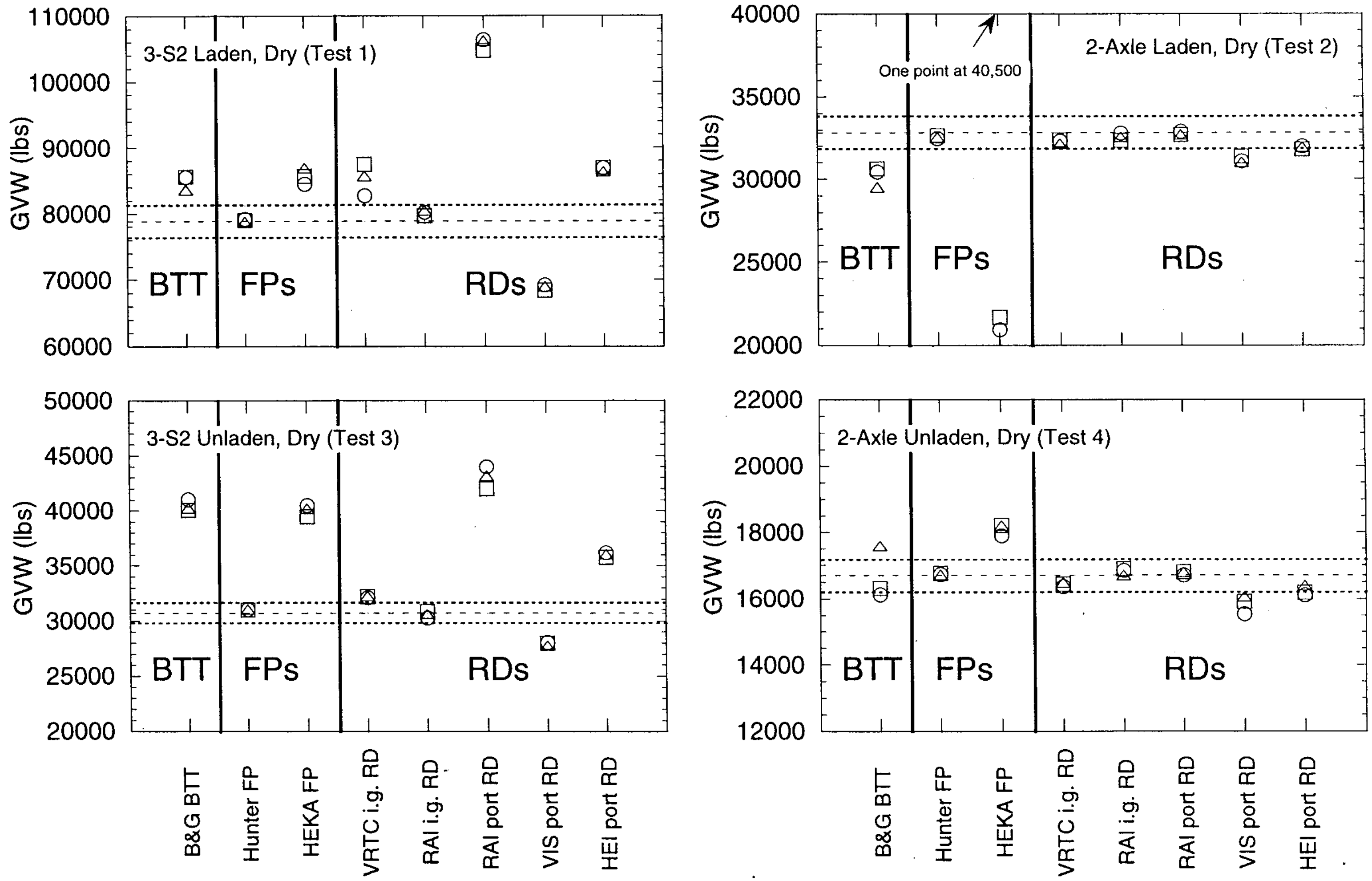

Figure 6. **GVW for weakly braked vehicles (Tests 1 - 4).**
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The upper and lower dashed lines show the acceptable range of applicability (± 3 %, as listed in Table 5). The middle line represents the reference GVW (measured with certified scales). If PBBT transducers have acceptable accuracy, PBBT or procedural modifications will be required to account for deviations beyond the acceptable range of applicability.

3.1.5 DECEL$_{EQ}$ – OVERALL VEHICLE EVALUATION - APPLICABILITY

No direct standards could be used to evaluate the accuracy of the decel$_{EQ}$ measurements. As such, the PBBT-reported decel$_{EQ}$ was compared to the on-road deceleration of the vehicle (indirect standard). By this method, the applicability of the PBBT to predict the 32.2 km/hr (20 mph) vehicle deceleration was evaluated. Results are shown in Figure 7. The Hunter FP results were acceptable in all tests. The results of the HEKA FP indicate that it may require additional development. Although there was some scatter, in general, the results indicate that most of the remaining PBBTs predicted the on-road deceleration very nearly within the bands of acceptability. Most of the deviations could be attributed to the GVW measurements as discussed in Section 3.1.4, and thus can be rectified with implementation of applicable procedures.

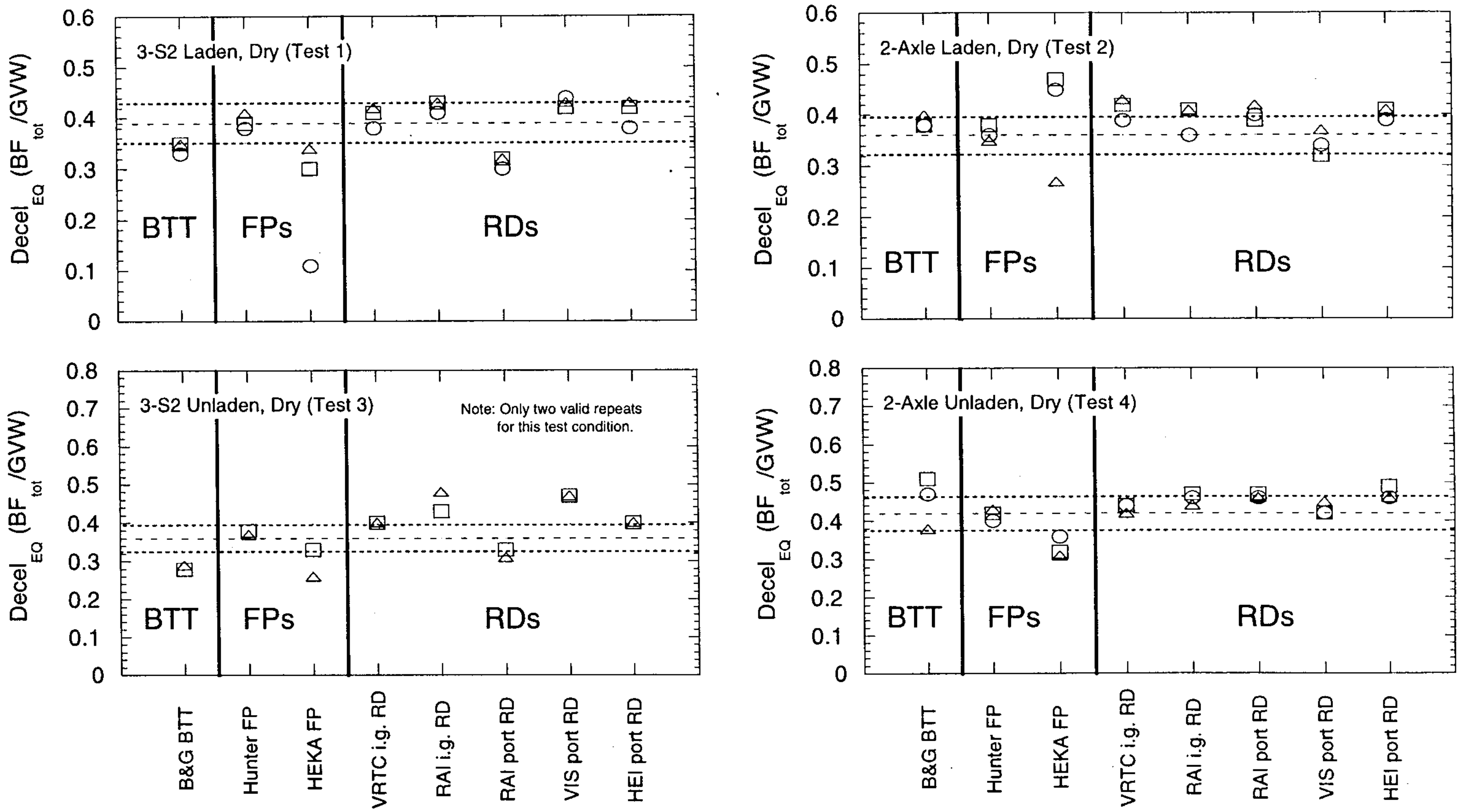

Figure 7. **$Decel_{EQ}$ (BF_{TOT}/GVW) for weakly braked vehicles (Tests 1 - 4).**
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The upper and lower dashed lines show the acceptable range of applicability (± 10 %, as listed in Table 5). The middle line represents the average deceleration from 32.2 km/hr (20 mph) on-road stops. If PBBT transducers have acceptable accuracy, PBBT or procedural modifications will be required to account for deviations beyond the acceptable range of applicability.

3.1.6 REPEATABILITY

In a manner identical to that used to develop the acceptable ranges for accuracy, the acceptable ranges for repeatability (ARR) were established (Table 5). These combined two uncertainty factors (as described in Appendix B), the acceptable range of accuracy listed in the proposed FMCSA functional performance specifications for PBBTs, and the "real-life" expected variations for brake forces and weights.

The acceptable ranges for repeatability are shown as error bars about the average of the minimum and maximum values from the replicate tests in Figures 8 through 11, in which the repeatability of BF measurements for individual weak brakes (Figures 8 and 9), overall GVW (Figure 10), and $decel_{EQ}$ (Figure 11) are plotted. The acceptable ranges for repeatability are: ± 7.5%, ± 3% and ± 10%, respectively.

In summary, approximately 93 percent of all measurements were within the ARRs (see Figures 8 through 11). The tests for which results were outside the ARRs were examined in detail. The deviations could be attributed to: operator error, variations in driver brake application, erroneous test results (e.g. HEKA, replicate 1, Test 1 in Table C1) or premature test termination. As such, all PBBTs could be considered acceptable after implementation of appropriate modifications or procedures to recognize and correct these erratic measurements.

3.1.6.1 Repeatability for individual weak brake BFs

The weak brakes were located on wheels 1 and 6 on the 3-S2, and wheels 1 and 4 on the two-axle straight truck (Figure 2). The BF repeatability results are shown in Figures 8 and 9.

Overall, the repeatability for identification of individual weak brakes was very good, with acceptability in 90 percent of the 192 test runs. Some variability in repeatability could be attributed to the vehicle brakes themselves. In particular, note that for wheel 6 for Test 1, a lower brake force was observed for replicate 1 for all PBBTs. This was also observed (to a lesser extent) for wheel 1. The vehicle brakes may not have been fully conditioned before the first test round and residual moisture from the previous night may have lowered the available BFs. Therefore, any deviation from the ARR due solely to BF values from the first replicate of the first test for wheels 1 and 6 should be discounted.

In the few other cases where the variations were significant, the sources of the variability were identified, and future corrective actions will be taken. These consisted of tests in which low BF was attributed to operator error (BTT), prematurely terminated tests, possible lift-off at wheel lock up[14] (RDs), or variability in driver brake application (both FPs).

3.1.6.2 Repeatability for overall GVW

The results for the repeatability assessment of GVW for Tests 1 through 4 are shown in Figure 10. Although it was suspected that the particular suspension and the axle geometry of the 3-S2 led to high reported-GVW values for several of the PBBTs, the repeatability for all PBBTs was excellent. 98 percent of 96 measurements were within the ARR. Replicate 3 of Test 4 (unladen 2-axle) was slightly high for the BTT, with the GVW just beyond the ± 3 percent ARR. The HEKA showed significant variability on all replicates of Test 2 (laden 2-axle). The extreme high and low reported values most likely resulted from software problems.

3.1.6.3 Repeatability for overall vehicle deceleration

The repeatability for reported values of overall vehicle equivalent deceleration is shown in Figure 11. The repeatability was acceptable in 95 percent of the 96 test runs. The exceptions included both laden vehicles and the unladen 3-S2 for the HEKA FP, and the unladen 2-axle for the B&G BTT. The low repeatability reported by the HEKA was due to apparent software problems resulting in several zero values and double values being reported. The B&G low repeatability was due to an erratic low BF on one wheel in a single test. This appeared to be due to an error in the transfer of the data to the file used in this report. Since these cases appear correctable, the repeatability for overall vehicle deceleration for all PBBTs was considered acceptable.

[14] An analysis of the lift-off phenomenon, which is more prominent on the rear axle of 2-axle vehicles, is presented in SAE paper 982829, "Understanding the Portable Roller Dynamometer", S.J. Shaffer and J.W. Kannel.

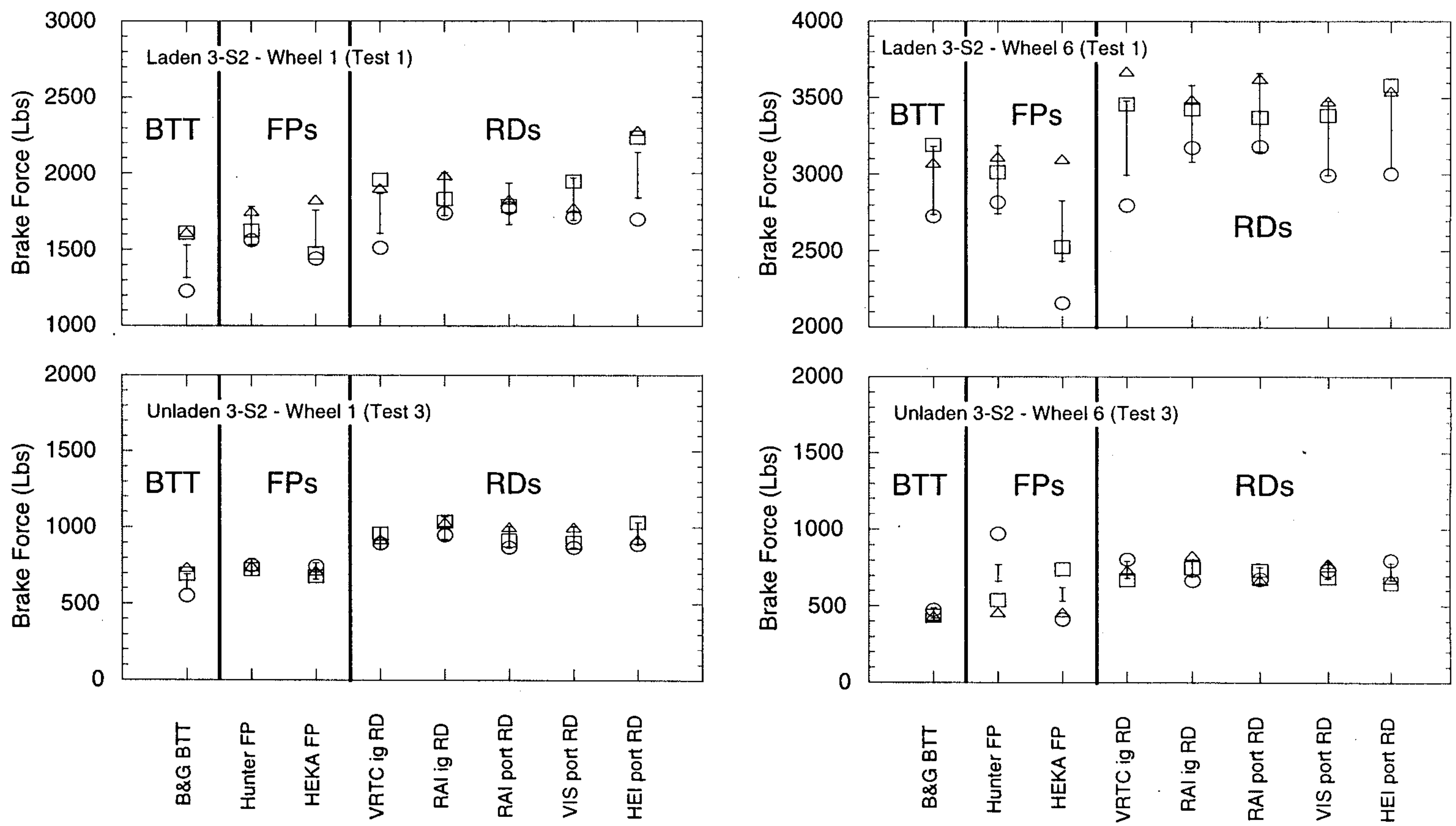

Figure 8. **Repeatability of PBBT-reported BF measurements for weak brakes on the 3-S2 vehicle (Tests 1 and 3). Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The error bars represent the acceptable repeatability range for BF (± 7.5 %, as listed in Table 5). All PBBTs showed lower BFs for Test 1, replicate 1, possibly as a result of residual moisture from the previous night. Any variation due to BF values from Test 1, replicate 1, should be discounted.**

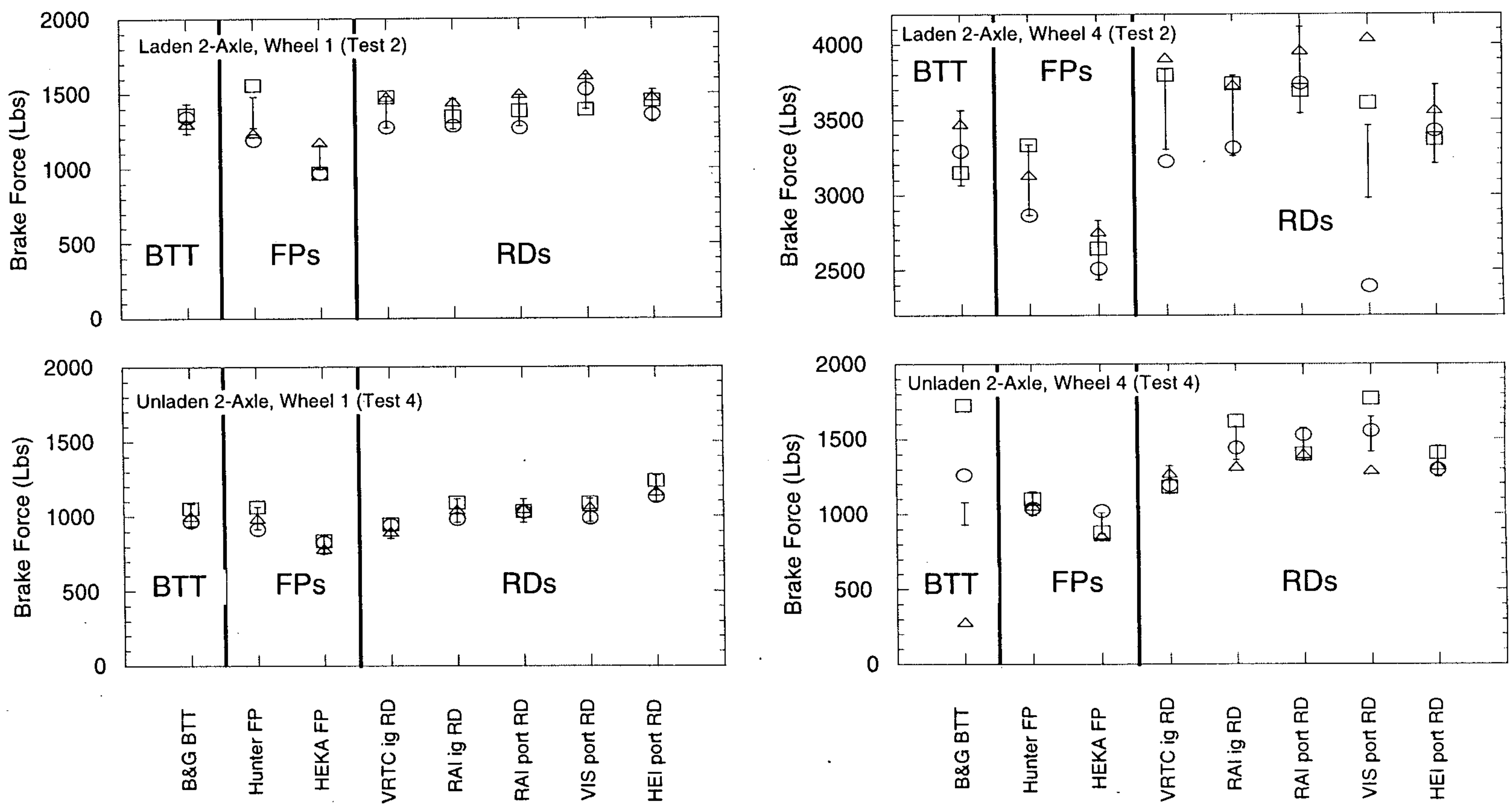

Figure 9. **Repeatability of PBBT-reported BF measurements for weak brakes on the 2-axle vehicle (Tests 2 and 4). Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The error bars represent the acceptable repeatability range for BF (± 7.5 %, as listed in Table 5).**

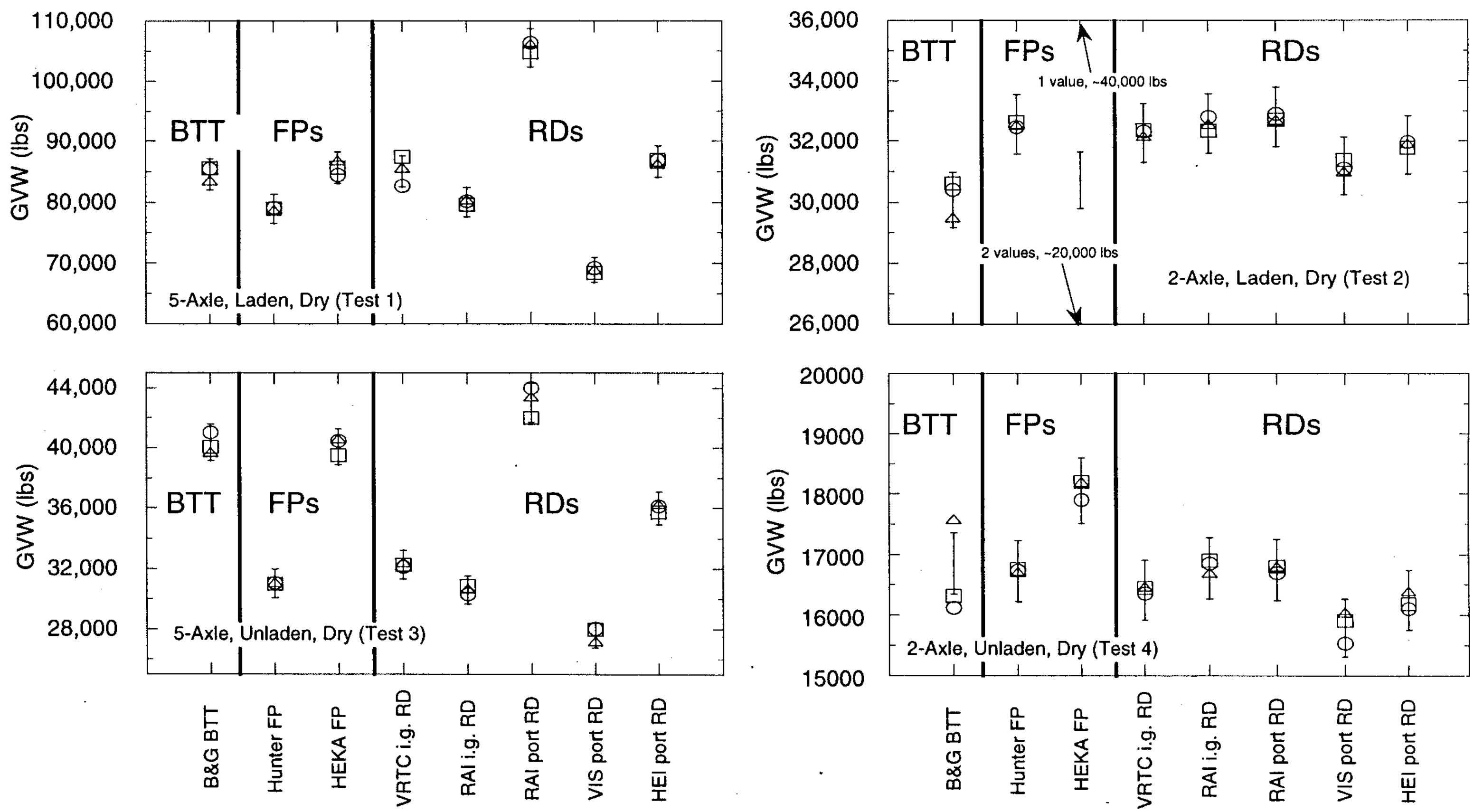

Figure 10. **Repeatability of PBBT-reported GVW measurements on the 3-S2 and the 2-axle vehicles (Tests 1 - 4). Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The error bars represent the acceptable repeatability range for GVW (± 3 %, as listed in Table 5).**

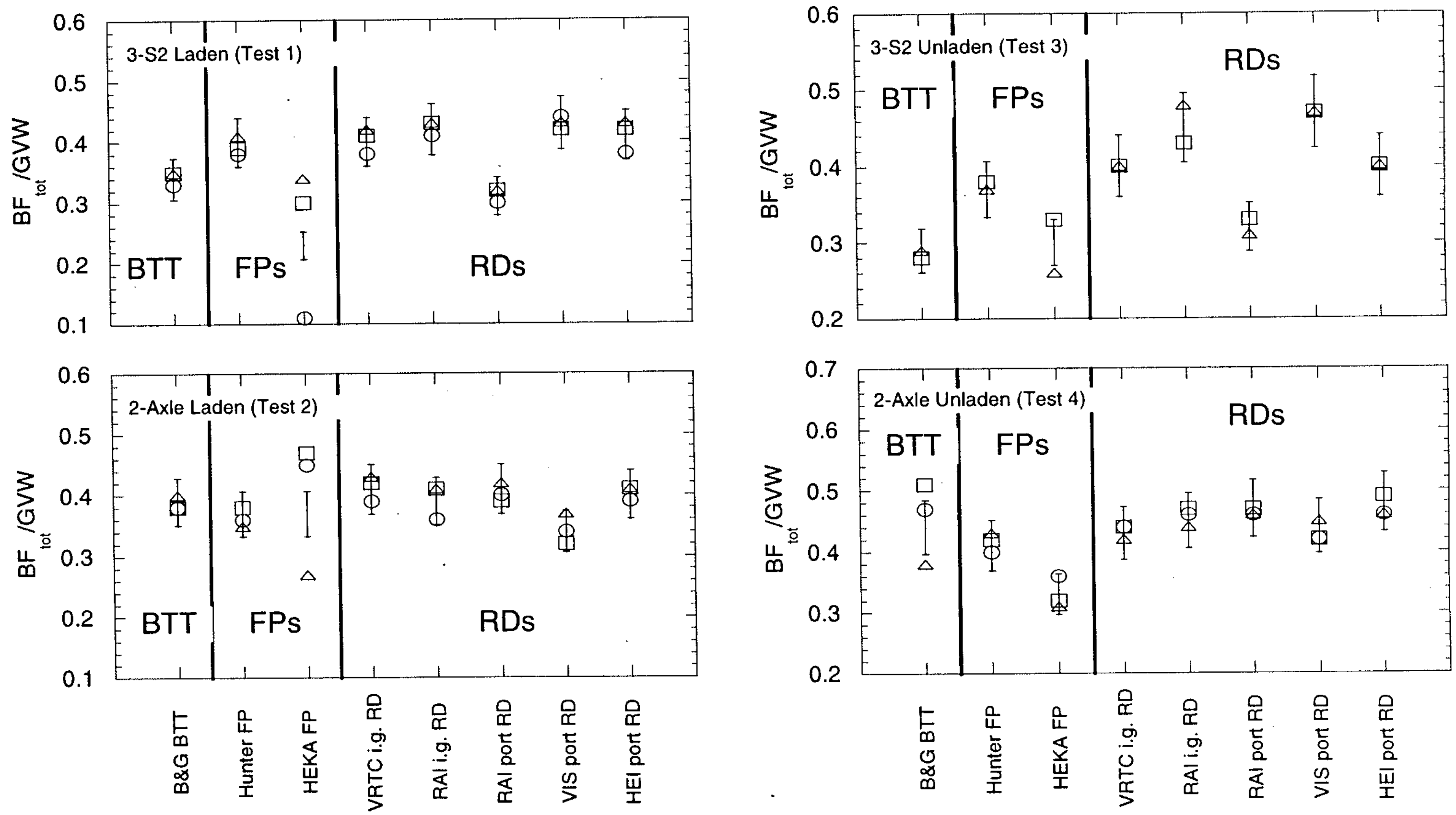

Figure 11. **Repeatability of PBBT-reported decel$_{EQ}$ (BF$_{TOT}$/GVW) for weakly braked vehicles (Tests 1 - 4). Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The error bars represent the acceptable repeatability range for decel$_{EQ}$ (± 10 %, as listed in Table 5).**

3.2 Vehicles with Fully-Adjusted, Strong Brakes (Tests 5-9)

This section investigates the ability of PBBTs to quantify strong brakes (i.e. high BF/WL ratios) as well as whether the BF measurements are affected by specific PBBT characteristics. Since variations in reported BF values affect predictions of vehicle on-road decelerations, it is important that their origin and magnitude are understood and documented. Such variations may have to be accounted for in enforcement activities.

A strongly braked vehicle was used in this second part of the round robin. The available brake force, i.e. the BF which the vehicle can transmit to the ground (or to the PBBT test surface) can be limited by both the load on a wheel, and by the traction between the tire and the road (or test surface). According to the equation $F=\mu N$, the maximum force (F) that can be transmitted before slip occurs is equal to the wheel load (N) times the traction coefficient (μ or COF). As such, variations in BF measurements were investigated in various loading and test surface conditions. The test surface traction was modified through the use of water.

The accuracy of the PBBT results for BF and WL measurements was investigated in the first part of the round robin. For the analyses conducted for the second part, it was assumed that the WL measurements were not affected by the level of braking capability or by the test surface conditions. This assumption was confirmed by a similar level of accuracy, applicability and repeatability of the WLs for the 2-axle truck in Part 1 (Figures 5, 6 and 10) and Part 2 (Figures 12-16). As such, variations in $decel_{EQ}$ observed in Part 2 can be directly attributed to variations in PBBT-reported BF_{TOT}. Therefore, this section focuses on the PBBT-reported brake forces.

3.2.1 APPLICABILITY OF PREDICTED DECEL$_{EQ}$ AND BF$_{TOT}$

The data from Tests 5 through 9, the strongly-braked 2-axle vehicle, were used in the evaluations in this section. For lightly loaded axles, or low traction test surfaces, the full braking capability of the vehicle may not always be measured by a PBBT. In most cases, the coefficient of friction (COF) between the tire and the test surface dictates the upper limit for BF measurements which, in turn, dictates the upper limit for $decel_{EQ}$.

Limitations on measured BF will not necessarily result in a safety hazard. A BF reported low due to low surface traction of the test surface will at least provide a minimum level of braking capability. Additional braking capacity may be available. On the other hand, the measurement of additional (reserve) BF beyond that dictated by the wheel load and the expected road/tire COF can in fact be beneficial. Knowledge of additional BF capacity can be used to determine adequate braking capability under heavier loading conditions, and may be used to define the vehicle's load limit for safe braking. However, at this time, the recommended performance-based regulations (see Table 1 in Section 1.1) are applicable to a vehicle under its current loading condition only.

The functional specifications under development for PBBTs call for a COF of at least 0.6 between the test surface and a standard tire to simulate road conditions. Variations from one PBBT to another observed during this portion of the test program do not necessarily indicate a problem with their use in enforcement. For example, a PBBT whose test surface has higher traction than the road (high traction gripper pads, FP grates and certain RD roller surfaces) has the capability of measuring BFs higher than the BFs achieved by the vehicle on the road. As long as the variation in the reported BF is known to result in a higher BF than the vehicle can achieve in a 32.2 km/hr (20 mph) stop, no safety concern exists. In such cases, applicability to vehicle on-road service conditions can be realized if proper account is taken of the ratio between the test surface traction and the road surface traction. The BTT presents a clear example of devices for which measured BFs are expected to differ from those achieved in a 32.2 km/hr (20 mph) road stop. Since the wheel typically can not slip in the gripping mechanism, the brake force measured by the BTT is independent of both wheel load and surface traction and is limited only by the method used for test termination.

The BF results for the strongly braked 2-axle vehicle (Tests 5 through 9) are presented in Figures 12 through 16[15].

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[15] Stopping tests were not run for Test 9, the strongly braked, empty two-axle vehicle on wet pavement. Since the BF/WL ratio was greater than the expected road/tire COF, skidding was expected to occur, and potential hazards would be incurred. In this case, a 0.5g deceleration was selected as the reference for comparisons to the PBBT results. The rationalization for this choice is as follows. The COF for skidding under dry conditions was assumed to be in the 0.6 to 0.63 range, equal to the measured deceleration of the strongly braked, empty two-axle vehicle on dry pavement. This range is consistent with the COF for a skidding tire being about 80 percent of that for a rolling tire (the tire/pavement COF for rolling is usually in the 0.75 to 0.8 range for truck tires). A further decrease in COF is expected for wet conditions. In the absence of any published studies on the decrease in COF under wet rolling conditions, 20 percent below the dry skidding case was assumed for the wet skidding case, i.e. 0.5g, in parallel to the observed reduction in COF found under rolling conditions (SAE 962153). However definitive conclusions should not be made using this assumption.

For Test 5, in the unladen, dry condition (Figure 12):

1) 7 of the 8 PBBTs predicted at least the BF_{REF}[16], and the on-road deceleration.
2) The VIS reported low BF_{TOT}, as a result of the left side roller (Appendix C).
3) The BTT and the FPs all predicted BF_{TOT} higher than those of the RDs, likely as a result of surfaces with higher traction.

For Test 6, in the 1/3 laden, dry condition (Figure 13):

1) 7 of the 8 PBBTs predicted at least the BF_{REF}, and the on-road deceleration.
2) Both FPs exhibited high scatter in their BF values.
3) The VIS reported low BF_{TOT}, as a result of the left side roller (Appendix C).

For Test 7, in the 2/3 laden, dry condition (Figure 14):

1) Only the Hunter FP predicted at least the BF_{REF}, and the on-road deceleration (2 of 3 replicates).
2) The BTT[17] and all RDs (except the VIS) predicted decelerations only slightly low.
3) Both FPs exhibited high scatter in their BF values.
4) The VIS reported low BFs, as a result of the left side roller (Appendix C).

For Test 8, in the 2/3 laden, wet condition (Figure 15):

1) 3 of the 8 PBBTs predicted at least the BF_{REF}, and the on-road deceleration.
2) The Hunter FP and the HEI experimental RD (RD2) exhibited higher scatter in the BF values.
3) The BTT and all RDs (except the RAI portable and the experimental HEI) predicted low $decel_{EQ}$ as a result of low BFs. This effect was most pronounced for the VRTC in ground, the VIS RD and the HEI RD. Again, the VIS reported low BFs for the left side wheels.

