FINAL REPORT

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Washington, DC

For:

Task Order #3

On-board Sensors For Determining Brake System Performance Report

Under the

Commercial Vehicle Safety Technology Diagnostics
And Performance Enhancement Program
Contract Number: DTFH61-99-C-00025

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ABSTRACT

The overall objective of this research is to document the performance and operational characteristics of leading-edge technological approaches for monitoring commercial vehicle braking systems. Improved methods and sensors to monitor braking system operation are needed because of the historical link between compromised braking performance and crashes, and the existing state of the practice for inspecting commercial braking systems.

The study focused on the ability of the various sensors to detect abnormalities, defects, and/or misadjustments of the brake system. The study presents a technical examination of the accuracy, responsiveness, resolution, and reliability of the various systems. This knowledge should prove useful to fleet operators in evaluating the capabilities and limitations of alternative approaches to brake sensing, and helpful in determining specifications for future truck purchases. The information should also be useful to brakes system suppliers and commercial vehicle manufacturers that are developing new brake monitoring systems. To this extent, the objectives for the study include providing fundamental research results to industry stakeholders concerning various means of monitoring braking systems.

EXECUTIVE SUMMARY

PROJECT FUNDING

Under Section 5117 of the Transportation Equity Act for the 21st Century of 1998 (TEA-21), Congress required the U.S. Department of Transportation to "conduct research on the deployment of a system of advanced sensors and signal processors in trucks and tractor trailers to determine axle and wheel alignment, monitor collision alarm, check tire pressure and tire balance conditions, measure and detect load distribution in the vehicle, and adjust automatic braking systems". The research program responding to this directive is called the "Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program", (i.e., "CV Sensor Study").

This CV Sensor Study was completed as a task under the CV Sensor Study Program.

BACKGROUND AND RATIONALE

The significant number of trucks operating on the highway with brake defects is a situation that has plagued the industry for years, despite attempts by many different groups to address the problem. Commercial vehicle inspection data shows that about 19% of all inspected vehicles—nearly one in five—were found to have one or more brake defects.[1] In 2002, the Commercial Vehicle Safety Alliance Roadcheck 2002 conducted a 72-hour inspection of 49,032 vehicles in Canada, Mexico, and the United States, and placed 22.1% of them out of service due to various defects and violations. Brake-related issues accounted for 53.3% of these vehicles being placed out of service.[2]

It is well understood that commercial vehicle braking system design and operation is directly linked to stopping distance, handling, and therefore overall safety. Properly maintained and performing brakes are clearly the driver's best ally in preventing and mitigating crash situations. Although vehicle defects on large trucks can rarely be pinpointed as the causative factors in crashes, when defects did occur, faulty brakes tended to be at fault.

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[1] The 1998 Motor Carrier Management Information System (MCMIS) Inspection File is operated and maintained by the FMCSA. The MCMIS Inspection File contains the results of all driver-vehicle safety inspections of interstate commercial motor vehicles performed by States participating in the Motor Carrier Safety Assistance Program (MCSAP). In 1998, 1.9 million inspections of interstate vehicles were conducted.

[2] Roadcheck 2002 conducted June 4-6, 2002, inspected 49,032 commercial vehicles at roadside inspection sites across Canada, Mexico, and the United States utilizing the CVSA Inspection Procedures. The Commercial Vehicle Safety Alliance is a non-profit organization of Federal, State, and provincial government agencies and representatives from private industry in Canada, Mexico, and the United States dedicated to improving commercial vehicle safety. www.cvsa.org

Optimally adjusted braking systems could help prevent or mitigate crashes even when the braking system itself was not the initial cause of the crash. Eliminating or mitigating key mechanical problems, including brake-related issues, would likely yield a significant reduction in the number and seriousness of injuries sustained in commercial vehicle related crashes.

STUDY OBJECTIVE

The overall objective of the research study was to document the performance and operational characteristics of leading-edge technological approaches to monitoring commercial vehicle braking systems. The study focused on the ability of the various sensors to detect abnormalities, defects, and/or misadjustments of the brake system. The brake sensing technologies examined in this study included:

- Anchor strain measurement to determine brake force at each wheel,
- Air chamber stroke measurement to assess brake adjustment at each wheel,
- Wheel slip measurement (using wheel speed sensor data) to determine brake force at each wheel,
- Deceleration measurement to determine total vehicle braking force (limited results due to system software issues), and
- Temperature measurement to determine brake “work” or energy balance.

There are safety benefits associated with having a sensor or “sensor package” onboard the commercial vehicle that would objectively and accurately measure the stopping potential of the vehicle, and dynamically and continuously measure the actual braking force at each wheel. Such a system would potentially have three primary applications or benefits:

1. Warning the driver and/or maintenance personnel if braking ability was degraded to an unsafe level—and help with diagnosis of the problem.
2. Providing information to enforcement personnel for use during roadside inspections.
3. Integrating brake performance sensing technologies with an electronically controlled brake system (ECBS) in a “closed-loop” fashion. The brake force information might be used to balance the braking action at each wheel to improve service life, and/or provide an additional input for controlling braking action at each wheel during emergency situations.

OVERVIEW OF PROJECT APPROACH

The various systems were installed (simultaneously) on a conventional tractor-trailer combination vehicle and tested under controlled braking maneuvers on a test track. (All work was conducted at the Transportation Research Center (TRC) in Columbus, Ohio by Radlinski and Associates, Inc.) The output of the various brake sensor systems could then be compared on the same vehicle under identical testing conditions. This approach facilitated objective, accurate comparison of the sensors, and eliminated problems associated with test procedure repeatability when comparing different systems.

In addition, numerous industry stakeholders were contacted and interviewed during the study—including suppliers of the various technologies examined. The companies and individuals contacted were extremely helpful in compiling the information contained in this report.

SUMMARY OF RESULTS

The following are key observations and results from the testing of the aforementioned sensor technologies.

Anchor Pin Strain Gauges

Pre-production instrumented anchor pins (interchangeable with conventional S-cam brake anchor pins) fitted with strain gauges are capable of measuring the shear stresses applied to the anchor pins of the drum brake assemblies used on heavy-duty S-cam trucks and buses. Each anchor pin is fitted with two strain gauges orientated 90 degrees apart, in the "X" and "Y" direction. The test vehicle was equipped with four instrumented anchor pins, two on each of the intermediate axle brake assemblies (one on the upper/secondary and one on the lower/primary brake shoes).

- Track testing shows a highly predictable relationship between force data generated by instrumented (strain-gauged) anchor pins and the vehicle's deceleration rate. Instrumented anchor pin force is therefore an accurate measure of a vehicle's braking performance.

- Instrumented anchor pins can accurately detect brake deficiencies in specific (individual) wheel assemblies, including out-of-adjustment, disconnected, and/or oil-soaked shoe linings. They can also measure the effect of an out-of-adjustment brake on the other (properly adjusted) brakes on a vehicle. This capability lends itself for application to advanced brake balancing control schemes that may be possible with electronic controlled braking systems.

- Instrumented anchor pins can accurately detect even low brake forces. By resolving the resultant force into the "X" (friction force) and "Y" (normal force) directions, the instrument anchor pins can differentiate between an out-of-adjustment brake and a brake with oil-soaked shoe linings. With an oil-soaked lining, less force is generated in the "X" direction when compared to an oil-free lining. This capability could likely be leveraged to improve diagnostic efficiency and overall brake maintenance planning.

- The instrumented anchor pins performed reliably throughout the testing.

Stroke Sensors

The test truck was equipped with two commercially available stroke sensor packages and a two laboratory-grade linear potentiometers mounted on the intermediate drive axle to measure stroke. Key observations and conclusions on the commercial brake stroke sensor packages, and on the utility of monitoring stroke in general, are as follows:

- Commercial brake chamber stroke sensor packages can detect brake deficiencies. Their accuracy varies depending on the load, deceleration rate, and type of brake deficiency. Both commercial systems tested had the most difficulty detecting brake deficiencies with the trailer unloaded and at low deceleration rates; however, both manufactures state that these systems are intended to detect overstroke conditions during hard braking applications.

- In-cab displays featuring indicator lights for all 10 brakes provide the driver with valuable real-time data on the overall condition of the vehicle's braking system.

- Unlike the instrumented anchor pins, brake stroke monitoring cannot differentiate between out-of-adjustment brakes and oil-soaked shoe linings. For example, with oil-soaked shoe linings the linear potentiometers recorded an overstroke condition.

- The resolution and accuracy of stroke sensors make them well-suited for use in detecting brake maintenance needs and potential brake safety issues—but they are probably not appropriate for use in brake balancing systems.

Wheel-Speed Sensors

Wheel-speed sensors are a standard component of anti-lock braking systems (ABSs) used on heavy-duty trucks and buses. ABS wheel-speed sensors can be used to measure individual wheel slip by comparing the calculated speed of each wheel to the calculated average for all wheels—or to some other "actual" speed reference such as a transmission signal or a contactless fifth wheel that measures ground speed.

- In general, ABS wheel-speed sensors are highly accurate and track closely with "actual" vehicle speed as measured by an instrumented fifth wheel.

- Wheel-speed sensors are sufficiently accurate to detect grossly out-of-adjustment and disconnected brakes. Wheel-speed sensors do not provide sufficient accuracy to detect brakes that are 1/8-inch or less beyond the readjustment limit.

- Wheel-speed sensors are sufficiently accurate to detect a problem due to oil-soaked brake linings. However, unlike instrumented anchor pins, wheel-speed sensors cannot differentiate between out-of-adjustment brakes and oil-soaked linings.

- Wheel-speed data broadcast on the J1939 network was significantly less accurate than data from actual ABS wheel-speed sensors.

- Although the wheel-speed sensor data broadcast over the J1939 network was less accurate than data from actual sensors, it was sufficient for detecting grossly out-of-adjustment, disconnected, and poorly performing brakes.

Brake Shoe Thermocouples

Standard Type J thermocouples were installed and tested as part of this program. These tests had two objectives: (1) evaluate the thermocouples to determine whether they could reliably be used to detect brake defects, and (2) use the thermocouples to assist in evaluating the other sensor "packages". Thermocouples were mounted at varying depths within the shoe lining to test their sensitivity for determining brake deficiencies.

- Response time of thermocouples in general is not sufficient to detect brake problems during singular, discrete braking events.

- Because of the unpredictable variations in initial brake temperature, the comparatively slow response time of thermocouples, and the general inaccuracies inherent with thermocouples, their ability to detect and differentiate brake deficiencies during discrete braking events was found to be very limited.

- During the simulated mountain testing, temperature patterns were detected and used to identify various brake deficiencies.

POTENTIAL SENSOR APPLICATIONS

Several applications for the sensor technologies were identified during the study, and described in this section.

Brake Balance Systems

The instrumented anchor pins were proven to accurately detect brake deficiencies and provided sufficiently accurate data to measure the increase in work done by the remaining brakes on a vehicle. This makes them ideal for use in brake balance applications with advanced "brake-by-wire" technologies. In this application, brake pressure could be tailored to individual brakes based on brake force output readings. The benefits include increased brake life due to improved brake lining wear and the ability to perform minor brake adjustments in real time.

Wireless Transfer of Brake Data

Companies in the transportation industry market products capable of wirelessly transferring maintenance data from the vehicle to a central data processing computer in a maintenance yard. These systems are currently configured to wirelessly transfer engine and transmission fault codes, for example, from the vehicle's network. The information generated from the commercial stroke sensor packages and instrumented anchor pins could be broadcast to the vehicle's network and similarly transferred to the maintenance yard. The data could assist in improving vehicle brake safety, scheduling brake work, and tailoring brake rebuild schedules.

Improving Regenerative Braking in Hybrid Applications

Many hybrid propulsion manufacturers currently use an open-loop approach to combining regenerative braking and friction braking. Basically, the initial application of the brake treadle valve is regenerative. Exceeding a preset limit energizes the friction brakes. This open-loop control methodology results in an arbitrary amount of regenerative braking force being applied, and less-than-optimal energy being captured during a braking event. Instrumented anchor pins can measure the beginning of a friction braking application and its applied force. By factoring in this measurement data, regenerative braking algorithms can be "closed-loop" in nature. A closed-loop regenerative braking system, although still isolated from the service brakes, can optimize the braking energy recovered as well as reduced emissions, improve brake wear, and improve fuel economy.

1. INTRODUCTION

This chapter is organized as follows:

- Background on the Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program
- Background and Rationale for this Research Project
- Current State of Brake Sensor Technology Development
- Project Objectives
- Overview of Process

1.1 CV SAFETY TECH. DIAGNOSTICS AND PERFORMANCE ENHANCEMENT

The purpose of this program (i.e., the "CV Sensor Study) is to "define performance requirements, assess benefits, and accelerate deployment of driver and vehicle assistance products and systems and, in particular, advanced sensor and signal processors in trucks and tractor trailers with an emphasis in onboard diagnostic and improved safety-related products."

The study emphasizes soliciting input from key industry stakeholders (fleet operators, manufacturers, and suppliers) on potential research initiatives, testing and demonstration procedures, equipment specifications, and data collection and reporting methodologies. The study is focused on conducting research that complements (rather than duplicates) efforts by private industry. Objectives of the research include evaluating the probable impact of selected vehicle technologies on improving overall trucking safety, and assessing their cost savings potential and/or operational benefits, thus helping to create market demand and encourage commercialization.

The following tasks were completed to help identify possible research areas:

- Conducting an extensive literature search of relevant technical journals and databases;
- Conducting individual interviews and discussions with representatives from truck and trailer manufacturers, fleet operators, owner operators, and industry suppliers, as well as staff at National Highway Traffic Safety Administration (NHTSA), FMCSA, and Federal Highway Administration (FHWA) who are involved in commercial vehicle safety research; and
- Convening a meeting of key industry stakeholders to review candidate research areas and make suggestions regarding future work under the CV Sensor Study.

As a result of this background research and interviews, the following candidate areas of research were identified:

- Brakes and related controls
- Tire inflation and condition monitoring systems
- Truck and tractor alignment ("dynamic alignment")
- Testing and analysis of high-speed data bus networks (J1939)
- Cost, benefits, and implementation issues
- "Active suspensions" and related associated with Event Data Recorders suspension research
- Advanced vehicle diagnostic and prognostic tools
- Issues related to implementation of "Smart Copilot" onboard systems.

This list is meant to be a "work in process" and to serve as a starting point for directing research. Project team members continue to monitor and assess new technologies that could improve vehicle safety, and to engage industry in discussions regarding the appropriateness of specific research projects. **The focus of this report is on the first research area on the list: Brakes and related controls.**

1.2 BACKGROUND AND RATIONALE FOR THIS STUDY

Improving methods or sensors to monitor braking system operation is justified by the historical link between compromised braking performance and crashes, and by the existing state of the practice for inspecting commercial braking systems. These issues are examined in this section.

1.2.1 Braking System Operation and Safety Implications

It is well understood that commercial vehicle braking system design and operation is directly linked to stopping distance, handling, and therefore overall safety. Brakes that are properly maintained and perform well are clearly the driver's best ally in preventing and mitigating crashes.

Yet although there is clearly a strong relationship between braking system performance and safety, quantifying this relationship is difficult. Data from the following databases can be used to identify trends:

- The National Automotive Sampling System/General Estimate System (NASS/GES), operated and maintained by NHTSA; and

- The Motor Carrier Management Information System (MCMIS) Inspection File, operated and maintained by the FMCSA.

The NASS/GES database comprises a nationally representative sample extracted from police traffic crash reports. For 1998, there were 55,562 crash records in the GES database; of these, 10,511 represented crashes involving large trucks.

Most crashes are not found to be the result of mechanical flaws or component failures, but rather are seen as resulting from driver error. Nevertheless, for each crash record within the GES database, the investigator makes an assessment about whether mechanical flaws might have contributed to the cause of the crash. When a mechanical flaw may have existed, an effort is made to identify the pertinent defect category: tires, brake system, steering system, suspension, etc. These data are recorded in the GES under "Vehicle Contributing Factors"

Where vehicle defects on the truck were identified as possible contributing factors, these defects most frequently involved brakes or tires. As shown in Exhibit 1.1, **when vehicle defect was a likely factor, an estimated 36 percent of 1998 NGA-reportable crashes identified the braking system as the factor involved.**

Exhibit 1.1 - Vehicle-based Contributing Factors in CV Crashes

Vehicle Factor	1998 Estimated Reportable Crashes	% Reportable Crashes
Brake System	3,574	36.8%
Tires	2,037	20.9%
Steering System	538	5.5%
Power Train	384	4.0%
Wheels	307	3.2%
Trailer Hitch	231	2.4%
Other Lights	77	0.8%
Mirrors	38	0.4%
Signal Lights	38	0.4%
Other Vehicle Factors	1,576	16.2%
No Details	922	9.5%
TOTAL	9,723	100.0%

As shown in Exhibit 1.2, (again using the NASS/GES data), crashes involving the brake system as a contributing factor accounted for almost half (49%) of all injuries associated with vehicle crashes. In addition, Exhibits 1.1 and 1.2 show that 19.4% (1,883 of 9,723) of all CV crashes involving vehicle defects were brake system related.

Exhibit 1.2 - Injuries in Crashes Where "Vehicle Defect" was a Contributing Factor

Vehicle Factor	1998 Estimated Injuries	% Injuries
Brake System	1,883	49.0%
Tires	807	21.0%
Steering System	115	3.0%
Other Vehicle Factors	653	17.0%
No Details	384	10.0%
TOTAL	3,843	100.0%

How prevalent are various vehicle defects among the population of large trucks? The MCMIS Inspection File contains the results of all driver-vehicle safety inspections of interstate commercial motor vehicles performed by States participating in the Motor Carrier Safety Assistance Program (MCSAP). In 1998, 1.9 million inspections of interstate vehicles were conducted. The results from that survey are summarized in Exhibit 1.3

Exhibit 1.3 - MCMIS Inspection Data: 1998

Vehicle Defect	Number of Inspected Vehicles With Defects	Percent Total Vehicles
Brakes	355,814	18.7%
Tires	180,703	9.5%
Suspension	79,948	4.2%
Steering Mechanism	40,214	2.1%
Other Vehicle Defects	759,351	39.9%
Inspections w/ No Vehicle Defects	485,990	25.6%
TOTAL	1,902,020	100.0%

In 1998, three out of every four inspections resulted in the detection of one or more vehicle defects. Of all inspected vehicles, 19% were found to have one or more brake defects.

Having a significant number of trucks operating on the highway with brake defects is a situation that has plagued the industry for years, despite attempts by many different groups to address it. The problem is not just limited to trucks, but also includes commercial buses and even school buses, as evidenced by accident investigations conducted by the National Transportation Safety Board (NTSB).

In summary, although vehicle defects on large trucks can rarely be pinpointed as the causative factors in crashes, when defects did occur, brakes tend to be at fault. Furthermore, optimally adjusted braking systems could have helped prevent or mitigate crashes even when the braking system was not the initial cause of the crash. Eliminating or mitigating key mechanical problems, including those related to brake systems, could likely prevent a significant number of injuries and save many lives annually.

1.2.2 Brake System Inspections and Performance Monitoring

The Federal Motor Carrier Safety Regulations (FMCSR) Parts 393 and 396 place the primary burden for checking brake performance on the driver. The driver is supposed to inspect the brakes every day before starting a trip and to write-up any problems experienced during his trip. Currently, the driver is, in effect, the primary "transducer" for assessing brake performance in commercial vehicle operations.

The visual pre-trip inspection for brakes specified in the FMCSR Parts 393 and 396 is problematic for two basic reasons:

1. It is not practical (as evidenced by the fact that it is not typically performed)
2. It does not assess or measure brake performance, it is simply a visual inspection of the various braking system components.

Furthermore, during normal driving and stopping at low- to mid-level deceleration rates, it is very difficult for a driver to tell if there is a problem with the brakes that could affect stopping performance in emergency or high-demand braking situations. Determining if there is a problem is difficult because of the valving used in air-braked vehicles. The driver could make a "test stop" at a high deceleration level, which would provide a better measure of brake performance, but the results would still be very subjective.[3]

Commercial vehicle need to have a sensor or "sensor package" on board that can objectively and accurately assess the stopping potential of the vehicle by dynamically and continuously measuring the actual braking force at each wheel. Such a system would potentially have three primary applications or benefits:

1. Warning the driver and/or maintenance personnel if braking ability was degraded to an unsafe level, and help with diagnosis of the problem.

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[3] Note: The need to make a relatively hard brake application to detect improper brake adjustment is due to the non-linear characteristic of a brake that is out of adjustment. This would be true for drum brakes as well as disc brakes since both use the diaphragm type of air brake chamber that reduces its force output in a non-linear fashion as its stroke increases. At low braking levels (i.e. low brake pressure), brake output is not affected unless the brake is grossly out of adjustment. It is only at high brake pressures, such as those used in an emergency stop, that the low brake force output becomes obvious. The fact that a driver cannot easily tell that his brakes are out of adjustment until he needs to make an emergency stop is likely the reason that out-of-adjustment brakes are such a common problem with commercial air-braked vehicles.

2. Providing information for enforcement personnel to use during roadside inspections.
3. Integrating such technologies with an electronically controlled brake system (ECBS) in a “closed loop” fashion. The brake force information could be used to balance the braking action at each wheel to improve service life, and/or provide an additional input for controlling braking action at each wheel in an emergency.

1.3 CURRENT STATE OF TECHNOLOGY DEVELOPMENT

Developing systems that provide drivers with brake status information has been a focus of the trucking industry over the past decade. Significant activity has occurred in this area recently as a result of the availability and affordability of new technologies. This section discusses the current state of brake technology development.

1.3.1 Brake Chamber Stroke Measurement

The only onboard sensors for brakes that have appeared in the marketplace are stroke indicators that measure air chamber push-rod stroke. Several different versions are currently available.

In the simplest form, the sensor is a mechanical indicator that requires the driver or mechanic to look at the brake where the sensor is located while the brake is fully applied. Since 1994, the Federal Motor Vehicle Safety Standards (FMVSS) 121 (CFR 49, Part 571) has required the use of visual stroke indicators, but only on brakes with exposed push rods. (Current disc brake designs do not have exposed push rods, nor other components that lend themselves to incorporation of a visual indicator.)

Systems are also available that use electrical stroke sensors, usually mechanical switches or Hall effect sensors, connected to a read-out in the cab. Although several different designs of these electrical stroke sensor systems have been marketed in the last few years, their market penetration has been minimal. Their major shortcoming is that they measure brake adjustment level only and cannot assess brake performance or output. For example, if the brake linings are covered with grease or other contamination that reduces the brake force output significantly, stroke sensors do not detect the problem.

Another problem with stroke measurement is that to assess stroke accurately, one must know the brake pressure. Because of the initial running clearance and the deflection in the brake assembly, stroke changes with pressure. At low pressures, stroke increases rapidly as the “slack” or free stroke in the system is taken up. Above 30 psi, deflection is relatively linear and a 10 psi change in brake pressure results in a stroke change in the order of 0.1 inch. This is a significant factor and could mean the difference between pass and fail in a roadside inspection, where the test pressure is supposed to be between 80 and 90 psi. It is difficult for an inspector to ensure that the driver is applying the correct pressure, and many stroke measurements are probably made incorrectly. None of the stroke-sensing systems that are commercially available measures brake pressure, nor are any of the systems designed to assess the adjustment level while the vehicle is moving and the driver is making “normal” brake applications.

1.3.2 Brake Force Measurement

In 1998/99, NHTSA funded a Small Business Innovative Research (SBIR) project that evaluated the use of strain-gauged pins to provide an indication of brake performance. The contractor, StrainSert, was a company that produces strain-gauged pins for various commercial measurement applications. As part of the project, these pins were used to replace the brake shoe anchor pins in conventional S-cam drum brakes. The preliminary laboratory testing that was conducted showed that pin force was proportional to brake force, indicating that the instrumented anchor pins offered a possible method for directly measuring brake forces. This test setup used multiple strain gauges affixed in different axes (or radial directions) on each anchor pin; both the upper and lower shoe assemblies were fitted with the strain gauges.

Such an installation was not considered cost effective or practical for “real-world” applications. In addition, the durability of these pins operating inside of commercial vehicle brakes and during maintenance operations would need to be proven. Furthermore, with air disc brakes on the horizon, these s-cam drum brake anchor pins could become obsolete. Disc brakes do not typically use anchor pins and it would be necessary to investigate strain measurement on other disc brake components, such as the torque plate that mounts the brake caliper to the axle.

1.3.3 Wheel Slip

Another method for measuring brake force that has received attention from ABS/ECBS suppliers is the use of wheel-speed sensor data to provide a measure of brake force. As a brake develops retarding force and transmits this force to the tire-road interface, the tire begins to slip and the wheel actually slows down relative to a freely rolling wheel. The amount of slippage is relatively small but measurable, and it is generally linear with respect to brake force. Wheel slip in a relatively high brake force application might be in the order of 10% on a dry road. Unfortunately, because vehicles have brakes on all wheels, during a brake application there are no freely rolling wheels to provide a reference signal for “true” vehicle speed.

Although wheel slip data could provide a measure of relative brake force on different axles and allow an ECBS to better control brake force balance, a separate vehicle speed transducer, independent of wheel velocity, might be necessary in order to accurately measure absolute brake forces at each wheel. Use of wheel slip has a great deal of potential as a low-cost means of determining brake condition, as the wheel-speed sensors already exist on vehicles with ABS.

1.3.4 On-Board Brake Performance Measurement

In a somewhat different approach to measuring brake performance, a company in Canada, Norcorp, has a patent on a system that uses an air pressure transducer to determine driver input to the brakes and an accelerometer to measure deceleration rate. The system compares the actual vehicle deceleration at a given brake pressure with reference data for a “good” braking system. If the pressure to achieve a given vehicle deceleration becomes too high, the system provides an indication that there is a problem with the brakes.

In order to calculate the appropriate deceleration rate, the system must be given the weight of the vehicle, since required braking force changes with weight. The driver can enter the weight manually via a keypad, or directly as a signal from an onboard weighing system. The advantages of such a system are that it uses relatively low-cost components, would be easy to retrofit to any vehicle, and it could be located in the cab in a controlled environment. A disadvantage is that it does not isolate the problem to a specific brake assembly, nor give any indication as to what is causing the problem. Also, internal research by the company owning the patent has shown that it is necessary to make a relatively hard brake application (up to about 65 psi control pressure) from at least 45 mph in order to obtain the resolution necessary to detect improper brake adjustment (by far the most common air brake defect that that is found in roadside inspections). It is not clear if this hard braking would cause any operational or highway safety problems.

1.3.5 Brake Temperature Measurement

Brake temperature provides a good measure of the amount of work the brake has been doing and is a very good indicator of whether the brake has been “overworked” to the point that it might start to fade (lose effectiveness due to heat) or wear excessively. In comparing brake temperatures on the vehicle, a brake that is running cool compared to others may mean that it has a defect or problem. Although nearly all standard testing procedures for brakes require that temperature be monitored during testing, onboard brake temperature measurement has never been offered as part of the instrumentation package available on regular production vehicles.

The use of off-board brake temperature measurement to assess brake performance is currently being studied by the USDOT. A relatively complex system that uses thermal imaging technology is being evaluated at roadside inspection facilities in several States. Also, testing is underway on a relatively inexpensive hand-held infrared device that infers brake temperature from measuring the temperature of the wheel studs. If the temperature measurement indicates that some brakes are cool relative to the other brakes on the vehicle, it could indicate that some brakes may not be functioning and others may be overworked. Off-board temperature measurement is most effective if it is used at locations where the vehicle has just experienced significant braking. This is not typical at most scale locations (where most roadside inspections are conducted), which are usually located on flat, wide-open Interstate highways.

Onboard brake temperature measurement does not provide an absolute measure of brake performance, and probably could not be used by itself for enforcement, yet it does provide an indication of the total work being expended by the brake assembly over a given duty cycle. Brake manufacturers might be able to integrate or utilize such information with an ECBS as part of a feedback loop to balance energy input to the brakes and optimize brake wear.

1.3.6 Lining Thickness Measurement

CVSA/FHWA roadside and annual inspection criteria consider a brake defective if its linings are thinner than ¼ inch for drum-type air brakes. While thin linings themselves do not necessarily result in degraded brake performance, the assumption is made that a problem will occur at some point in the near future when metal begins to contact metal. Another potential problem with thin linings is that if the drums are also worn excessively or oversized, the S-cam could rotate to the point that the shoe rollers drop off the tip of the cam, rendering the brake completely inoperative. This is called a "cam-over" brake condition.

Brake lining wear indication systems that provide some sort of warning light on the instrument panel have been used in some models of passenger vehicles for many years. One truck brake supplier has developed an electronic camshaft rotation sensor that detects thin linings and/or oversize drums.

1.4 RESEARCH OBJECTIVE

The overall objective of this research program is to document the performance and operational characteristics of leading-edge technological approaches to monitoring commercial vehicle braking systems. This study focused on examining the ability of various sensors to detect abnormalities, defects, and/or misadjustments of the brake system. The output of this study is a technical examination of the accuracy, responsiveness, resolution, and reliability of the various systems. This knowledge should prove useful to fleet operators in evaluating the capabilities and limitations of alternative brake sensing approaches, and in determining specifications for future truck purchases. The information should also be useful to brakes system suppliers and commercial vehicle manufacturers that are developing new brake monitoring systems. To this extent, the objectives for the study include providing fundamental research results to industry stakeholders concerning various means of monitoring braking systems.

Specific objectives and questions to be addressed by the study include the following:

- **Instrumented anchor pins for S -cam drum brakes** – Does the output provide an accurate representation of braking forces? Is it necessary to instrument both upper and lower anchor pins? How responsive is the output? How could the sensors be used to detect defects? Is a "simplified" design possible?

- **Wheel-speed sensing** – Can ABS wheel speed sensors be used to determine wheel slip and its relationship to brake force be used to detect brake system defects?

- **Air chamber stroke sensing systems** are already available in the marketplace. How accurate and reliable are such systems? What defects can they detect? What malfunctions might they miss or not detect? Is it important to monitor brake stroke continuously, or is measurement of over/under stroke sufficient?

- **Deceleration measurements** – Comparing deceleration with air brake pressure input to determine total brake force can be used to detect brake defects. However, several important design issues remain unanswered. How accurate do the accelerometer and pressure transducers need to be? What is the allowable tolerance on input of the vehicle weight to produce reliable results? How does the system respond to normal brake wear? Does the system produce excessive "false positives" such that warnings might be ignored? Also, the operational issues associated with having to make a hard "test" brake application at over 40 mph in order to catch adjustment problems needs to be studied, although this is also an issue with other methods that measure brake force.

- **On-board brake temperature measurement** – As noted, relatively low-cost thermocouples could readily be affixed to brake system components. But, could the output be reliably used to detect defects? How responsive are such sensors?

1.5 OVERVIEW OF PROCESS APPROACH

The generalized technical approaches for monitoring braking systems examined in this project include:

- Air chamber stroke measurement to assess brake adjustment at each wheel;
- Anchor strain measurement to determine brake force at each wheel;

- Wheel slip measurement to determine brake force at each wheel;
- Deceleration measurement to determine total vehicle braking force; and
- Temperature measurement to determine brake "work" or energy balance.

The various systems were installed (simultaneously) on a conventional tractor-trailer combination vehicle and tested under controlled braking maneuvers on a test track. (Radlinski and Associates, Inc., completed all work at the Transportation Research Center [TRC] in Columbus, Ohio). The output of the various brake sensor systems could then be compared on the same vehicle under identical testing conditions. This approach facilitated objective, accurate comparison of the sensors, and eliminates problems associated with test procedure repeatability when comparing different systems.

A test matrix was developed and executed that included a variety of braking maneuvers, including low to high deceleration rates executed on dry and wet pavement, on both level and graded surfaces, and in loaded (GVW) and unloaded (Lightly Loaded Vehicle Weight, LLVW) test conditions. Baseline performance and sensor outputs were first established with all wheel/brake assemblies on the vehicle optimally adjusted and with no defects. Braking performance of the vehicle was verified using a roller dynamometer Performance Based Brake Tester (PBBT). This methodology allowed for comparison of the brake force measurements from the various sensors with an accepted reference standard. The test matrix included introducing pre-planned faults or defects on selected brake assemblies and repeating various braking maneuvers. The outputs from the sensor packages were then examined to determine their ability to detect brake defects under a variety of braking conditions. Defects examined included various levels of out-of-adjustment brakes, disconnected brakes, and oil-soaked brakes.

Data from the sensors packages were recorded using an onboard PC-based data-logging system capable of recording digital, analog, and discrete sensor outputs. The system was also capable of simultaneously monitoring data (such as wheel speed output) on the J1939 data bus. The data was then processed off-board using conventional database and engineering plotting tools.

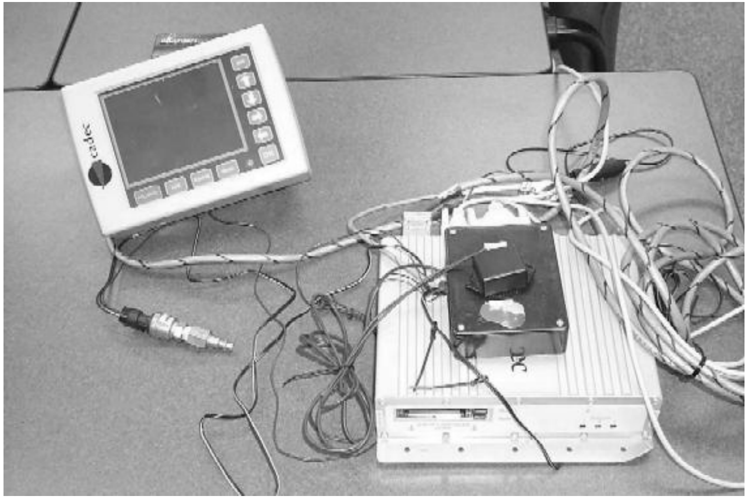
2. DESCRIPTION OF BRAKE SENSOR PACKAGES

Brake sensor technologies evaluated during the study included general-purpose sensors such as thermocouples and pressure transducers, as well as sensors specifically designed to monitor brake performance. This section presents a description of all brake sensors installed on the test vehicle and evaluated under this program.