[16] Recall that BF_{REF} is the total BF calculated from the road stop data, using the average deceleration times the GVW.

[17] The BTT was set up intentionally to terminate the test if the BF on a wheel reached one half of the GAWR. It was observed that the total BF measured for all conditions of Tests 5 through 9 was the same.

For Test 9, in the empty, wet condition (Figure 16):

1) 6 of the 8 PBBTs predicted at least the BF_{REF}, and the on-road deceleration.
2) The Hunter FP and the HEI experimental RD (RD2) exhibited higher scatter in BF values.
3) The VIS RD and the HEI RD predicted low $decel_{EQ}$ as a result of low BFs. The VIS reported low BFs for the left side wheels (Appendix C).
4) The BTT, the HEKA FP, the RAI portable RD and the HEI experimental RD (RD2) measured high BF as a result of high test surface traction.

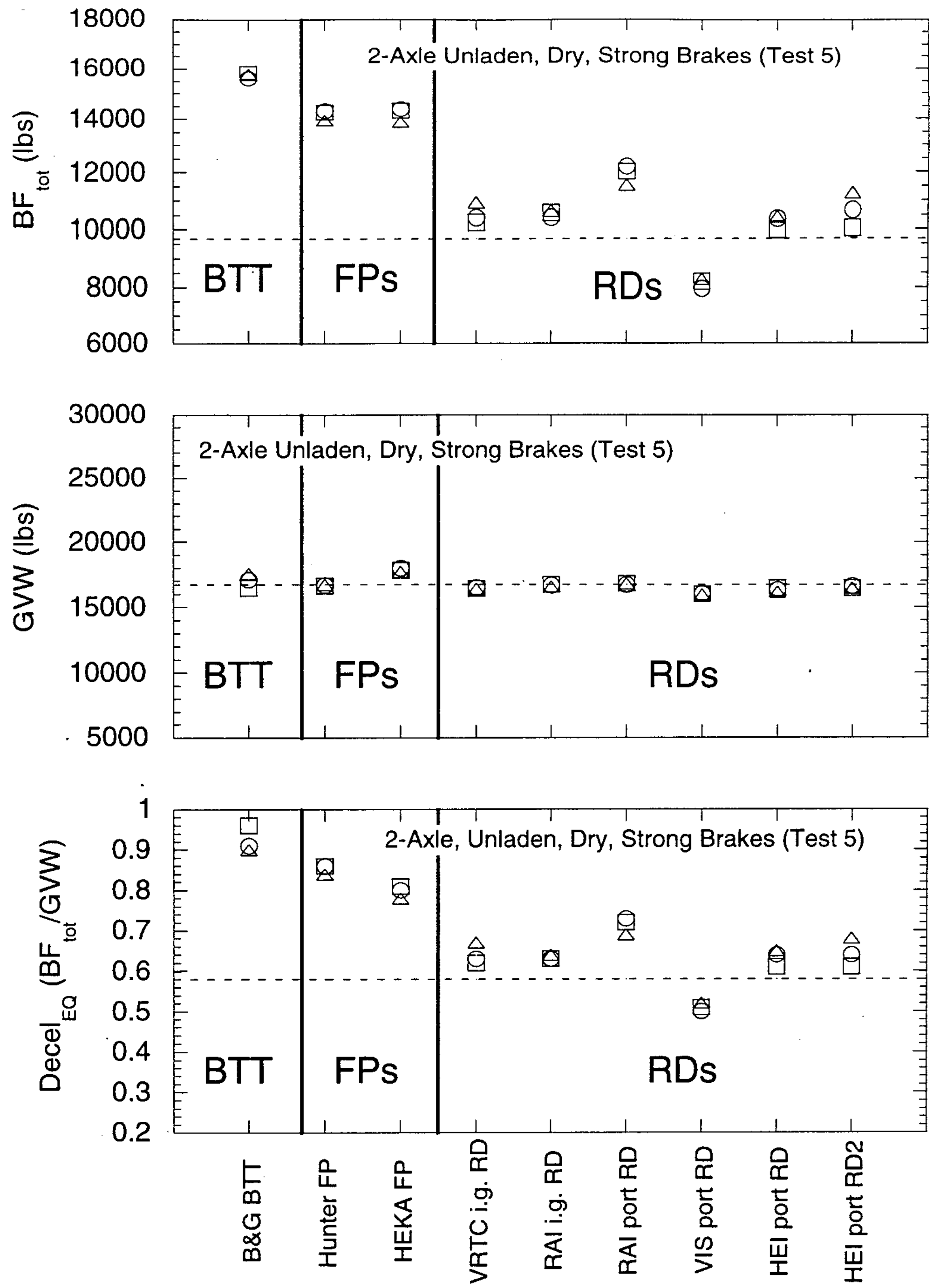


Figure 12. Strongly braked 2-axle vehicle, unladen, dry (Test 5).
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The dashed lines represent the reference data from 32.2 km/hr (20 mph) on-road stops and certified scale weight measurements.

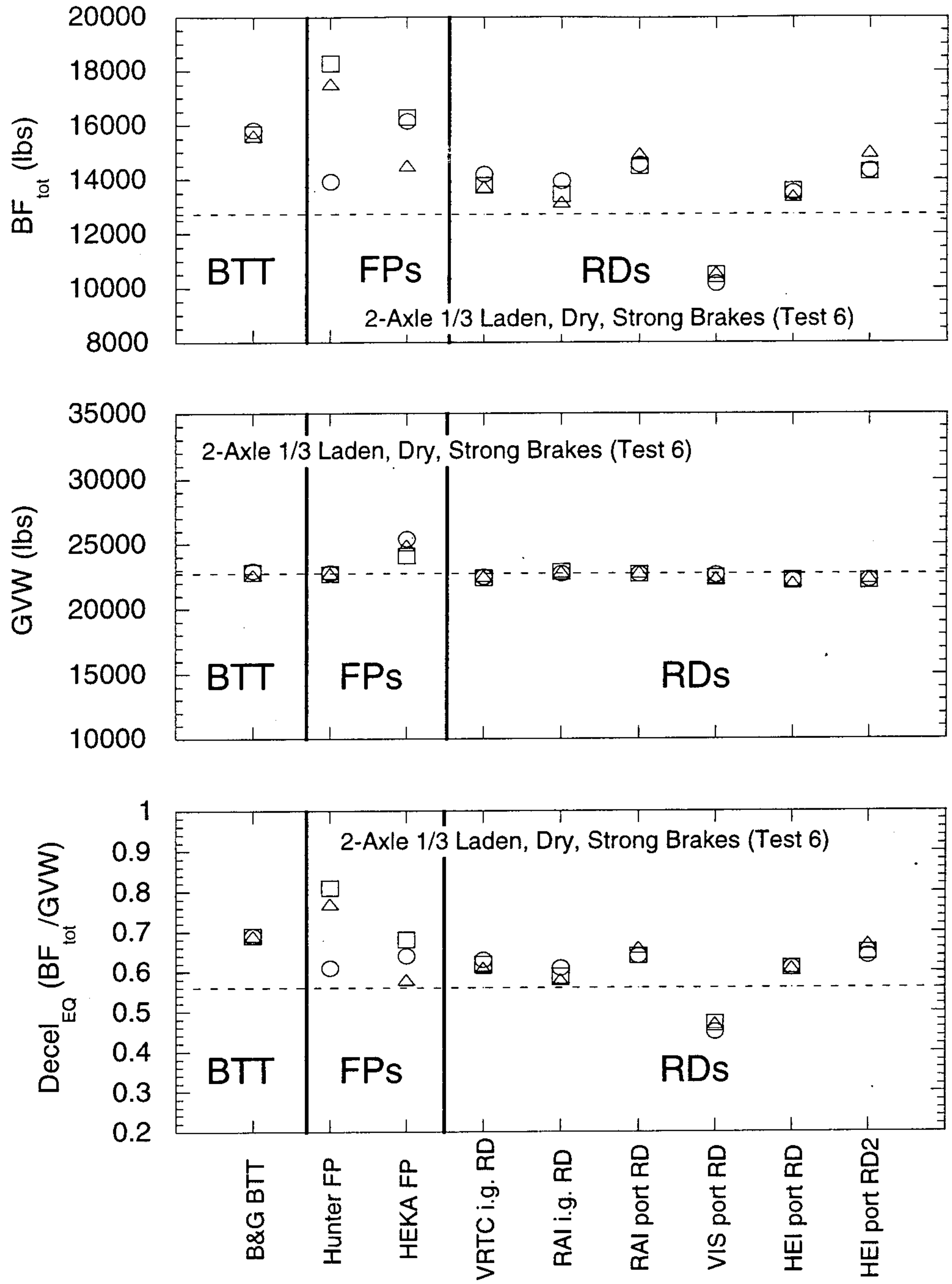


Figure 13. **Strongly braked 2-axle vehicle, 1/3 laden, dry (Test 6).**
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The dashed lines represent the reference data from 32.2 km/hr (20 mph) on-road stops and certified scale weight measurements.

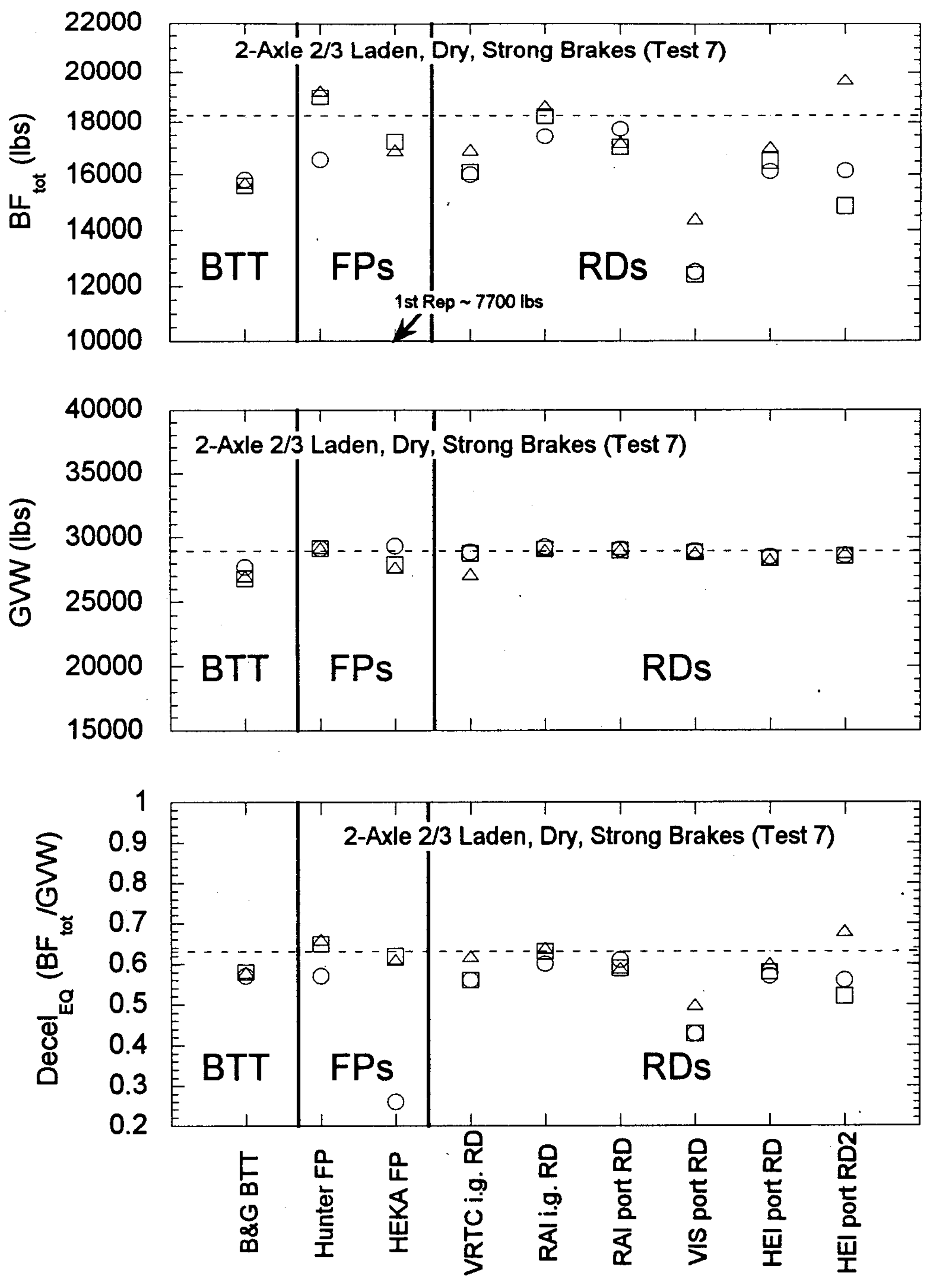


Figure 14. Strongly braked 2-axle vehicle, 2/3 laden, dry (Test 7).
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The dashed lines represent the reference data from 32.2 km/hr (20 mph) on-road stops and certified scale weight measurements.

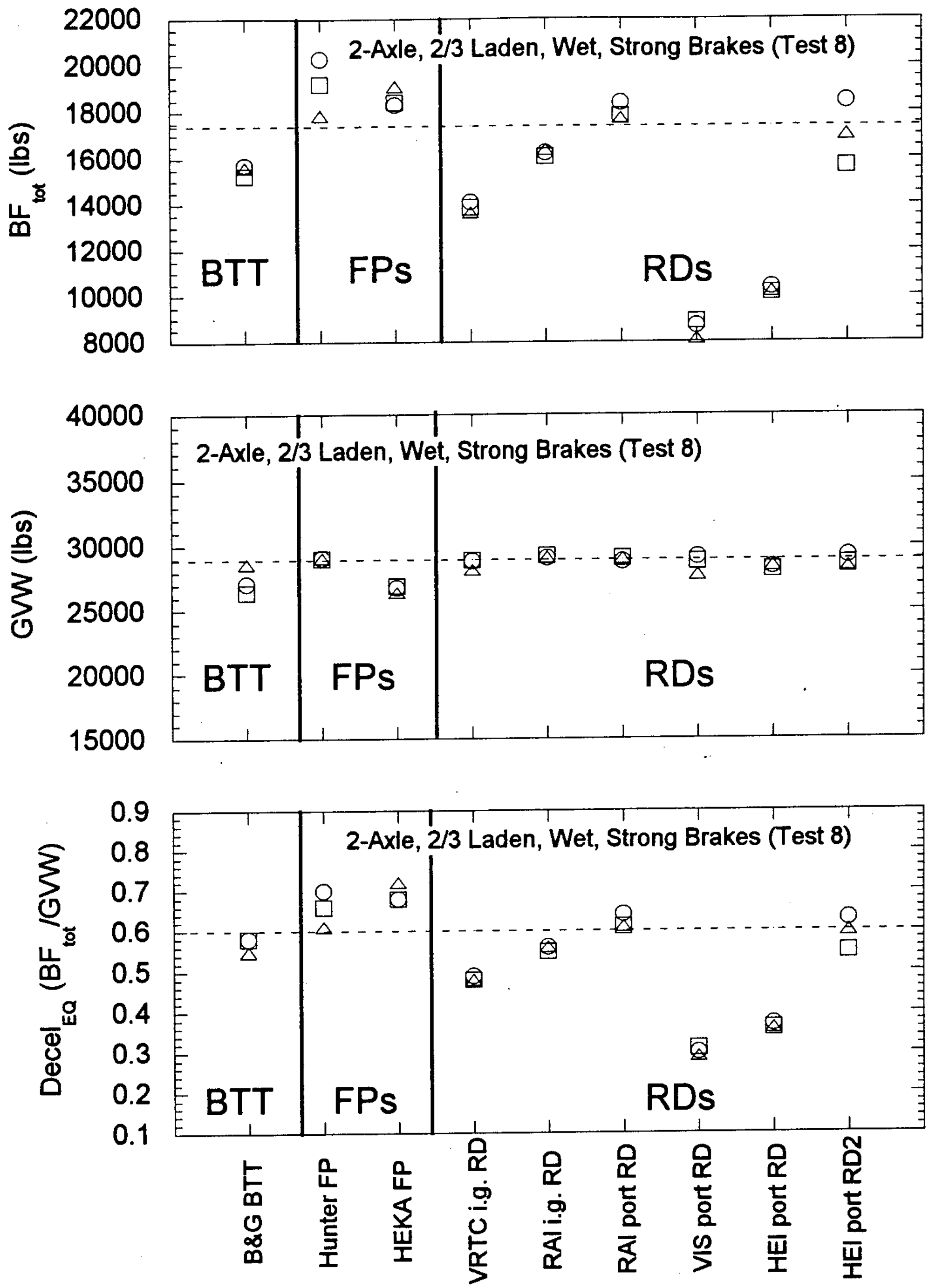


Figure 15. Strongly braked 2-axle vehicle, 2/3 laden, wet (Test 8).
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The dashed lines represent the reference data from 32.2 km/hr (20 mph) on-road stops and certified scale weight measurements.

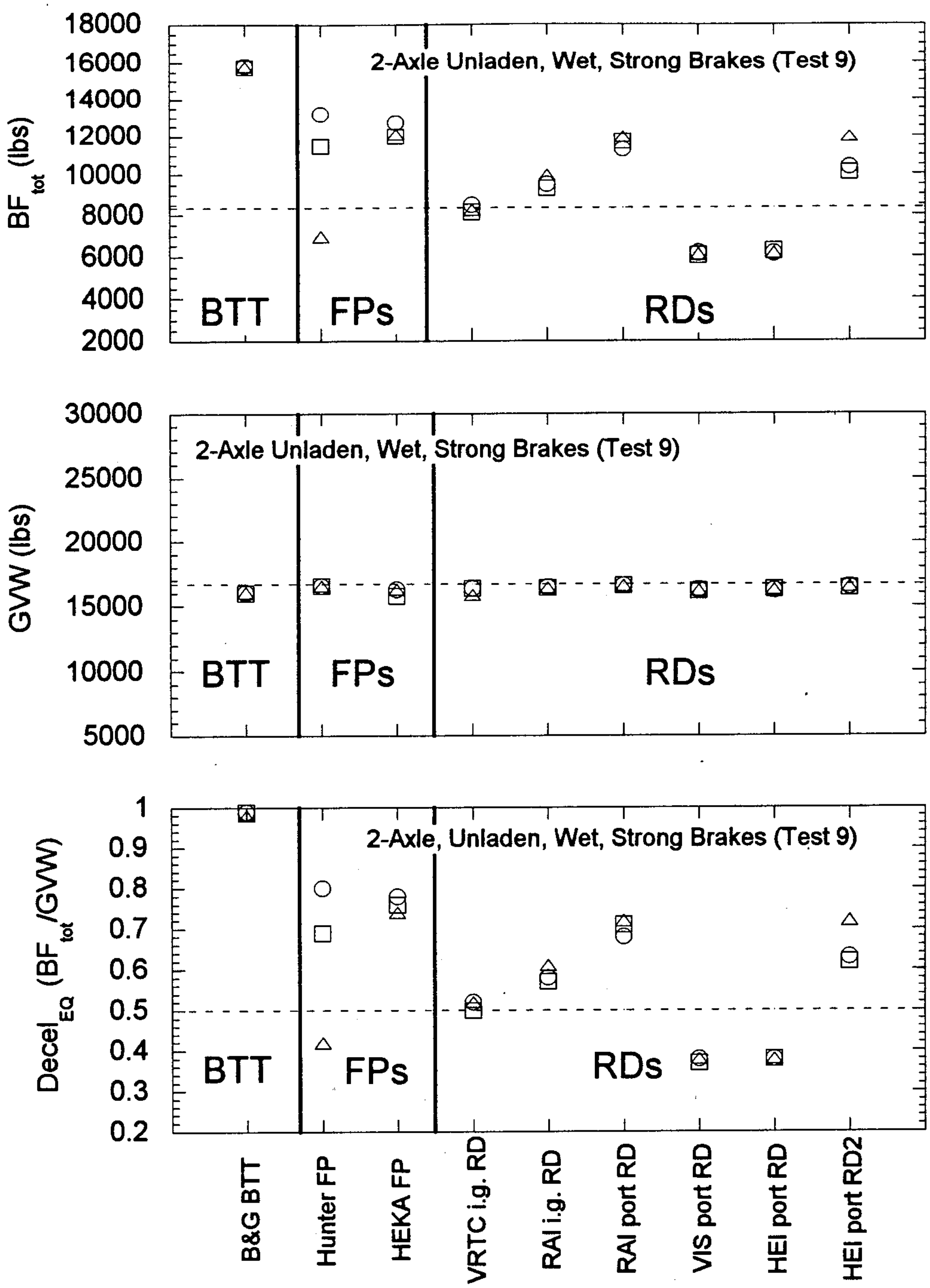


Figure 16. Strongly braked 2-axle vehicle, unladen, wet (Test 9).
Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The dashed lines represent the reference data from 32.2 km/hr (20 mph) on-road stops and certified scale weight measurements.

In summary, the following observations on $decel_{EQ}$ and BF_{TOT} were made for the strongly braked vehicle:

- The different test surfaces and test methods of the PBBTs led to different results for each class of PBBTs. Except for the VIS, the PBBTs could at a minimum predict the measured on-road deceleration of the vehicle in the dry condition, in all loading conditions tested except the 2/3 laden. In the 2/3 laden case, the $decel_{EQ}$ appears to be limited by test surface COF, and is above 0.5 for all PBBTs except the VIS RD. As such, the variations observed in the results are not a safety concern. However, some accommodation must be made to incorporate the expected road/tire COF for accurate stopping distance predictions.
- The FP testers showed higher BF_{TOT} variability in these tests of strongly braked vehicles (Tests 5-9) than in tests of the weakly braked vehicles (Tests 1-4). This may be an indication of the sensitivity of this FP testers to driver performance because at higher BF, a wheel can lock. It may also be that skidding created some dynamic loading effects for the FP testers that affected the results. If skidding occurs, Hunter does not consider the results valid and requires a retest.
- The VIS RD showed lower BFs compared with all the other PBBTs, as well as compared with the other RDs. This indicates either a lower COF surface or an earlier test termination which limited the maximum measurable BF. These possible causes should be investigated and resolved.
- The BTT reported a high $decel_{EQ}$ for the unladen and 1/3 laden tests (Tests 5, 6 and 9) compared with the reference value, but a low reported $decel_{EQ}$ for the 2/3 laden cases. Analysis of the results indicated that the BTT measured the same BF_{TOT} (approximately 15,700 lbs.) for all vehicle conditions, independent of loading or the presence of water. This is consistent with its mode of operation. At the time of the round robin, the BTT software was set to terminate the test when the BF on a wheel reached 0.5 times the GAWR/2. For a given COF[18], as the load increases, the BF available at the tire/road or tire/test surface interface increases as well. Therefore, BF_{REF} increases as the load increases. In Test 5 (unladen), BF_{REF} is equal to 9,686 lbs. while in Test 8 (2/3 laden), BF_{REF} is equal to 17,382 lbs. In the 2/3 laden case, the value of the pre-set cut-off of 0.5

[18] From elementary physics, the frictional force, F, is proportional to the normal load, N, through the coefficient of friction (COF), μ, as shown in the equation $F=\mu N$.

times the GAWR/2 was smaller than 17,382 lbs, the BF developed (and measured on the other PBBTs or during the road stop), whereas in the unladen case, the value equal to 0.5 times the GAWR/2 was greater than 9,686 lbs, the BF developed during the on-road stops or the other PBBT tests. As such, the BF_{TOT} reported by the BTT was low in the 2/3 laden tests while it was high in the unladen and 1/3 laden tests.

3.2.2 REPEATABILITY

In part 2, the influence of the loading and surface conditions on repeatability of BF measurements was evaluated for axle 2 of the strongly braked vehicle. As the vehicle GVW is increased, the load of axle 2 changes more than that of axle 1. In addition, lift-off (for RDs only) is more significant for axle 2 than for axle 1.

3.2.2.1 Repeatability for overall GVW

Figures 12-16 confirm that the repeatability of GVW measurements was not affected by the vehicle's braking capability or the COF of the test surface. 97 percent of the measurements were within the ARR for GVW (± 3 percent, as listed in Table 5).

3.2.2.2 Repeatability for strong BFs

Figure 17 shows that 93 percent of the measurements fell within the ARR.

- One Hunter FP measurement was low and outside the ARR in both wet tests (Tests 8 and 9). This was likely due to wheel lockup, or variation in brake application by the driver. Both cases would require re-testing.
- The HEKA FP had one low value on Test 7, apparently due to data acquisition problems (Table C7)
- The VIS RD reported a high BF for the third replicate of Test 7 (cause unknown).
- Finally, the HEI experimental RD (RD2) reported high values for the third replicate in three of the five cases.
- All other PBBTs showed acceptable repeatability for measuring strong BFs, independent of loading and test surface conditions.

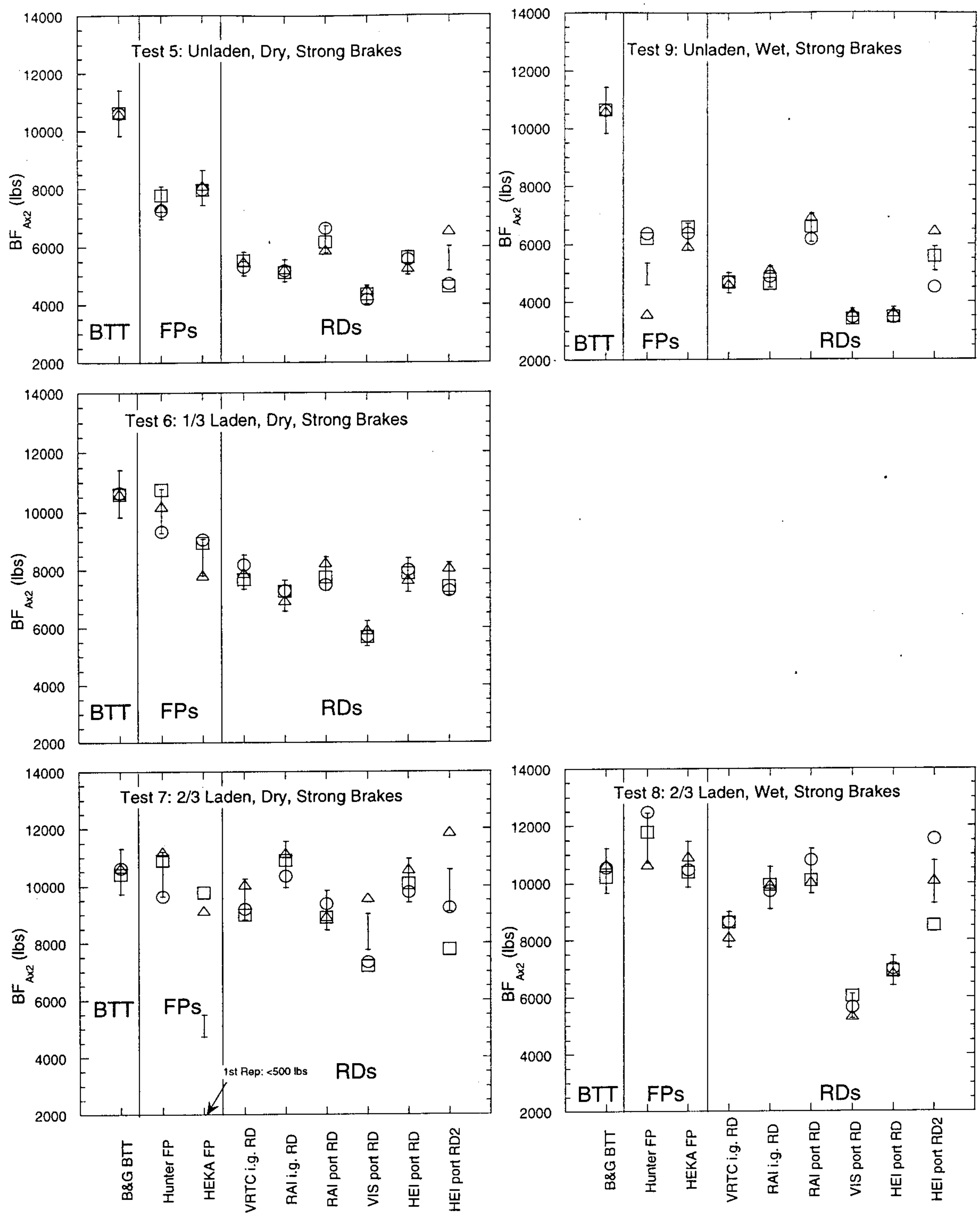


Figure 17. **Repeatability of PBBT-reported BF measurements for axle 2 on the strongly-braked 2-axle vehicle (Tests 5 - 9).**

Data for replicate 1 (○), replicate 2 (□) and replicate 3 (△) are plotted. The error bars represent the acceptable repeatability range for BF (± 7.5 %, as listed in Table 5).

For the RD tests in which the BF was outside the ARR, the results obtained for the third replicate indicate that chocking of the wheels may have contributed to an increased measurable BF. The increase in BF may be related to a decrease in the effect of lift-off. As such, standard test procedures for use in enforcement should take wheel chocking into consideration.

3.2.3 EFFECT OF TEST SURFACE

The effect of the test surface condition was also examined during the second part of the testing program. The PBBT results were obtained for two loading configurations (empty and 2/3 laden) under both dry and wet conditions. Since the GVW measurements did not change with roller surface condition, the maximum measured BFs were compared to assess the effect of the test surface condition on PBBT results. Since the maximum measured BF is dependent on the frictional force (F) between the test surface and the tire[19], for the same loading conditions (N), the apparent available BF will be affected in proportion to the COF (μ) between the test surface and the tire. As such, a wet test surface (i.e., lower COF) may be expected to show some decrease in BF. If this decrease is on the order of 10 percent or less, then the effect of test surface is not considered significant because the expected real life variations are ± 5% (see Table 5 in Section 3.1).

Photographic documentation of the "wet" tests is presented in Appendix A. Brake forces obtained under dry and wet conditions are plotted in Figure 18 for each PBBT, in both the (a) unladen and (b) 2/3 laden truck configurations. The error bars represent the minimum and the maximum measured BF_{TOT} of the three replicate measurements.

The B&G BTT was affected by less than one percent by the wet conditions. The total BFs measured by the BTT for the unladen vehicle was the highest of any of the PBBTs. This was the result of the principle of operation of the BTT, since the BF is not limited by slip of the tire against the test surface.

The results of the RAI portable RD and the HEI experimental RD (RD2) were also minimally affected by the wet surface, for both the empty and the 2/3 laden trucks, with variations on the order of 2.5 percent or less.

[19] According to $F=\mu N$, for a given load (N), the frictional force (F) is proportional to the coefficient of friction (μ).

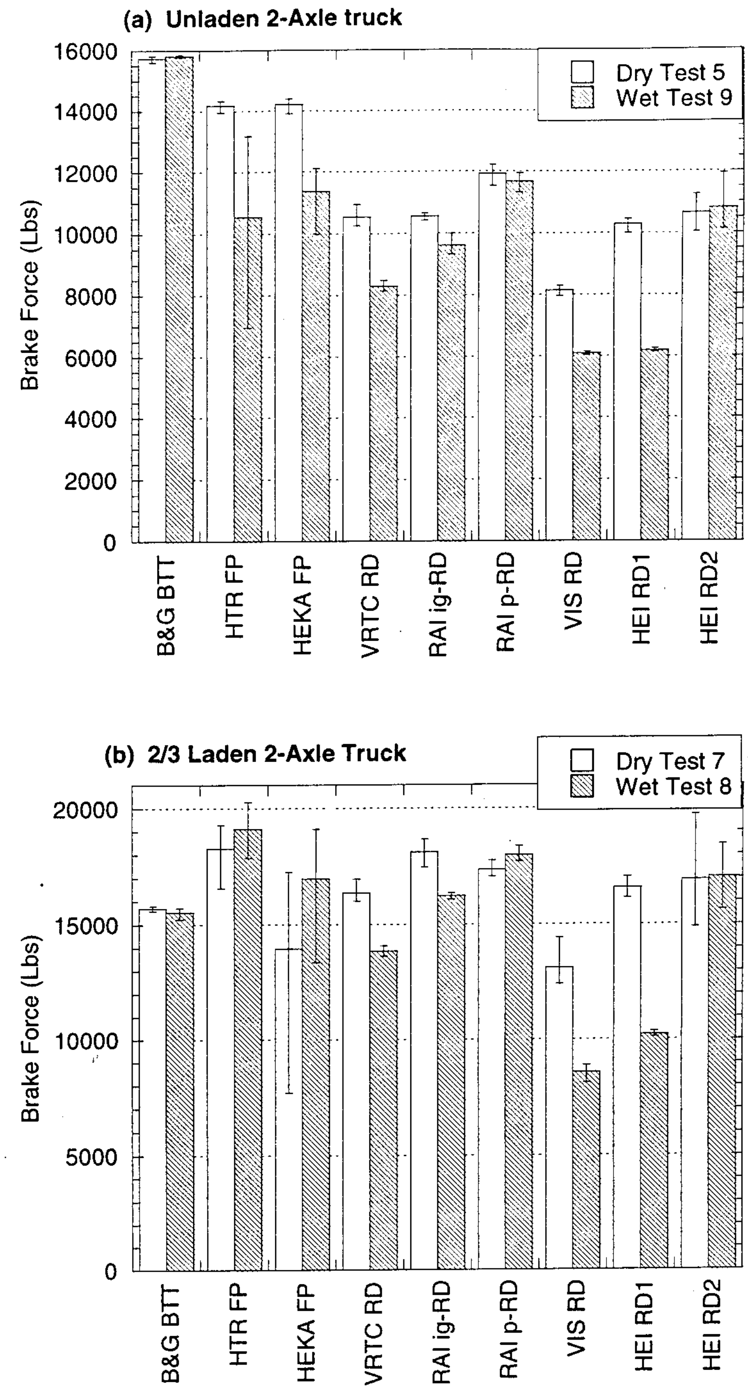


Figure 18. Total Brake Forces (Average of 3 tests) as a function of dry and wet PBBT test surface for (a) unladen and (b) 2/3 laden 2-axle truck with fully adjusted and strong brakes. The error bars represent the minimum and the maximum measured BF_{TOT}.

The RAI in-ground RD showed a moderate effect of wet versus dry conditions, with up to a 10 percent reduction in maximum measured brake force.

A clear effect on the maximum measured brake force was observed for several PBBTs. The reduction of reported BF was up to 21%, 35%, and 40% for the VRTC RD, the VIS RD and the HEI (standard roller surface) RD, respectively. This effect is considered unacceptable, and recommendations were made to the manufacturers at the time of the round robin.

For both the Hunter and the HEKA FP brake testers, the effect of a wet surface on the results was inconsistent and, in some cases, the data were scattered. For both FP testers, the BFs measured in the wet tests showed an approximate 20% decrease compared to the dry test for the unladen vehicle. Conversely, from dry to wet, for the 2/3 laden vehicle, BFs measured by the Hunter and the HEKA FPs increased by 4% and 21%, respectively.