2.1 NORCORP SYSTEMS BRAKE EFFECTIVENESS MONITORING DEVICE

Norcorp Systems, based in Vancouver, Canada, submitted for testing a prototype Brake Effectiveness Monitoring Device. This patented brake monitoring device consists of a compact decelerometer, a pressure transducer, and a compact touch-screen computer, as shown in Exhibit 2.1.

Exhibit 2.1 - Norcorp System Hardware



Based on extensive empirical track testing, Norcorp developed a relationship algorithm between brake system control pressure and vehicle deceleration performance. The vehicle's brake condition is determined by:

- Collecting and plotting deceleration versus control pressure data on specific vehicle configurations, (i.e. vehicle make, model, and braking systems specifications), and under varying vehicle weight (load) conditions; and
- Comparing the actual deceleration performance during revenue service with the predicted performance.
-

The reference data (deceleration versus control pressure) is recorded after the Norcorp system is installed, the brakes have been properly adjusted, and the brakes have accumulated sufficient mileage to ensure properly burnished brake linings.

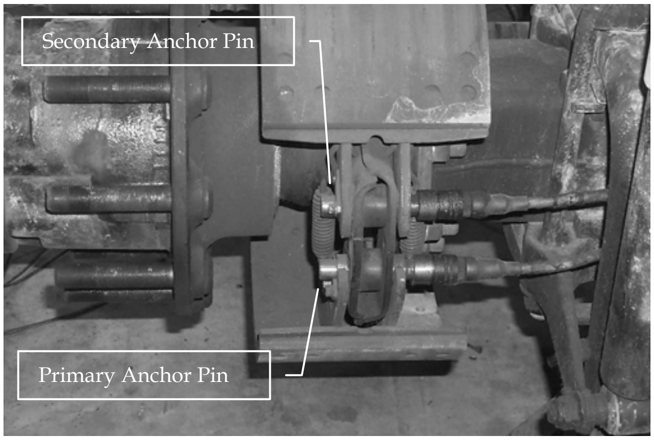
If the pressure to achieve a given vehicle deceleration becomes too high, the system provides an indication that there is a problem with the brakes. In order to perform this calculation, it is necessary that the system be given the weight of the vehicle, as deceleration versus pressure changes with vehicle weight. Weight can be entered manually by the driver, via the touch-screen computer, or directly as a signal from an onboard weight sensor. The system requires a controlled calibration stop from 45 mph at a control pressure of 65 psi. For best results, the manufacturer recommends that the system be recalibrated whenever major repairs are performed on the brake systems.

The Norcorp system received was an early prototype unit. Software issues that arose during testing prevented the evaluation of this system.

2.2 STRAINSERT ANCHOR PIN STRAIN GAUGES

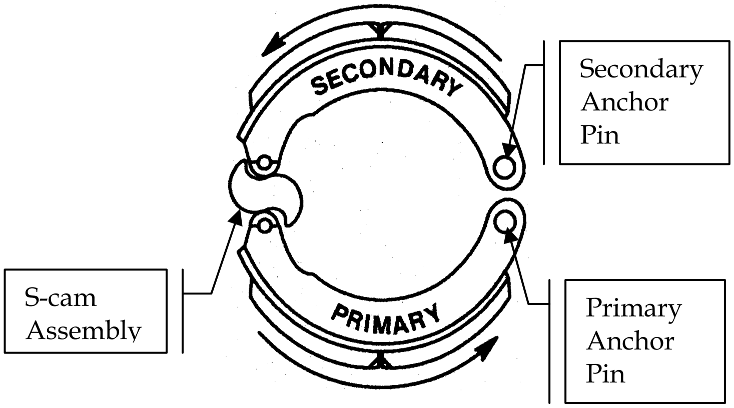
StrainSert, based in West Conshohocken, PA, submitted pre-production instrumented anchor pins for testing. The anchor pins are fitted with strain gauges capable of measuring the shear stresses applied to the anchor pins of the drum brake assemblies used on heavy-duty S-cam trucks and buses. These pins are designed to be interchangeable with conventional anchor pins and are held in place using a simple keeper plate, as shown in Exhibit 2.2.

Exhibit 2.2 - StrainSert Anchor Pins



When the brakes are applied, the S-cam mechanism rotates, thereby opening the brake shoes in a clam-like fashion. As the S-cam end of the shoe opens, the other end rotates about the anchor pins. (See Exhibit 2.3 for a diagram of a S-cam brake assembly.) The primary shoe is always the shoe that immediately follows the S-cam mechanism in the direction of wheel travel. Real world fleet experience has shown that the primary shoe typically experiences higher braking forces (and therefore accelerated wear) than the secondary shoe. Likewise, the primary anchor pin should see higher forces.

Exhibit 2.3 – Left Intermediate Axle Brake Shoe Diagram



Each anchor pin is fitted with two strain gauges oriented 90 degrees apart, roughly in the "X" and "Y" direction. One of the strain gauges is mounted normal to the direction of rotation, (the "Y" direction) and is intended to predominantly measure the mechanical non-friction force exerted by the movement of the brake shoe as it moves against the drum. The "X" axis strain gauge is offset 90 degrees from normal and is intended to primarily measure the rotational friction force between the drum and the lining. The StrainSert anchor pins can be continuously monitored by measuring the electrical signal (voltage) generated by the strain gauges internal to the pins. A force-voltage curve was provided by StrainSert to translate the voltage signal output to an actual applied force measurement. StrainSert developed this force-voltage relationship in a laboratory setting by applying a known load on the pin and recording the output voltage.

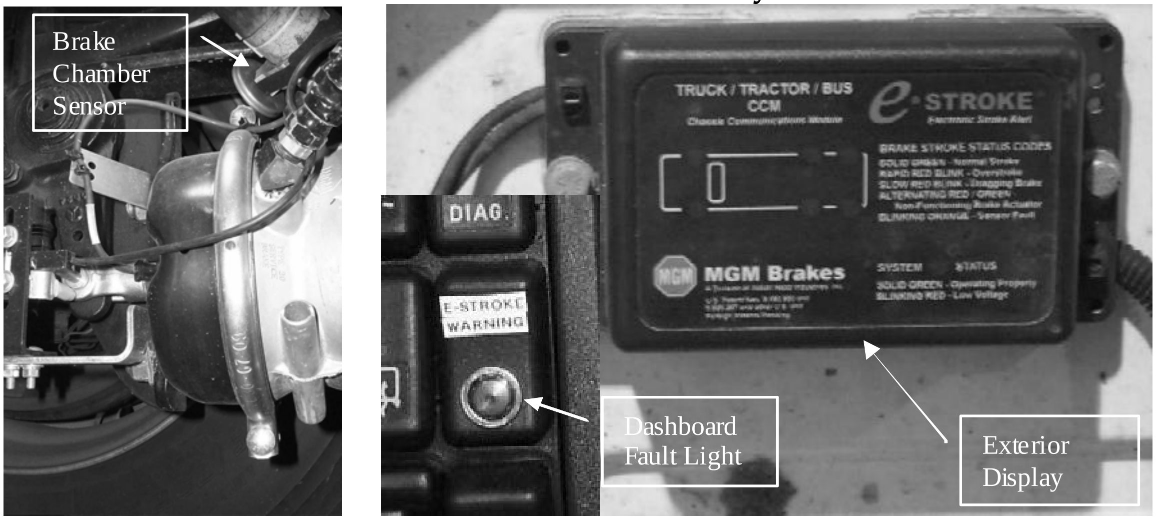
The hypothesis going into the project was that the instrumented anchor pins offered an innovative method for **directly** measuring brake force very accurately and with high resolution. For example, if it was known that a particular brake assembly on a tractor-trailer was generating less force than that of other brake assemblies (due to it being out of adjustment, defective, worn, or oil-soaked), it is theoretically possible that with an advanced air brake system (i.e., on electronically controlled brake systems), the pressure could be tailored to increase the effort of that specific brake assembly.

2.3 MGM E-STROKE

MGM Brakes of Charlotte, NC, the leading supplier of brake chambers (70 percent of the market), provided the study team with a commercial production electronic stroke monitoring system. The E-Stroke system, consists of a Hall-effect sensor and a magnet that strokes in parallel with the actuator piston rod to induce a voltage change. A communication module that determines the status of the brake system processes this voltage change. The communication module is capable of detecting normal stoke, over stroke, dragging brake, and a non-functioning brake actuator. The sensing hardware is contained within the air brake chamber, eliminating packaging interference with other components and protecting the hardware from the environment. Retrofitting a tractor with the E-Stroke system would thus require replacement of the standard brake chambers.

The E-stroke system is designed to augment pre-trip inspections. Drivers are instructed to apply 100 psi of application pressure to the brake system while the vehicle is at rest and the parking brake is off. The driver is then instructed to exit the cab and view the communication modules. Separate communication modules or "displays" for the tractor and trailer are mounted to the outside of the cab and trailer, respectively. These displays include a series of red and green lights that flash at different rates indicating the brake systems status . Although the system is designed as a pre-trip inspection tool, the system continuously monitors the brake system. A single fault light can be integrated inside the cab to alert the driver that there is an issue with the brakes on the truck “real time”. The E-Stroke system, shown in Exhibit 2.4, is commercially available.

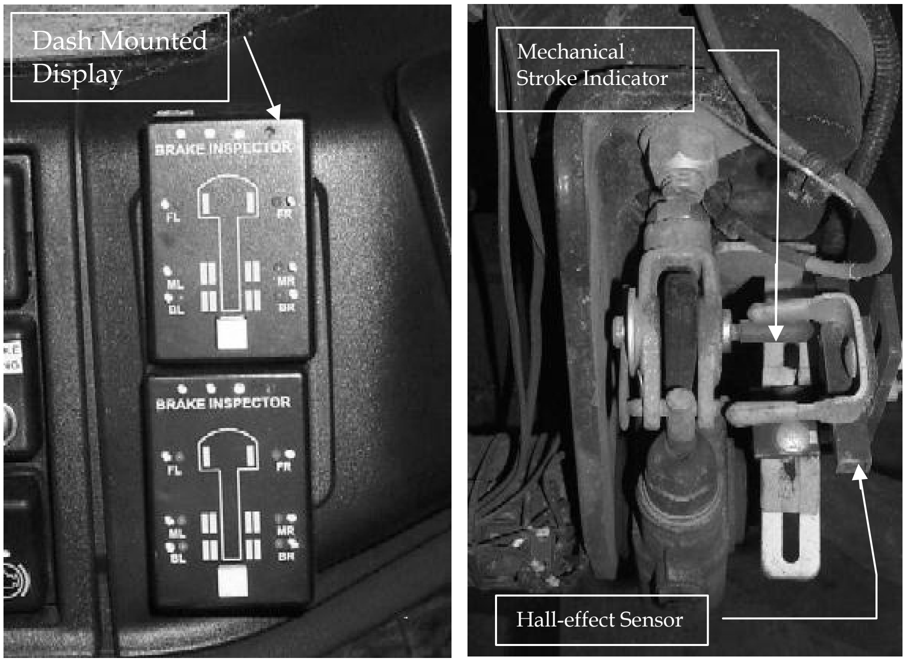
Exhibit 2.4 - MGM E-Stroke System



2.4 SPECTRA PRODUCTS BRAKE INSPECTOR

Spectra Products, Inc. of Etobicoke, Ontario, provided a commercial production brake chamber stroke sensor system for testing called the Brake Inspector. This system is similar to the MGM system in function, using a single Hall-effect sensor, but the sensor hardware is mounted outside the brake chamber, as shown in Exhibit 2.5. Therefore, unlike the MGM E-Stroke system, the Spectra system can be retrofitted to existing tractors without complete replacement of the brake chambers. The signals from the sensors are routed to a display module mounted inside the cab. The Spectra system is designed to assist the driver determine the status of the brake system during a pre-trip inspection. However, like the MGM system, the system continuously monitors the brake system and the interior display module can provide the driver with real-time information on each of the individual brakes from within the cab. Spectra also provides a mechanical measurement indicator that is mounted on a clevis pin that provides a visual means to check the brakes in the event of a power or display failure.

Exhibit 2.5 - Spectra Brake Inspector



2.5 THERMOCOUPLES

Standard Type J thermocouples were installed and tested as part of this program with two objectives:

1. The thermocouples were evaluated to determine whether they could reliably be used to detect brake defects. Brakes that are out of adjustment run either cooler (in the case of disconnected or backed-off brakes), or hotter (in the case of a dragging brake) than properly adjusted brakes. Thermocouples were mounted at varying depths within the shoe lining to test their sensitivity in determining brake deficiencies. The challenges of using thermocouples for this application included:

    a. Slow reaction times compared with strain, pressure, or actuator movement measurements; and

    b. No clear temperature threshold that defines a potential problem situation; rather, braking effectiveness (and/or ineffectiveness) would be better measured by dissipated energy for a given desired braking force. However, this relationship is likely complex and difficult to measure given the thermal inertia of various components in a brake assembly—and the associated temperature swings that are common during real-world applications.

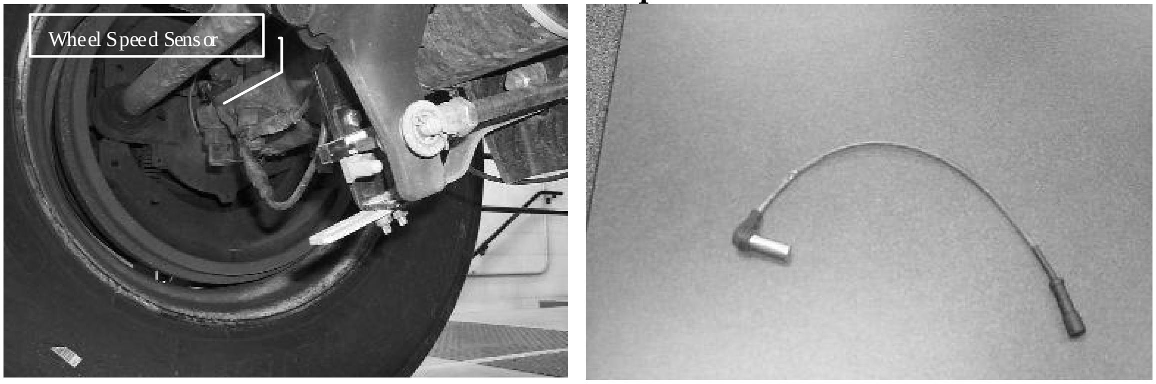
2. The thermocouples were used to assist in evaluating the other sensor "packages". The thermocouples provided a temperature reference to evaluate the performance of the commercial sensor packages under both normal and high-temperature conditions.

Note: It is recognized that temperature (heat) can be a very effective means of detecting the <u>relative</u> performance of different brake assemblies on any specific truck. Remote infrared heat measurement is already used successfully to detect high (or low) temperature brake assemblies (compared with the average brake temperature) on tractors just after they have executed a sustained heavy braking application. However, the reaction times of such heat detection systems are slow—and valid comparisons can only be made in repetitive, controlled situations.

2.6 ABS WHEEL-SPEED SENSORS

Wheel-speed sensors are a standard component of ABS systems used on heavy-duty trucks and buses. The most common type of wheel-speed sensor used in the industry is the variable-reluctance sensor. Variable-reluctance sensors use a small internal magnet and coil of wire to generate a signal to the ABS control module. Each wheel and axle assembly is equipped with a gear-shaped tone wheel that rotates near the sensor (see in Exhibit 2.6). As the tone wheel rotates, a magnetic field fluctuates around the sensor and induces alternating current (AC) voltage in the internal coil windings. AC voltage is sent through a two-wire connector and harness to the ABS control module. The ABS controller interprets the AC voltage and frequency from the variable reluctance sensor as a wheel-speed signal input.

Exhibit 2.6 – Wheel-Speed Sensors



ABS wheel-speed sensors can be used to measure individual wheel slip by comparing the calculated speed of each wheel against the calculated average for all wheels—or against some other "actual" speed reference such as a transmission signal or an optical fifth wheel that measures ground speed. This wheel-speed comparison capability is in fact what enables the ABS as well as traction-control functions. Further, it has been demonstrated under controlled conditions that the braking force at each wheel impacts the rotational speed of that wheel compared with other wheels. If the braking force is low on a given wheel assembly, it will tend to rotate a fraction faster than the other wheels. Conversely, if the braking force is high, it will rotate slightly slower.

The primary research question is whether the output of the standard ABS wheel-speed sensors are sufficiently accurate and have enough resolution to detect the amount of wheel slip that might occur due to various brake system anomalies (out of adjustment, oil soaked, excessive wear, etc.).

The tractor-trailer used for this program came equipped with a Wabco 4S/4M (two sensors on front axle and two sensors on the rear drive axle) anti-lock system (ABS) on the tractor and a Wabco 2S/2M (two sensors on the rear trailer axle) on the trailer.

Wheel-speed signals measured both directly (via the actual output of the ABS sensors) and indirectly (from the message broadcast on the J1939 network by the ABS control module) were evaluated for their brake system “diagnostic” capabilities.