The current proposed specifications require a COF of 0.6 in the dry condition only. Since a clear effect on the PBBT-reported BFs was observed in the wet versus dry tests for some of the PBBTs, possible inclusion in the specifications of a minimum wet COF requirements should be considered.

4. Conclusions

The round robin was the first of its kind and constituted a significant milestone in the FMCSA's program to explore the use of PBBTs as a tool for law enforcement.

- Under most test conditions, the accuracy and repeatability of most of the participating PBBTs, regardless of the principle of operation, were acceptable for meeting the functional specifications, and therefore for use in law enforcement.
- The Hunter FP and the RAI in-ground RD showed the most immediate potential for use in law enforcement on weakly braked vehicles based on accuracy, repeatability of results, and when compared to measured vehicle decelerations in a 32.2 km/hr (20 mph) road stop.
- Where needed, factors or modifications to obtain acceptable PBBT performance for use in enforcement fell into one of two categories:
    1) Modifications consistent with the PBBT functional specifications that had been developed for eligibility for funding through the Motor Carrier Safety Assistance Program (MCSAP).
    2) Procedural modifications to improve the applicability of the PBBT results relative to on-road stopping results.
- Weight measurements were found to be affected by specific characteristics of the vehicles, or by the elevation and ramp configurations of the portable PBBTs.
- Consideration should be given to using additional criteria for judging brake effectiveness in cases where weights are unavailable or cannot be measured in a representative manner due to vehicle configuration. For example, when wheel lock up occurs, if the traction between the tire and the test surface is at least equal to 0.6 (as required in the PBBT functional specifications), the braking capability of the wheel would be considered adequate, regardless of the weight measurements. When the brakes are too weak to lock up the wheels, the weight measurements are critical, and alternative procedures and/or criteria would be required.
- The PBBT-measured BFs were in good agreement with the BFs measured with the torque wheel. Deviations were attributed to one of two causes:

  - The algorithm used by PBBT manufacturers to acquire and manipulate the raw data and report a single BF value.
  - In the case of the flat plate testers, the effect of dynamic loading.

- The roller dynamometers, as a class, reported slightly higher BFs for weakly-braked vehicles on dry pavement than the corresponding reference values derived from road stops. It was suspected that this was a result of either geometry of the wheel/roller contact patch or changes in brake torque output as a function of speed: the portable RDs operate at less than 2 km/hr (1.2 mph), while the road stops were performed at 32.2 km/hr (20 mph). Additional data are required in this area.

- Finally, the following recommendations were made to PBBT manufacturers to assist them in meeting the functional specifications:
  - Alter the test surface to meet minimum COF requirements.
  - Standardize test protocols, including data analysis and reporting procedures.
  - Develop appropriate calibration procedures.

- Some PBBTs showed that their BF results were unaffected by the condition of the test surfaces. Although the COF in wet conditions is not part of the proposed PBBT functional specifications at this time, PBBTs for which BF measurements were affected by the test surface conditions should address this problem.

5. Remaining Challenges

Remaining challenges for use of PBBTs in law enforcement include:

- Establishing appropriate test termination, data reduction and reporting algorithms for the PBBTs such that consistent results are obtained from machine to machine for a given vehicle.
- Developing standard test procedures for each type of PBBT.
- Developing training materials for inspectors using PBBTs for enforcement, including calibration and operating protocols.
- Establishing a list of special considerations for certain vehicle configurations (e.g. axle load or BF measurement applicability limitations). When applicable, modified testing procedures should be implemented.
- Developing regulations for individual brake pass/fail evaluation that are independent of WL, when WL measurements are either unavailable or significantly altered by the vehicle configuration.
- Establishing a policy or procedure for compliance testing, including documentation of calibration requirements necessary to meet potential legal challenges.

For a fundamental understanding of the relationship between PBBT testing and vehicle on-road performance, the following challenges are posed:

- Characterizing and understanding the sensitivity of brake force to velocity, static versus dynamic testing, wheel contact geometry or COF limitations as they are needed to establish the correlation between PBBT measurements and 32.2 km/hr (20 mph) road stops.

APPENDIX A

PHOTOGRAPHS OF THE PBBT ROUND ROBIN

VRTC Testing Grounds

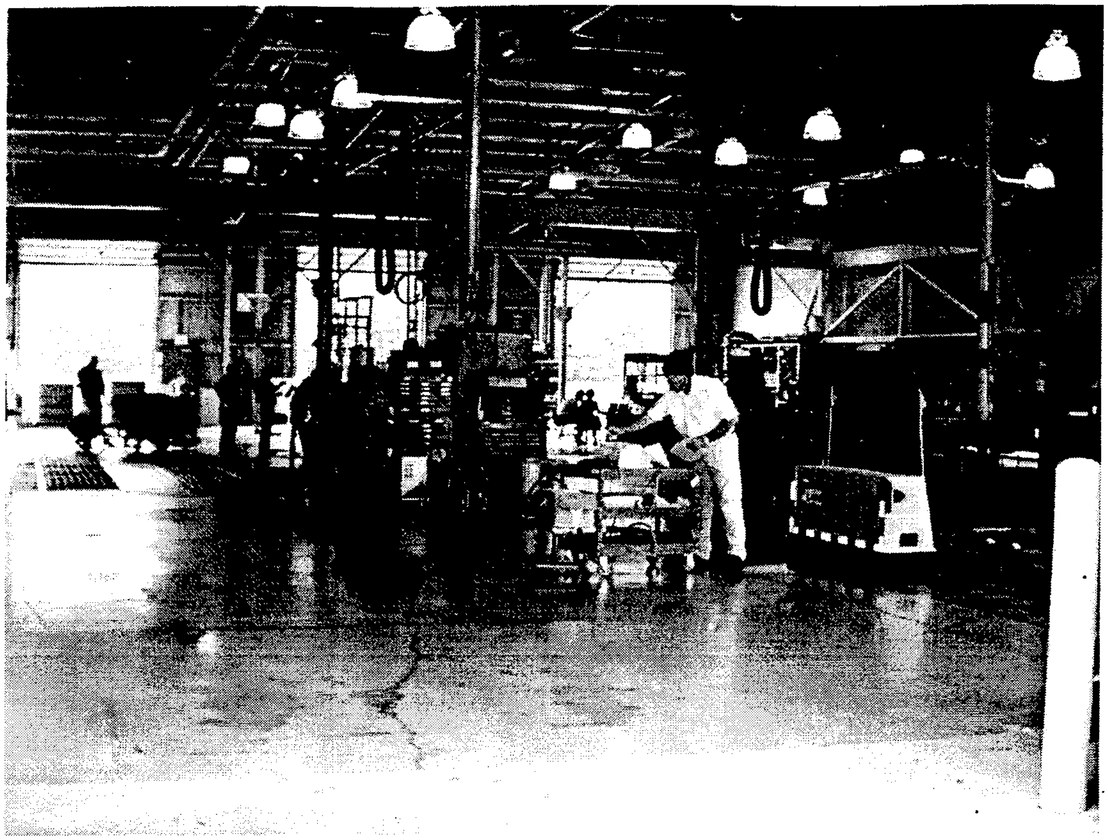


Figure A1. VRTC bay where testing was conducted.

Test Vehicles

Figure A2. Test vehicles: 3-S2 tractor trailer combination (top) and 2-axle straight truck (middle), equipped with a fifth wheel. Loading and unloading with concrete blocks was facilitated by the use of flatbed trailers (bottom).

Portable Certified Scales

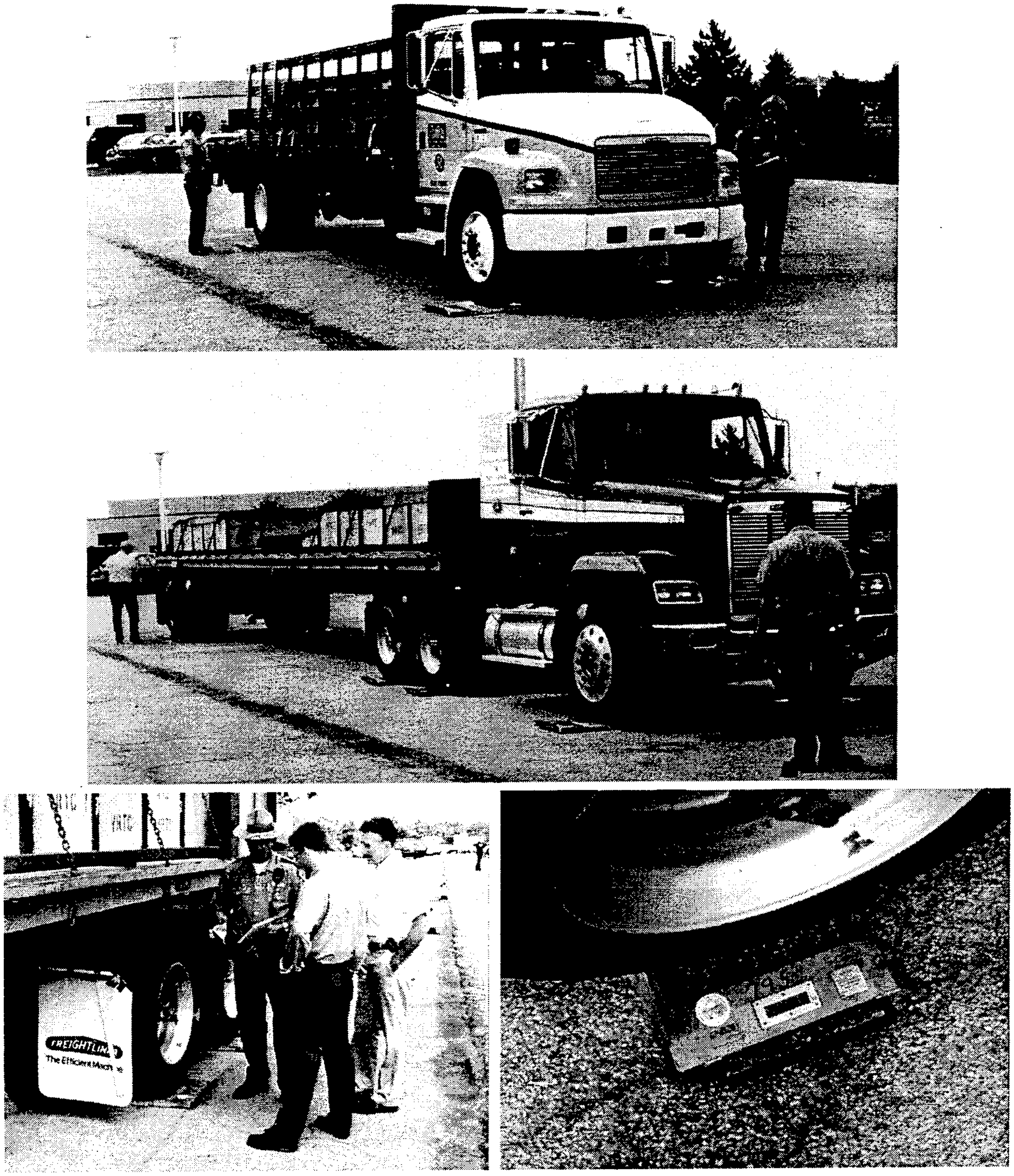


Figure A3. Axle and vehicle weights were measured using in-ground and portable certified scales. The use of portable scales increases accuracy as the vehicle is level with respect to the ground and all wheels are weighted simultaneously.

Instrumented Torque Wheel

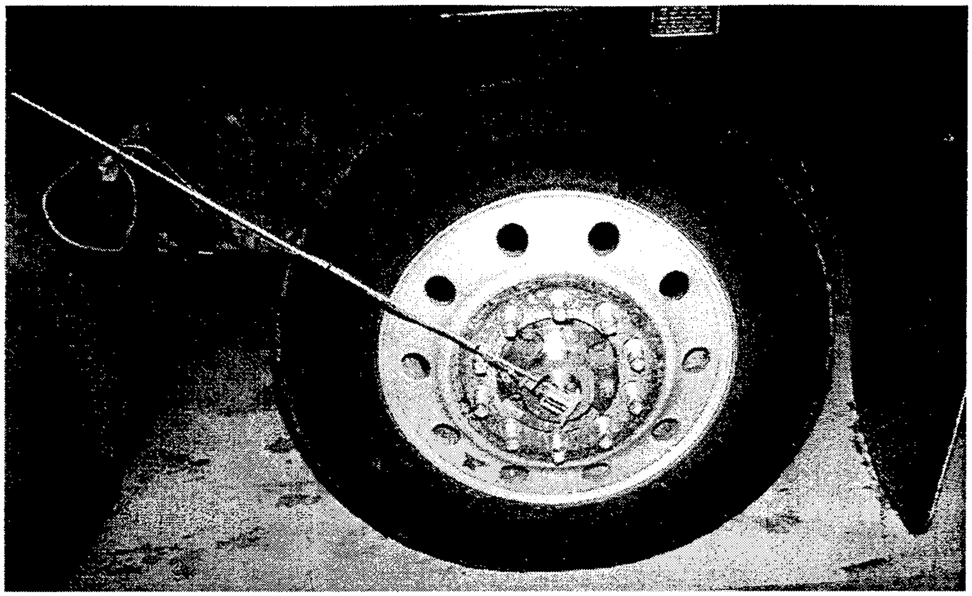


Figure A4. Wheel 5 of the 3-S2 was fitted with an instrumented torque wheel.

B&G Breakaway Torque Tester

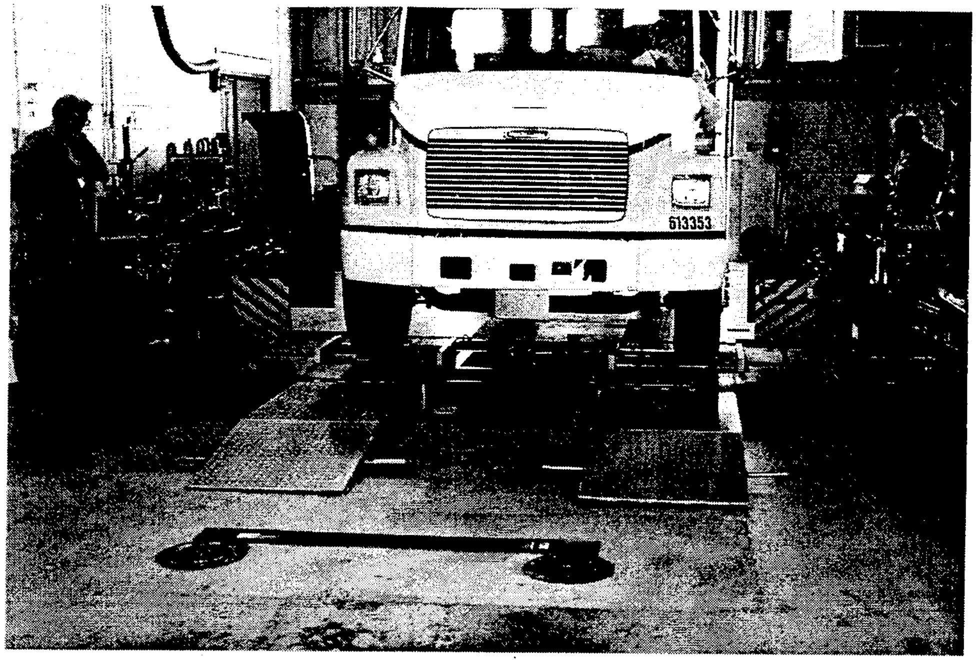


Figure A5. The B&G breakaway torque tester, BTT: general view.

B&G Breakaway Torque Tester (continued)

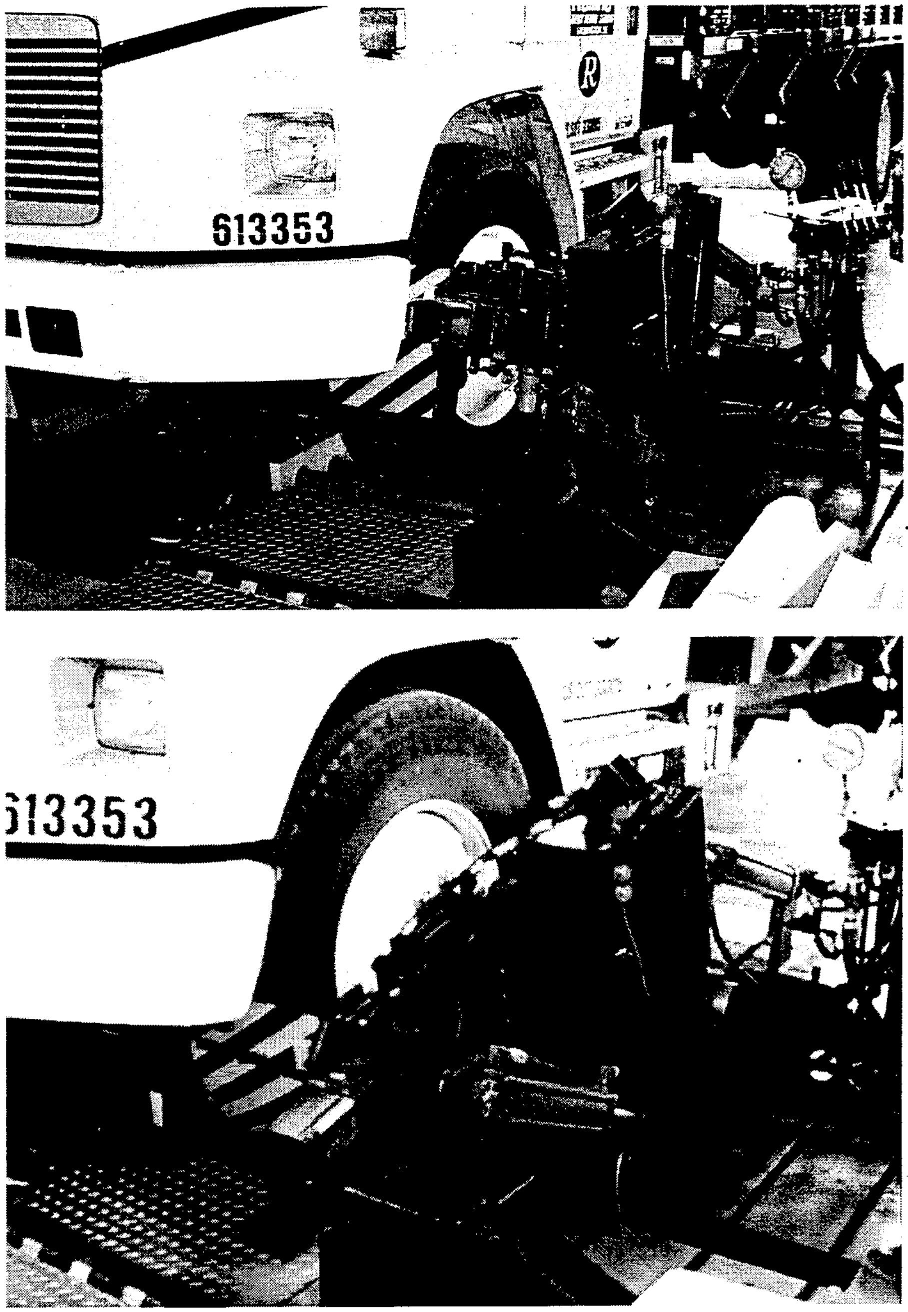


Figure A6. Principle of operation of the B&G breakaway torque tester. The friction pads (yellow and black striped) grab the tire (top) and, while the brakes are applied, the machine determines the force required to turn the wheel (bottom).

Hunter Flat Plates

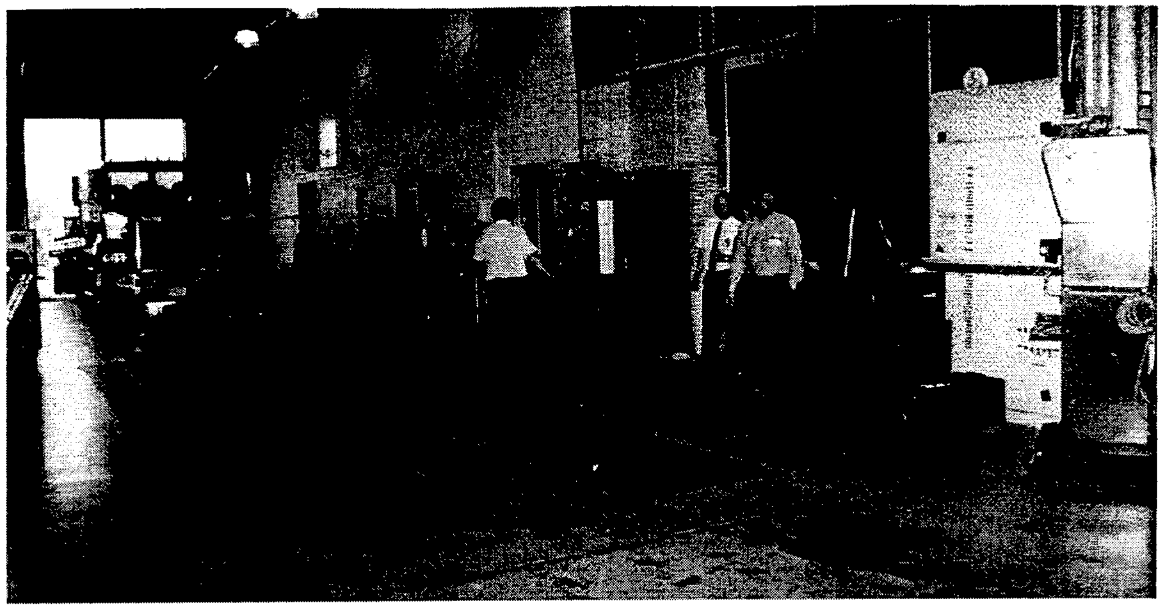
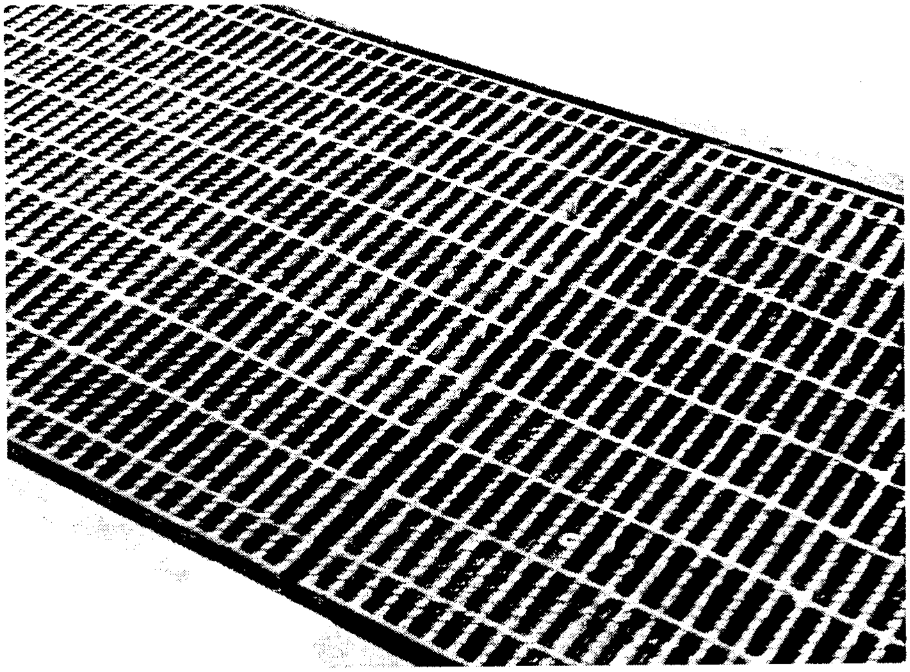


Figure A7. Hunter flat plate brake tester: overview (top) showing the two parallel sets of plates, installed in the testing ground permanently. The test vehicle stops on the plates (bottom) and several axles can be tested in one test.



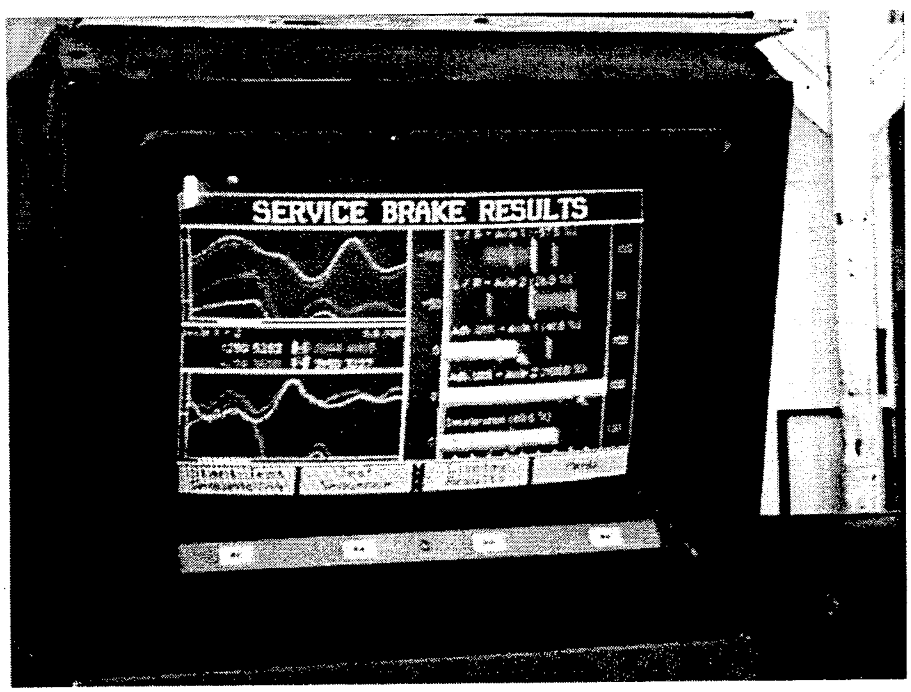


Figure A8. Hunter flat plate brake tester: test surface (top) and display of results (bottom).

HEKA Flat Plates

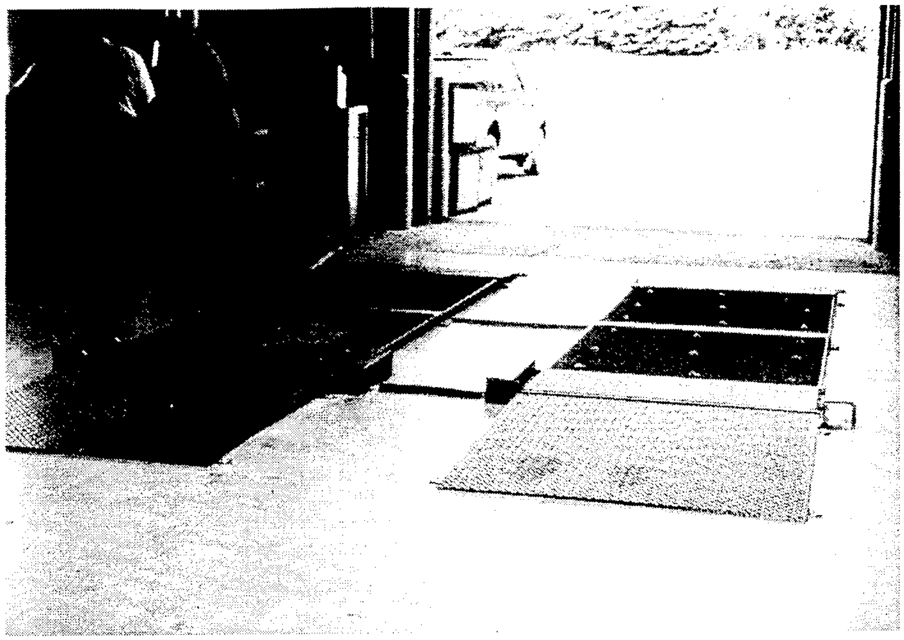


Figure A9. HEKA flat plate brake tester: overview (top) and display of results (bottom). The HEKA plates are short and a limited number of axles can be tested at a time.

HEKA Flat Plates (continued)

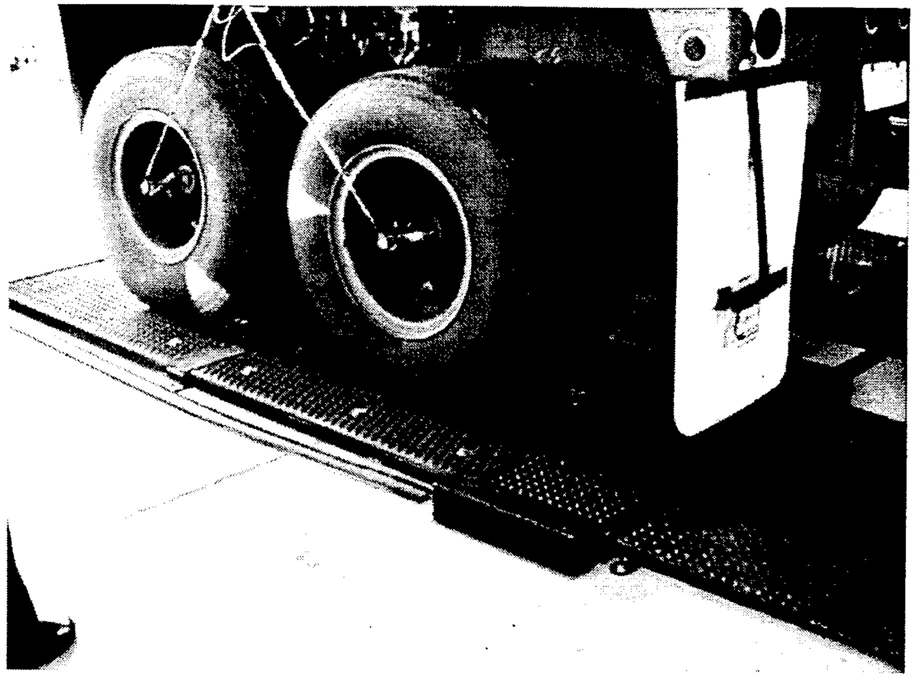


Figure A10. The HEKA flat plate brake tester is a portable device where the test surface is nearly leveled with the ground (top). Detail of the test surface (bottom).

VRTC In-Ground Roller Dynamometer

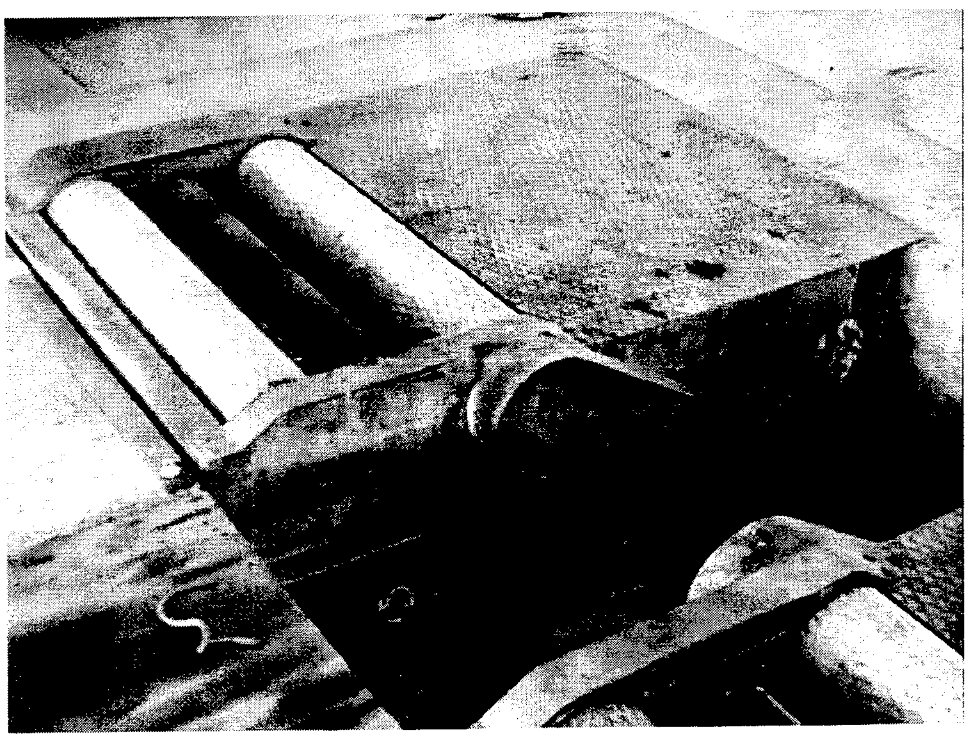
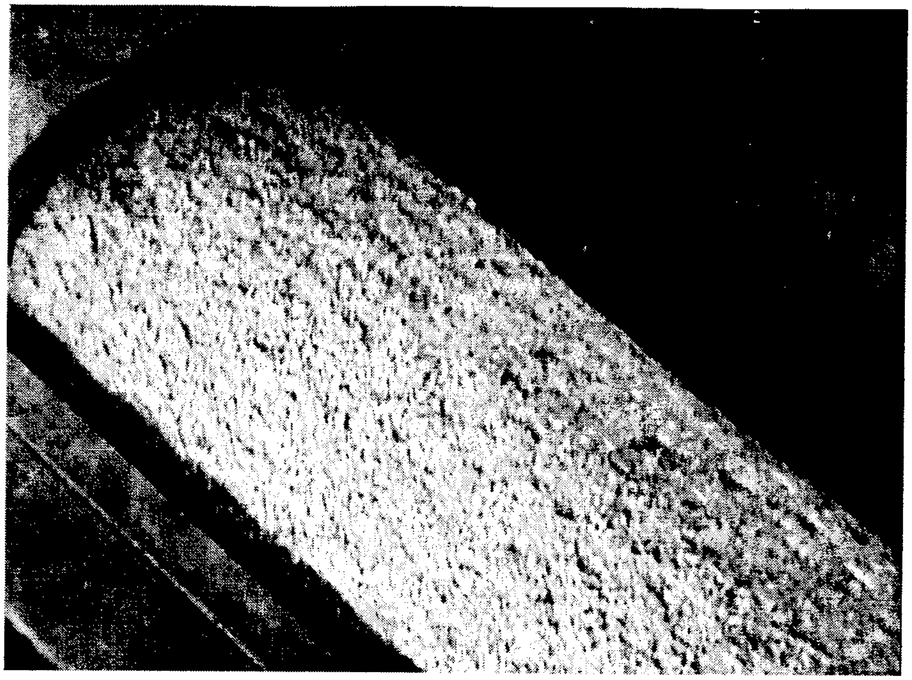


Figure A11. VRTC/BM in-ground roller dynamometer: overview (top) and detail (bottom) showing the sets of two driving rollers as well as the third smaller roller which monitors the wheel speed and the presence of a vehicle axle.



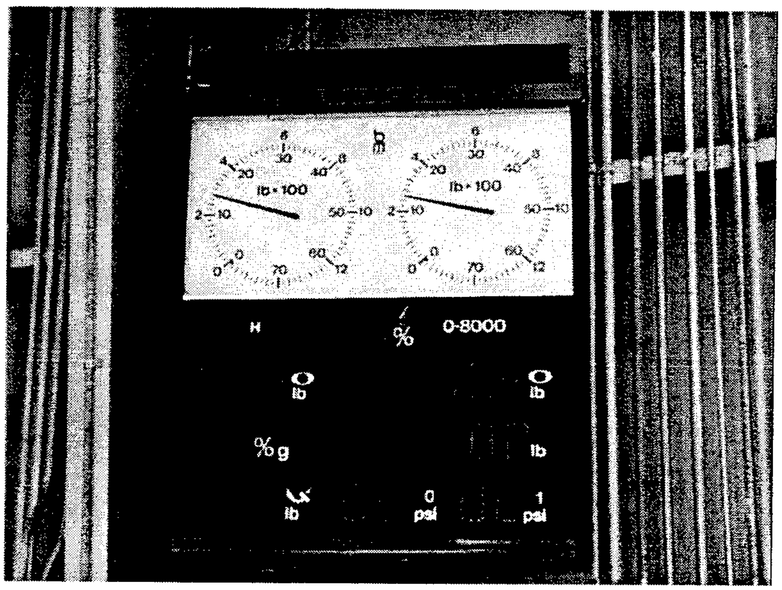
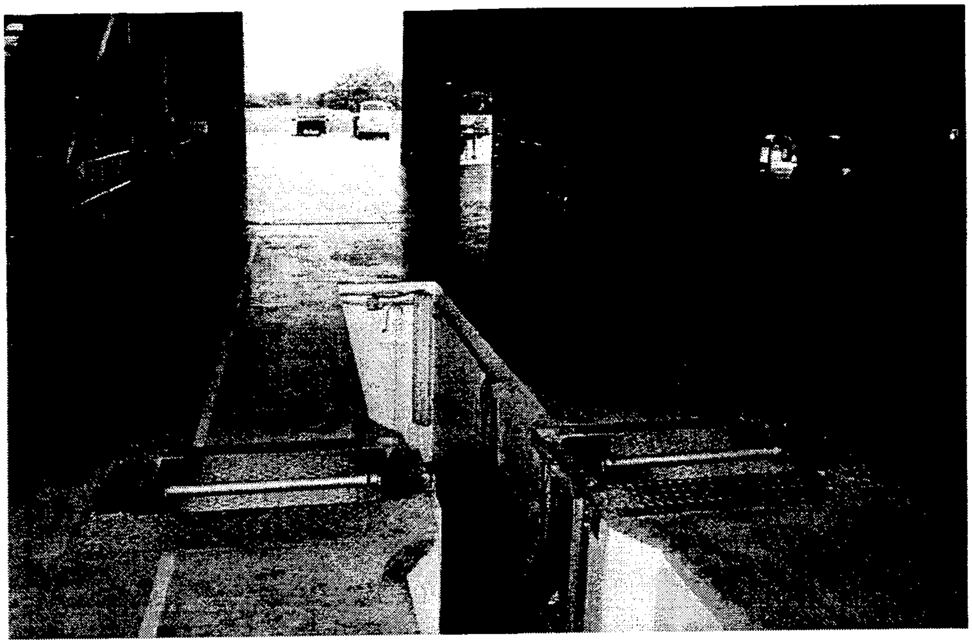


Figure A12. VRTC/BM in ground roller dynamometer: test surface (top) and display of measurements for driver and operator (bottom).

RAI In-Ground Roller Dynamometer



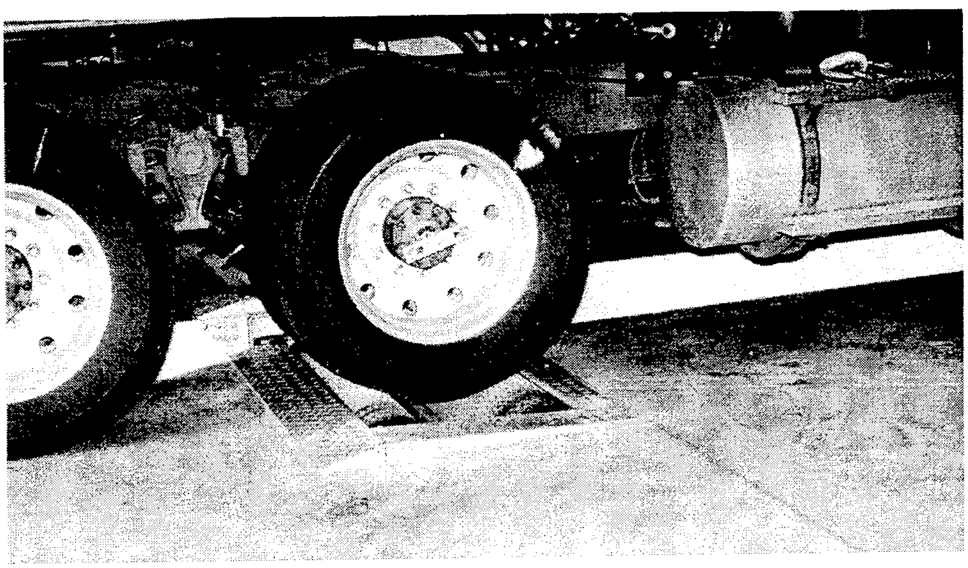


Figure A13. Radlinski and Associates, Inc. (RAI)/BM in-ground roller dynamometer: overview (top) and detail (bottom) showing that the back roller is slightly elevated with respect to the front roller.

RAI In-Ground Roller Dynamometer (continued)

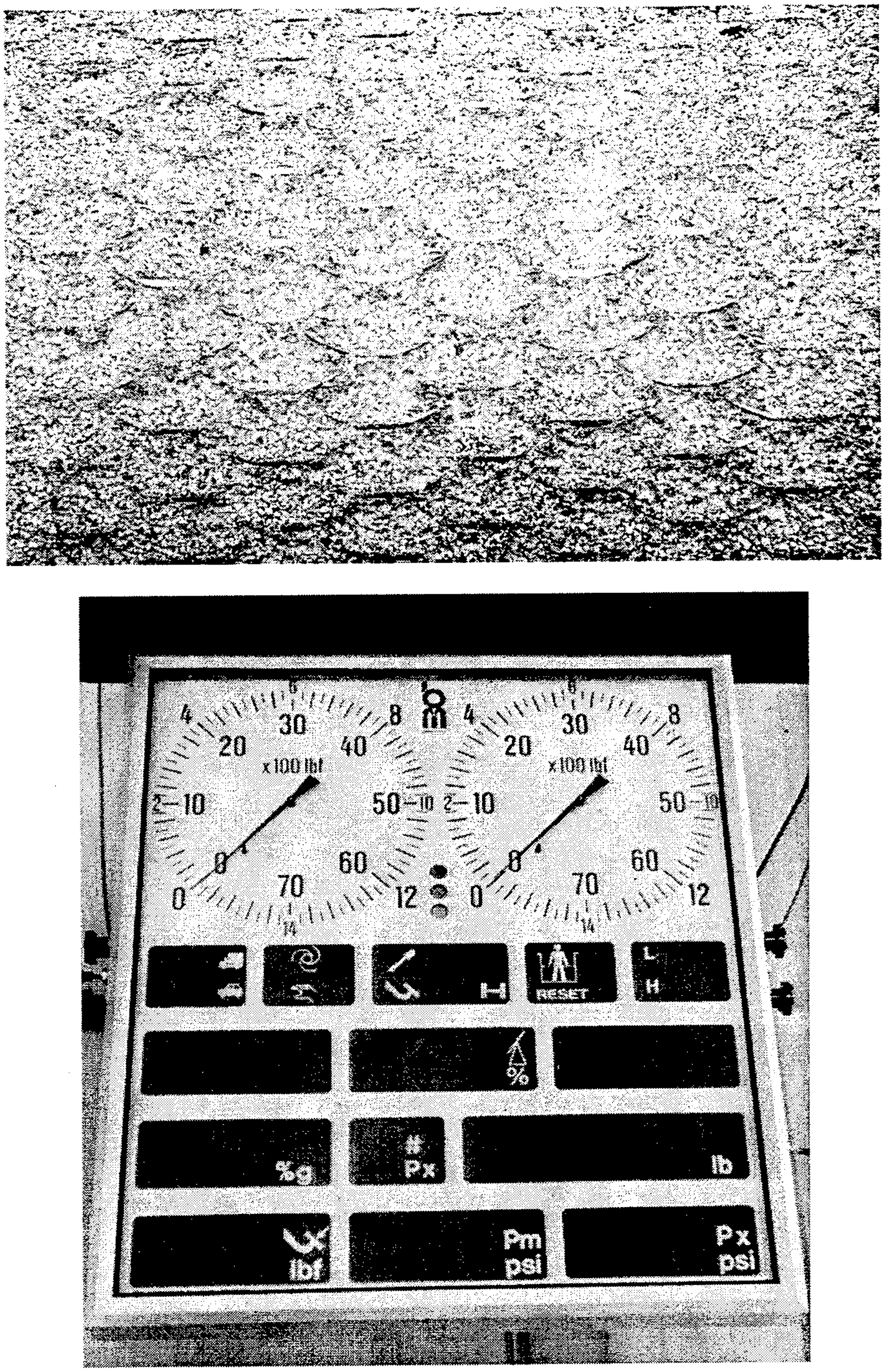


Figure A14. Radlinski and Associates, Inc. (RAI)/BM in ground roller dynamometer: test surface (top) and display panel (bottom).

RAI Portable Roller Dynamometer

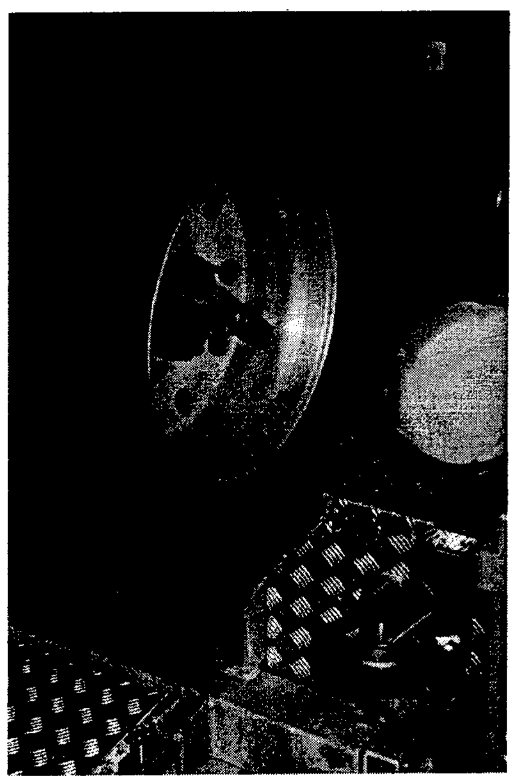
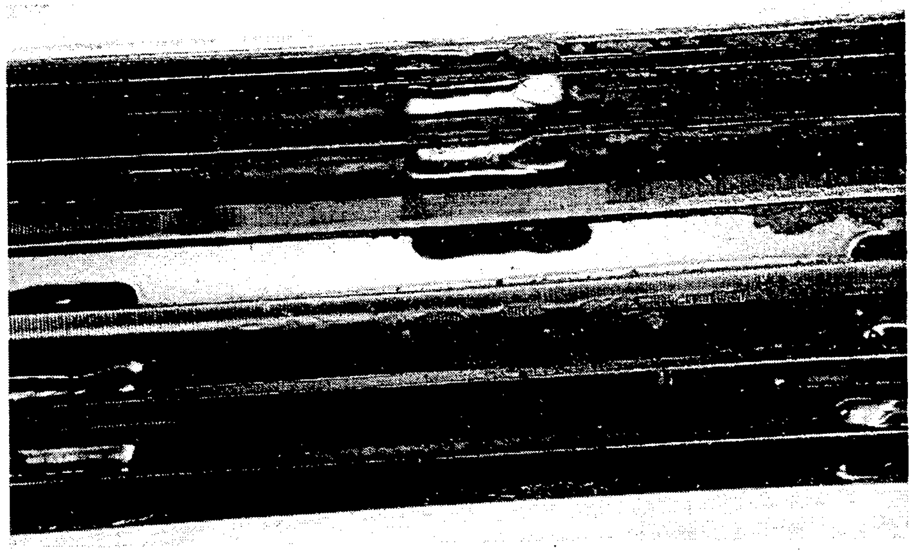


Figure A15. Radlinski and Associates, Inc. (RAI)/BM portable roller dynamometer: side view while testing the 3-S2 steer axle (top) and detail (bottom) showing the positioning of the wheel on the right side roller.

RAI Portable Roller Dynamometer (continued)



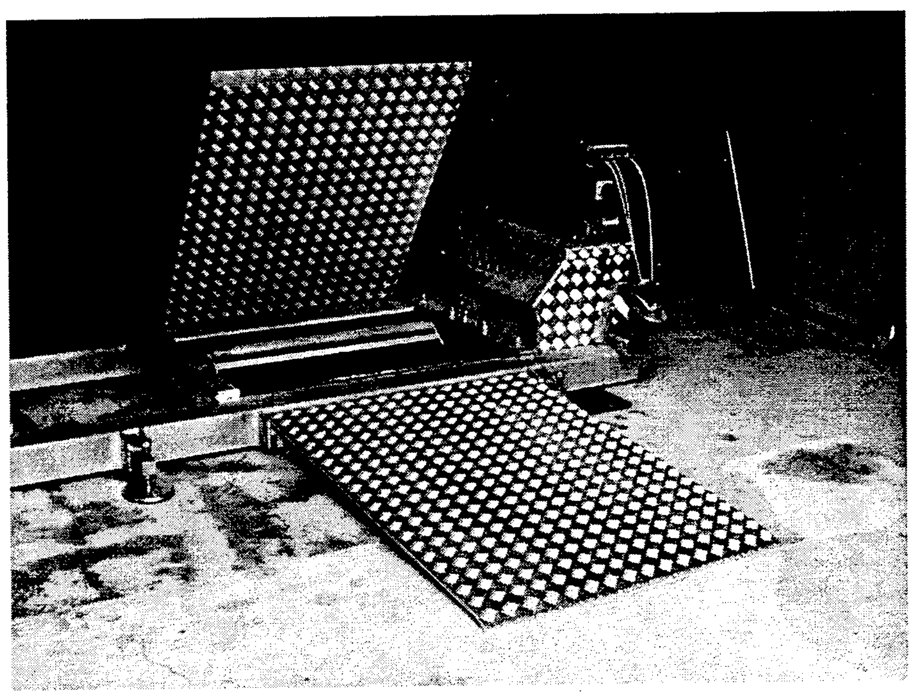


Figure A16. Radlinski and Associates, Inc. (RAI)/BM portable roller dynamometer: test surface (top) and brake tester frame (bottom).

VIS Portable Roller Dynanometer

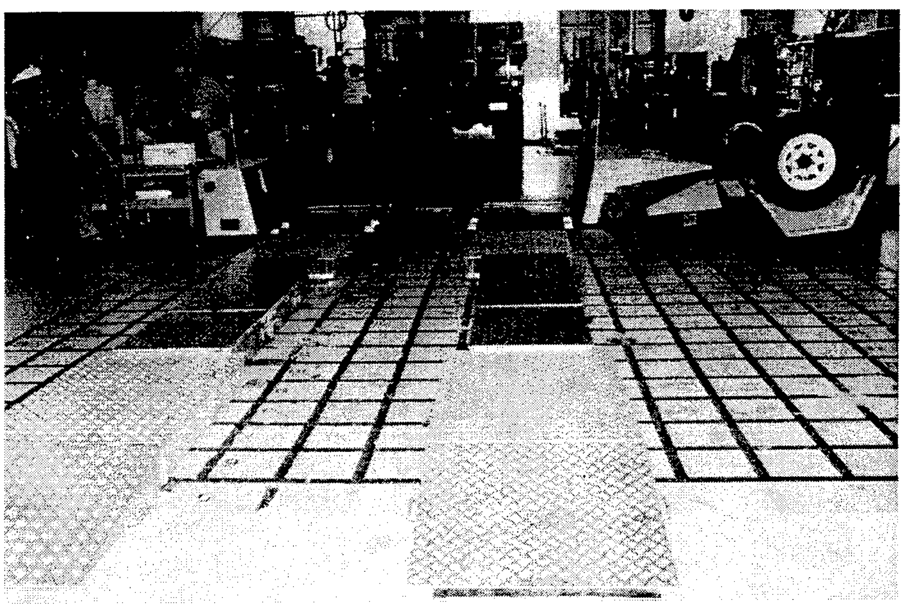
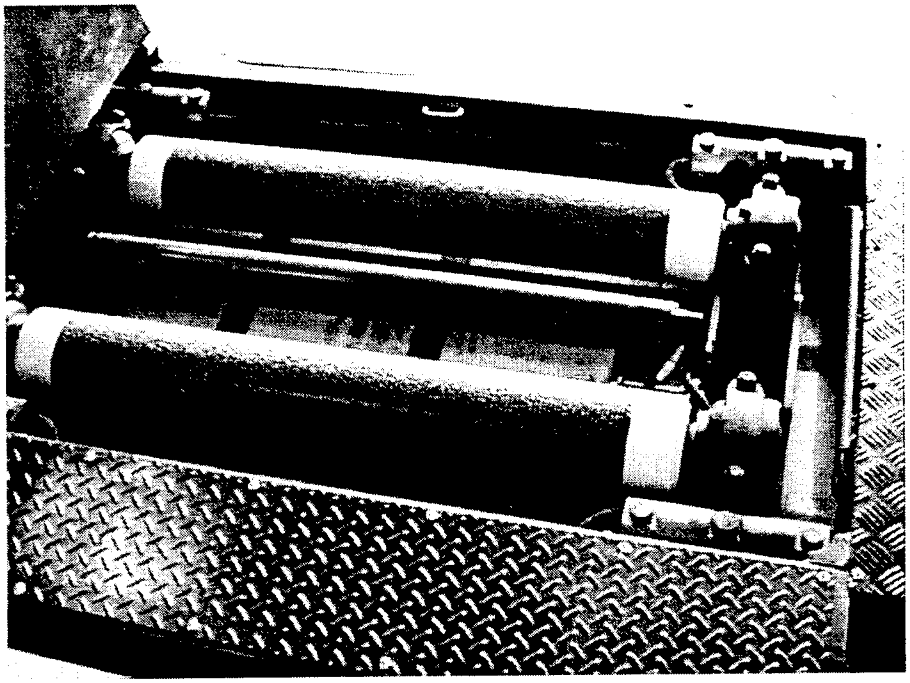


Figure A17.Vehicle Inspection Systems (VIS) portable roller dynamometer: showing the PBBT testing the steer axle of the 3-S2 vehicle (top) and showing the implementation of long ramps to reduce the problems associated with the elevation of the tested axle with respect to the axles on the ground (bottom).

VIS Portable Roller Dynanometer (continued)



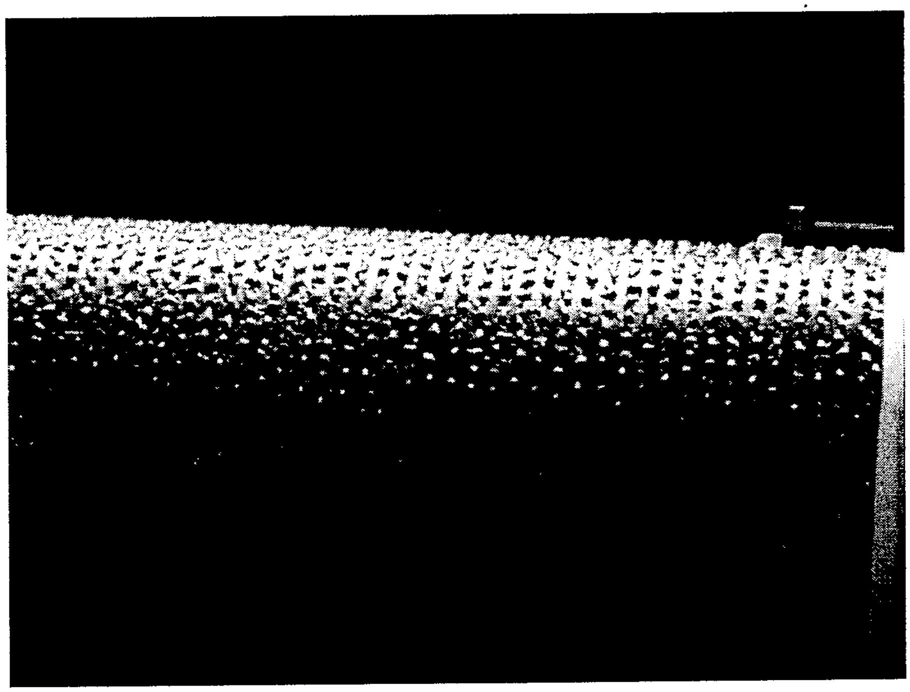
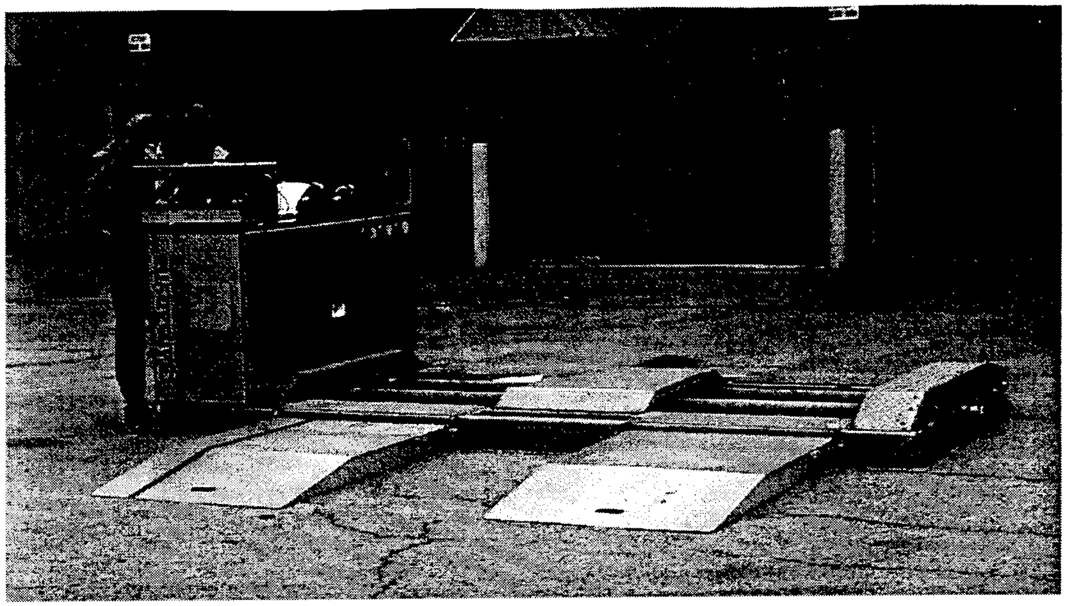


Figure A18. Vehicle Inspection Systems (VIS) portable roller dynamometer showing the two drive rollers and the smaller speed sensing and vehicle position roller (top) and detail of the test surface (bottom).

HEI Portable Roller Dynanometers



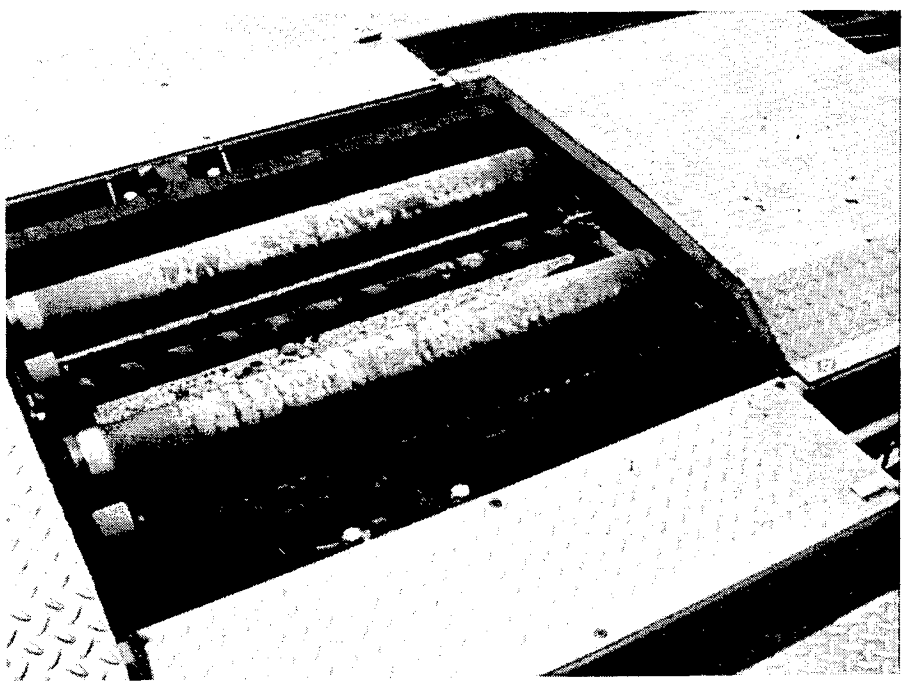
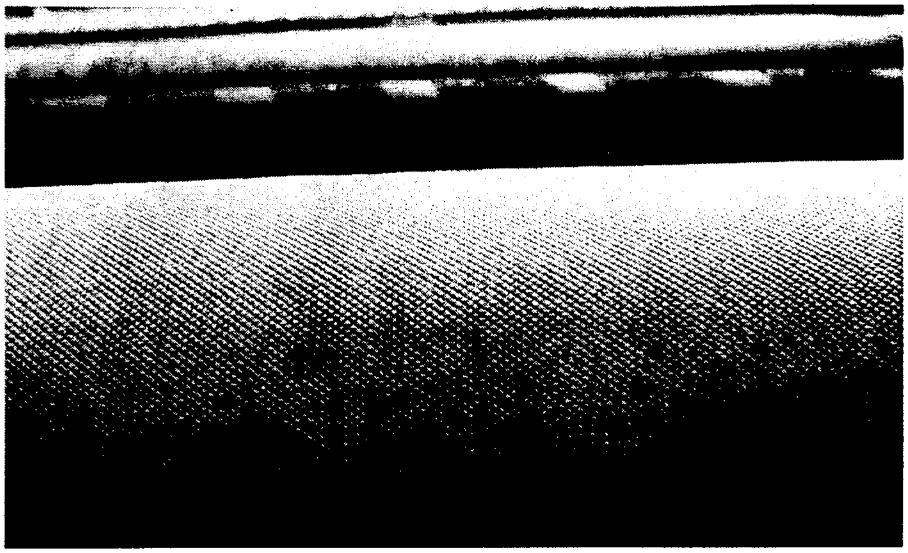


Figure A19. Hicklin Engineering, Inc. (HEI) portable roller dynamometer: overview (top) showing the ramps, the rollers and the operating console. The bottom picture details the two drive rollers and the smaller speed and vehicle position sensing roller on one side of the tester.



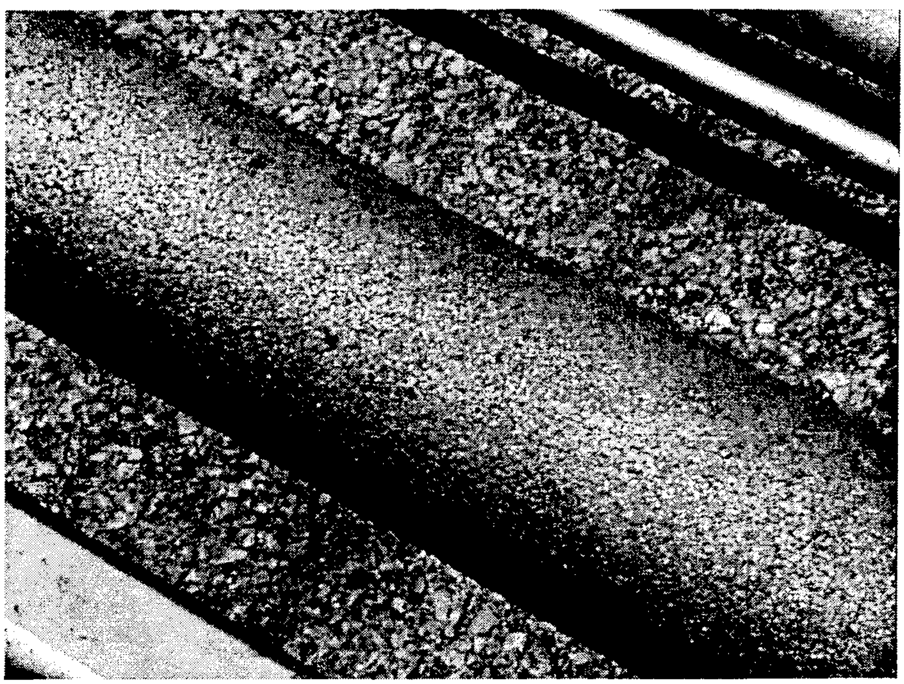


Figure A20. Hicklin Engineering, Inc. (HEI) portable roller dynamometer: original roller surface finish (top) and experimental high coefficient of friction (bottom) test surface.

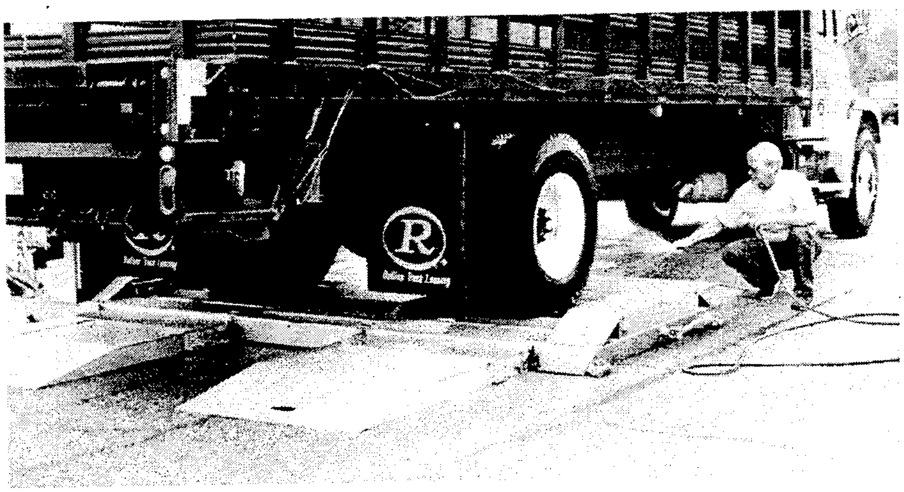
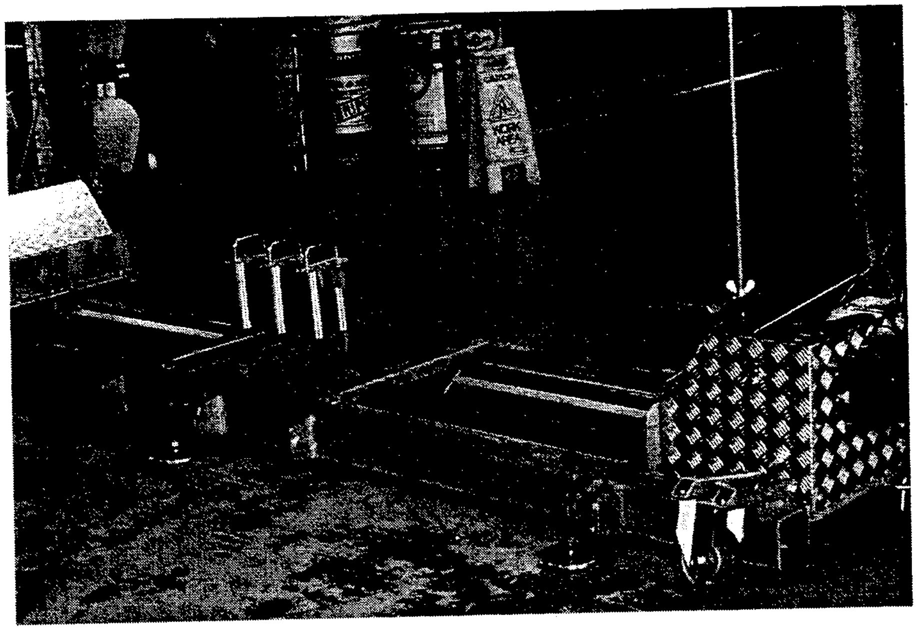


Figure A21. The effect of wetting the test surface on the maximum brake force measurements.

Calibrations



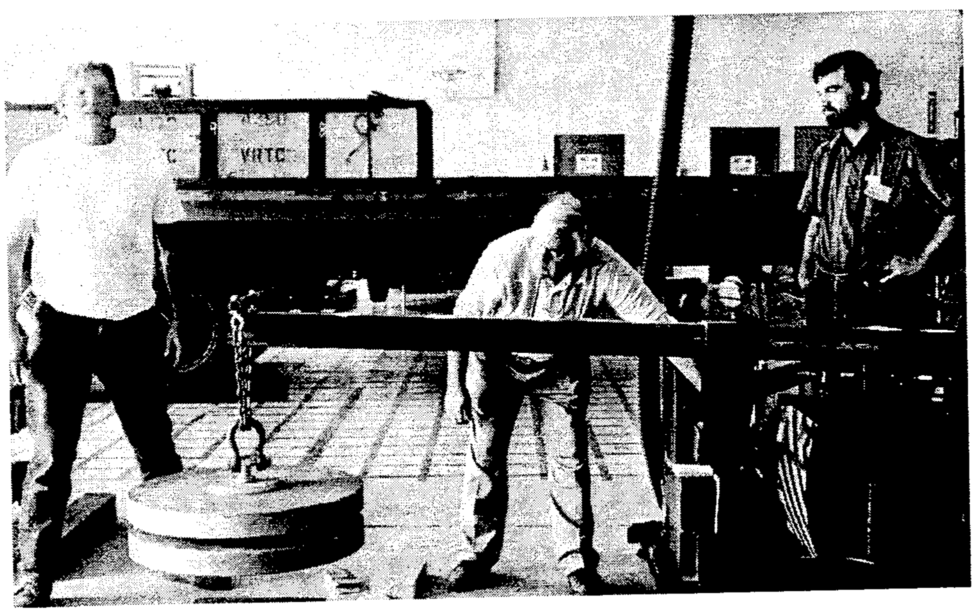


Figure A22. Brake force calibration of the Radlinski and Associates, Inc. (RAI)/BM portable roller dynamometer and the B&G portable breakaway torque tester.