2.7 LINEAR POTENTIOMETERS

Measurement of brake chamber stroke provides an indication of the driver's input to the air brake system. Laboratory grade, special-purpose linear potentiometer sensors were mounted to the brake chamber push rods to measure their linear displacement during braking. The potentiometers assisted in evaluating the limits of brake chamber stroke movement in detecting and determining brake defects. The potentiometers were also used to assist in evaluating the accuracy of commercial brake stroke sensor packages and as a reference signal for interpreting the performance of the other sensor systems. The linear potentiometers, model number JP73213, were manufactured by Penny and Giles Controls, LTD.

2.8 PRESSURE TRANSDUCER

Control pressure can provide an accurate measurement of the driver's input into the air brake system via the treadle valve, and therefore serves as a reference for various sensors under test. By knowing brake system input, the level of brake output could be better evaluated, permitting substandard brake performance to be identified. A low-cost pressure transducer was installed on the test vehicle to assist in evaluating the other sensor packages. The pressure transducer was from Texas Instruments, part number 84HP062T00150GSOC.

3. TEST HARDWARE AND SETUP

All brake sensor packages and general-purpose sensors were installed on the test vehicle per manufacturers′ recommendations and instructions. The test vehicle was also equipped with a data acquisition system and other instrumentation such as fifth-wheel sensors. After installation, all sensors were calibrated according to the manufacturers' instructions. This section of the report provides specifics on the test platform and instrumentation used to acquire, store, and analyze data for the study. Radlinski and Associates completed all test activities related to vehicle setup, instrumentation installation, and data acquisition setup and programming.

3.1 TEST PLATFORM

The test vehicle was a 2001 Volvo VNL 64T Series tractor, shown in Exhibit 3.1, coupled to a tandem axle flatbed semi-trailer. The tractor came from a local truck leasing company with 823 miles on its odometer. This newer tractor was selected for the program to ensure the inclusion of ABS and to limit the potential for introducing unwanted variables from use of older equipment. The flatbed trailer design provided easy loading and unloading with a forklift. Concrete blocks (4,300 pounds each) were chained to the deck of the semi-trailer in order to achieve an 80,000-pound maximum load. The vehicle accumulated 4,627 miles during the test program. Detailed specifications on the tractor, trailer, and brake hardware are provided in Exhibit 3.2.

Exhibit 3.1- Test Vehicle

Exhibit 3.2 - Test Vehicle Specification

TRACTOR		**TRAILER**	
Tractor Model	Volvo VNL 64T	Trailer Model	Manac Flatbed
Serial Number	4V4NC9JH91N317953	Serial Number	2M512146311075573
Model Year	2001	Model Year	2001
Engine	Cummins	Suspension	Spring
Transmission	Meritor 10-speed	Length (feet)	48
Front Suspension	Spring	Wheelbase (inches)	477
Rear Suspension	Air	ABS	Wabco 2S2M
Wheelbase (inches)	214		
ABS	Wabco 4S4M		
GVWR (pounds)	50,350		

BRAKES			
	Front	**Intermediate /Rear Drive**	**Trailer**
Manufacturer	ArvinMeritor	ArvinMeritor	Semac
Type	S-Cam Drum	S-Cam Drum	S-Cam Drum
Size (inches)	15 x 4 Q-plus	16-1/2 x 7 Q-plus	16-1/2 x 7
Lining	R301FF	R301FF	CM18FF
Slack Adjusters	ArvinMeritor 5-1/2"	ArvinMeritor 5-1/2"	Haldex 5-1/2"
Chamber Type	MGM 20	MGM 3030	TSE 3030
Drum	Gunite 5890507	Webb 66864B	Webb 66864B

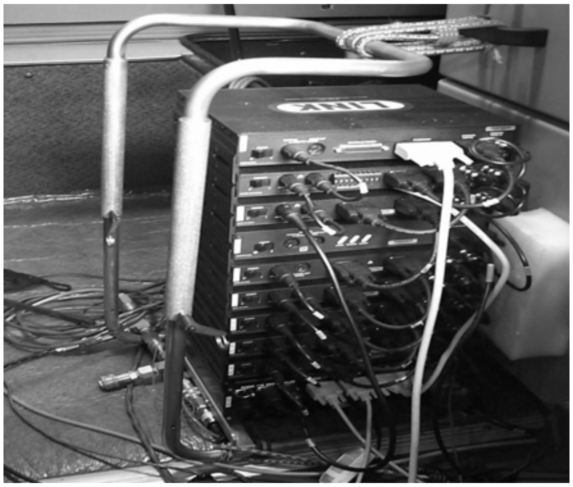
TIRES			
	Front	**Intermediate /Rear Drive**	**Trailer**
Manufacturer	Bridgestone	Bridgestone	Bridgestone
Make/Type	R227	M726	R196
Size	295/75R22.5	295/75R22.5	11R22.5
Pressure (psi)	110	110	105

WEIGHT DISTRIBUTION				
	Front Axle	**Drive Tandem**	**Trailer Axles**	**Total**
GAWR/GVWR	12,500	38,000	40,000	90,500
Loaded w/Trailer	11,950	33,640	34,030	79,620
Empty w/Trailer	11,410	13,280	8,920	33,610
Bobtail	11,210	8,350	N/A	19,560

3.2 DATA ACQUISITION SYSTEM

The sensor data was electronically processed by a data acquisition system (DAS) manufactured by Link Engineering Company of Detroit, MI, as shown in Exhibit 3.3. A PC-based laptop computer operates the system, stores data as it is acquired, and performs real-time analyses. The system software supports a variety of interface options ranging from direct user interaction with the system during measurement to completely autonomous operation based on various pre-programmed “trigger” events that cause the system to begin data collection. The system is also capable of issuing driver prompts.

Exhibit 3.3-Link DAS



For this program, the brake pedal was fitted with a contact switch, which, when depressed, activated the DAS. The system is modular and for this test program was configured with eight multi-channel signal-processing modules. See Exhibit 3.4 for complete specifications.

Exhibit 3.4 - Links DAS Specification

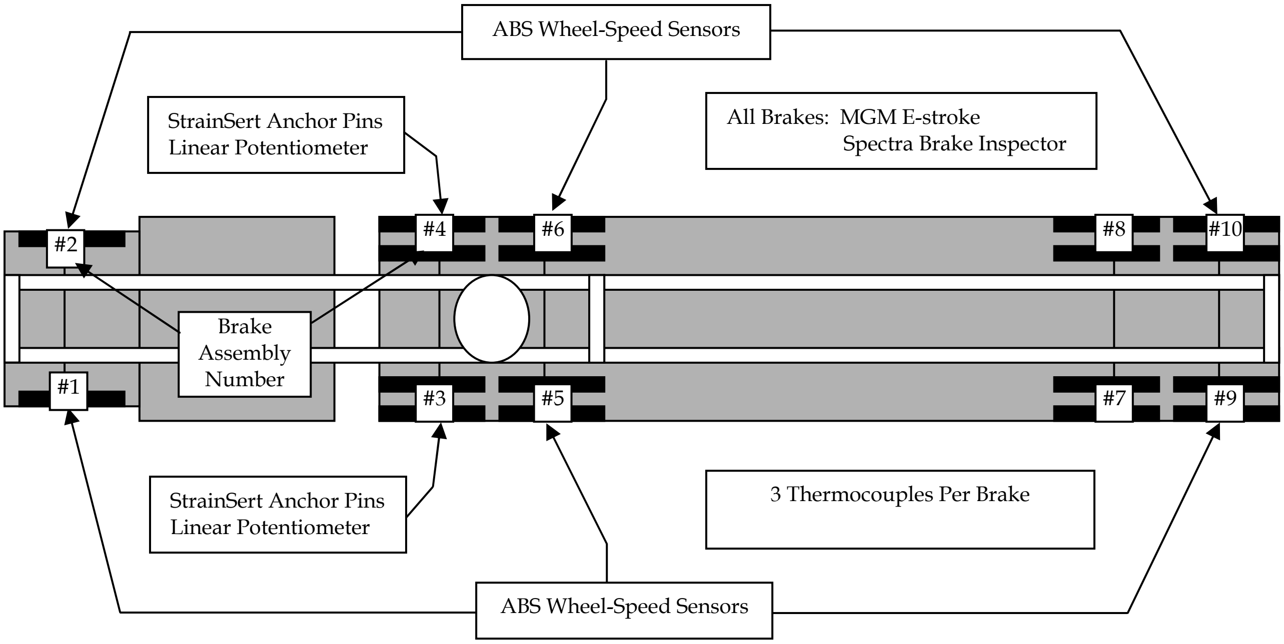
Specification	
Model Number	2060
Noise, Vibration and Harshness Channels	5-32
Base Analog Channels	8
Maximum Additional Analog Channels	64
Maximum Samples per Second: General Analog High-Speed NVH (Noise/Vibration/Harshness)	 1,000 51,200
Temperature Channels	8-64
Thermocouple Type	J or K
Real-Time Data Display	Yes
Heads-up Driver Display	Yes
Review Data in Vehicle	Yes
Continuous Data Sampling	Yes
Real-Time Spectrum Analysis	25,000 Hz for 5 channels sampled simultaneously
Typical System Dimensions	11″ wide x 8.5″ deep x 5.5″ high
Power Requirements – Volts	9 to 15
Power Requirements – Amps	4 Max.

The processing modules included three thermocouple modules, one pressure module, one force module, one frequency counter module, one network module, and the master module. The master module housed the power supply, computer, and heads-up display ports. A memory cache within the Link system stores one second of data before the beginning of a braking event.

3.3 SENSOR INSTALLATION

Before beginning testing, all commercial sensor packages and general-purpose sensors were installed on the tractor-trailer. This required removing the wheels, disassembling the brakes, and routing wire bundles to the DAS mounted in the cab of the truck. Exhibit 3.5 shows a diagram of a tractor-trailer and illustrates the installation location of each of the commercial or prototype sensor packages, as well as the general-purpose sensors evaluated under this program. Individual wheel and brake assemblies are numbered for purposes of referencing the location of the sensor readings and brake conditions throughout this report.

Exhibit 3.5- Sensor Locations



Reference	Location	Reference	Location
# 1	Left steer	# 6	Right rear tractor
# 2	Right steer	# 7	Left front trailer
# 3	Left intermediate tractor	# 8	Right front trailer
# 4	Right intermediate tractor	# 9	Left rear trailer
# 5	Left rear tractor	# 10	Right rear trailer

Following is a brief description of the sensor installation.

3.3.1 Norcorp Brake Effectiveness Monitoring Device

The entire system, including the decelerometer, was self-contained and mounted to the floor inside the cab.

3.3.2 MGM E-Stroke

All 10 brake chambers were replaced by the instrumented brake stroke chambers provided by MGM. In addition to the brake chambers, the system hardware included a power cable, wiring harness, chassis communications module (CCM), and sensor cables and connectors. Sensor cables were anchored by strain relief brackets to prevent damage. The system required electrical connections to the power, ground, and stoplight circuits. The tractor CCM was mounted externally to the back side (rear wall) of the cab, which met the 12-foot and 40-foot manufacturer installation requirement for the distance between the CCM and drive axles and CCM and front axle, respectively. The trailer CCM was mounted to the trailer's frame rail 12 feet from the trailer axle. The system also came with a single fault indicator that was mounted inside the cab on the dashboard.

3.3.3 Spectra Brake Inspector

The system required electrical connections to power, ground, and stoplight circuit. This system came with a single display unit that was mounted inside the cab on the dashboard. The visual display provided fault-monitoring lights for each individual brake.

3.3.4 StrainSert Anchor Pins, General Purpose Sensors, and Testing Instrumentation

In total, 56 individual sensor signals were fed to the DAS for processing. Most signals were general-purpose sensors and test equipment used for evaluating the brake sensor packages. The following signals were simultaneously monitored during all testing:

- **StrainSert Anchor Pins (8, analog)** - A set of instrumented anchor pins was installed on both brakes of the intermediate axle[4] and held in place by a simple keeper plate. Each pin has two strain gauges housed within the pin (one in the X and one in the Y direction). Installation required removing the old pins and drilling holes in the dust plate for routing wires.

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[4] A drive axle was chosen over the front (steer) axle for installation of the StrainSert anchor pins and the linear potentiometers due to the higher braking forces generated on drive axles. StrainSert supplied four instrumented anchor pins for measuring the force on the primary and secondary brake shoes on both sides of the axle.

- **Thermocouples (30, analog)** - Three Type J thermocouples were installed in the primary shoe lining on all 10 brakes (both tractor and trailer) at depths of 0.040-inches, rivet depth (0.25-inches above shoe table), and welded to the back side of the shoe table.

- **Pressure Transducer (1, analog)** - A pressure transducer was installed at the brake treadle valve to provide a reference control pressure. Installation required removing the treadle valve and splicing a tee into the air-line.

- **Fifth-Wheel Sensors (2, analog)** - A contact and a non-contact (optical) fifth wheel were installed on the tractor to provide a reference vehicle speed. Both systems were hard-mounted to opposite sides of the driver-side frame rail just aft of the cab.

- **Vehicle Deceleration (1, analog)** – An accelerometer was mounted in the cab to monitor vehicle deceleration.

- **Linear Potentiometers (2, analog)** - Two general-purpose linear potentiometers were installed on the brake chamber push rods of the intermediate axle brakes.

- **Wheel-Speed Sensors (6, analog)** - All six ABS wheel-speed sensors on the tractor-trailer were spliced into and hardwired to the DAS. The wheel-speed sensor resolution is 1/412 mph/bit.

- **J1939 Wheel-Speed Sensor (6, digital)** - The DAS was also connected to the tractor's J1939 network and acquired wheel-speed data broadcast by the ABS control module. This information was compared to the true wheel-speed sensor data (from the ABS wheel speed transducers) to evaluate the differences in resolution from these two sources. The Wabco 4S4M ABS control module broadcasts six individual signals:

  1. Vehicle speed – Calculated from a sensor on the output shaft of the transmission (1/26 mph/bit gain, transmission rate 10 Hz);

  2. Front axle speed – Calculated by averaging the front left and right wheel speeds (1/26 mph/bit gain, trans. rate 10 Hz);

  3. Left front relative speed – Relative speed difference between the left front wheel and the front axle (1/26 mph/bit gain, trans. rate 10 Hz);

  4. Right front relative speed – Relative speed difference between the right front wheel and the front axle (1/26 mph/bit gain, trans. rate 10 Hz);

5. Left rear relative speed – Relative speed difference between the left rear wheel and the front axle (1/26 mph/bit gain, trans. rate 10 Hz); and
6. Right rear relative speed – Relative speed difference between the right rear wheel and the front axle (1/26 mph/bit gain, trans. rate 10 Hz).

4. TEST PLAN

Each of the sensor packages was installed on the tractor-trailer and then they were tested simultaneously by subjecting the vehicle to a series of braking tests under both empty and loaded conditions. As tests were completed and results analyzed, the program's test plan was modified by either eliminating certain planned test sequences that were not productive, or by adding tests to investigate specific issues or new areas of interest. This section of the report describes the:

- Pre-planned brake failure modes to be evaluated,
- Specific brake testing regimens performed under this program, and
- Process used for collecting data.

All track testing occurred at the Transportation Research Center in East Liberty, OH, using drivers employed by Radlinski and Associates, Inc.

4.1 Brake Deficiencies

The major objective of this test program was to evaluate the ability of the various sensor technologies to detect brake problems. Ten different brake deficiency scenarios ranging in severity from no deficiencies to four fully disconnected brakes were examined. In an effort to equate the deficiencies to those used by the trucking industry, the deficiency codes were matched up to the defect quantification definitions used by the Commercial Vehicle Safety Alliance (CVSA).[5] Exhibit 4.1 provides a listing of the 10 brake deficiency scenarios used to evaluate the brake sensor packages.