Calibrations (continued)

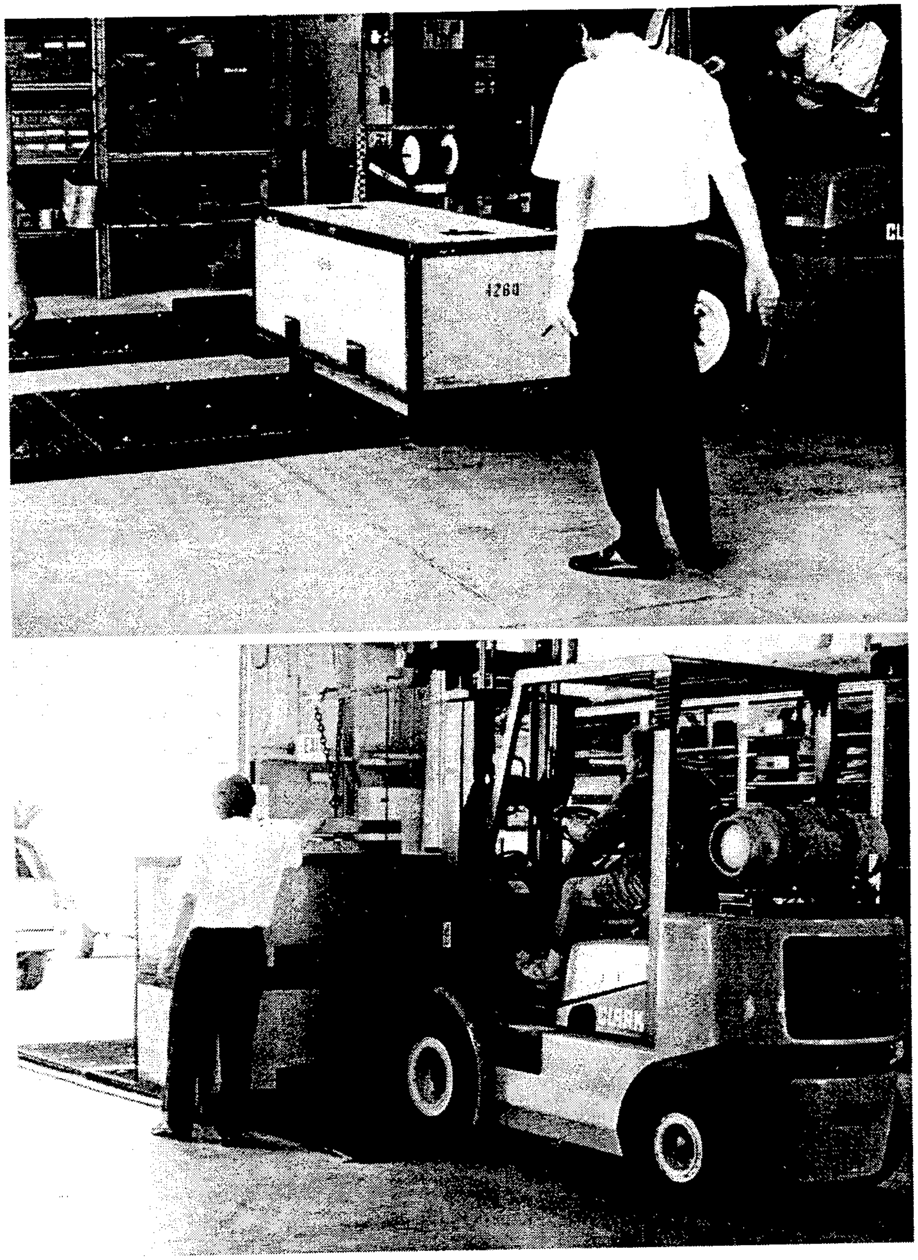


Figure 23. Weight calibration of the HEKA flat plate brake tester: Concrete blocks are stacked on each side of the tester, allowing independent calibration of the weight measurements.

Calibrations (continued)

Figure 24. Weight calibration of the Radlinski and Associates, Inc. (RAI)/BM portable roller dynamometer.

APPENDIX B

REFERENCE DATA:

ROAD STOP DATA

TORQUE WHEEL DATA

VEHICLE WEIGHTS

Stopping Distance and Deceleration

Computation of Stopping Distance

Stopping distances were obtained in two ways: 1) from the fifth wheel, and 2) from the Labeco instrumentation. In the first method, the vehicle instrumentation directly reported the distance traveled from the time the brake pedal was first depressed to the time the vehicle came to rest. While this definition is commonly used, the variability of the resulting stopping distances is strongly dependent upon the time required for the vehicle to begin decelerating. The second method relied on the integration of the velocity-versus-time profile (taken from the fifth-wheel data), when a decrease in the velocity was first observed. The second method provided more consistent results between vehicle configurations and thus was used in this work.

We attempted to obtain stopping from an initial velocity of 20 mph. Where the actual velocity slightly differed from 20 mph, a normalized stopping distance was computed using the following formula:

$$s_{20} = s\left(\frac{(v_{20})^2}{v^2}\right),$$

where s_{20} is the stopping distance from 20 mph (ft), s is the measured stopping distance (ft), v_{20} is equal to 29.33 ft/s (20 mph), and v is the actual initial velocity (ft/s). This formula is valid only for corrections under 2 mph.

Computation of Vehicle Deceleration

The deceleration from the 20-mph stops could be obtained in one of three ways: (1) indirectly from the fifth-wheel, (2) indirectly from the Labeco instrumentation, or (3) directly from the on-board accelerometer. Insufficient data were collected by the accelerometer to be reported herein. The deceleration was primarily computed from the fifth wheel data using regression analysis of the linear portion (Region B) of the velocity-versus-time profile (Figure B1).

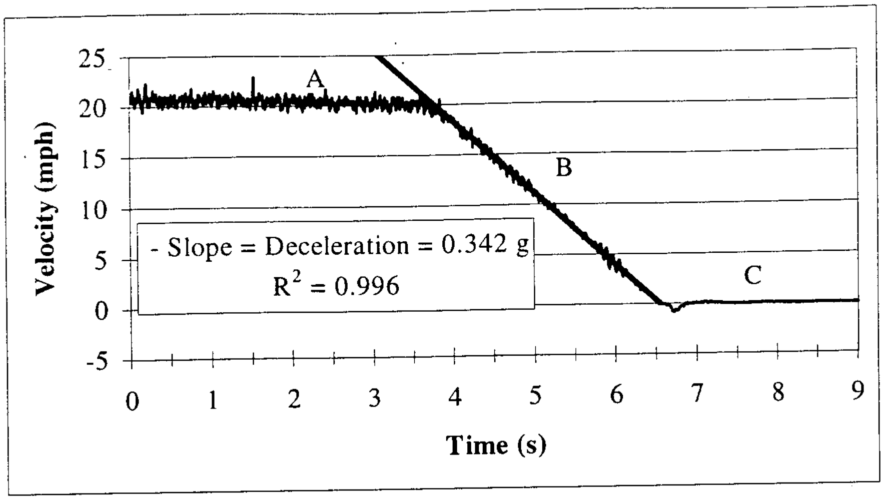


Figure B1. Vehicle velocity data as a function of time during a 20-mph stop (fifth wheel data). The trace in Region B is used for regression analysis and computation of the assumed constant deceleration of the vehicle.

When fifth-wheel data was not available, the deceleration was back-calculated from the Labeco data and assuming that the deceleration profile was similar to the profile shown in Figure B2. The Labeco system is triggered by a sensor placed on the foot brake pedal of the vehicle. As soon as the driver's foot touches the brake pedal, the distance traveled is recorded by the Labeco instrumentation even though, for a brief period of time, no brake force is developed and the vehicle initial velocity remains unchanged. The distance calculated from the recorded data was estimated to be approximately 3 percent lower than that measured by the Labeco. In Figure B2, region I (of duration T_0) refers to the portion of the overall stop for which no change in velocity is seen even though the driver's foot is in contact with the brake pedal. Region II (of duration T_1) corresponds to the portion of the overall stop for which the vehicle starts to decelerate but full brake forces (assumed equivalent to maximum deceleration) are not yet achieved. A linear increase is assumed. Region III refers to the portion of the overall stop for which brake forces are fully applied and assumed constant until the complete immobilization of the vehicle. No in-stop fade of brake forces (and therefore deceleration) is assumed since it was not observed in any of the on-road 20-mph stops. The assessment of the times T_0 and T_1 is critical. Based on observations of the available data recorded by the fifth-wheel for the two-axle truck, these times were both estimated to be equal to 0.125 second.

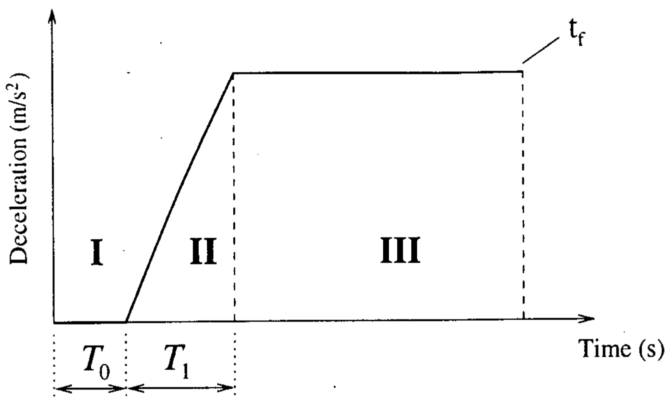


Figure B2. Assumed profile of the deceleration as a function of time used for computation of stopping distance.

In a similar manner, using T_0 and T_1 equal to 0.125 second, the stopping distance of the trucks can be obtained from the ratio BF_{TOT}/GVW measured with the PBBTs. In this case, the deceleration during Stage III is taken as $\frac{BF_{tot}}{GVW} \times g$, where g is the acceleration due to gravity (9.8 m/s^2 or 32.2 ft/s^2). This deceleration during Stage III is ultimately the quantity that will be estimated and used in a pictorial display software developed by Battelle to predict vehicle stopping distances from PBBT results. The stopping distances and decelerations (where available) for the nine vehicle configurations are presented in Table B1.

20 mph Road Stop Reference Data

Table B1. Stopping distances and average decelerations during 20 mph on-road stops.

Conditions			Test #	Number of Rep.	From Labeco: Average Stopping Distance normalized to 20 mph (ft)			Calculated from fifth wheel data: Average Stopping Distance normalized to 20 mph (ft)			Calculated from fifth wheel data: Average Deceleration (g)		
					Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Part 1: Vehicles with Weak Brake Dry Conditions													
3-S2	Laden		1	9	43.0	40.7	45.0	36.8	33.9	43.2	0.39	0.38	0.41
	Unladen		3	3[a]	50.4	44.7	60.9	45.2	38.7	55.8	0.25	0.25	0.25
				6[a]	45.4	44.7	46.4	40.6	38.7	42.6	0.36	0.34	0.37
2-Axle	Laden		2	3	-----	-----	-----	38.5	34.9	41.2	0.36	0.34	0.38
	Unladen		4	2	-----	-----	-----	31.4	31.0	31.7	0.42	0.41	0.43
				3	41.5	40.9	42.0	39.7[c]	-----	-----	0.40[c]	-----	-----
Part 2: 2-axle vehicle Fully Adjusted, Strong Brakes													
2-Axle	Unladen	Dry	5	3	30.3	27.7	31.8	28.9[c]	-----	-----	0.58[c]	-----	-----
	1/3 Laden	Dry	6	3	31.2	29.6	32.0	29.8[c]	-----	-----	0.56[c]	-----	-----
	2/3 Laden	Dry	7	6[b]	27.8	26.3	28.3	26.6	24.3	27.9	0.63	0.61	0.65
	2/3 Laden	Wet	8	3	28.8	28.5	29.3	28.2	27.3	28.8	0.60	0.59	0.61
	Unladen	Wet	9	0	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t

n/t not tested ----- not available

a The 9 replicates are separated due to the improper brake settings during the first round of testing in this condition.

b A 2nd set of 3 replicate stops was conducted in the 2/3 laden condition during the "wet" test sequence. Since these tests were conducted dry, the results are included in the "2/3 loaded and dry" test series.

c The deceleration is back-calculated from Labeco stopping distances.

Road Stops Uncertainties

For use in enforcement, performance-based regulations to be used with PBBTs must take into account the accuracy and repeatability of the PBBTs, must be based on safety, and must also consider the variations typically found in actual vehicle stopping behavior.

There are three sources of uncertainty to be considered in establishing the allowable window of deviations from the desired minimum stopping capability.

1) The stopping distances or the computed decelerations of a given vehicle under identical conditions will vary from stop to stop. Statistically, as the number of samples (replicate tests) increases, the level of confidence in the results increases accordingly. Since only three replicates were conducted, variabilit observed in the test results was high, and the extremes may not have represented those found in a large number of tests (Table B1). For the 20 mph stops conducted during the round robin, the maximum range of variation of the deceleration (from minimum to maximum) for a given truck configuration (weak and strong brakes) was approximately 10 percent, i.e. ± 5 percent. This type of uncertainties is referred to as "real-life braking variations".
2) The second type of uncertainty is "data measurement" variations, which are manifest in the range of reported values the PBBT exhibit under controlled (usually static) conditions. These are due to transducer accuracy and/or data manipulation or reduction. The proposed specifications call for ± 2.5 percent on the weight and brake force measurements. When combined, these lead to an approximate ± 5 percent variation on the deceleration (BF_{TOT}/GVW).
3) The third type of uncertainty is introduced by the specific interacttion of the vehicle tested and the PBBT used. These "dynamic" variations can originate from test geometry (design characteristics of trucks such as total number of axles, position of axles, type of suspensions, etc.) and data manipulation (filtering, smoothing, brake force calibration algorithm, etc.), and variability in the way the driver/operator conducts the tests.

Brake Forces

COMPUTATION OF REFERENCE BRAKE FORCE FROM TORQUE WHEEL DATA

The calibration check on the torque wheel indicated an accuracy within 0.5 percent. To compute the brake forces from the measured torques, a radius of 19.25 inches was used for the fully laden condition, and 19.6 inches was used for the unladen condition. The accuracy on the radius measurement was approximately 1.3 percent (0.25 inch). Additionally, the variation of the contact geometry due to deflection on the rolls or gripper pads is estimated to contribute to the variation of the radius by 0.5 inch (~ 2.6 percent) for the RDs and 0.25 inch (~ 1.3 percent) for the BTT. No additional geometry factor is expected for the flat plate testers. As such, the total estimated uncertainty in measured torque values is ± 4.3 percent for FPs, ± 5.6 percent for BTTs, and ± 6.9 percent for RDs, respectively. On the 3-S2 vehicle, torque data was collected during all tests by a torque wheel installed on wheel 5.

Figure B3 illustrates typical brake force versus time traces as well as the methods used for computing a single value for the brake force from the data. As the vendors' algorithms for computing brake forces were not all known at the time of this report, three different methods were used to determine brake force data from torque wheel data. For all three PBBT types, method 1 reported the maximum brake force ("Max") during the test. Method 2 calculated the average of data points greater than 80 percent of the maximum brake force ("0.8 avg"). Method 2 helps average data for which a nominal plateau is reached during the test or for which a spike occurs. However, if a large spike occurs with no filtering, for example, of magnitude 20 % greater than the plateau, then none of the plateau data would be included. Finally, for all PBBTs except FP testers, Method 3 determined the brake force at the time of test termination ("Term"). No averaging of the torque wheel data was performed.

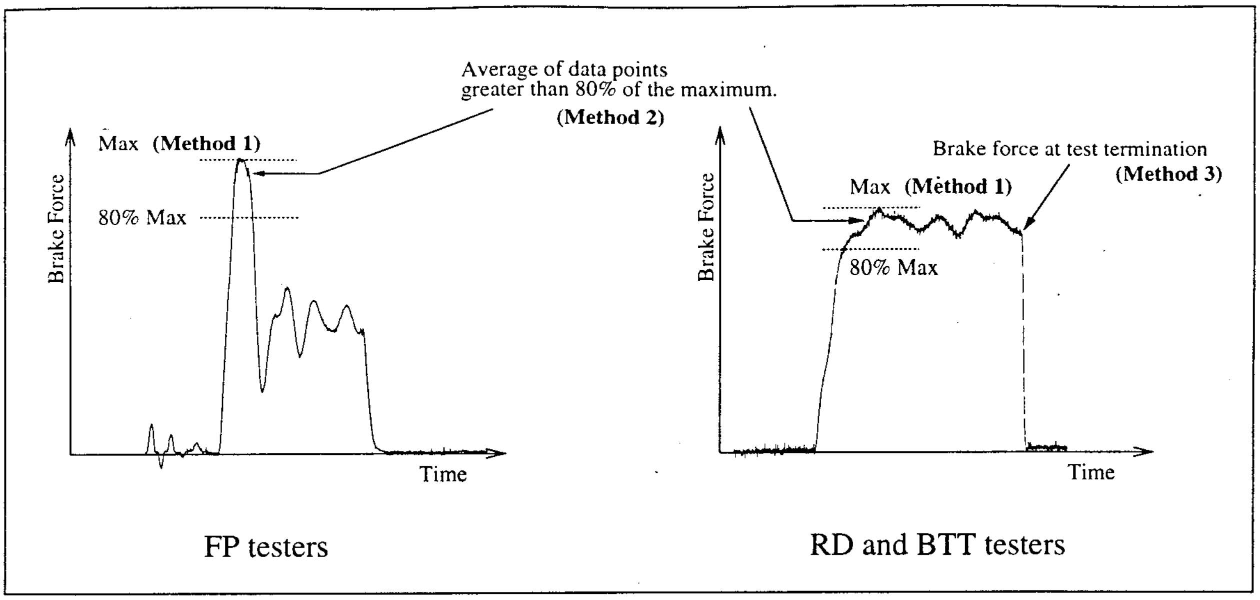


Figure B3. Methods for computing the brake force from torque wheel data.

REFERENCE BRAKE FORCE DATA

Table B2 summarizes the brake forces reported by the PBBTs (indicated by "Rep." in the "PBBT" column, standing for "as reported") and the brake forces obtained from the torque wheel data. Data are presented for laden and unladen conditions.

Table B2. Brake forces (in pounds) for wheel 5 of the 3-S2 reported by PBBTs and computed from the reference torque wheel data (Appendix D).

LADEN CONDITIONS													
		Replicate 1				Replicate 2				Replicate 3			
		PBBT	Torque wheel			PBBT	Torque wheel			PBBT	Torque wheel		
Machine		Rep.	Max.	0.8 avg	Term	Rep.	Max.	0.8 avg	Term	Rep.	Max.	0.8 avg	Term
B&G BTT	6	4362	4690	4241	4690	4369	4646	4182	4646	4333	5330	4812	5330
HTR FP	1	5395	5807	5501	n/a	5343	6068	5773	n/a	5791	7330	6954	n/a
HEKA FP	7	3797	5406	5040	n/a	4563	4999	4624	n/a	4651	5161	4711	n/a
VRTC RD	4	5604	5911	5580	5911	6077	6499	5995	6499	6147	6415	6180	6415
RAI RD-ig	9	5873	6045	5890	5965	6106	6317	6044	6234	5850	6290	6089	6001
RAI RD-p	2	5212	5701	5099	4638†	4892	5398	4805	5157†	4964	5566	4912	5046†
VIS RD	3	4078	4772	4265	4772	2308	2623	2246	2623	2200	2426	2106	2426
HEI RD1	5a	4957	5403	4864	5403	5169	5898	5314	5898	3989	4356	3957	4356
HEI RD2	5b	----	----	----	----	----	----	----	----		3937	3491	
20mph st.	8	----	5816	5582	n/a	----	5779	5507	n/a	----	5916	5584	n/a

LADEN CONDITIONS													
		Replicate 1				Replicate 2				Replicate 3			
		PBBT	Torque wheel			PBBT	Torque wheel			PBBT	Torque wheel		
Machine		Rep.	Max.	0.8 avg	Term	Rep.	Max.	0.8 avg	Term	Rep.	Max.	0.8 avg	Term
B&G BTT	6	1287	1326	1250	1326	1559	1635	1556	1635	1597	1635	1547	1635
HTR FP	1	1792	1518	1385	n/a	1815	1896	1717	n/a	1684	1792	1630	n/a
HEKA FP	7	1356	1116	1023	n/a	2114	1789	1659	n/a	1691	1411	1294	n/a
VRTC RD	4	1544	1640	1504	1448	1640	1801	1595	1523	1592	1914	1769	1689
RAI RD-ig	9	1601	1737	1535	1631	1727	1923	1760	1734	1943	2090	1961	1977
RAI RD-p	2	1579	1626	1543	1579	1988	2021	1901	1967	1767	1915	1770	1785
VIS RD	3	1426	1585	1378	1585	1520	1635	1415	1635	1466	1793	1544	1793
HEI RD1	5a	1624	1617	1496	1476	1431	1649	1533	1649	1366	1567	1442	1567
HEI RD2	5b	----	----	----	----	----	----	----	----	----	----	----	----
20mph st.	8	n/a	1519	1389	n/a	n/a	1778	1639	n/a	n/a	1767	1621	n/a

Rep.=reported; Max.=maximum; 0.8 avg=average of data greater than 80% maximum; Term=at test termination.
* Average of last 10 points prior to test termination.
† Test termination prior to the upsurge, as specified on Figure xx11.

Vehicle Weights

Table B3. Weights (in pounds) measured using certified scales

Wheel Number	Wheel Position	3-S2 Laden	3-S2 Empty	2-Axle Laden	2-Axle Empty	2-Axle 1/3 Laden	2-Axle 2/3 Laden
1	1L	6,050	5,100	6,000	4,100	4,790	5,310
2	1R	5,850	4,850	5,450	3,700	4,510	4,980
Axle 1		***11,900***	***9,950***	***11,450***	***7,800***	***9,300***	***10,290***
3	2L	9,150	3,000	11,300	4,700	6,940	9,810
4	2R	8,150	2,750	10,050	4,200	6,490	8,870
Axle 2		***17,300***	***5,750***	***21,350***	***8,900***	***13,430***	***18,680***
5	3L	8,400	2,900				
6	3R	8,100	2,900				
Axle 3		***16,500***	***5,800***				
Total Tractor		**45,700**	**21,500**				
7	4L	8,700	2,400				
8	4R	8,700	2,050				
Axle 4		***17,400***	***4,450***				
9	5L	7,900	2,350				
10	5R	7,800	2,400				
Axle 5		***15,700***	***4,750***				
Total Trailer		**33,100**	**9,200**				
Total Vehicle		**78,800**	**30,700**	**32,800**	**16,700**	**22,730**	**28,970**

APPENDIX C

PBBT DATA FOR TESTS 1 - 9:

Brake Forces

and

Wheel Loads

Table C1. Data from 3 replicates for Test 1: Laden 3-S2 with weak brakes.

Replicate 1	3s-2	Laden	some weak brakes		
Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1564	6270	1979	6020
Hunter FP	2	2494	8730	3800	7990
	3	5395	8530	2816	8480
	4	3975	8050	2622	8350
	5	3039	8370	2398	8340
2	1	1776	6450	2001	6450
RAI RD	2	2698	14000	4659	14000
	3	5212	8600	3184	8600
	4	3935	14000	3022	14000
	5	2999	10100	2599	10100
3	1	1716	5637	1985	5570
VIS RD	2	2732	9606	4804	9257
	3	4078	6357	2994	6734
	4	3607	6640	2826	6801
	5	2954	6162	2826	6471
4	1	1515	6481	2108	5536
VRTC	2	2498	8302	4372	7401
Fixed RD	3	5604	8167	2797	7759
	4	3991	11729	2933	10069
	5	2930	9015	2416	8266
5	1	1701	6164	1991	6164
Hicklin RD1	2	2758	11011	4685	11011
	3	4957	7108	3005	7108
	4	4278	10358	3357	10358
	5	3324	8793	2888	8793
6	1	1230	5970	2464	6642
B&G BTT	2	2325	10006	4268	10463
	3	4362	6986	2729	8470
	4	3851	9344	2406	10722
	5	2637	7869	2286	9069
7	1	1444	7300	1418	7300
HEKA FP	2	61	10550	96	10550
	3	3797	8000	2158	8000
	4		11850		11850
	5		0		0
9	1	1741	5450	2127	5750
RAI fixed RD	2	2622	9500	4411	8450
	3	5873	8400	3175	7950
	4	3746	9300	3395	8800
	5	3251	8250	2838	8350
5b	1	1805	6324	2517	6324
Hicklin RD2	2	3375	10692	4536	10692
	3	4103	7125	3593	7125
	4	4469	10313	3218	10313
	5	4206	8155	3140	8155

Replicate 2	3s-2	Laden	some weak brakes		
Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1625	6180	1911	6070
Hunter FP	2	2679	8710	3976	8070
	3	5343	8370	3014	8500
	4	3931	8220	2918	8430
	5	3290	8170	2510	8260
2	1	1790	6400	2051	6400
RAI RD	2	2954	14000	4353	14000
	3	4892	8300	3373	8300
	4	4362	13750	3269	13750
	5	3355	9900	2954	9900
3	1	1951	5307	2018	5328
VIS RD	2	2563	9970	5134	9916
	3	2308	5254	3384	5590
	4	2193	7895	3687	8348
	5	2321	5220	2853	5597
4	1	1960	6517	2153	5364
VRTC	2	2743	11362	4446	10144
Fixed RD	3	6077	7622	3458	7293
	4	4290	11736	3620	9686
	5	3720	9404	3127	8348
5	1	2236	6209	2335	6209
Hicklin RD1	2	3001	10892	5601	10892
	3	5169	7306	3582	7306
	4	4212	10198	3719	10198
	5	3435	8889	3287	8889
6	1	1612	5679	1668	6445
B&G BTT	2	2562	9397	4254	11507
	3	4369	7569	3191	9028
	4	3511	8002	3148	10618
	5	2777	7878	2586	9482
7	1	1480	6350	1682	6350
HEKA FP	2	2422	9900	3471	9900
	3	4563	8050	2528	8050
	4	3444	11300	2096	11300
	5	2387	7250	1585	7250
9	1	1835	5200	2172	5750
RAI fixed RD	2	2662	9500	4402	8700
	3	6106	7850	3427	7950
	4	4150	9050	3314	8950
	5	3436	8150	2842	8550
5b	1	1932	6050	2176	6050
Hicklin RD2	2	3268	10675	4615	10675
	3	6284	6734	3609	6734
	4	4141	10620	3344	10620
	5	3722	8138	3001	8138

Replicate 3	3s-2	Laden	some weak brakes		
Station #	xle #	LBF	LWT	RBF	RWT
1	1	1752	6180	1960	6030
Hunter FP	2	2996	8530	4335	8120
	3	5791	8370	3115	8480
	4	3725	8090	2967	8530
	5	3243	8230	2553	8180
2	1	1830	6300	1992	6300
RAI RD	2	2986	13750	4474	13750
	3	4964	8900	3624	8900
	4	4245	14050	3427	14050
	5	3499	10100	2793	10100
3	1	1776	5281	2261	5334
VIS RD	2	2503	9835	5383	10124
	3	2200	5213	3479	5348
	4	2422	8207	4138	8685
	5	2220	5381	3176	5610
4	1	1904	6552	2239	5192
VRTC	2	2939	10926	4831	10332
Fixed RD	3	6147	7333	3674	7096
	4	4267	11747	3259	9400
	5	3796	9302	3047	7796
5	1	2281	6160	2614	6160
Hicklin RD1	2	3249	10839	5713	10839
	3	3989	6976	3543	6976
	4	4421	10178	4347	10178
	5	3753	9006	3287	9006
6	1	1616	5679	3146	6125
B&G BTT	2	3099	9989	0	9771
	3	4333	7118	3076	8263
	4	3535	7975	4005	10987
	5	3289	8002	2884	9637
7	1	1832	6500	1568	6500
HEKA FP	2	2828	10250	3480	10250
	3	4651	8050	3101	8050
	4	4220	11350	2801	11350
	5	3189	7300	2185	7300
9	1	1988	5400	2222	5800
RAI fixed RD	2	2752	9450	4735	8750
	3	5850	8250	3490	8150
	4	4002	8900	3053	9100
	5	3543	8200	2815	8450

Table C2. Data from 3 replicates for Test 2: Laden 2-axle with weak brakes.

Replicate 1

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1191	5870	3274	5600
Hunter FP	2	4305	10570	2865	10420
2	1	1273	5750	3283	5750
RAI RD	2	4834	10700	3741	10700
3	1	1527	5429	3270	5328
VIS RD	2	3452	10329	2395	10010
4	1	1277	5850	3301	5410
VRTC	2	4803	10913	3223	10145
5	1	1361	5566	3106	5566
Hicklin RD1	2	4566	10423	3427	10423
6	1	1343	5025	2411	5526
B&G BTT	2	4417	9423	3293	10443
7	1	969	10470	2308	10470
HEKA FP	2	3665	0	2511	0
9	1	1286	5800	2851	5600
RAI fixed RD	2	4510	10750	3314	10650
5b	1	1605	5560	3241	5560
Hicklin RD2	2	4980	10273	3417	10273

Replicate 2

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1558	5870	3097	5600
Hunter FP	2	4466	10710	3334	10450
2	1	1385	5700	3112	5700
RAI RD	2	4712	10650	3692	10650
3	1	1393	5617	2987	5368
VIS RD	2	1998	10279	3613	10111
4	1	1475	5968	3395	5311
VRTC	2	4869	10829	3795	10264
5	1	1452	5530	3561	5530
Hicklin RD1	2	4540	10363	3370	10363
6	1	1364	5105	2523	5443
B&G BTT	2	4460	9326	3150	10753
7	1	969	10845	2572	10845
HEKA FP	2	4052	0	2643	0
9	1	1349	5900	3242	5400
RAI fixed RD	2	5005	10700	3737	10350

Replicate 3

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1242	5890	2864	5570
Hunter FP	2	4293	10640	3133	10430
2	1	1498	5700	3508	5700
RAI RD	2	4690	10650	3962	10650
3	1	1621	5536	3102	5267
VIS RD	2	2617	10178	4044	10030
4	1	1479	5955	3297	5209
VRTC	2	5089	11296	3913	9702
5	1	1475	5542	3390	5542
Hicklin RD1	2	4512	10421	3566	10421
6	1	1301	4963	2530	5474
B&G BTT	2	4515	9194	3476	9875
7	1	1180	10200	2731	10200
HEKA FP	2	4070	10050	2757	10050
9	1	1444	5800	3197	5450
RAI fixed RD	2	4924	10750	3732	10550

Table C3. Data from 3 replicates for Test 3: Empty 3-S2 with weak brakes.

Replicate 1 3s-2 Empty some weak brakes

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	750	5120	1732	4970
Hunter FP	2	1075	3010	225	2750
	3	1792	2980	973	2960
	4	718	2280	373	2300
	5	327	2390	297	2300
2	1	868	5100	1664	5100
RAI RD	2	1192	6150	1057	6150
	3	1579	2800	675	2800
	4	1178	4700	639	4700
	5	545	3250	486	3250
3	1	868	4715	1716	4806
VIS RD	2	1258	3512	1144	3498
	3	1426	1805	733	2833
	4	1231	2105	780	2294
	5	625	1070	612	1413
4	1	896	5143	1994	4791
VRTC	2	1191	2836	1034	2697
Fixed RD	3	1544	2568	806	2409
	4	1056	4022	830	2847
	5	584	2542	488	2261
5	1	890	4968	1860	4968
Hicklin RD1	2	1347	4972	1132	4972
	3	1624	2270	799	2270
	4	1268	3294	773	3294
	5	663	2578	553	2578
6	1	553	5228	1400	6022
B&G BTT	2	1050	5175	701	5960
	3	1287	2579	474	2324
	4	568	3895	438	4245
	5	320	2508	401	3088
7	1	748	5550	1471	5550
HEKA FP	2	995	4550	546	4550
	3	1356	3150	414	3150
	4	660	4300	343	4300
	5	405	2300	273	2300
9	1	949	4550	1799	5050
RAI fixed RD	2	1147	2950	1196	2800
	3	1601	2750	666	2700
	4	1120	2450	572	2300
	5	572	2250	374	2500

Replicate 2 3s-2 Empty some weak brakes

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	725	5080	2101	4980
Hunter FP	2	1370	3030	1009	2930
	3	1815	2920	542	2800
	4	1637	2300	886	2200
	5	884	2360	671	2380
2	1	913	5100	2028	5100
RAI RD	2	1498	6000	1767	6000
	3	1988	2700	733	2700
	4	1750	4250	1255	4250
	5	976	2950	976	2950
3	1	901	4820	2039	4750
VIS RD	2	1574	3491	1675	3582
	3	1520	2035	686	2203
	4	1547	2175	1123	2175
	5	1056	1301	989	1455
4	1	960	5659	1848	4270
VRTC	2	1512	3109	1604	2668
Fixed RD	3	1640	2958	668	1933
	4	1744	3981	1189	2638
	5	1040	2674	847	2343
5	1	1034	4970	2153	4970
Hicklin RD1	2	1627	4768	1736	4768
	3	1431	2302	649	2302
	4	1820	3304	1356	3304
	5	1258	2523	1132	2523
6	1	691	4487	2104	5134
B&G BTT	2	1470	5582	1313	5722
	3	1559	2535	436	2128
	4	1188	4204	1008	4442
	5	841	2570	765	3264
7	1	678	5350	2229	5350
HEKA FP	2	2440	4450	1409	4450
	3	2114	3000	740	3000
	4	1242	4800	792	4800
	5	872	2150	660	2150
9	1	1039	4700	2267	4850
RAI fixed RD	2	1448	3000	1597	2750
	3	1727	2800	751	2650
	4	1367	2500	1201	2750
	5	1030	2350	792	2500

Replicate 3 3s-2 Empty some weak brakes

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	742	5080	2017	4920
Hunter FP	2	1294	3120	1296	2920
	3	1684	2920	460	2880
	4	1424	2300	943	2230
	5	928	2360	633	2340
2	1	1003	5150	2087	5150
RAI RD	2	1484	6000	1736	6000
	3	1767	2750	670	2750
	4	1705	4750	1107	4750
	5	1102	3050	864	3050
3	1	1002	4799	2139	4708
VIS RD	2	1500	3414	1520	3428
	3	1466	1987	780	2147
	4	1366	2140	1164	2224
	5	962	979	935	1371
4	1	920	5483	2076	4355
VRTC	2	1496	3014	1498	2472
Fixed RD	3	1592	2649	733	2725
	4	1472	4225	1148	2613
	5	1056	2713	871	2149
5	1	924	4862	2279	4862
Hicklin RD1	2	1746	4708	1955	4708
	3	1366	2186	679	2186
	4	1979	3627	1368	3627
	5	1165	2756	968	2756
6	1	736	5069	1881	5774
B&G BTT	2	1423	5184	1430	5681
	3	1597	2588	436	2169
	4	1586	3577	872	4152
	5	835	2464	645	3047
7	1	713	5450	1894	5450
HEKA FP	2	1277	4450	1048	4450
	3	1691	3250	458	3250
	4	1198	4900	766	4900
	5	837	2250	537	2250
9	1	1035	4800	2073	4950
RAI fixed RD	2	1570	3000	2015	2800
	3	1943	2750	832	2650
	4	1925	2550	1237	2500
	5	1201	2200	828	2450

Table C4. Data from 3 replicates for Test 4: Empty 2-axle with weak brakes

Replicate 1

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	915	4060	2086	3770
Hunter FP	2	2601	4650	1040	4260
2	1	1026	3900	2096	3900
RAI RD	2	3044	4450	1529	4450
3	1	989	3720	2113	3531
VIS RD	2	1931	4292	1554	4002
4	1	942	4316	2192	3282
VRTC	2	2791	5077	1194	3685
5	1	1130	3757	2372	3757
Hicklin RD1	2	2637	4298	1296	4298
6	1	965	3692	2450	3873
B&G BTT	2	2971	4027	1263	4535
7	1	828	4250	1788	4250
HEKA FP	2	2748	4700	1022	4700
9	1	981	4150	2348	3900
RAI fixed RD	2	3004	4500	1439	4300

Replicate 2

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	1063	4090	2059	3740
Hunter FP	2	2840	4650	1102	4280
2	1	1035	3900	2316	3900
RAI RD	2	3179	4500	1399	4500
3	1	1090	3854	2025	3572
VIS RD	2	1877	4433	1769	4056
4	1	948	4321	2277	3350
VRTC	2	2834	4805	1182	3969
5	1	1236	3792	2614	3792
Hicklin RD1	2	2688	4301	1405	4301
6	1	1052	3559	2375	3935
B&G BTT	2	3149	4310	1725	4514
7	1	837	4250	1682	4250
HEKA FP	2	2440	4850	881	4850
9	1	1093	4050	2321	3850
RAI fixed RD	2	2829	4600	1619	4400

Replicate 3

Station #	Axle #	LBF	LWT	RBF	RWT
1	1	989	4090	2180	3730
Hunter FP	2	2884	4620	1057	4270
2	1	1050	3900	2074	3900
RAI RD	2	3200	4500	1400	4500
3	1	1063	3834	2018	3624
VIS RD	2	2826	4393	1292	4197
4	1	898	4421	1832	3265
VRTC	2	2838	4713	1273	4076
5	1	1167	3868	2330	3868
Hicklin RD1	2	2755	4330	1322	4330
6	1	1000	4177	2284	4741
B&G BTT	2	3038	4142	285	4524
7	1	784	4250	1585	4250
HEKA FP	2	2361	4850	854	4850
9	1	1044	3950	2186	3900
RAI fixed RD	2	2874	4450	1318	4400

Table C5. Test 5: Empty 2-axle with fully adjusted brakes, dry (3 replicates).