Exhibit 4.1 - Brake Deficiency Scenarios

Code	Description	Brake Assembly Location(s)	CVSA Defect Quantification	Out of Service
0	None (all brakes correctly adjusted, baseline)		None	No
1	1 brake out of adjustment: 2-3/8 inches stroke	# 3	10% defective	No
2	2 brakes out of adjustment: 2-3/8 inches stoke	# 3, 6	20% defective	Yes
3	4 brakes out of adjustment: 2-3/8 inches stroke	# 3, 6, 7, 10	40% defective	Yes
4	2 brakes out of adjustment: 2-1/8 inches stroke	# 3, 6	10% defective	No
5	4 brakes out of adjustment: 2-1/8 inches stroke	# 3, 6, 7, 10	20% defective	Yes
6	2 brakes oil-soaked	# 3, 6	20% defective	Yes
7	2 brakes disconnected	# 3, 6	20% defective	Yes
8	3 brakes disconnected	# 3, 6, 7	30% defective	Yes
9	4 brakes disconnected	# 3, 6, 7, 10	40% defective	Yes

For example, Code 1 places the brake assembly on the intermediate axle, driver side, out of adjustment by 2-3/8 inches. In this case, the brake chamber push rod would have to

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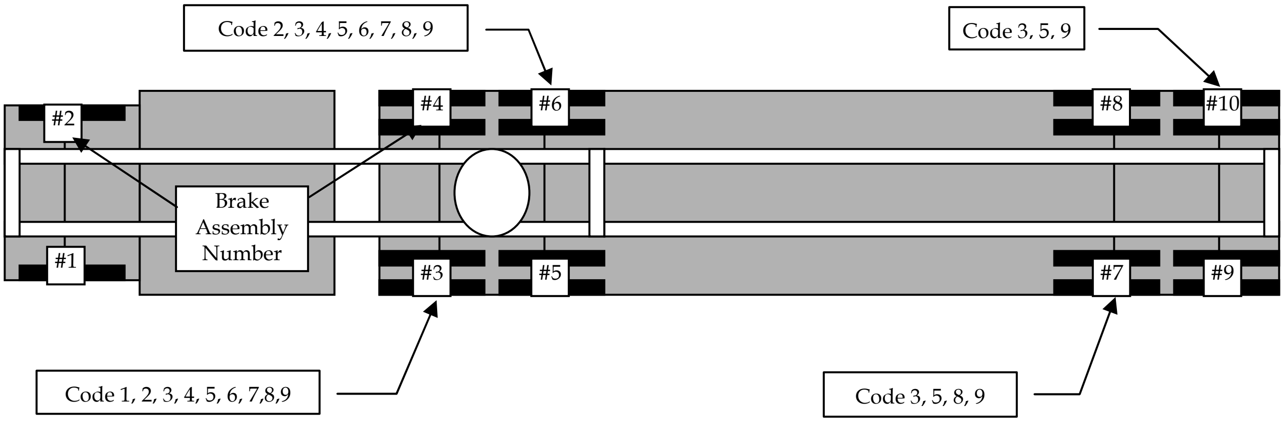
[5] Commercial Vehicle Safety Alliance. North American Standard Out-of-Service Criteria. Bethesda, MD: 2002

travel 2-3/8 inches prior to the brake shoe lining making contact with the brake drum. To maintain the stroke adjustment, the automatic adjustment feature of the slack adjuster was disabled on the affected brakes. As shown in Exhibit 4.1, Codes 1 through 5 and 7 through 9 affect the adjustment of one or more brake assemblies. For Code 6, two sets of brake shoes were soaked in oil before being installed and properly adjusted on the tractor. To simplify the analysis, no more than one deficiency was introduced to any given wheel or axle. Exhibit 4.2 provides a visual representation of the defect scenarios applied to various wheel assemblies.

Exhibit 4.2 - Brake Deficiency Codes and Affected Brake Assemblies



4.2 Controlled Deceleration Tests

The testing program was designed to subject sensor packages and products to a comprehensive series of brake tests under a variety of operating conditions in order to evaluate their sensitivity and accuracy for detecting brake defects. These conditions included various initial braking speeds, deceleration rates, and surface conditions. The first phase of the testing focused on establishing the vehicle's (and sensors') baseline performance with properly adjusted brakes. Next, the brake defect codes previously described were systematically introduced to determine the sensors' abilities to detect problems with respect to dry and wet surfaces, empty and loaded conditions, low and high speeds, and low and high deceleration rates. This proved to be an effective approach since, for example, some sensors provided reliable detection of brake defects during hard braking—but could not detect a problem during more routine brake maneuvers at lower deceleration rates.

The test matrix, shown in Exhibit 4.3, lists the specific braking tests performed. As shown, the first series of brake tests (Segment 1) occurred on dry pavement with a full payload. The operator was first required to brake from a target speed of 30 mph at a deceleration rate of 5 ft/sec/sec, (a fairly mild braking event). The brakes for the first test run were at a Code 0 status, indicating that all 10 brakes were in proper working condition. The operator repeated each test run (at a given set of conditions) three times before moving on to the next set of test conditions in the segment. For Segment 1, for example, deceleration maneuvers were repeated at 60 mph, and for moderate (10ft/sec/sec) and hard (15 ft/sec/sec) braking maneuvers. For each of these deceleration conditions, the test vehicle was reconfigured between runs to simulate defect Codes C0 thru C9. To complete all possible combinations of test conditions for Segment 1 alone would have resulted in 180 separate braking events; (2 initial speeds x 3 deceleration rates x 10 defect codes = 60 different test conditions with each test repeated three times for accuracy). In actuality, Segment 1 included 120 different combinations of tests that required approximately five full days to complete. (As noted earlier, output data were briefly reviewed in "real time" after each test run, and the need for additional repetitions of specific tests was evaluated based on the results. Some flexibility in tailoring the test matrix was permitted in order to utilize resources effectively.)

Exhibit 4.3 - Controlled Deceleration Test Matrix

Segment (#)	Speeds (mph)	Decel. (ft/sec/sec)	Defects (Code 0-9)	Friction (Dry, Wet)	Loading (GCW)
500-mile brake burnish and shakedown					
1	30, 60	5, 10, 15	C0-C9	High	Full
2	30, 60	5, 10, 15	C0-C9	High	Empty
3	30	5, 10, 15	C0, C7, C9	Low	Empty
4	30	5, 10, 15	C0, C7, C9	Low	Full
5	City	Varies	None	High	Full
6	SimMtn.	Varies	C0-C9	High	Full
7	SimCity	Varies	C0-C9	High	Full
8	SimCity	Varies	C0-C9	High	Empty

4.3 Simulated Mountain and City Tests

In addition to the controlled deceleration tests, the brake sensor packages were subjected to simulated road tests (Segments 5 through 8). These road tests simulated the duty cycle that a vehicle would follow during extended mountainous and city driving. These simulated tests were designed to evaluate the performance of the brake sensor packages when subjected to high brake temperatures and varying deceleration rates. For the simulated mountain test, the Jennerstown[6] mountain test procedure, an industry-recognized test, was simulated for use on a flat, closed test track (this procedure is similar to the SAE simulated mountain test standard).

The Jennerstown test procedure requires repeated brake snubs from 34 to 19 mph at a specified cycle time using a deceleration rate of 7.4 ft/sec/sec. The test begins with initial

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[6] The Jennerstown test is an industry-recognized procedure used to evaluate the mountain descent performance of service brake systems.

brake temperatures (IBTs) between 150 and 200° F. In an effort to account for any degradation in baseline brake performance as a result of the testing itself, and to provide a reference performance measurement, this procedure is repeated four times with cycle times of 125, 20, 70, and 40 seconds. The brakes were evaluated prior to the start (cold) by conducting a hard stop from 30 mph at a deceleration rate of 15 ft/sec/sec and again at the end of the test for the same speed and deceleration rate. A description of the Jennerstown mountain test is provided in Exhibit 4.4.

Exhibit 4.4 - Simulated Mountain Test

Segment	# of Snubs	Decel. Rate (ft/sec/sec)	Snub Speed (mph)	Defects (Code 0-9)	Cycle Time (sec)
Initial Brake Temperature (IBT) 150 to 200° F					
1	34	7.4	34 to 19	C0-C9	30
2	7	7.4	34 to 19	C0-C9	125
3	42	7.4	34 to 19	C0-C9	20
4	18	7.4	34 to 19	C0-C9	70
5	57	7.4	34 to 19	C0-C9	40

Following the mountain test, a city test was conducted that simulated operation in an urban environment. This test was designed specifically for this program. The intent of this test was to evaluate the sensitivity of the sensor packages at lower deceleration rates. Exhibit 4.5 provides a description of the duty cycle used for this simulated city test.

Exhibit 4.5 - Simulated City Test

Segment	# of Snubs	Initial Speed	Decel. Rate (ft/sec/sec)	Defect (Code 0-9)	Stop Interval (miles)
Initial Brake Temperature of 150 to 200° F					
1	3	60	8	C0-C9	1
2	10	40	5	C0-C9	0.5
Travel 3.0 miles @ 40mph and make stop at 8 ft/s/s					
3	10	35	3	C0-C9	0.5
Travel 5.0 miles @ 40 mph and make stop at 8 ft/s/s					
4	10	35	3	C0-C9	0.5
5	57	35	3	C0-C9	0.5
Accelerate to 60 mph and make stop at 8 ft/s/s					

4.4 Performance-Based Brake Tester

A performance-based brake tester (PBBT) was incorporated into the program to assist in evaluating the performance of the instrumented anchor pins. The PBBT used in this study is a roller chassis dynamometer-based system that is capable of evaluating air brake systems on trucks and buses. PBBTs are commercially available and assist vehicle manufacturers and fleet operators with dynamically measuring the rolling resistance, brake threshold pressure, service brake force, parking brake force, and anti-lock braking systems (sensors, valves, and wiring). The PBBT essentially provides an industry-accepted reference measurement of brake performance. For this program, a PBBT was used to evaluate and compare the brake force measured by the instrumented anchor pins to the true service brake force measured between the tires and rollers.

4.5 Brake Burnish

The test vehicle, equipped with a new set of brake linings, was subjected to FMVSS 121 S6.1.8 brake burnishing procedures. These procedures required 500 brake snubs to be made from an initial speed of 40 mph and an exit speed of 20 mph at a deceleration rate of 10 feet/sec/sec. The brake snubs were performed at an interval of 1 mile. During this procedure, brake lining temperatures can reach 500° F or higher.

During the 500-mile burnish, brake sensor packages and testing instrumentation were monitored and adjusted where necessary. Data was collected and used to determine that the sensors were working properly.

4.6 Data Collection Process

The Link DAS system received information from 59 individual channels at a frequency of 50 Hertz. Six of those channels were digital and were broadcast from the J1939 network. A complete list of channels is shown in Exhibit 4.6. A contact switch mounted to the brake treadle valve activated the DAS. Data was collected until the vehicle reached a complete stop. A memory cache built into the DAS recorded 1 second of data prior to the start of a braking event.

The actual data from each test run was stored in individual files on a Windows- based laptop computer that was mounted to the dashboard of the truck. The average braking event lasted about 3 to 8 seconds and generated approximately 17,000 data points, (59 channels x 6 seconds x 50 data points per second). The data was downloaded to a compact disk at the completion of each day of testing. In total, the testing program generated approximately 375 Mb of data.

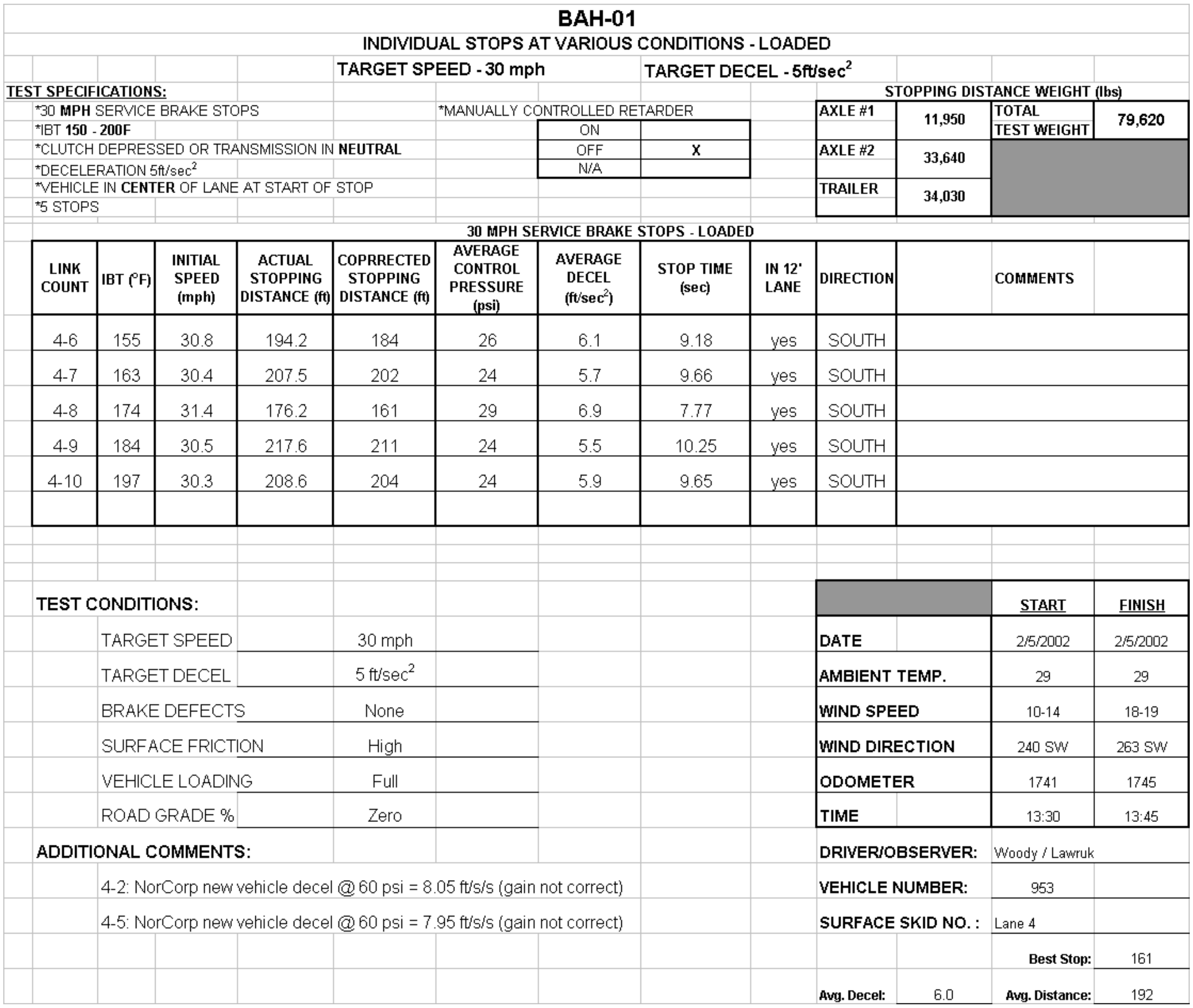
The operator was responsible for manually recording the test identification number and other specific information including environmental conditions, initial brake temperatures (IBT), average control pressure, stopping distance, and the time required to stop the vehicle. A sample Driver Test Run Description form is shown in Exhibit 4.7. The operator was also responsible for monitoring and documenting data generated from three sensor packages (NORCORP, MGM, and Spectra). These self-contained systems were not connected directly to the Link DAS, as they did not have signal output suitable for recording.

Exhibit 4.6 – Sensor Channels

Channel #	Channel Name	Description	Units
1	CtrlPres	Control Pressure	psi
2	Decel	Vehicle Deceleration	ft/sec/sec
3	PrExci	Pressure Excitation	volt
4	DclExci	Decel Excitation	volt
5	5thExci	Fifth Wheel Excitation	volt
6	LftStroke	Left Stroke Potentiometer	inches
7	RtStroke	Right Stroke Potentiometer	inches
8	VehSpd	Vehicle Speed, Contact Fifth Wheel	mph
9	NonConSpd	Non Contact 5th Wheel Speed	mph
Wheel-Speed Sensors			
10	LFWhlSpd	ABS Sensor (1)- Left Front Wheel Speed	mph
11	RFWhlSpd	ABS Sensor (2)- Right Front Wheel Speed	mph
12	LRWhlSpd	ABS Sensor (3)- Left Rear Wheel Speed	mph
13	RRWhlSpd	ABS Sensor (4)- Right Rear Wheel Speed	mph
14	TrlLWhlSpd	ABS Sensor (5)- Trailer Left Wheel Speed	mph
15	TrlRWhlSpd	ABS Sensor (6)- Trailer Right Wheel Speed	mph
J1939 Broadcasted Wheel Speeds			
16	JVehSpd	J1939 Vehicle Speed (geared off transmission)	mph
17	JFrontSpd	J1939 Front Axle Speed (avg. front ABS sensors)	mph
18	JLFRelSpd	J1939 Left Front Relative Speed	mph
19	JRFRelSpd	J1939 Right Front Relative Speed	mph
20	JLRRelSpd	J1939 Left Rear Relative Speed	mph
21	JRRRelSpd	J1939 Right Rear Relative Speed	mph
StrainSert Anchor Pins			
22	FPLftTopX	Force Pin (1a), Left, Top, X Dir	lb
23	FPLftTopY	Force Pin (1b), Left, Top, Y Dir	lb
24	FPLftBotX	Force Pin (2a), Left, Bottom, X Dir	lb
25	FPLftBotY	Force Pin (2b), Left, Bottom, Y Dir	lb
26	FPRtTopX	Force Pin (3a), Right, Top, X Dir	lb
27	FPRtTopY	Force Pin (3b), Right, Top, Y Dir	lb
28	FPRtBotX	Force Pin (4a), Right, Bottom, X Dir	lb
29	FPRtBotY	Force Pin (4b), Right, Bottom, Y Dir	lb
Thermocouples			
30	TraLF40	(1) Tractor Left Front, 0.040 Depth	degrees F
31	TraLFRiv	(2) Tractor Left Front, Rivet Depth	degrees F
32	TraLFShoe	(3) Tractor Left Front, Shoe	degrees F
33	TraRF40	(4) Tractor Right Front, 0.040 Depth	degrees F
34	TraRFRiv	(5) Tractor Right Front, Rivet Depth	degrees F
35	TraRFShoe	(6) Tractor Right Front, Shoe	degrees F
36	TraLI40	(7) Tractor Left Intermed., 0.040 Depth	degrees F
37	TraLIRiv	(8) Tractor Left Intermed., Rivet Depth	degrees F
38	TraLIShoe	(9) Tractor Left Intermed., Shoe	degrees F
39	TraRI40	(10) Tractor Right Intermed, 0.040 Depth	degrees F
40	TraRIRiv	(11) Tractor Right Intermed., Rivet Depth	degrees F
41	TraRIShoe	(12) Tractor Right Intermed., Shoe	degrees F

Channel #	Channel Name	Description	Units
42	TraLR40	(13) Tractor Left Rear, 0.040 Depth	degrees F
43	TraLRRiv	(14) Tractor Left Rear, Rivet Depth	degrees F
44	TraLRShoe	(15) Tractor Left Rear, Shoe	degrees F
45	TraRR40	(16) Tractor Right Rear, 0.040 Depth	degrees F
46	TraRRRiv	(17) Tractor Right Rear, Rivet Depth	degrees F
47	TraRRShoe	(18) Tractor Right Rear, Shoe	degrees F
48	TrlLF40	(19) Trailer Left Front, 0.040 Depth	degrees F
49	TrlLFRiv	(20) Trailer Left Front, Rivet Depth	degrees F
50	TrlLFShoe	(21) Trailer Left Front, Shoe	degrees F
51	TrlRF40	(22) Trailer Right Front, 0.040 Depth	degrees F
52	TrlRFRiv	(23) Trailer Right Front, Rivet Depth	degrees F
53	TrlRFShoe	(24) Trailer Right Front, Shoe	degrees F
54	TrlLR40	(25) Trailer Left Rear, 0.040 Depth	degrees F
55	TrlLRRiv	(26) Trailer Left Rear, Rivet Depth	degrees F
56	TrlLRShoe	(27) Trailer Left Rear, Shoe	degrees F
57	TrlRR40	(28) Trailer Right Rear, 0.040 Depth	degrees F
58	TrlRRRiv	(29) Trailer Right Rear, Rivet Depth	degrees F
59	TrlRRShoe	(30) Trailer Right Rear, Shoe	degrees F

Exhibit 4.7 – Driver-Completed Test Run Description Form



BAH-01

INDIVIDUAL STOPS AT VARIOUS CONDITIONS - LOADED

TARGET SPEED - 30 mph **TARGET DECEL - 5ft/sec^2**

TEST SPECIFICATIONS:

*30 **MPH** SERVICE BRAKE STOPS
*IBT **150 - 200F**
*CLUTCH DEPRESSED OR TRANSMISSION IN **NEUTRAL**
*DECELERATION 5ft/sec^2
*VEHICLE IN **CENTER** OF LANE AT START OF STOP
*5 STOPS

*MANUALLY CONTROLLED RETARDER

ON	
OFF	X
N/A	

STOPPING DISTANCE WEIGHT (lbs)

AXLE #1	**11,950**	**TOTAL TEST WEIGHT**	**79,620**
AXLE #2	**33,640**		
TRAILER	**34,030**		

30 MPH SERVICE BRAKE STOPS - LOADED

LINK COUNT	IBT (°F)	INITIAL SPEED (mph)	ACTUAL STOPPING DISTANCE (ft)	COPRRECTED STOPPING DISTANCE (ft)	AVERAGE CONTROL PRESSURE (psi)	AVERAGE DECEL (ft/sec^2)	STOP TIME (sec)	IN 12' LANE	DIRECTION	COMMENTS
4-6	155	30.8	194.2	184	26	6.1	9.18	yes	SOUTH	
4-7	163	30.4	207.5	202	24	5.7	9.66	yes	SOUTH	
4-8	174	31.4	176.2	161	29	6.9	7.77	yes	SOUTH	
4-9	184	30.5	217.6	211	24	5.5	10.25	yes	SOUTH	
4-10	197	30.3	208.6	204	24	5.9	9.65	yes	SOUTH	

TEST CONDITIONS:

TARGET SPEED	30 mph
TARGET DECEL	5 ft/sec^2
BRAKE DEFECTS	None
SURFACE FRICTION	High
VEHICLE LOADING	Full
ROAD GRADE %	Zero

	START	FINISH
DATE	2/5/2002	2/5/2002
AMBIENT TEMP.	29	29
WIND SPEED	10-14	18-19
WIND DIRECTION	240 SW	263 SW
ODOMETER	1741	1745
TIME	13:30	13:45

ADDITIONAL COMMENTS:

4-2: NorCorp new vehicle decel @ 60 psi = 8.05 ft/s/s (gain not correct)
4-5: NorCorp new vehicle decel @ 60 psi = 7.95 ft/s/s (gain not correct)

DRIVER/OBSERVER: Woody / Lawruk
VEHICLE NUMBER: 953
SURFACE SKID NO. : Lane 4
Best Stop: 161
Avg. Decel: 6.0 **Avg. Distance:** 192

5. TEST RESULTS

This chapter presents a summary of the results from the testing program, and offers some observations regarding the accuracy, sensitivity, and applicability of various advanced brake sensor technologies for determining braking performance and detecting brake defects. In this chapter, we will show that:

- Anchor pin strain gauges located on the primary brake shoe can provide sufficient resolution to: (1) determine out-of-adjustment and disconnected brakes, (2) accurately differentiate between out-of-adjustment brakes and oil-soaked brake linings, and (3) detect unbalanced braking effort among the brake assemblies on a particular vehicle. Further, it would appear to be technically feasible to feed this additional brake performance data in a real-time fashion to an electronically controlled braking system (ECBS) to enable the balancing of braking effort via a closed loop control system. Such a capability should result in improved service life, reduced maintenance, and improved overall braking performance and control.

- Stroke sensing systems can determine out-of-adjustment and disconnected brake assemblies during heavy braking maneuvers, but can only detect overstroke conditions and therefore cannot reliably determine the difference between out-of-adjustment brakes and oil-soaked brake linings. The commercial stroke sensing systems detected were not intended to discern oil-soaked brake linings.

- ABS relative wheel-speed sensors have sufficient resolution to identify a problem due to out-of-adjustment, disconnected, and/or oil-soaked brake assemblies (although, like stroke sensors, they cannot differentiate between out-of-adjustment brakes and oil-soaked linings).

- Although J1939 wheel-speed data also has sufficient resolution to determine grossly out-of-adjustment, disconnected, and/or oil-soaked brakes, the message size limitations of the J1939 network impact the resolution considerably.

- During single braking maneuvers, brake shoe thermocouples do not accurately detect out-of-adjustment, disconnected, and/or oil-soaked brakes.

- Anchor pin strain gauges located on the primary brake shoe (the brake shoe that is first in line with the direction of wheel rotation from the s-cam assembly) provide better, higher-resolution tracking of true braking performance and a more linear correlation with actual braking force than the anchor pin strain gauge located on the secondary brake shoe.

- Stroke sensing systems do not appear to offer sufficient correlation, accuracy, or resolution with actual braking force to support the implementation of balanced braking algorithms using ECB systems.

It is important to note that due to the very large volume of data generated (375 Mb) it is not practical to plot data from all test runs and/or perform comprehensive comparisons among all sensors for all test scenarios. In this chapter, the analyses are tailored on the basis of various hypotheses regarding the abilities and limitations of the sensor technologies. This was a typical engineering-oriented iterative investigation. New hypotheses were introduced on the basis of interim results. New analyses were then developed to validate or refute the new hypotheses. Testing continued until it was possible to make valid observations, establish relationships, and/or identify trends in the data.

The results and observations presented in this chapter are not exhaustive; however, extensive data was collected and supports significant additional statistical analyses. Other brake researchers may wish to examine the data and draw independent conclusions on brake performance and the utility of the various sensors examined in this program. To this extent, an electronic database has been developed and made available from the government project sponsor.[7] The database is user-friendly and allows for the quick and convenient plotting of output data from different sensors and from different test scenarios (i.e. braking maneuvers). The database is described more fully in Section 5.1.

This chapter is organized as follows:

- A brief overview of the brake sensor database and analysis tools developed;
- An introduction to the fundamental braking principals used to evaluate the sensor packages;
- An analysis of the data collected from the Strainsert anchor pin strain gauges;
- Stroke sensor analysis using linear potentiometers, internal brake chamber stroke sensor packages, and external brake chamber stroke sensor packages;
- An analysis of the applicability of using ABS wheel speed sensors and/or J1939 wheel speed data to detect brake system defects; and
- An analysis of brake shoe thermocouples used to detect conditions of brake fade due to increased temperature during simulated city and simulated mountain test runs.

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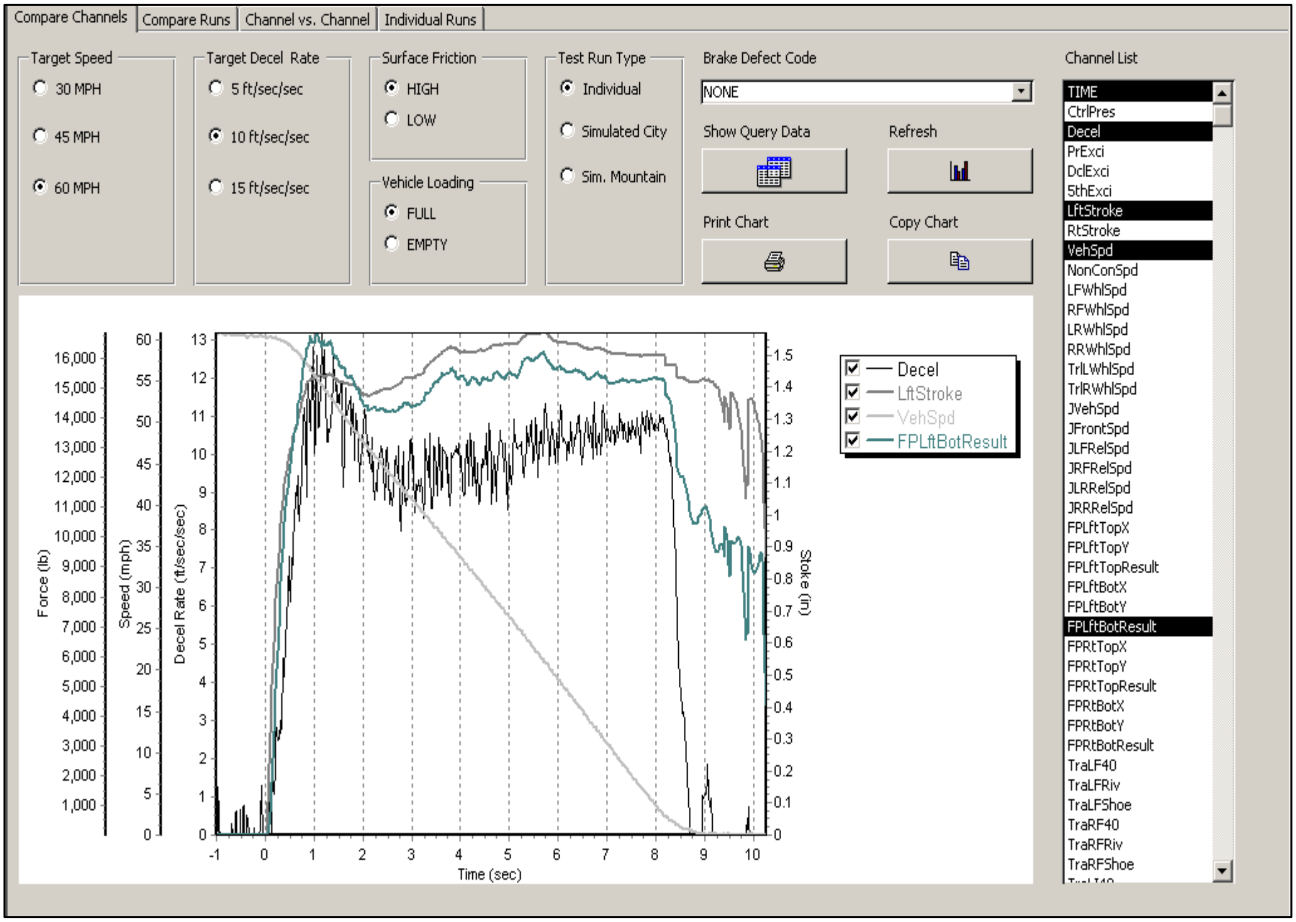
[7] The brake sensor performance testing database and analysis tool developed for this project requires Microsoft Access 2000 version 9.0 or newer.

5.1 BRAKE SENSOR TEST DATABASE

The data generated from the brake test program was imported into a Microsoft Access database specifically developed for this project. A graphing applet (Tee Chart Pro, Steema Software SL, Catalonia, Spain) capable of presenting multiple sensor outputs and scales on a single chart was embedded into the database. This chart-developing capability was instrumental in sifting through and identifying trends in the data. Exhibits 5.1 through 5.4 show screen captures of the four user interfaces developed specifically for the brake-testing database.

The data from any one, or all, of the 55 individual sensors can be displayed simultaneously for any specified test run meeting a given set of conditions, including: initial speed, deceleration rate, surface friction, loading, and defect code criteria. For example, Exhibit 5.1, shows a screen capture with the “Compare Channel” user interface tab depressed. This menu screen permits the user to graph multiple channels from a given test run simultaneously versus time. (Actually, the average of three identical test runs meeting the specified conditions is displayed. This averaging of test runs was done in pre-processing operation to simplify the database.) In this example, the users selected a target speed of 60 mph, a deceleration rate of 10 ft/sec/sec, a high surface friction (dry pavement), a fully loaded vehicle, and no brake defects. The user also selected four channels (deceleration rate, brake stroke, vehicle speed, and the resultant force of the driver-side bottom anchor pin) to all be displayed versus time. As shown, 9 seconds elapsed to bring the truck to a stop from 60 mph. The anchor pin force recorded during this braking event exceeded 16,000 pounds and the stroke peaked at 1.5 inches.

Exhibit 5.1- Database Screen Capture: Single Run


Target Speed: ○ 30 MPH ○ 45 MPH ● 60 MPH

Target Decel Rate: ○ 5 ft/sec/sec ● 10 ft/sec/sec ○ 15 ft/sec/sec

Surface Friction: ● HIGH ○ LOW

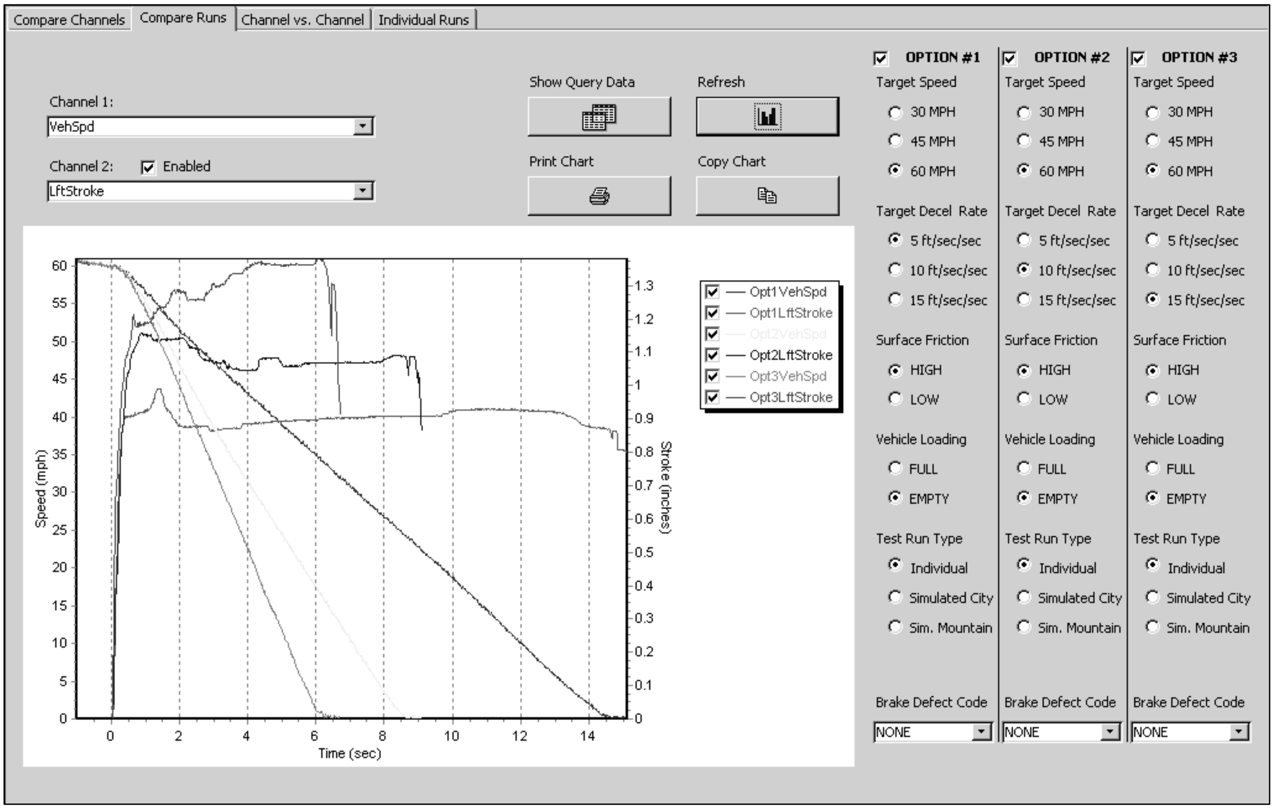
Vehicle Loading: ● FULL ○ EMPTY

Test Run Type: ● Individual ○ Simulated City ○ Sim. Mountain

Brake Defect Code: NONE

Exhibit 5.2 shows a screen capture with the “Compare Runs” user interface tab depressed. This menu screen permits the user to display up to three runs and two data channels simultaneously versus time. It differs from the compare channels tab by allowing the user to display data between different runs or braking maneuvers. In this particular example, the user wished to graphically view vehicle speed and stroke sensor output for three different brake maneuvers versus time. All three brake maneuvers occur at a target speed of 60mph, on dry pavement, and with an empty load, but with different target deceleration rates (5, 10, 15 ft/sec/sec). As one would anticipate, the higher the deceleration rate, the higher the brake chamber stroke, and the faster the truck came to a stop. Also note that the graph was generated with no brake deficiencies as seen in the bottom right-hand side of the screen capture. As shown, the elapsed time required to stop the truck varied between approximately 6 and 14 seconds; brake stroke travel varied between 0.9 and 1.4 inches.