Replicate 1		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3631	4060	0.89	3452	3740	0.92	3748	4600	0.81	3505	4280	0.82
2	RAI RD	2972	3900	0.76	2604	3900	0.67	3377	4450	0.76	3260	4450	0.73
3	VIS RD	1534	3834	0.40	2254	3659	0.62	1917	4372	0.44	2247	4183	0.54
4	VRTC	2716	4225	0.64	2409	3481	0.69	2680	5150	0.52	2610	3648	0.72
5	HEI RD1	2547	3840	0.66	2271	3840	0.59	2793	4329	0.65	2770	4329	0.64
6	B&G BTT	2566	3842	0.67	2433	4256	0.57	5329	4389	1.21	5287	4617	1.15
7	HEKA FP	3295	4250	0.78	3118	4250	0.73	4405	4750	0.93	3568	4750	0.75
8	20mph stop												
9	RAI fixed RD	2999	4050	0.74	2244	3650	0.61	2658	4500	0.59	2518	4450	0.57
5b	HEI RD2-n	3143	3864	0.81	2823	3864	0.73	2433	4438	0.55	2269	4438	0.51
5c	HEI RD2-ILRSD	2590	3894	0.67	2304	3894	0.59	2572	4270	0.60	2165	4270	0.51
Replicate 2		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3352	4070	0.82	3139	3690	0.85	4168	4640	0.90	3603	4230	0.85
2	RAI RD	2923	3950	0.74	2937	3950	0.74	2977	4450	0.67	3184	4450	0.72
3	VIS RD	1668	3799	0.44	2187	3617	0.60	2025	4386	0.46	2328	4197	0.55
4	VRTC	2423	3766	0.64	2315	3892	0.59	2874	4669	0.62	2641	4091	0.65
5	HEI RD1	2240	3852	0.58	2123	3852	0.55	2865	4375	0.65	2766	4375	0.63
6	B&G BTT	2579	3709	0.70	2606	3842	0.68	5335	4389	1.22	5298	4535	1.17
7	HEKA FP	3268	4150	0.79	3118	4150	0.75	4202	4750	0.88	3744	4750	0.79
8	20mph stop												
9	RAI fixed RD	3004	4050	0.74	2469	3750	0.66	2703	4600	0.59	2406	4300	0.56
5b	HEI RD2-n	2910	3878	0.75	2501	3878	0.64	2455	4350	0.56	2166	4350	0.50
5c	HEI RD2-ILRSD	2749	3858	0.71	1728	3858	0.45	2850	4277	0.67	2069	4277	0.48
Replicate 3		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	
1	Hunter FP	3364	4050	0.83	3229	3720	0.87	3852	4660	0.83	3510	4260	0.82
2	RAI RD	2986	3900	0.77	2658	3900	0.68	2662	4500	0.59	3224	4500	0.72
3	VIS RD	1756	3806	0.46	2005	3638	0.55	1857	4365	0.43	2664	4155	0.64
4	VRTC	2791	4106	0.68	2674	3499	0.76	2778	4820	0.58	2699	3952	0.68
5	HEI RD1	2692	3821	0.70	2471	3821	0.65	2685	4269	0.63	2599	4269	0.61
6	B&G BTT	2576	3992	0.65	2608	4380	0.60	5353	4442	1.21	5257	4731	1.11
7	HEKA FP	2951	4050	0.73	2828	4050	0.70	4299	4800	0.90	3814	4800	0.79
8	20mph stop												
9	RAI fixed RD	3022	4150	0.73	2397	3550	0.68	2748	4550	0.60	2478	4300	0.58
5b	HEI RD2-n	2453	3921	0.63	2215	3921	0.56	3566	4305	0.83	3017	4305	0.70
5c	HEI RD2-ILRSD	1843	3834	0.48	1467	3834	0.38	3113	4215	0.74	2331	4215	0.55

Table C6. Test 6: 1/3 laden 2-axle with fully adjusted brakes, dry (3 replicates).

Replicate 1		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	2421	4870	0.50	2183	4510	0.48	4723	6990	0.68	4605	6410	0.72
2	RAI RD	3472	4650	0.75	3593	4650	0.77	3930	6700	0.59	3566	6700	0.53
3	VIS RD	1904	4736	0.40	2550	4512	0.57	2240	6919	0.32	3465	6478	0.53
4	VRTC	3027	5226	0.58	2993	3976	0.75	4169	7313	0.57	4025	5977	0.67
5	Hicklin RD1	2876	4521	0.64	2642	4521	0.58	3997	6573	0.61	4004	6573	0.61
6	B&G BTT	2533	4645	0.55	2650	5051	0.52	5345	6562	0.81	5294	6673	0.79
7	HEKA FP	3700	5150	0.72	3383	5150	0.66	4845	7550	0.64	4211	7550	0.56
8	20mph stop												
9	RAI fixed RD	3436	4800	0.72	3224	4500	0.72	3755	6900	0.54	3526	6550	0.54
5b	Hicklin RD2	3788	4556	0.83	3244	4556	0.71	3879	6575	0.59	3417	6575	0.52
5c	Hicklin RD2	3379	4608	0.73	2765	4608	0.60	3060	6502	0.47	1288	6502	0.20
Replicate 2		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3866	4870	0.79	3686	4430	0.83	5489	6940	0.79	5250	6440	0.82
2	RAI RD	3512	4650	0.76	3220	4650	0.69	3989	6700	0.60	3764	6700	0.56
3	VIS RD	1991	4694	0.42	2833	4456	0.64	2052	6856	0.30	3613	6436	0.56
4	VRTC	3175	4589	0.69	2959	4572	0.65	3831	7317	0.52	3844	5930	0.65
5	Hicklin RD1	2987	4535	0.66	2712	4535	0.60	3946	6603	0.60	3932	6603	0.60
6	B&G BTT	2555	4487	0.57	2521	4937	0.51	5334	6535	0.82	5266	6859	0.77
7	HEKA FP	3823	5200	0.74	3515	5200	0.68	4731	6850	0.69	4211	6850	0.61
8	20mph stop												
9	RAI fixed RD	3350	4850	0.69	2847	4550	0.63	3876	6900	0.56	3395	6550	0.52
5b	Hicklin RD2	3596	4556	0.79	3269	4556	0.72	3915	6527	0.60	3519	6527	0.54
5c	Hicklin RD2	3730	4562	0.82	2553	4562	0.56	4010	6532	0.61	2044	6532	0.31
Replicate 3		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT		BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3775	4870	0.78	3558	4460	0.80	5205	6940	0.75	4993	6460	0.77
2	RAI RD	3620	4650	0.78	3085	4650	0.66	4258	6750	0.63	3993	6750	0.59
3	VIS RD	1931	4652	0.42	2691	4442	0.61	2180	6800	0.32	3748	6450	0.58
4	VRTC	2930	4686	0.63	2909	4551	0.64	4009	7135	0.56	3890	6135	0.63
5	Hicklin RD1	2956	4545	0.65	2765	4545	0.61	3873	6465	0.60	3789	6465	0.59
6	B&G BTT	2535	4389	0.58	2483	4793	0.52	5342	6562	0.81	5263	6848	0.77
7	HEKA FP	3524	4900	0.72	3162	4900	0.65	4202	7550	0.56	3629	7550	0.48
8	20mph stop												
9	RAI fixed RD	3521	5000	0.70	2712	4400	0.62	3543	6900	0.51	3409	6550	0.52
5b	Hicklin RD2	3818	4620	0.83	3098	4620	0.67	4258	6576	0.65	3830	6576	0.58
5c	Hicklin RD2	1970	4516	0.44	2080	4516	0.46	4206	6534	0.64	3392	6534	0.52

Table C7. Test 7: 2/3 laden 2-axle with fully adjusted brakes, dry (3 replicates).

Replicate 1		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3400	5530	0.61	3510	5040	0.70	5208	9800	0.53	4433	8780	0.50
2	RAI RD	4366	5250	0.83	3998	5250	0.76	4811	9300	0.52	4573	9300	0.49
3	VIS RD	1931	5359	0.36	3263	4974	0.66	2180	9858	0.22	5161	8752	0.59
4	VRTC	3509	5795	0.61	3307	4550	0.73	5008	10472	0.48	4188	7990	0.52
5	Hicklin RD1	3374	5093	0.66	2971	5093	0.58	4943	9163	0.54	4850	9163	0.53
6	B&G BTT	2598	4919	0.53	2573	5268	0.49	5377	8655	0.62	5252	8842	0.59
7	HEKA FP	3841	5400	0.71	3392	5400	0.63	458	9250	0.05	0	9250	0.00
8	20mph stop												
9	RAI fixed RD	3723	5400	0.69	3391	5050	0.67	5513	9900	0.56	4834	8900	0.54
5b	Hicklin RD2	3454	5189	0.67	3463	5189	0.67	4897	9116	0.54	4344	9116	0.48
5c	Hicklin RD2	4604	5171	0.89	2289	5171	0.44	6023	9083	0.66	2600	9083	0.29
Replicate 2		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	4016	5530	0.73	4085	4990	0.82	5901	9790	0.60	5004	8820	0.57
2	RAI RD	4218	5200	0.81	3917	5200	0.75	4775	9300	0.51	4137	9300	0.44
3	VIS RD	1965	5310	0.37	3257	4967	0.66	2456	9879	0.25	4751	8654	0.55
4	VRTC	3618	5491	0.66	3499	4852	0.72	5050	10082	0.50	3949	8336	0.47
5	Hicklin RD1	3198	5075	0.63	3223	5075	0.64	5156	9136	0.56	4934	9136	0.54
6	B&G BTT	2572	4593	0.56	2625	4927	0.53	5377	8381	0.64	5021	8924	0.56
7	HEKA FP	4079	4750	0.86	3409	4750	0.72	5286	9200	0.57	4484	9200	0.49
8	20mph stop												
9	RAI fixed RD	3813	5400	0.71	3494	5000	0.70	6192	9850	0.63	4717	8850	0.53
5b	Hicklin RD2	3688	5194	0.71	3393	5194	0.65	4242	9091	0.47	3546	9091	0.39
5c	Hicklin RD2	2765	5148	0.54	2594	5148	0.50	5582	9139	0.61	3373	9139	0.37
Replicate 3		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	4070	5500	0.74	4006	5010	0.80	5913	9880	0.60	5289	8780	0.60
2	RAI RD	4299	5200	0.83	3989	5200	0.77	4569	9350	0.49	4380	9350	0.47
3	VIS RD	1958	5345	0.37	2880	4960	0.58	4730	9732	0.49	4858	8808	0.55
4	VRTC	3376	5174	0.65	3495	4602	0.76	5485	9515	0.58	4581	7879	0.58
5	Hicklin RD1	3329	5105	0.65	3124	5105	0.61	5476	9043	0.61	5110	9043	0.57
6	B&G BTT	2522	4601	0.55	2545	5010	0.51	5360	8284	0.65	5281	9121	0.58
7	HEKA FP	4096	5100	0.80	3682	5100	0.72	4969	8750	0.57	4185	8750	0.48
8	20mph stop												
9	RAI fixed RD	4047	5300	0.76	3458	5050	0.68	6232	9850	0.63	4928	8850	0.56
5b	Hicklin RD2	4432	5297	0.84	3387	5297	0.64	6403	9117	0.70	5491	9117	0.60
5c	Hicklin RD2	3121	5154	0.61	2643	5154	0.51	6256	9001	0.69	2919	9001	0.32

Table C8. Test 8: 2/3 laden 2-axle with fully adjusted brakes, wet (3 replicates).

Replicate 1		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3952	5480	0.72	3839	5040	0.76	5754	9870	0.58	6731	8700	0.77
2	RAI RD	3844	5266	0.73	3715	5277	0.70	5288	9276	0.57	5525	8951	0.62
3	VIS RD	1406	5422	0.26	1621	5030	0.32	2543	9963	0.26	3115	8752	0.36
4	VRTC	2683	5807	0.46	2751	4531	0.61	4486	10438	0.43	4158	8060	0.52
5	Hicklin RD1	1827	5036	0.36	1522	5036	0.30	3853	9144	0.42	3150	9144	0.34
6	B&G BTT	2562	4645	0.55	2605	5092	0.51	5285	8796	0.60	5264	8563	0.61
7	HEKA FP	4185	4900	0.85	3656	4900	0.75	5524	8500	0.65	4942	8500	0.58
8	20mph stop												
9	RAI fixed RD	3242	5400	0.60	3251	5000	0.65	5203	9900	0.53	4515	8800	0.51
5b	Hicklin RD2	3174	5150	0.62	3697	5150	0.72	6182	9467	0.65	5366	9467	0.57
Replicate 2		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3791	5470	0.69	3643	5040	0.72	5567	9820	0.57	6222	8730	0.71
2	RAI RD	3772	5314	0.71	3981	5317	0.75	5045	9206	0.55	5052	9272	0.54
3	VIS RD	1419	5282	0.27	1406	4952	0.28	3008	9767	0.31	3035	8801	0.34
4	VRTC	2842	5467	0.52	2393	4879	0.49	4880	9928	0.49	3755	8627	0.44
5	Hicklin RD1	1602	5026	0.32	1600	5026	0.32	4022	9060	0.44	2903	9060	0.32
6	B&G BTT	2465	4566	0.54	2568	4855	0.53	4907	8814	0.56	5311	8191	0.65
7	HEKA FP	4070	5000	0.81	3947	5000	0.79	5541	8450	0.66	4845	8450	0.57
8	20mph stop												
9	RAI fixed RD	3067	5400	0.57	3071	5100	0.60	5382	9800	0.55	4569	8950	0.51
5b	Hicklin RD2	3670	5167	0.71	3435	5167	0.66	3836	9143	0.42	4683	9143	0.51
Replicate 3		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3667	5460	0.67	3518	5050	0.70	5207	9850	0.53	5463	8740	0.63
2	RAI RD	3913	5275	0.74	3757	5307	0.71	5092	9235	0.55	4946	9232	0.54
3	VIS RD	1366	5338	0.26	1406	4988	0.28	2395	8731	0.27	2947	8731	0.34
4	VRTC	3077	5050	0.61	2417	4739	0.51	4893	9803	0.50	3237	8545	0.38
5	Hicklin RD1	1793	5059	0.35	1539	5059	0.30	4018	9156	0.44	2819	9156	0.31
6	B&G BTT	2544	5167	0.49	2415	5351	0.45	5341	8620	0.62	5314	9493	0.56
7	HEKA FP	4052	5050	0.80	4105	5050	0.81	5735	8150	0.70	5207	8150	0.64
8	20mph stop												
9	RAI fixed RD	3391	5400	0.63	3004	5000	0.60	5351	9800	0.55	4609	8950	0.51
5b	Hicklin RD2	3948	5119	0.77	2937	5119	0.57	4739	9069	0.52	5362	9069	0.59

Table C9. Test 9: Empty laden 2-axle with fully adjusted brakes, wet (3 replicates).

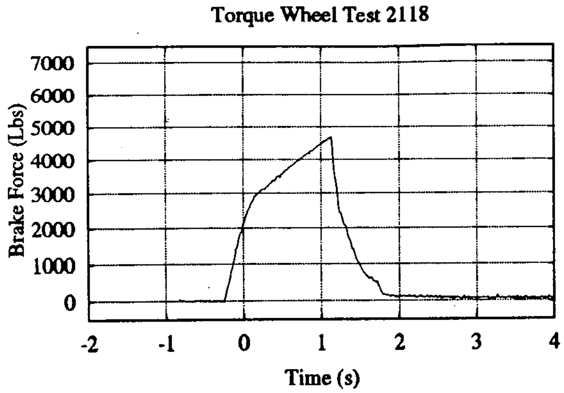
Replicate 1		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3706	4030	0.92	3105	3690	0.84	3283	4590	0.72	3084	4250	0.73
2	RAI RD	2617	3850	0.68	2536	3850	0.66	3049	4450	0.69	3121	4450	0.70
3	VIS RD	1318	3932	0.34	1379	3624	0.38	1668	4582	0.36	1783	4141	0.43
4	VRTC	1693	4083	0.41	2106	3499	0.60	2216	4541	0.49	2477	4266	0.58
5	Hicklin RD1	1524	3784	0.40	1142	3784	0.30	1710	4337	0.39	1753	4337	0.40
6	B&G BTT	2545	3701	0.69	2657	3966	0.67	5372	4001	1.34	5276	4349	1.21
7	HEKA FP	3268	3800	0.86	3074	3800	0.81	3638	4350	0.84	2748	4350	0.63
8	20mph stop												
9	RAI fixed RD	2352	3900	0.60	2303	3700	0.62	2563	4550	0.56	2312	4300	0.54
5b	Hicklin RD2	3354	3818	0.88	2496	3818	0.65	2104	4434	0.47	2400	4434	0.54
Replicate 2		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	3056	4010	0.76	2247	3710	0.61	3252	4590	0.71	2943	4250	0.69
2	RAI RD	2680	3850	0.70	2446	3850	0.64	3148	4450	0.71	3449	4450	0.78
3	VIS RD	1345	3855	0.35	1292	3638	0.36	1736	4554	0.38	1668	4169	0.40
4	VRTC	1454	4053	0.36	1997	3530	0.57	2296	4852	0.47	2392	3930	0.61
5	Hicklin RD1	1496	3825	0.39	1280	3825	0.33	1816	4330	0.42	1659	4330	0.38
6	B&G BTT	2550	3639	0.70	2571	3935	0.65	5384	4054	1.33	5275	4359	1.21
7	HEKA FP	3154	3800	0.83	2246	3800	0.59	3735	4100	0.91	2863	4100	0.70
8	20mph stop												
9	RAI fixed RD	2491	3900	0.64	2217	3650	0.61	2446	4550	0.54	2163	4300	0.50
5b	Hicklin RD2	2439	3809	0.64	2115	3809	0.56	2900	4405	0.66	2668	4405	0.61
Replicate 3		Wheel 1L			Wheel 1R			Wheel 2L			Wheel 2R		
		BF	WT	decel	BF	WT	decel	BF	WT	decel	BF	WT	decel
1	Hunter FP	1997	4040	0.49	1375	3680	0.37	1975	4540	0.44	1615	4290	0.38
2	RAI RD	2671	3850	0.69	2348	3850	0.61	3665	4450	0.82	3269	4450	0.73
3	VIS RD	1271	3876	0.33	1224	3652	0.34	1776	4547	0.39	1837	4134	0.44
4	VRTC	1575	4218	0.37	2062	3398	0.61	2507	4416	0.57	2110	3836	0.55
5	Hicklin RD1	1527	3817	0.40	999	3817	0.26	1714	4327	0.40	1911	4327	0.44
6	B&G BTT	2568	3480	0.74	2604	3739	0.70	5311	4283	1.24	5317	4586	1.16
7	HEKA FP	3524	3850	0.92	2660	3850	0.69	3321	4300	0.77	2607	4300	0.61
8	20mph stop												
9	RAI fixed RD	2428	3850	0.63	2442	3800	0.64	2734	4450	0.61	2392	4300	0.56
5b	Hicklin RD2	2973	3866	0.77	2504	3866	0.65	3692	4389	0.84	2784	4389	0.63

APPENDIX D

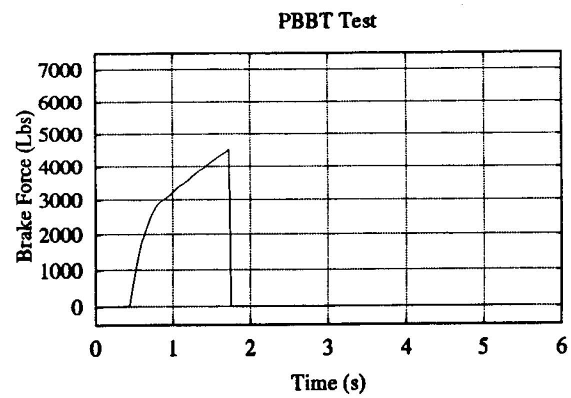
BRAKE FORCE HISTORY PLOTS

Tests 1 and 3:

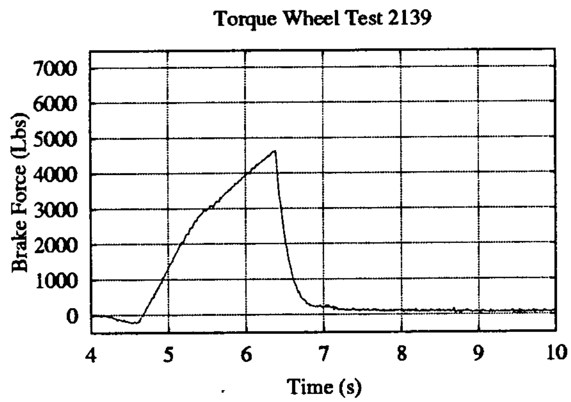
PBBT and Torque Wheel Results



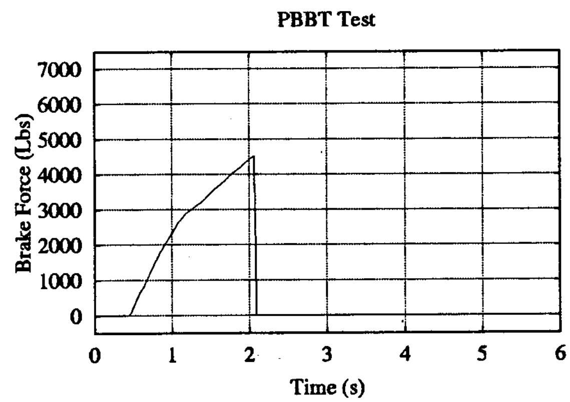
Replicate 1



Replicate 1



Replicate 2



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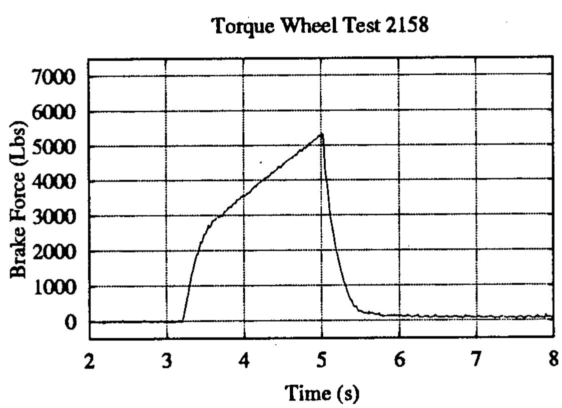
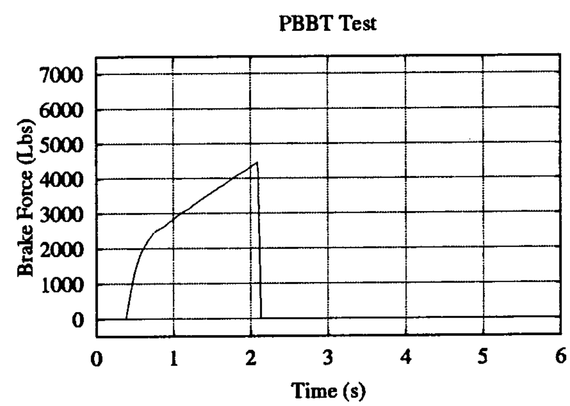
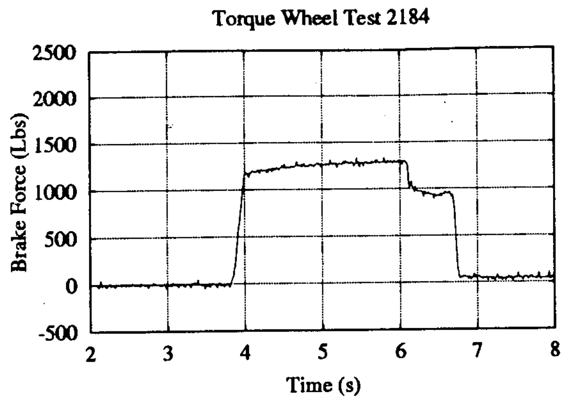


Replicate 3

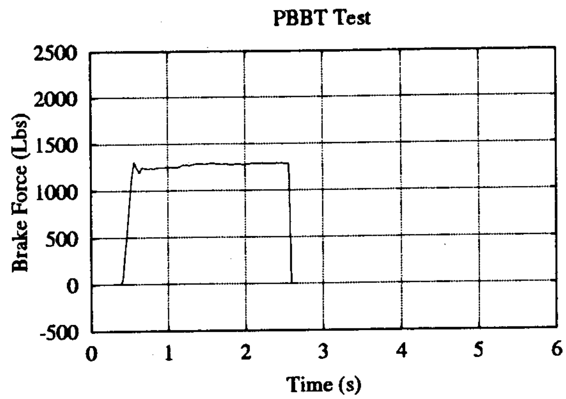


Replicate 3

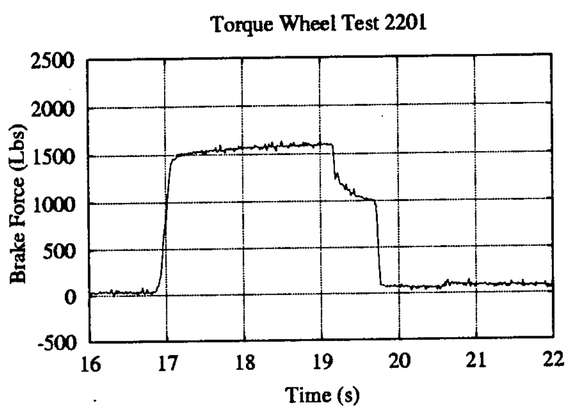
Figure D1. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the B&G BTT. Left column plots illustrate the torque wheel data. Right column plots illustrate B&G BTT data.



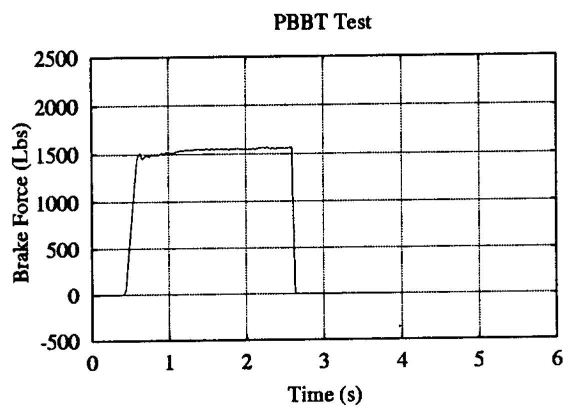
Replicate 1



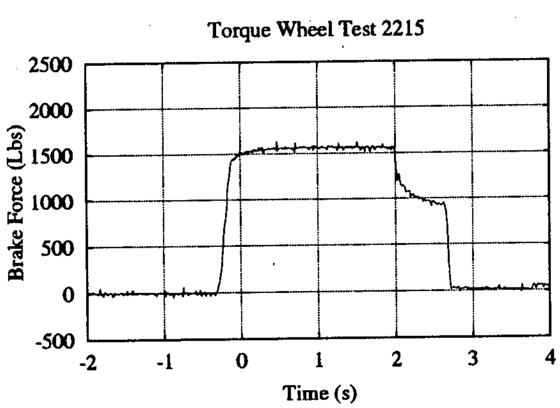
Replicate 1



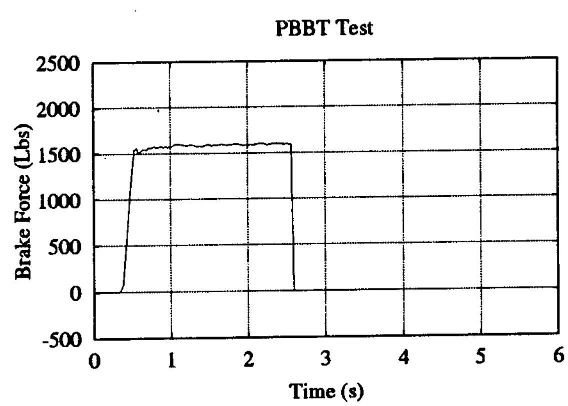
Replicate 2



Replicate 2



Replicate 3



Replicate 3

Figure D2. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the B&G BTT. Left column plots illustrate the torque wheel data. Right column plots illustrate B&G BTT data.

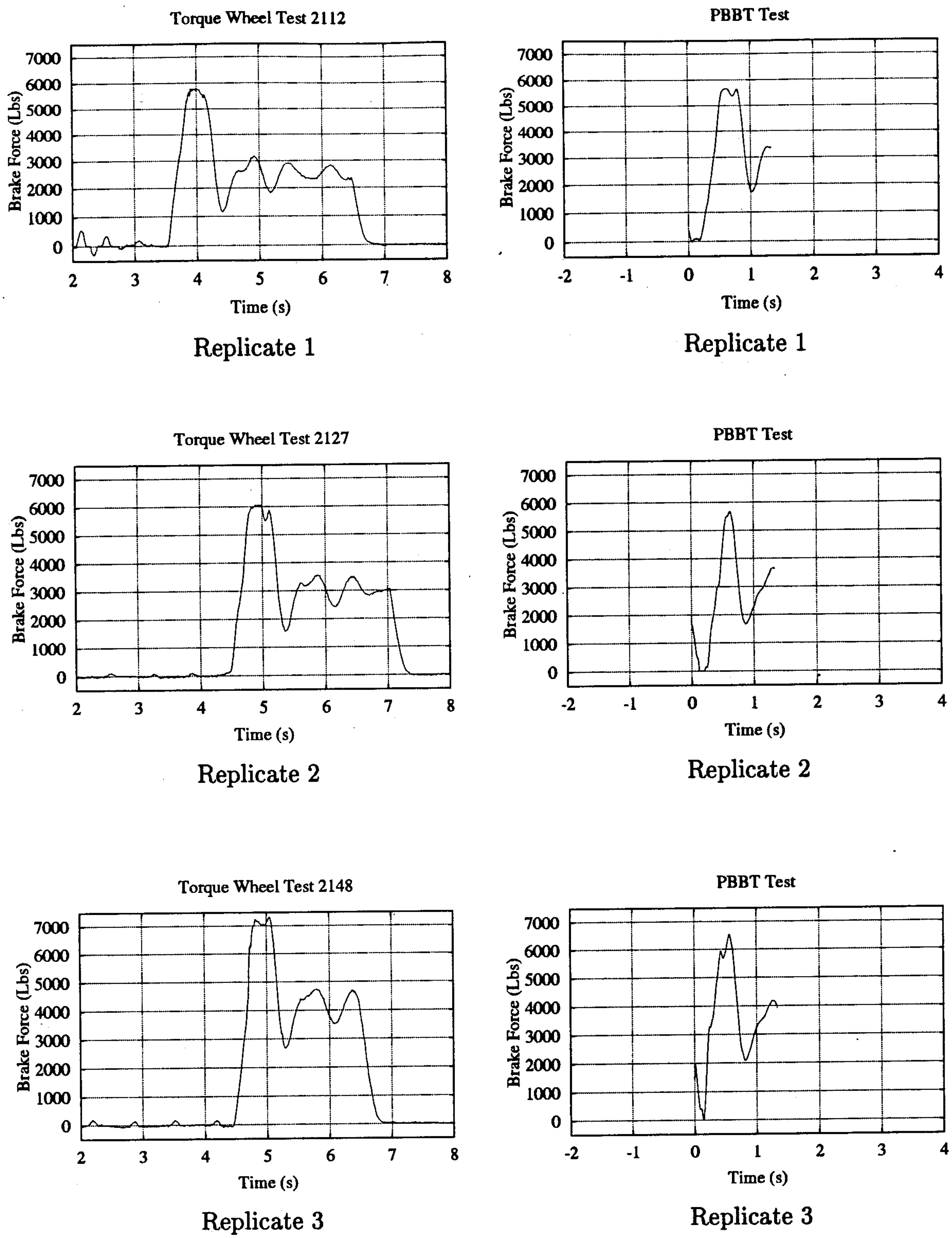
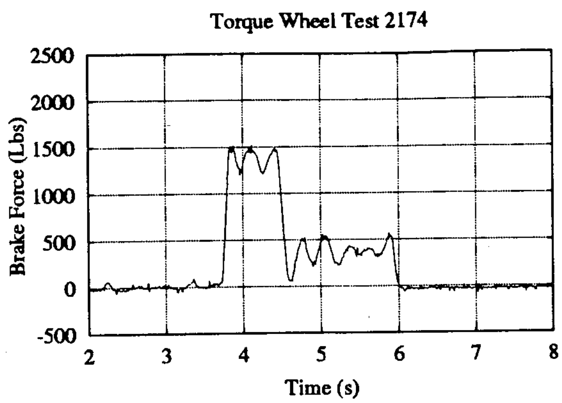
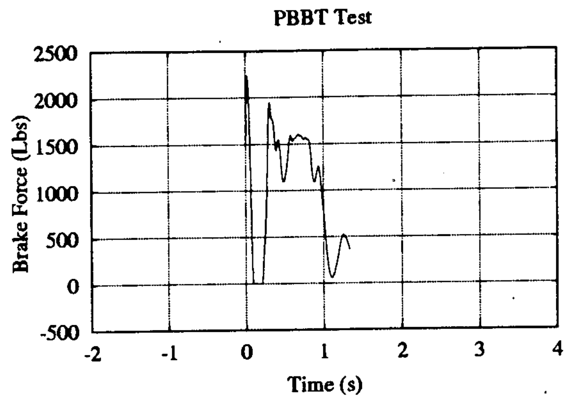


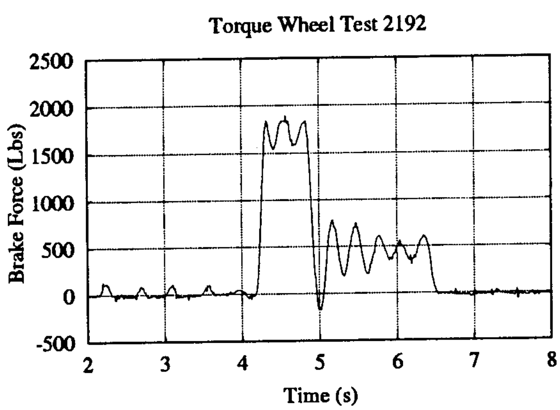
Figure D3. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the Hunter FP. Left column plots illustrate the torque wheel data. Right column plots illustrate Hunter FP data.