Exhibit 5.2- Database Screen Capture: Multiple Runs



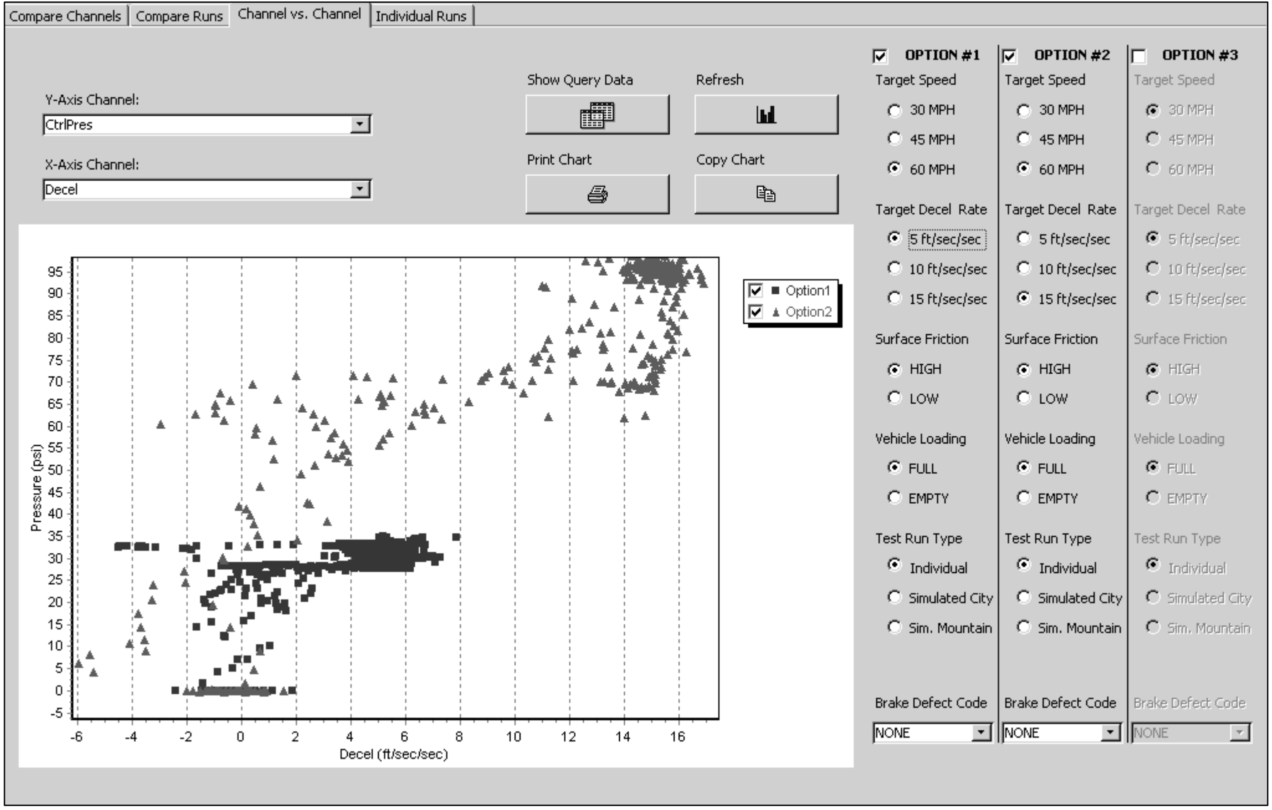
Channel 1: VehSpd

Channel 2: ☑ Enabled LftStroke

☑ OPTION #1	☑ OPTION #2	☑ OPTION #3
Target Speed	Target Speed	Target Speed
○ 30 MPH	○ 30 MPH	○ 30 MPH
○ 45 MPH	○ 45 MPH	○ 45 MPH
● 60 MPH	● 60 MPH	● 60 MPH
Target Decel Rate	Target Decel Rate	Target Decel Rate
● 5 ft/sec/sec	○ 5 ft/sec/sec	○ 5 ft/sec/sec
○ 10 ft/sec/sec	● 10 ft/sec/sec	○ 10 ft/sec/sec
○ 15 ft/sec/sec	○ 15 ft/sec/sec	● 15 ft/sec/sec
Surface Friction	Surface Friction	Surface Friction
● HIGH	● HIGH	● HIGH
○ LOW	○ LOW	○ LOW
Vehicle Loading	Vehicle Loading	Vehicle Loading
○ FULL	○ FULL	○ FULL
● EMPTY	● EMPTY	● EMPTY
Test Run Type	Test Run Type	Test Run Type
● Individual	● Individual	● Individual
○ Simulated City	○ Simulated City	○ Simulated City
○ Sim. Mountain	○ Sim. Mountain	○ Sim. Mountain
Brake Defect Code	Brake Defect Code	Brake Defect Code
NONE	NONE	NONE

Exhibit 5.3 shows a screen capture with the "Channel vs. Channel" user interface tab depressed. This menu screen is similar to the previous screen, but there is one significant difference. The menu screen provides the user with the capability to plot one channel versus another channel (instead of versus time as in the two previous menu options) . As shown in Exhibit 5.3, the user chose to plot pneumatic control pressure versus deceleration for two different brake maneuvers--the first at a deceleration rate of 5 ft/sec/sec and the second at a deceleration rate of 15 ft/sec/sec. Intuitively, the brake maneuver conducted at the higher deceleration rate resulted in the recording of a higher control pressure (~95psi).

Exhibit 5.3- Database Screen Capture: Channel versus Channel



Y-Axis Channel: CtrlPres

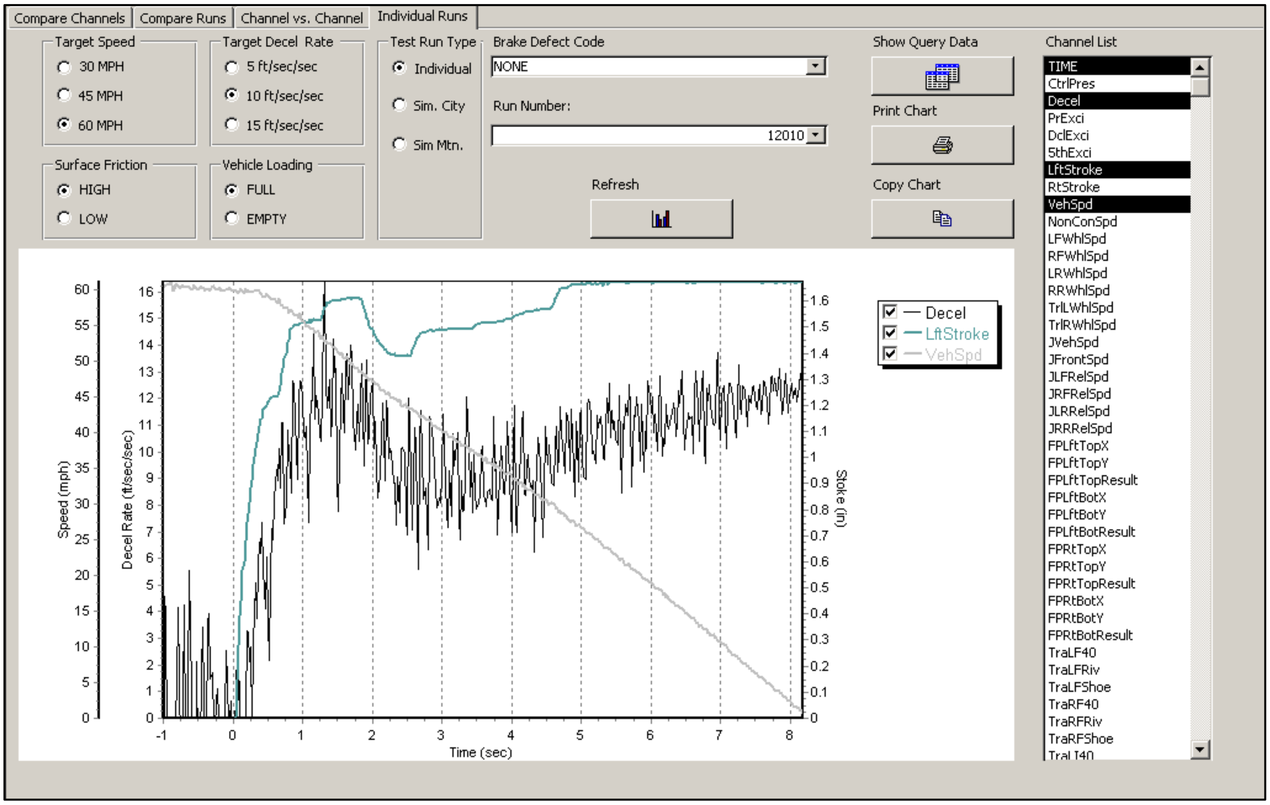
X-Axis Channel: Decel

	☑ OPTION #1	☑ OPTION #2	☐ OPTION #3
Target Speed	○ 30 MPH ○ 45 MPH ● 60 MPH	○ 30 MPH ○ 45 MPH ● 60 MPH	● 30 MPH ○ 45 MPH ○ 60 MPH
Target Decel Rate	● 5 ft/sec/sec ○ 10 ft/sec/sec ○ 15 ft/sec/sec	○ 5 ft/sec/sec ○ 10 ft/sec/sec ● 15 ft/sec/sec	● 5 ft/sec/sec ○ 10 ft/sec/sec ○ 15 ft/sec/sec
Surface Friction	● HIGH ○ LOW	● HIGH ○ LOW	● HIGH ○ LOW
Vehicle Loading	● FULL ○ EMPTY	● FULL ○ EMPTY	● FULL ○ EMPTY
Test Run Type	● Individual ○ Simulated City ○ Sim. Mountain	● Individual ○ Simulated City ○ Sim. Mountain	● Individual ○ Simulated City ○ Sim. Mountain
Brake Defect Code	NONE	NONE	NONE

Finally, Exhibit 5.4 shows a screen capture with the "Individual Runs" user interface tab depressed. This menu screen is unique in that it allows the user with to explore the data collected during an individual run. As previously noted, in the other three interface tabs, the data presented for each brake maneuver (or test run) was actually the average of three test runs conducted back-to-back and then averaged together. In this menu screen, the user can select from a list of individual run number repetitions.

For example in Exhibit 5.4, data is displayed for run number 12010. Run number 12010 corresponds to a brake maneuver initiated from a target speed of 60 mph at a deceleration rate of 10 ft/sec/sec, on dry pavement, with a full load, and with no brake defects. It is important to note that knowing the specifics of an individual test run is not necessary to operate this menu screen. As the user selects from a list of parameters (i.e. target speed, decel. rate, etc.), the database automatically queries the data for run numbers meeting those requirements. The matching run numbers are then displayed in a drop-down display box under the heading "Run Number". In this example, vehicle speed, deceleration rate, and stroke are plotted versus time. As shown, the deceleration rate swings as the driver modulates the treadle valve attempting to close in on a 10 ft/sec/sec deceleration rate. During this event, the stroke reaches a maximum of 1.6 inches.

Exhibit 5.4- Database Screen Capture: Individual Runs



Target Speed
○ 30 MPH
○ 45 MPH
● 60 MPH

Target Decel Rate
○ 5 ft/sec/sec
● 10 ft/sec/sec
○ 15 ft/sec/sec

Test Run Type
● Individual
○ Sim. City
○ Sim Mtn.

Surface Friction
● HIGH
○ LOW

Vehicle Loading
● FULL
○ EMPTY

Brake Defect Code: NONE

Run Number: 12010

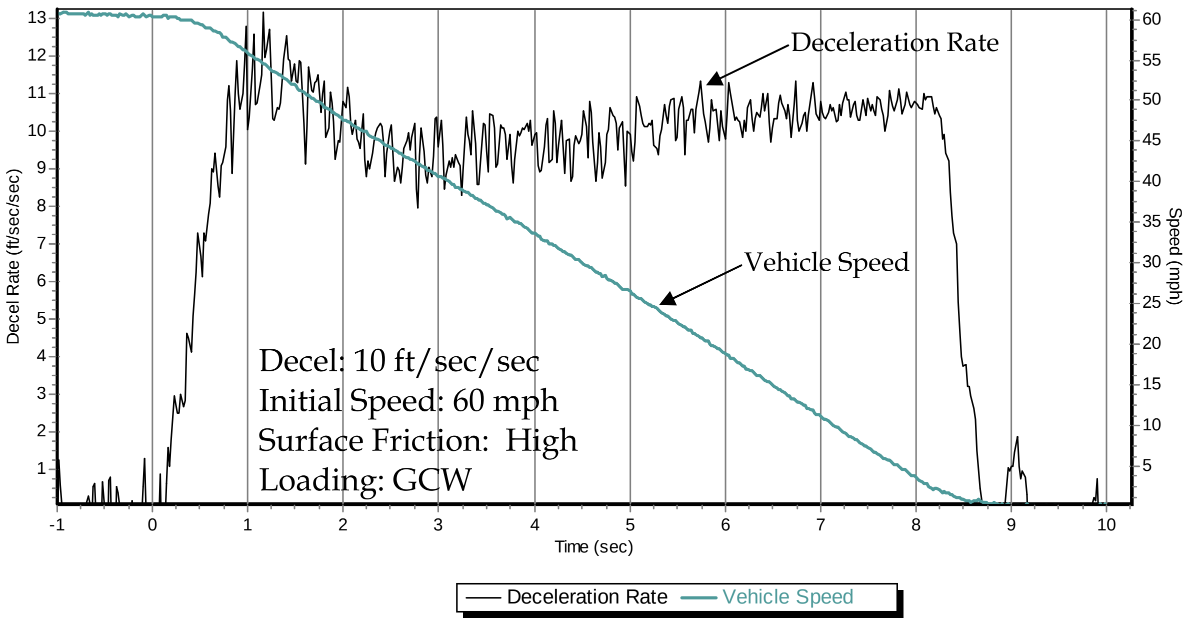
<u>Note:</u> In a majority of the remaining graphics throughout this report, the sensor output data shown is actually the average of three individual test runs at identical conditions. However, there were cases where graphing individual test runs was preferred, particularly when analyzing wheel-speed sensor and temperature data. In these cases, the individual run number was noted.

5.2 BRAKE PERFORMANCE

A vehicle's braking performance is affected by several variables, including: surface friction of the road, tire compound, driver input, vehicle weight, and the braking system. The series of graphs presented in this section illustrate the relationship between control pressure, brake chamber stroke, deceleration rate, and vehicle speed. It is intended to introduce the reader to fundamental braking principles that are used in the evaluation of sensor packages in the following sections.

Exhibit 5.5 shows a moderate-level braking maneuver (decelerating at 10 ft/sec/sec) from 60 mph on dry pavement with a fully loaded (maximum GCW) vehicle. At time t=0, the driver first hit the brake pedal (actually approximately 0.05 seconds before t=0 since there was a slight delay in triggering the data acquisition system electronics) and the vehicle deceleration rate increased rapidly. After the initial deceleration began, the driver then tried to modulate the brake pedal to maintain a constant 10 ft/sec/sec deceleration rate (approx. t= 1 second). Exhibit 5.5 shows that the driver succeeded in maintaining an average deceleration rate during the braking maneuver of approximately 10 ft/sec/sec. Since there was a constant deceleration rate, the vehicle speed decreased linearly throughout most of the braking maneuver.

Exhibit 5.5 – Vehicle Speed and Deceleration Rate: Moderate Braking Maneuver



Braking maneuvers at 5, 10, and 15 ft/sec/sec deceleration rates from 60 mph are shown in Exhibit 5.6. As expected, as the average deceleration rate increased, the vehicle speed decreased more rapidly. At a 5 ft/sec/sec deceleration rate, the truck took about 17 seconds to stop, compared with 9 seconds at 10 ft/sec/sec, and 7 seconds at 15 ft/sec/sec.