Replicate 1



Replicate 1



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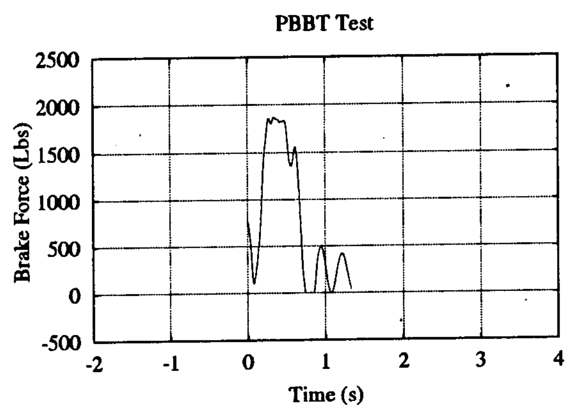

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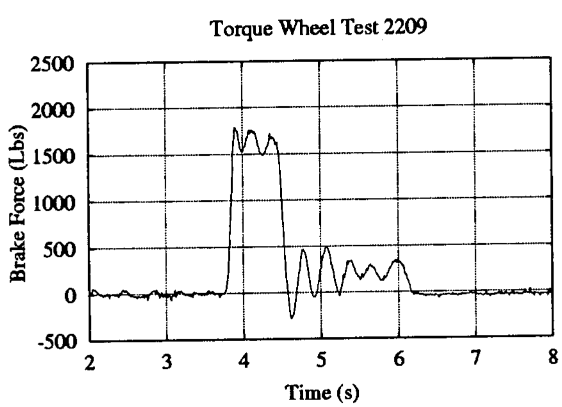

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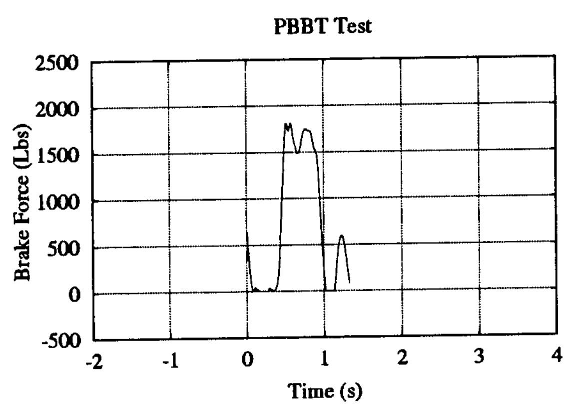
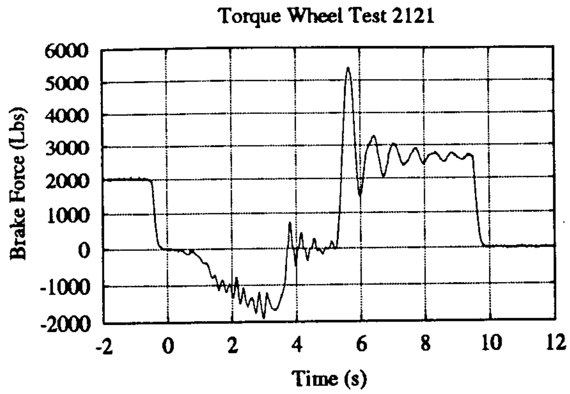
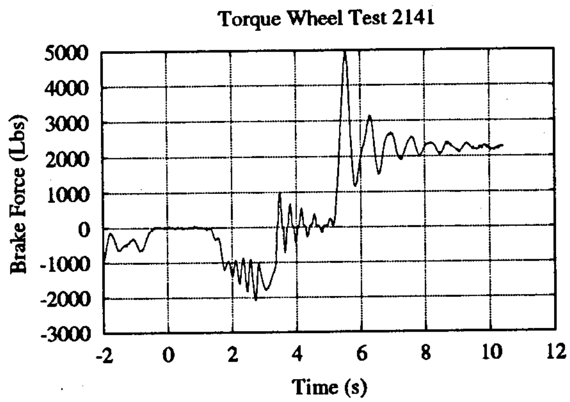


Replicate 3

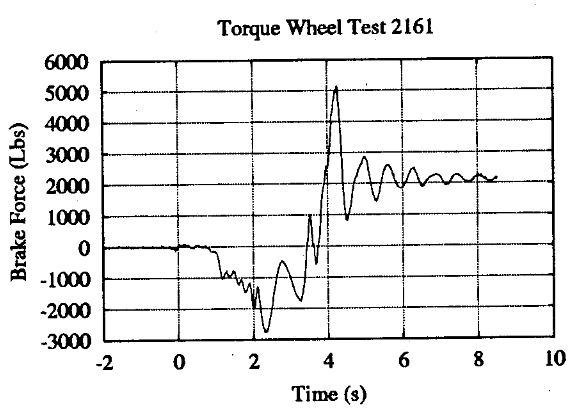
Figure D4. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the Hunter FP. Left column plots illustrate the torque wheel data. Right column plots illustrate Hunter FP data.



Replicate 1

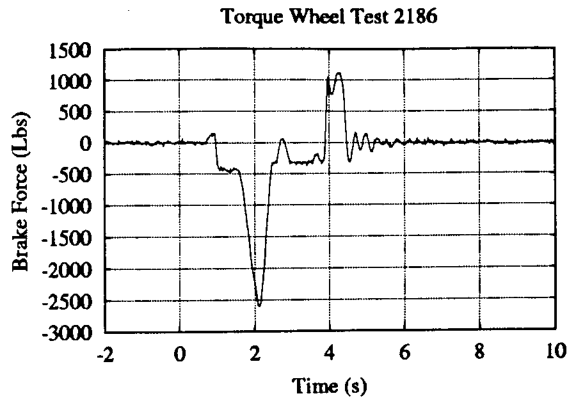


Replicate 2

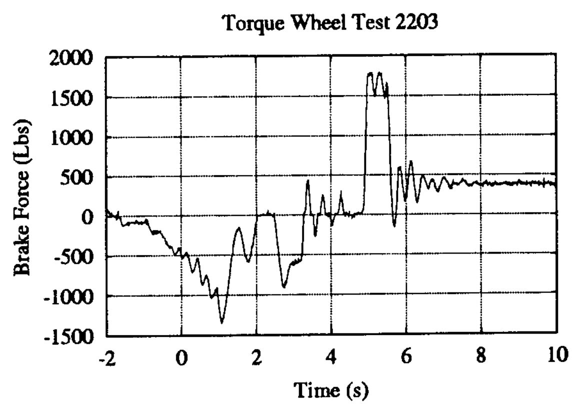


Replicate 3

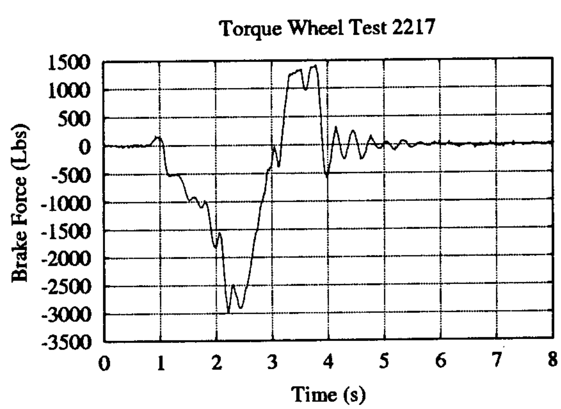
Figure D5. Brake force (collected by the torque wheel) versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the Heka FP.



Replicate 1

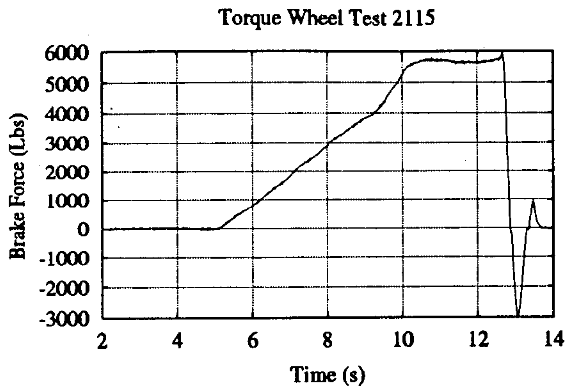


Replicate 2

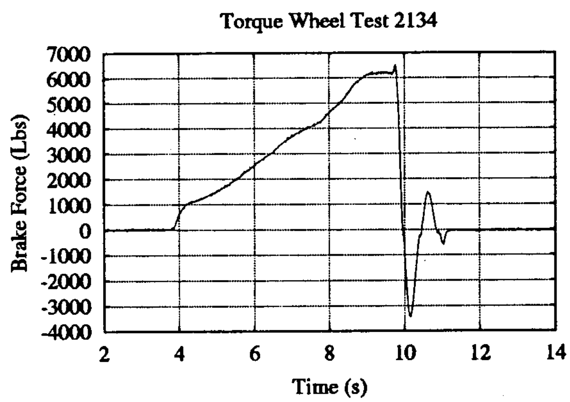


Replicate 3

Figure D6. Brake force (collected by the torque wheel) versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the Heka FP.



Replicate 1



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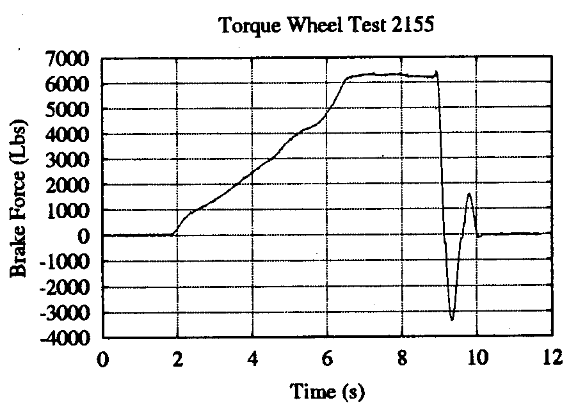
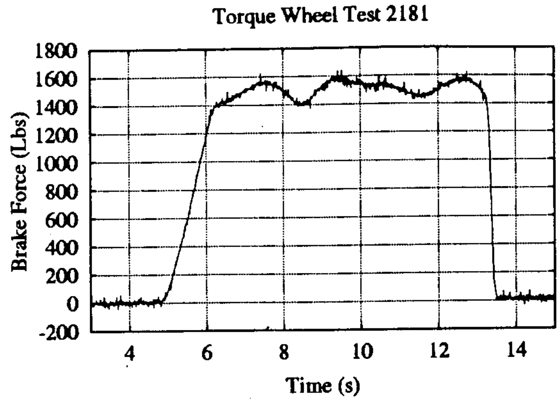
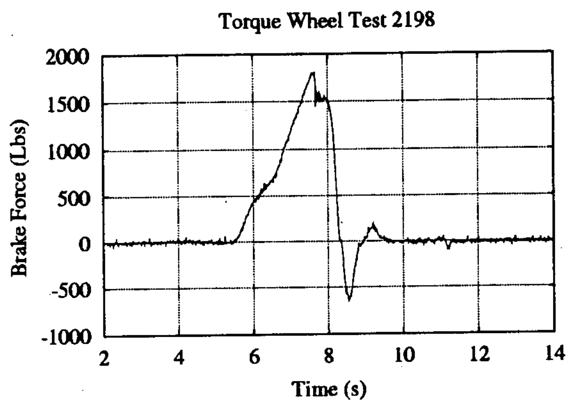


Replicate 3

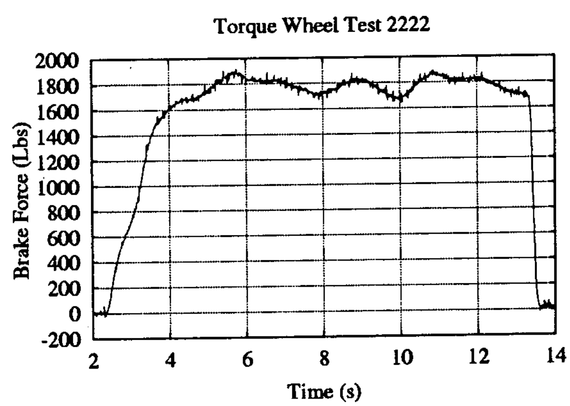
Figure D7. Brake force (collected by the torque wheel) versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the VRTC RD.



Replicate 1

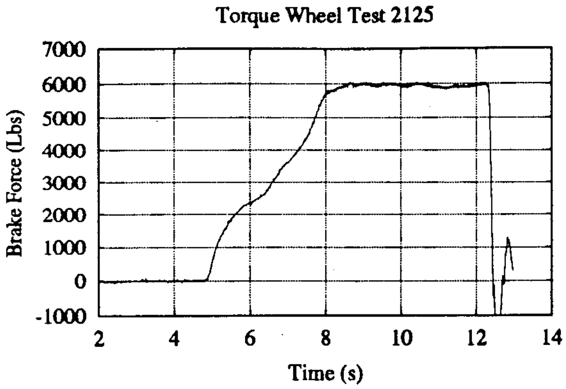


Replicate 2

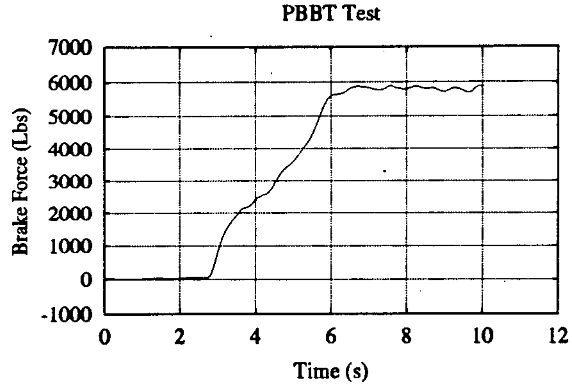


Replicate 3

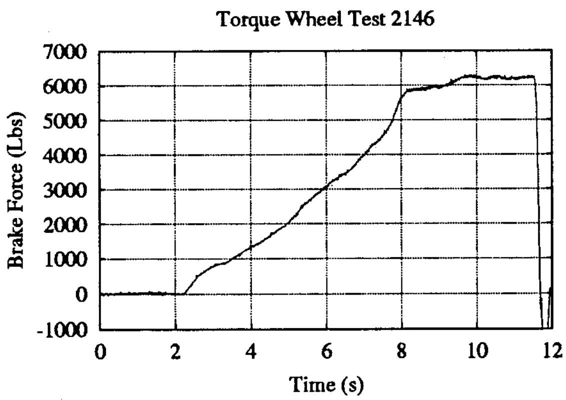
Figure D8. Brake force (collected by the torque wheel) versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the VRTC RD.



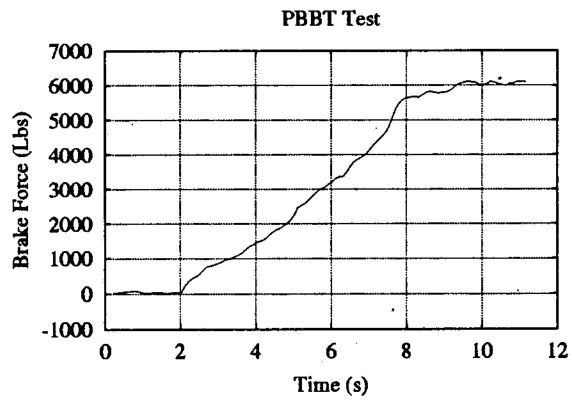
Replicate 1



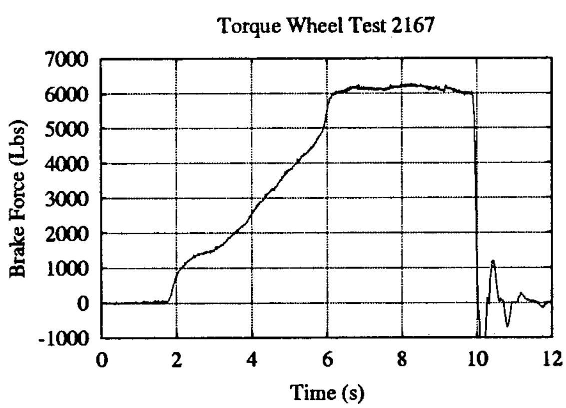
Replicate 1



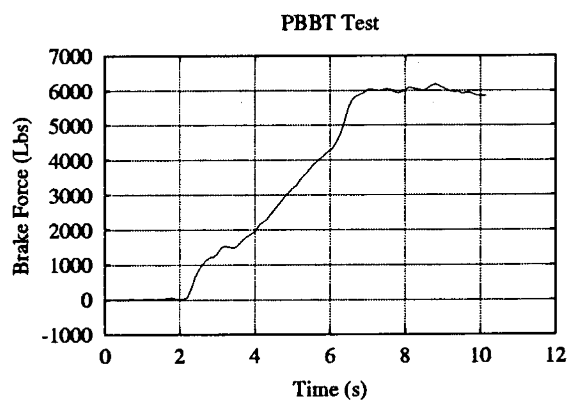
Replicate 2



Replicate 2

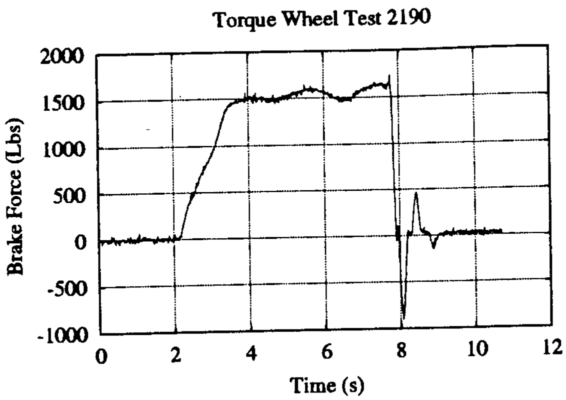


Replicate 3

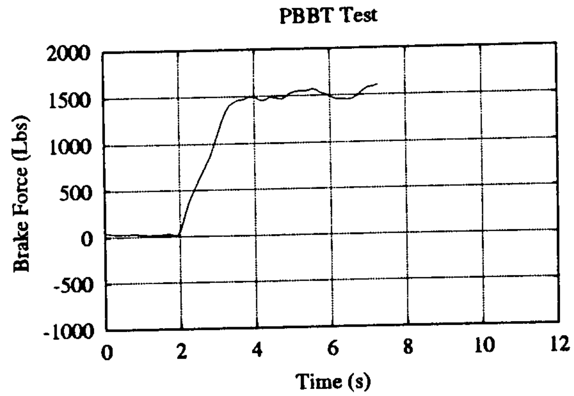


Replicate 3

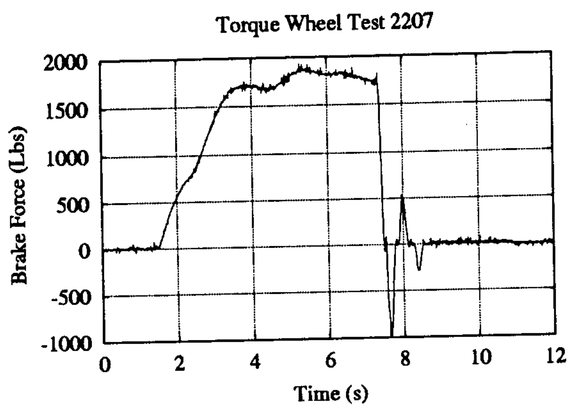
Figure D9. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the RAI In-Ground RD. Left column plots illustrate the torque wheel data. Right column plots illustrate RAI In-Ground RD data.



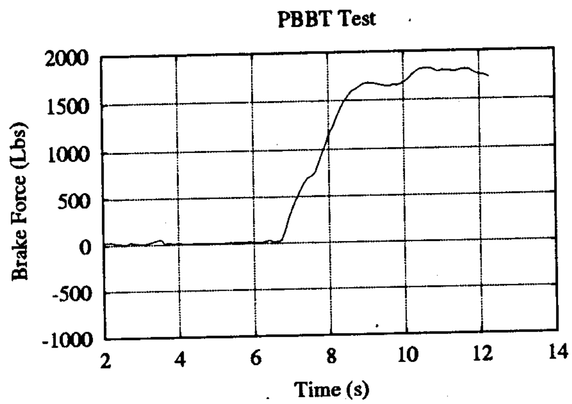
Replicate 1



Replicate 1



Replicate 2



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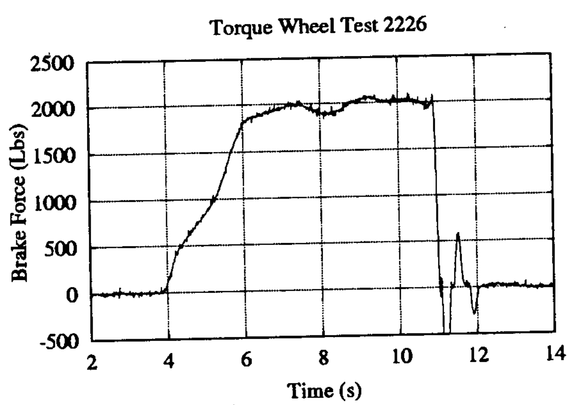

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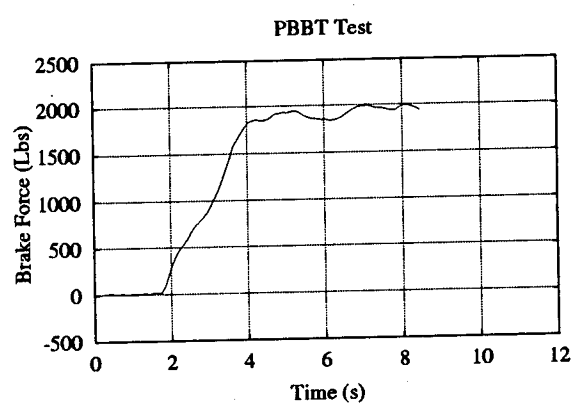
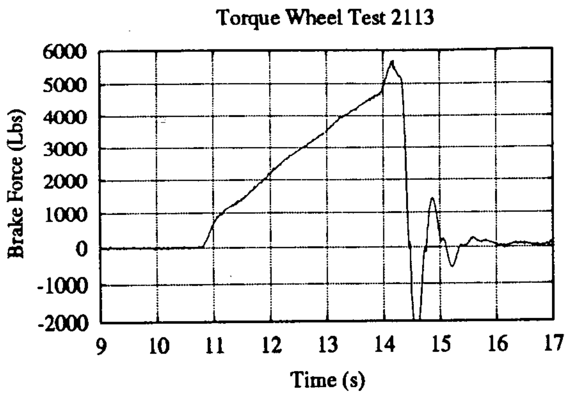
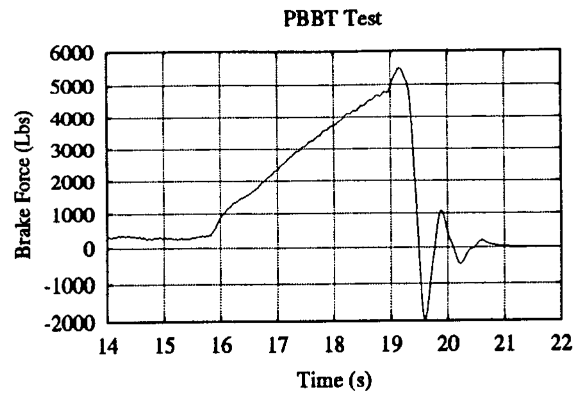


Replicate 3

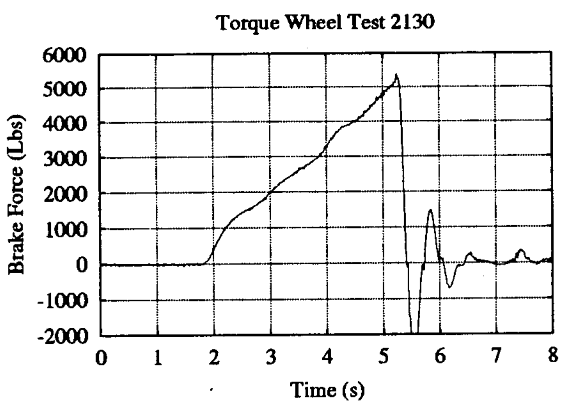
Figure D10. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the RAI In-Ground RD. Left column plots illustrate the torque wheel data. Right column plots illustrate RAI In-Ground RD data.



Replicate 1



Replicate 1



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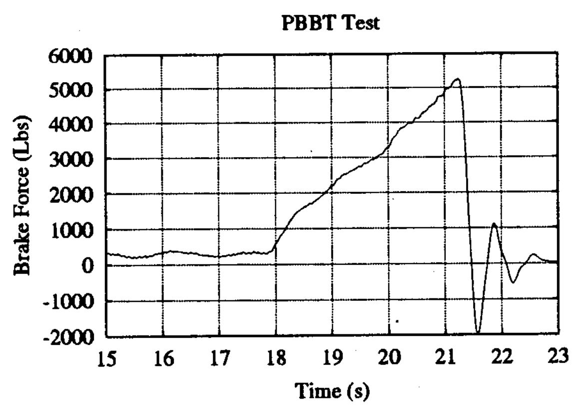

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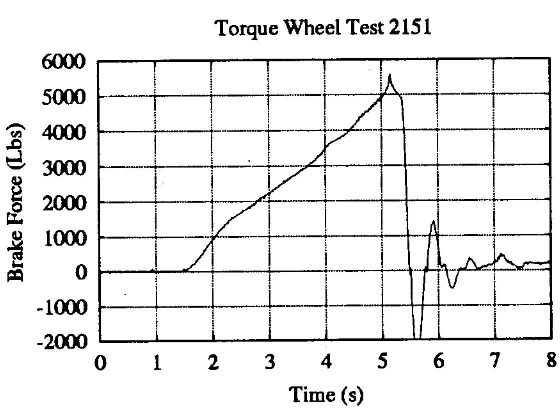

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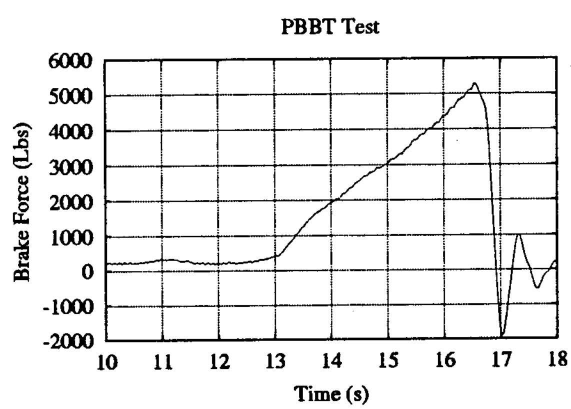
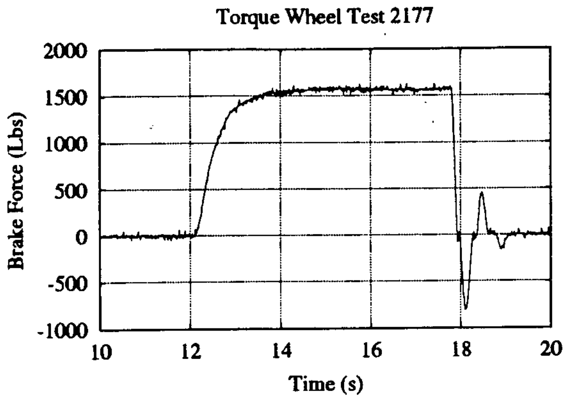


Replicate 3

Figure D11. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the RAI portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate RAI portable RD data.



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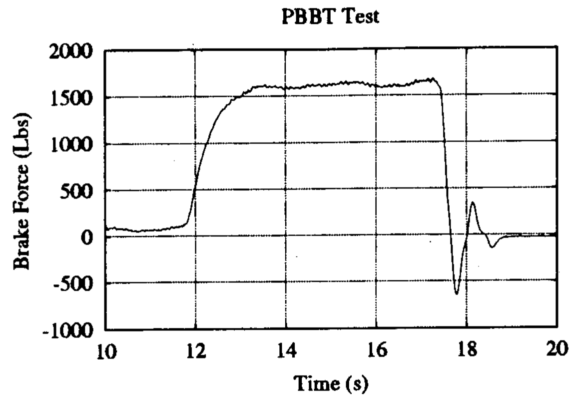

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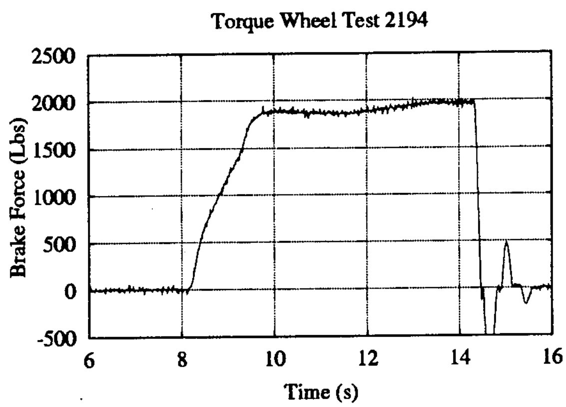

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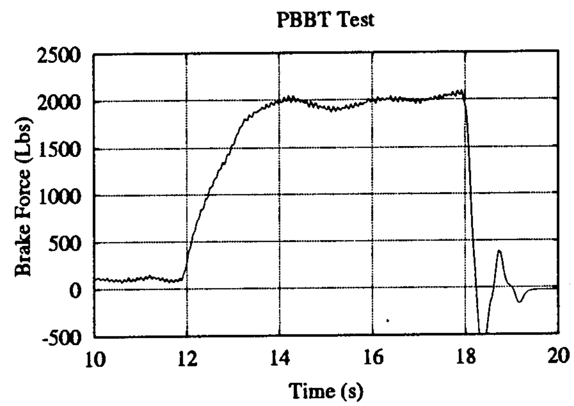

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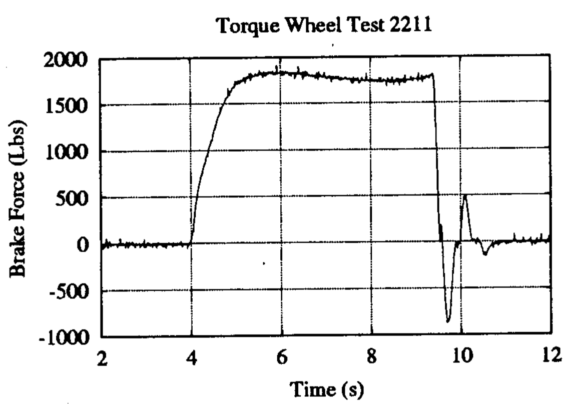
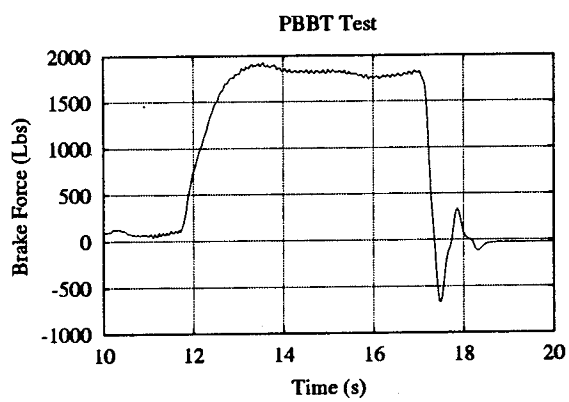
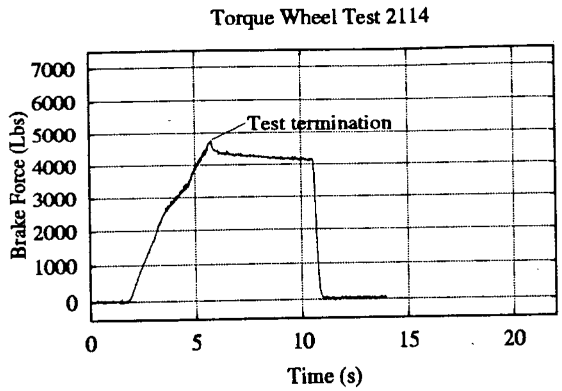


Replicate 3

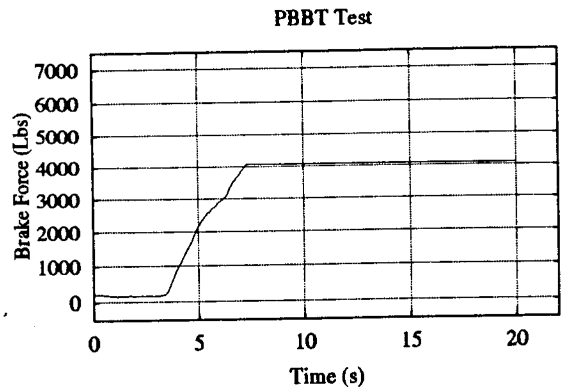


Replicate 3

Figure D12. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the RAI portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate RAI portable RD data.



Replicate 1



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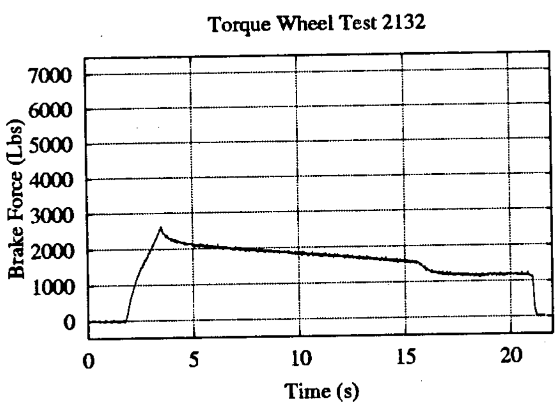

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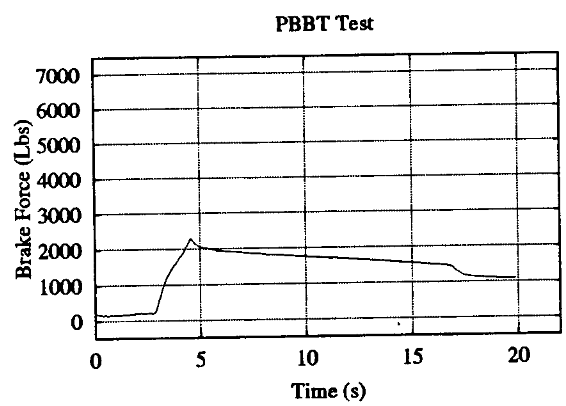

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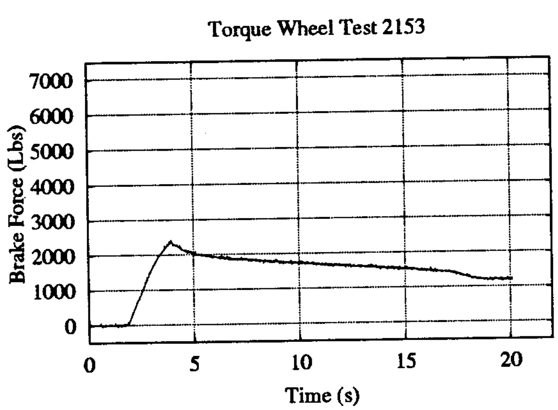
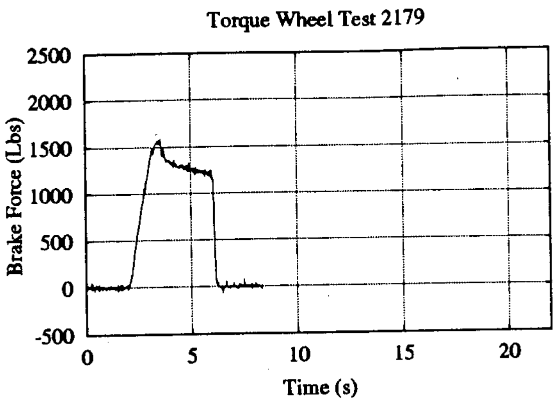


Replicate 3

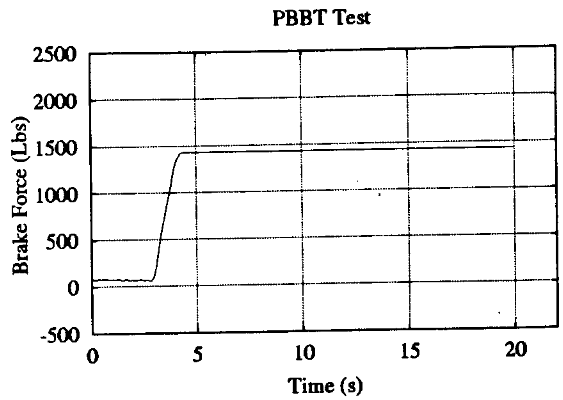
(Data not available)

Replicate 3

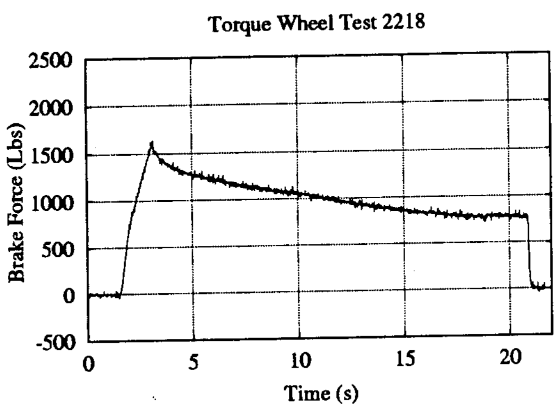
Figure D13. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the VIS portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate VIS portable RD data.



Replicate 1



Replicate 1



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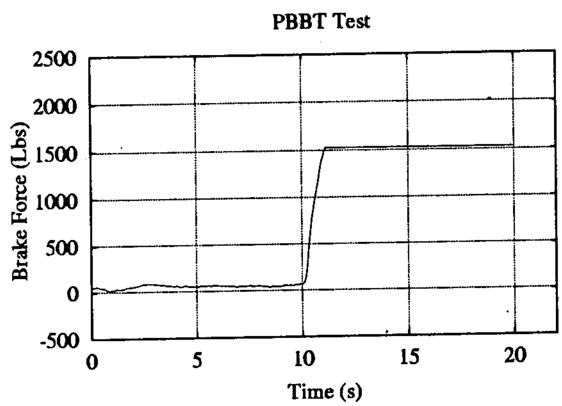

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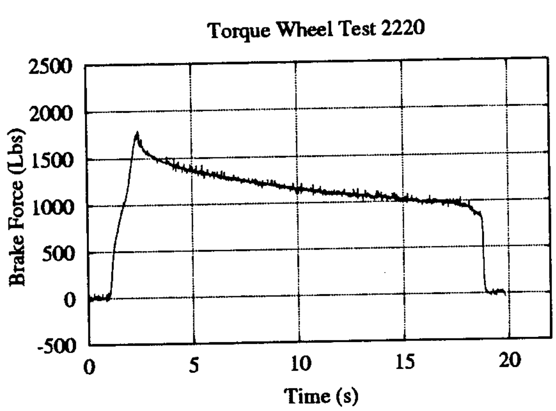

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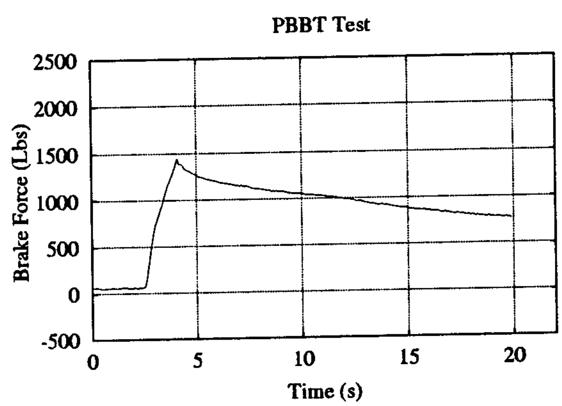


Replicate 3

Figure D14. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the VIS portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate VIS portable RD data.

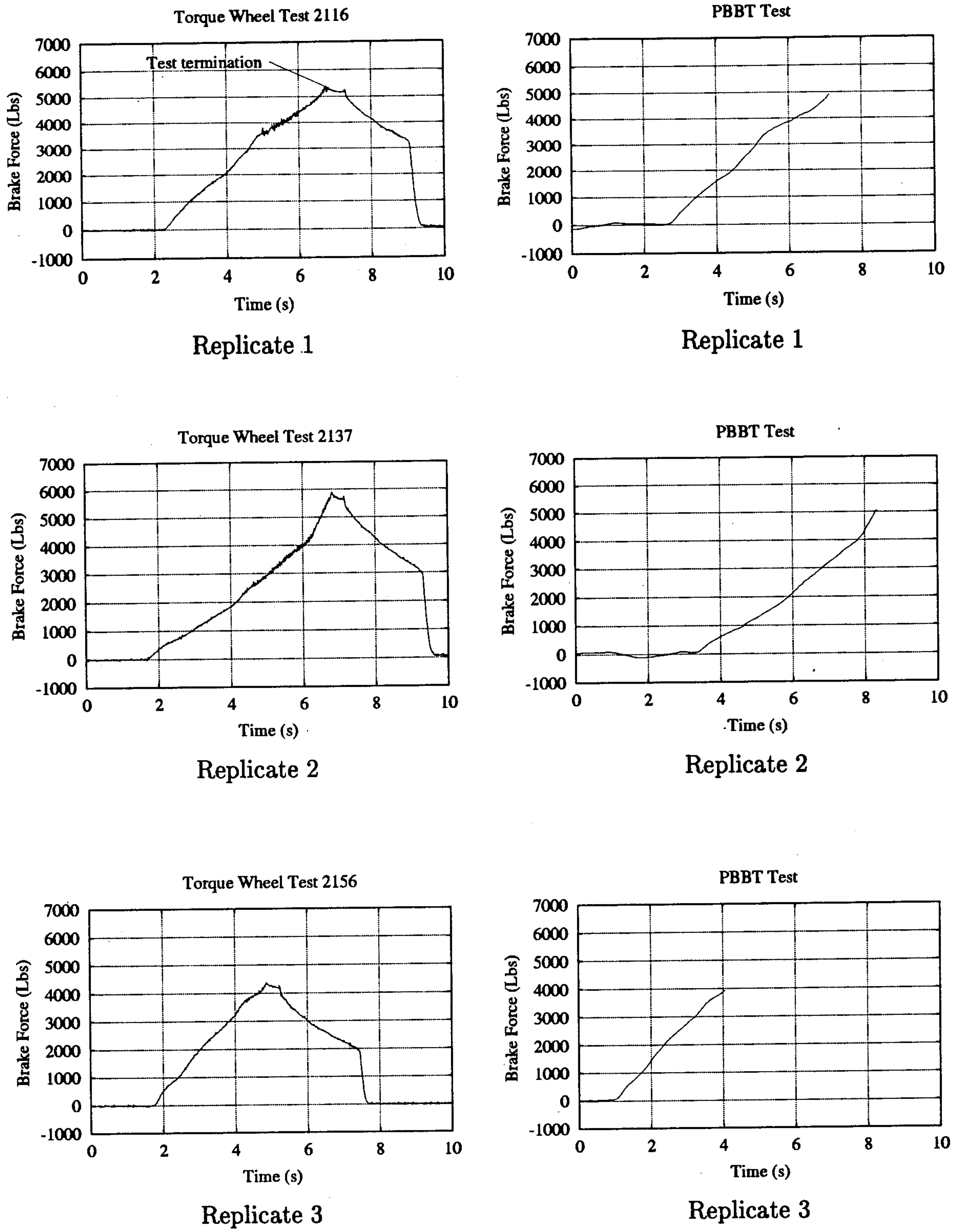
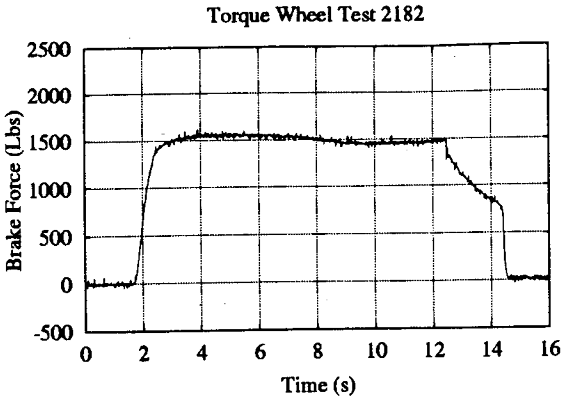
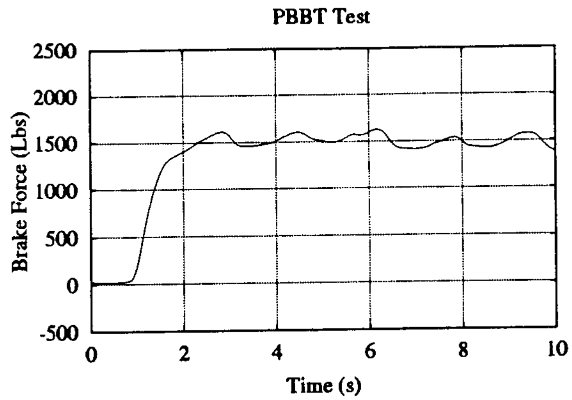


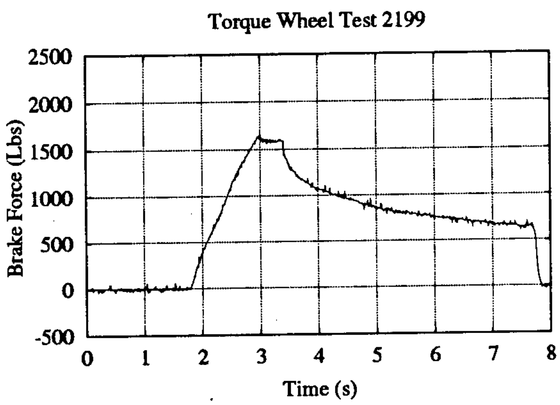
Figure D15. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests with the HEI portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate HEI portable RD data.



Replicate 1



Replicate 1



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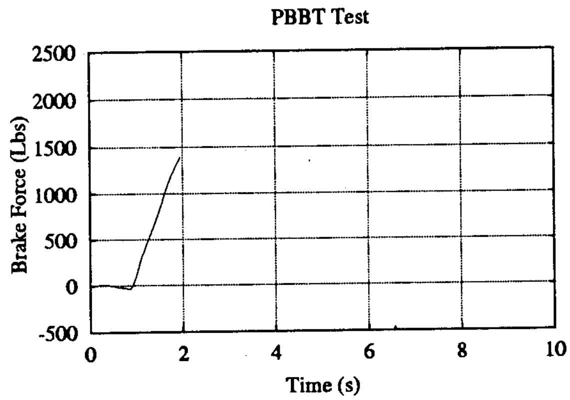

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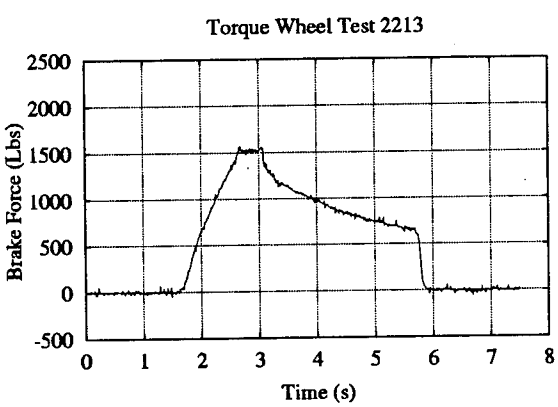

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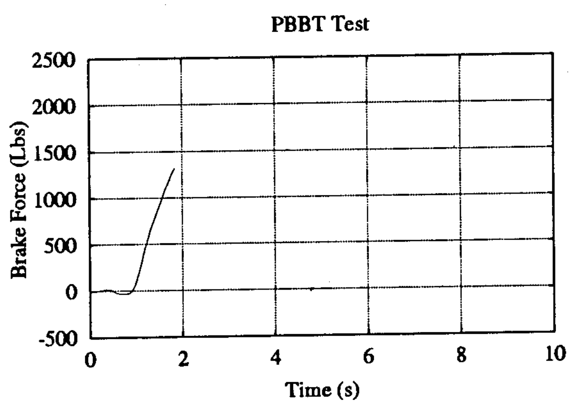


Replicate 3

Figure D16. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests with the HEI portable RD. Left column plots illustrate the torque wheel data. Right column plots illustrate HEI portable RD data.

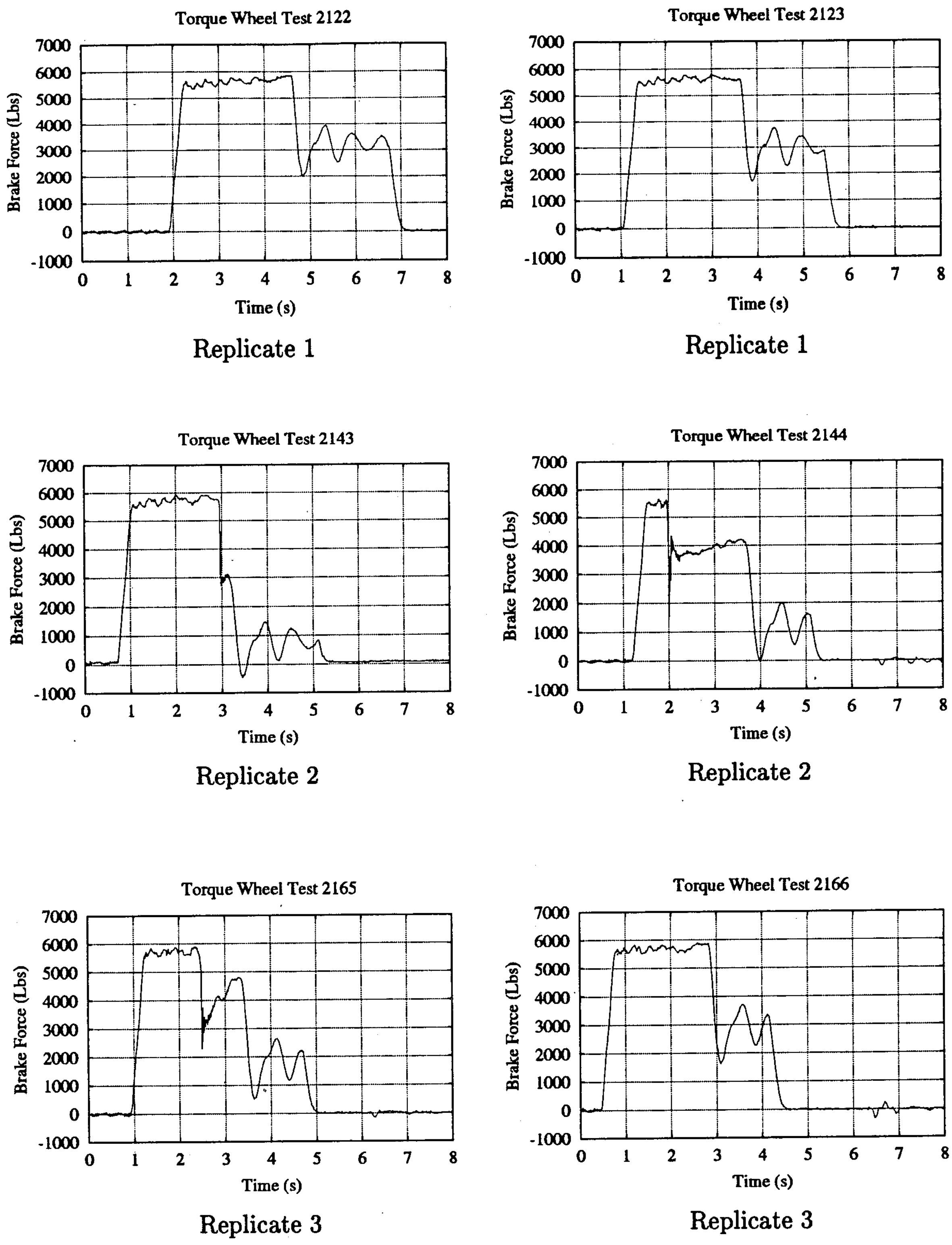
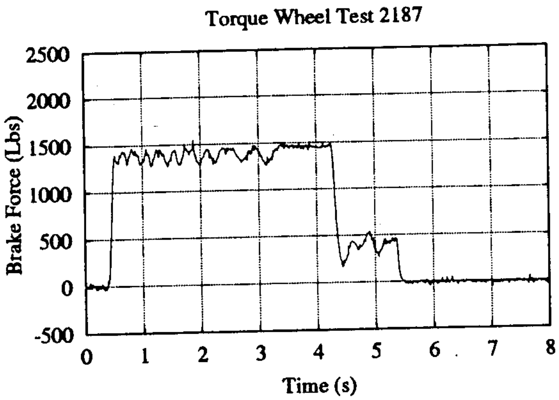
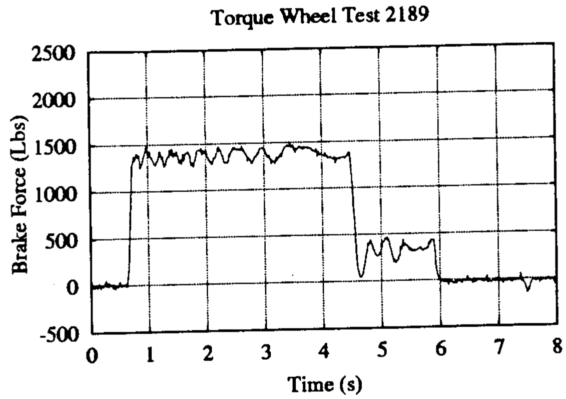


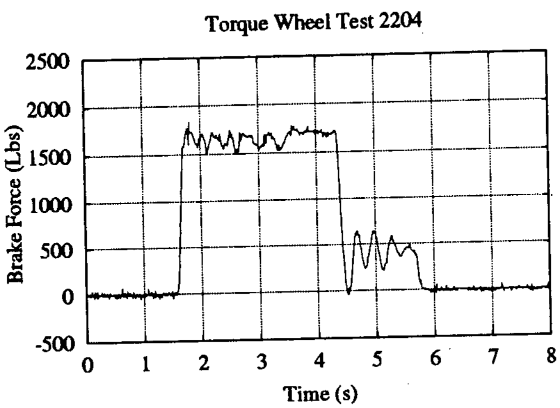
Figure D17. Brake force versus time for wheel 5 of the laden 3S-2 vehicle for 3 replicate tests (2 successive tests in each replication) during 20 mph stops.



Replicate 1



Replicate 1



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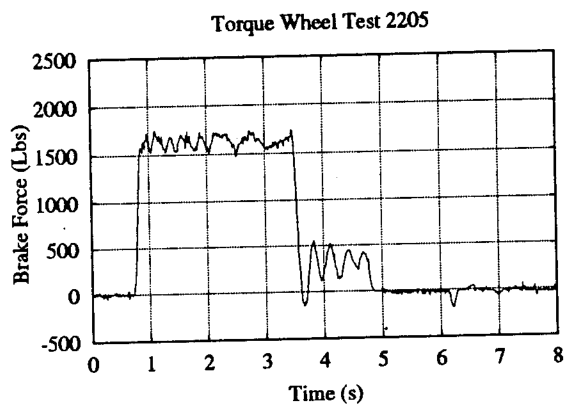
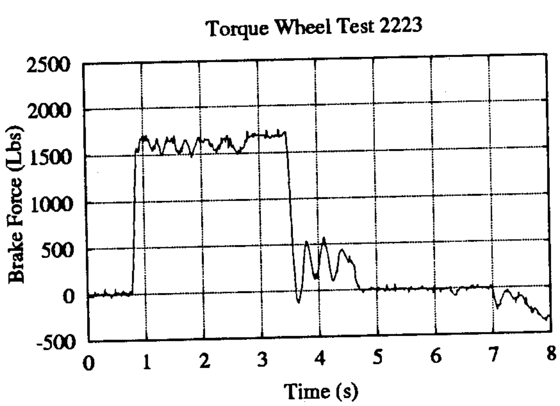
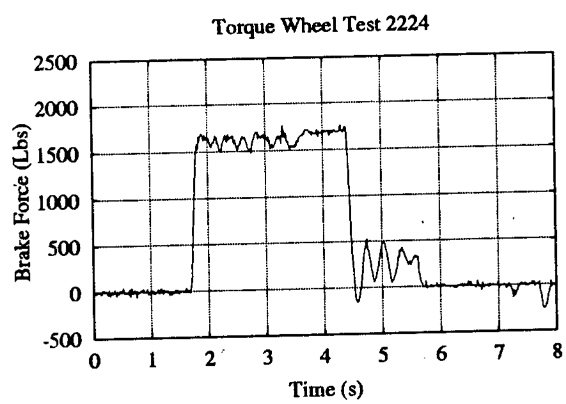


Replicate 2



Replicate 3



Replicate 3

Figure D18. Brake force versus time for wheel 5 of the unladen 3S-2 vehicle for 3 replicate tests (2 successive tests in each replication) during 20 mph stops.

APPENDIX E

PBBT INDIVIDUAL AXLE LOAD MEASUREMENTS:

3-S2 Tractor Trailer Combination

2-Axle Straight Truck

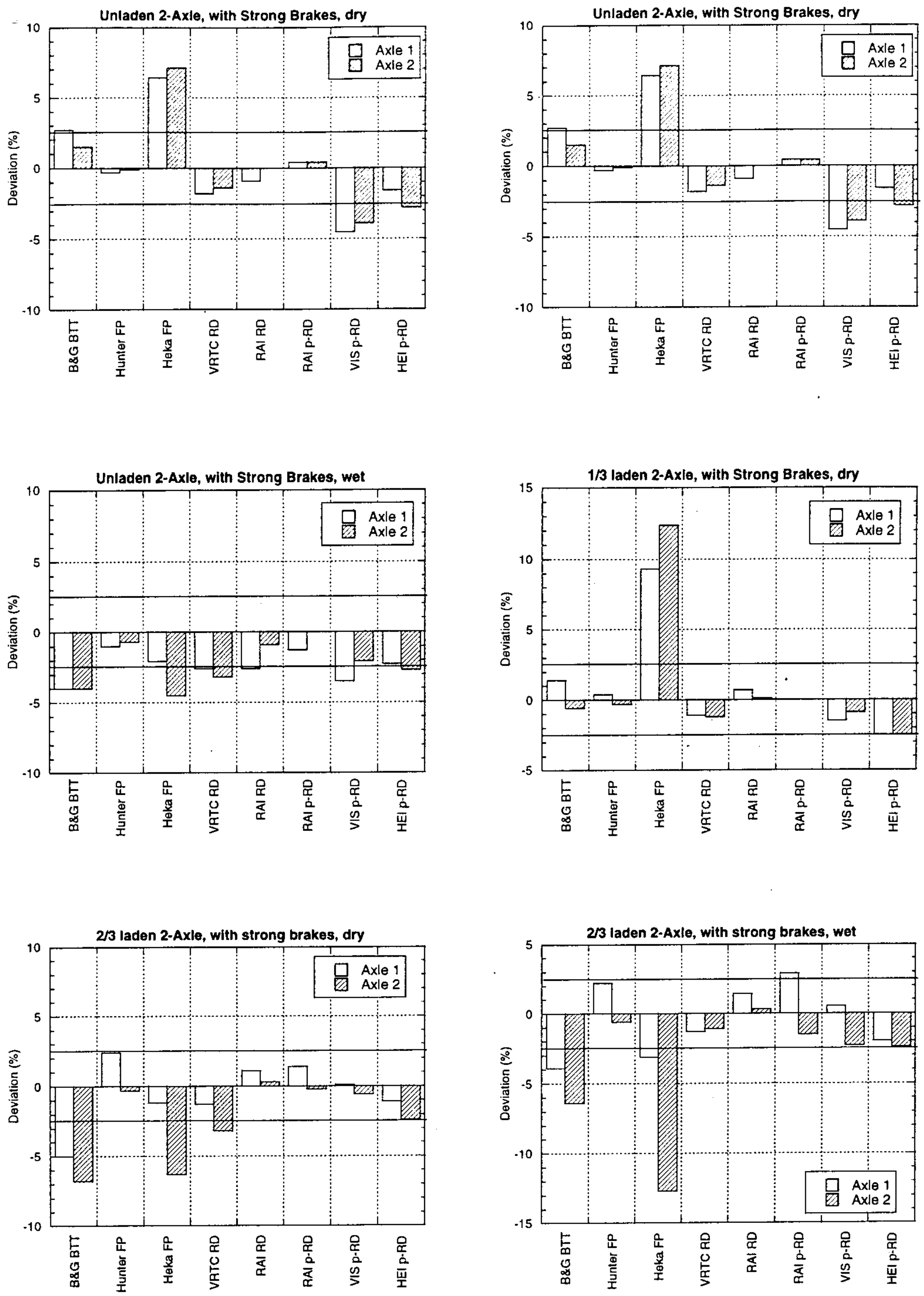


Figure E1. Deviations of Individual Axle Loads from Reference Axle Loads for the 2-axle Vehicle. Reference weights were measured with certified scales. PBBT-reported weight measurements must be 2.5 percent accurate.

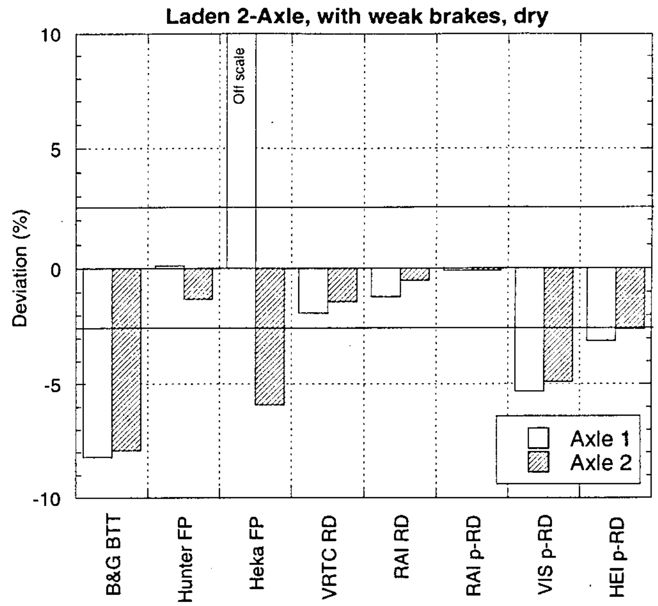


Figure E1 (Continued). Deviations of Individual Axle Loads from Reference Axle Loads for the 2-axle Vehicle. Reference weights were measured with certified scales. PBBT-reported weight measurements must be 2.5 percent accurate.

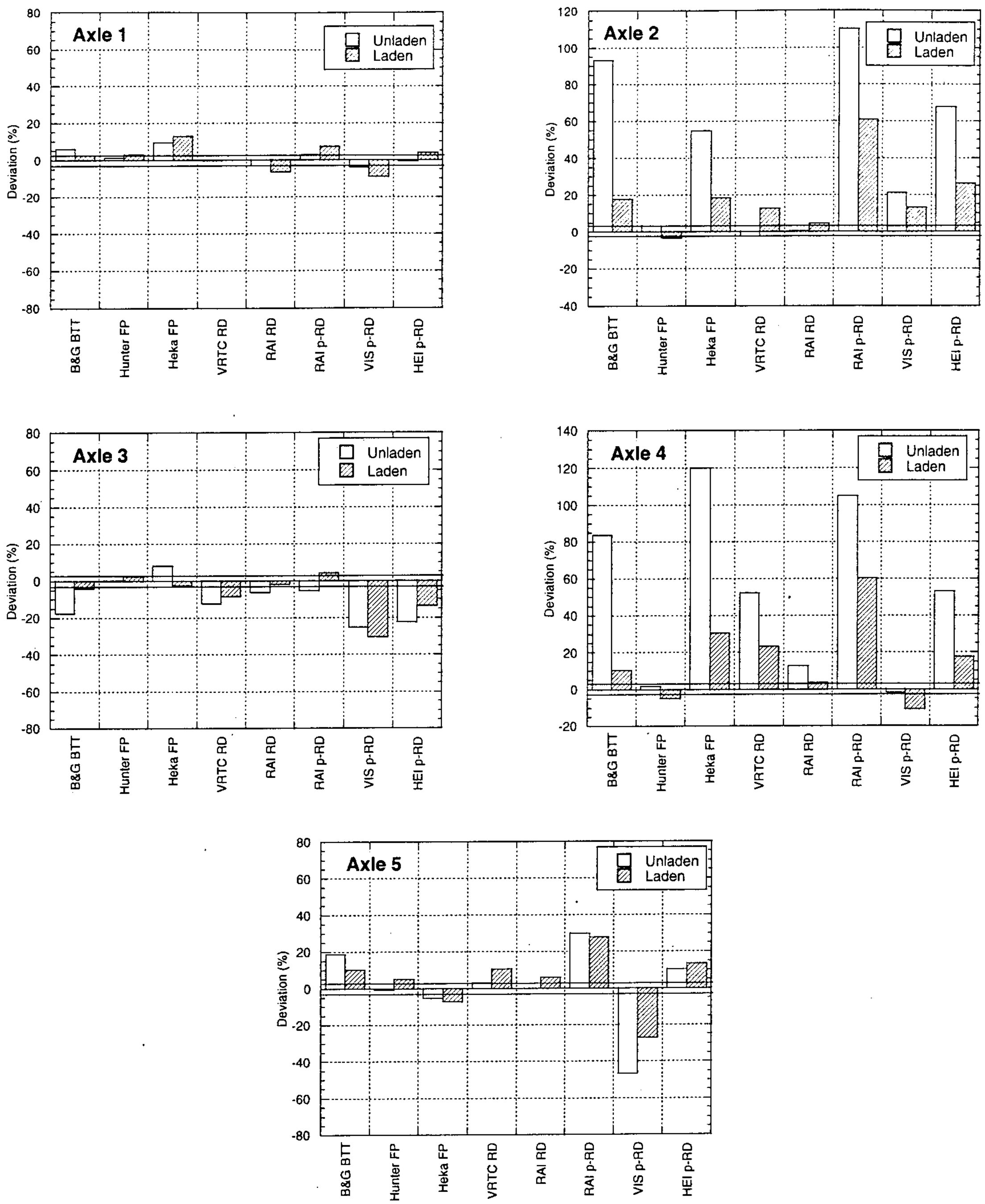


Figure E2. Deviations of Individual Axle Loads from Reference Axle Loads for the 3-S2 Tractor Trailer Combination Vehicle. Reference weights were measured with certified scales. PBBT-reported weight measurements must be 2.5 percent accurate.

APPENDIX F

PARTICIPATING PBBT MANUFACTURERS, VENDORS & REPRESENTATIVES

B&G Engineering (B&G)

Stanley J. Ball
Secretary/Treasurer
B & G Technologies, Inc.
P.O. Box 11177
Prescott, Arizona 86301
Phone: (520) 445-0005
Fax: same as phone
e-mail: **bgtech@primenet.com**

HEKA

Horst Behncke
HEKA
110 North Main St.
P.O. Box 750
Brooklyn, Michigan 49230
Phone: (517) 592-8123
Fax: 8562

Herbert Kallinich
HEKA Auto Test GmBH
Ensisheimer Str. 4
D-79110 Freiburg
Germany
Phone: 07 61 8 1089
Fax: 80
e-mail: **hekausa@modempool.com**

Hicklin Engineering, Inc. (HEI)

Scott Giles
Vice President
Hicklin Engineering
3001 N.W. 104th Street
Des Moines, Iowa 50322
Phone: (515) 254-1654
Fax: 1656
e-mail: **hicklin@hicklin.com**

Hunter Engineering, Inc. (Hunter)

Doug Woolverton
Director
Hunter Engineering Company
995 Plowshare Road
Yardley, Pennsylvania 19067
Phone: (215) 321-0166
Fax: 7119

Radlinski and Associates, Inc. (RAI)

Richard Radlinski
President
Radlinski & Associates, Inc.
3143 County Road 154
East Liberty, Ohio 43319
Phone: (937) 666-5006
Fax: 5010
e-mail: **braketruck@aol.com**

Mogens Norlem
Owner & Technical Manager
BM Autoteknik Moldrup ApS
Erhvervsvej 2
DK 9632 Moldrup
Denmark
Phone: 45 86 69 2022
Fax: 2199

Vehicle Inspection Systems (VIS)

Miles Fuller
Managing Director
Vehicle Inspection Systems
3/6 Maxwell Place
Narelian
Sydney NSW 2567
Australia
Phone: 61 2 4647 6868
Fax: 6568
e-mail: **truckalyser@msn.com**
Mobile: (0418) 670 587

Dave Long
Sales & Marketing Manager
Vehicle Inspection Systems
Suite 200
10200 Pioneer Blvd
Santa Fe Springs CA 90670
Phone: (562) 944 2287
Fax: 5866
e-mail: **dlongvis@earthlink.net**

Bob Fisher
ETCO, Inc.
12790 Stephens Avenue
Tustin, California 92682
Phone: (714) 730-2163
Fax: 2079