Exhibit 5.6 – Service Brake Stops at 5, 10, and 15 ft/sec/sec Deceleration Rates

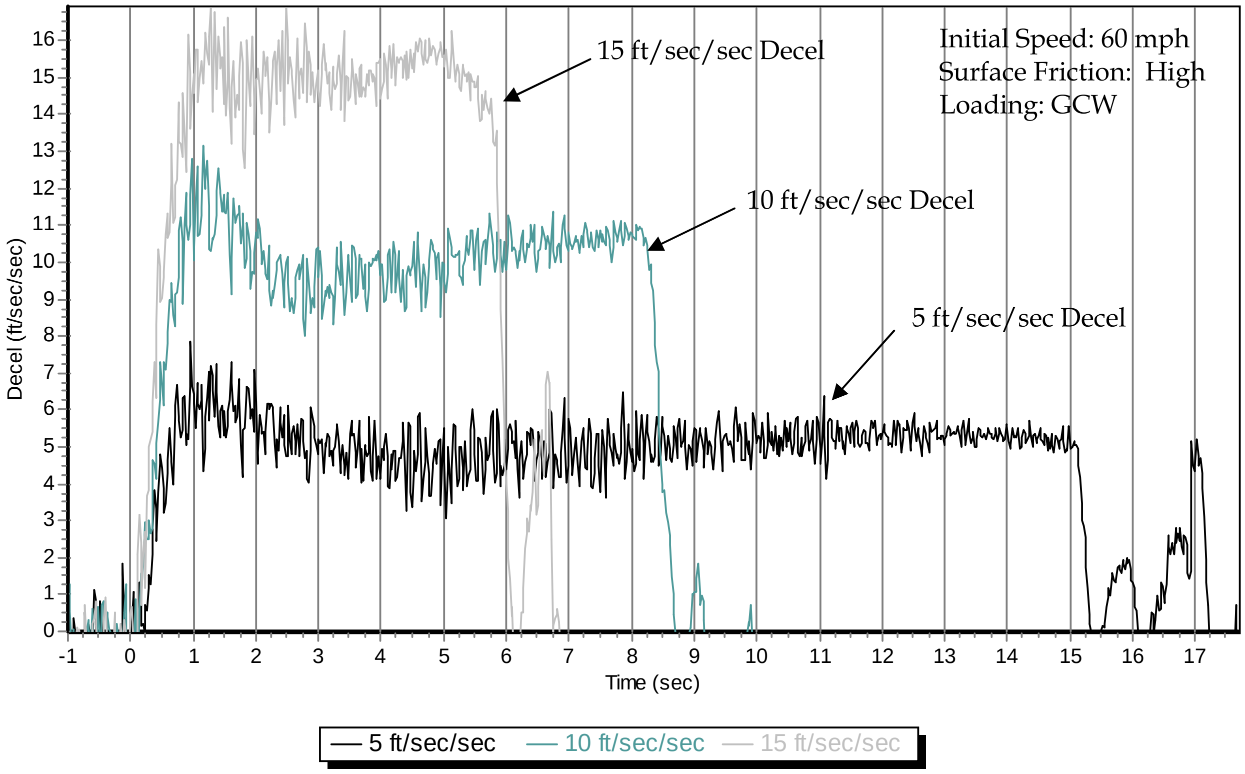
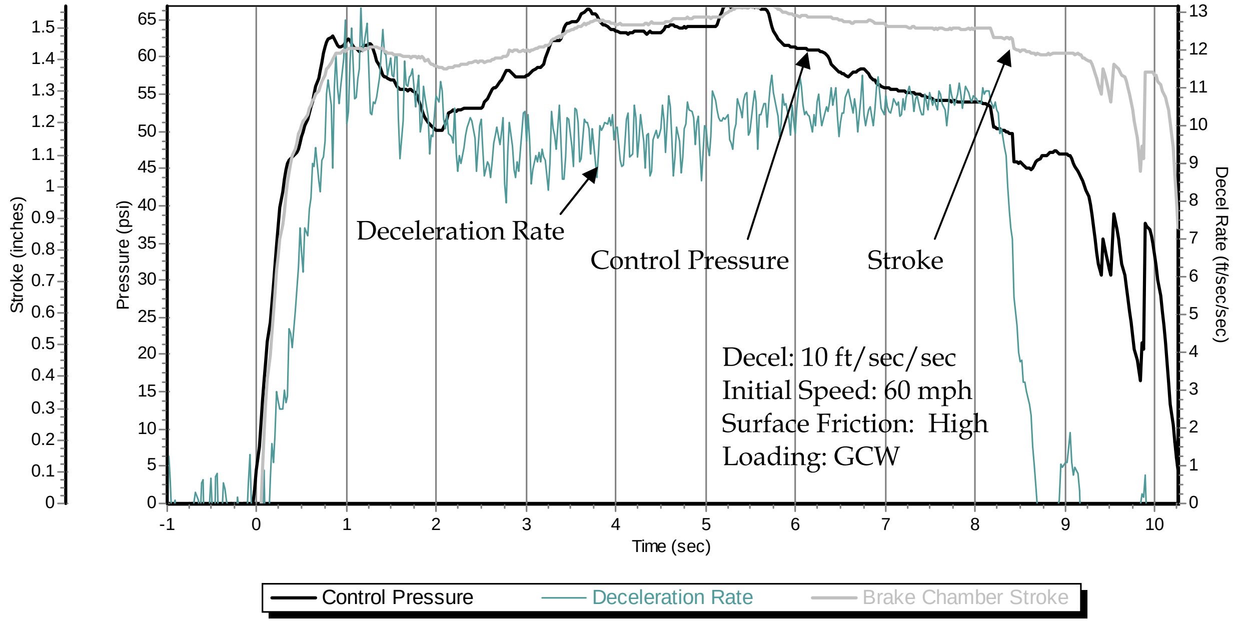


Exhibit 5.7 depicts the control pressure, brake chamber stroke, and deceleration rate for a 10 ft/sec/sec braking maneuver from 60 mph. Control pressure is directly related to the force the driver exerts on the pedal, and is measured by a pressure transducer in the control lines.

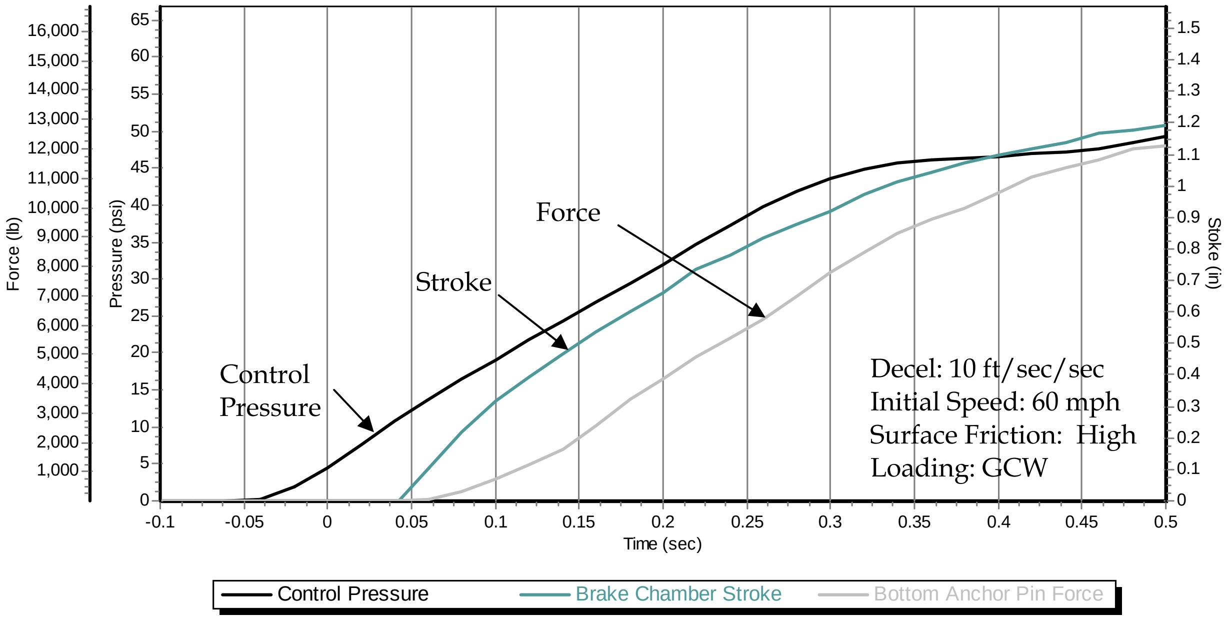
Exhibit 5.7 – Control Pressure and Brake Chamber Stroke

(left intermediate brake assembly)



There was an additional 0.01-second delay between the moment the brake chamber began to stroke and when a change in anchor pin force was registered.

Exhibit 5.8 – Brake System Activation Timeline and Delay
(left intermediate brake assembly)



At 60 mph, this total delay (0.085 seconds) resulted in 7.5 ft of travel between the time a driver pressed the brake pedal and when force was actually applied to the brake drum.

5.3 ANCHOR PIN STRAIN GAUGES

Heavy-duty tractor and trailer drum brake assemblies utilize two brake shoes positioned around the inner diameter of the brake drum. The shoes are anchored and pivot around straight pins (anchor pins) at one end, while the other end has rollers that follow the movement of the twisting camshaft. This assembly is depicted in Exhibit 5.9. The primary brake shoe is located first inline with the direction of wheel travel from the s-cam assembly. Therefore, it is the first to experience a change in force due to the rotation of the s-cam. For testing, the anchor pin strain gauge replaced the standard steel anchor pins and contained two strain gauges per pin, oriented 90 degrees apart from each other (roughly along the X and Y axes). A resultant force was calculated and stored in the database for each anchor pin. The four anchor pins on the tractor's intermediate axle (two on the left side and two on the right side) were replaced with the StrainSert anchor pins.[8]

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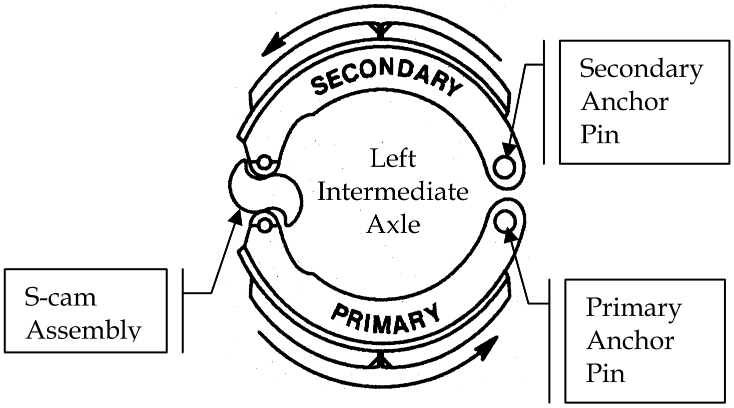
[8] See footnote 2, page 3-6

Exhibit 5.9 – Left Intermediate Axle Brake Shoe Diagram



5.3.1 Correlation Between Anchor Pin Strain Gauges and Deceleration Rate

Exhibit 5.10 shows the output of the anchor pin strain gauges located in the tractor's left-side intermediate axle's brake assembly during a moderate (10 ft/sec/sec) brake application from 60 mph. The primary anchor pin force tracked closely with the overall deceleration rate as the driver modulated the braking force in an attempt to maintain a constant deceleration rate.

Exhibit 5.10 – Primary and Secondary Anchor Pin Force During Moderate Deceleration
(left intermediate brake assembly)

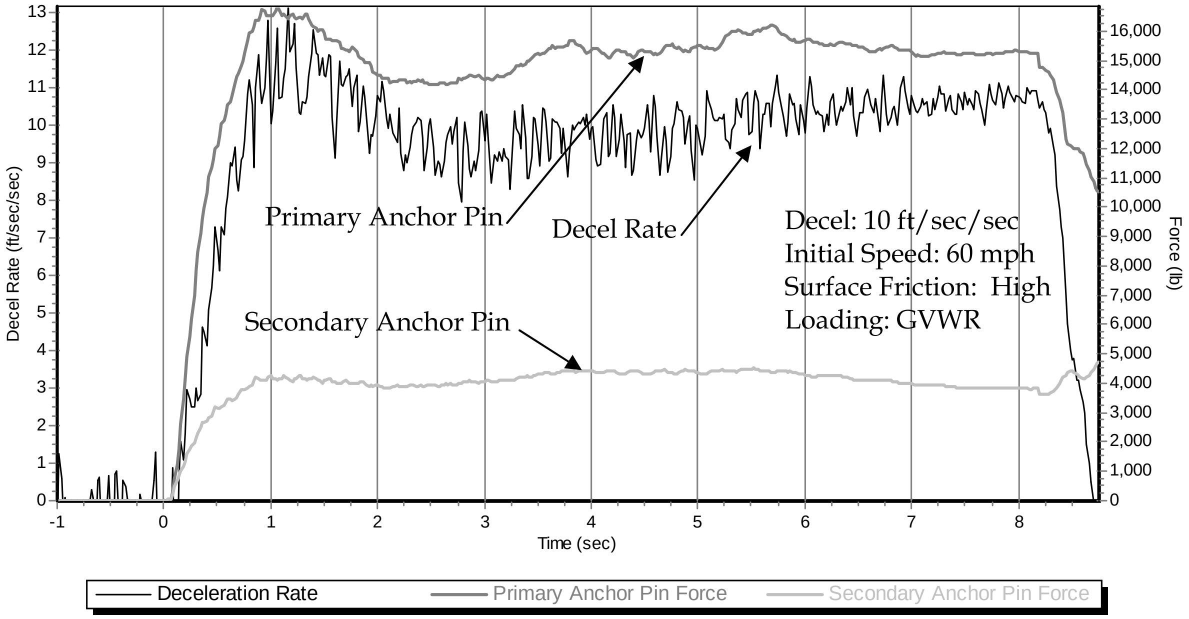
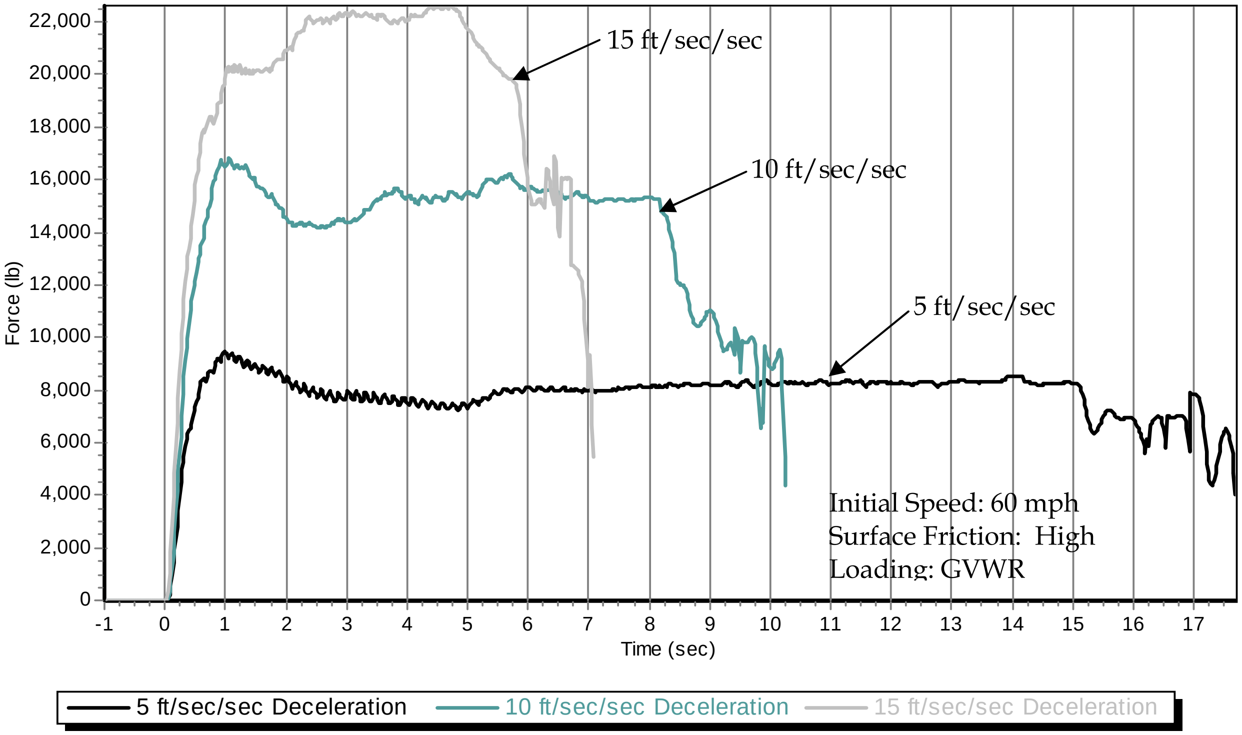


Exhibit 5.10 suggests that the primary (bottom) anchor pin strain gauge provided a more precise and responsive measurement of strain, and therefore braking force, than the secondary (top) anchor pin. This phenomenon likely resulted from the primary anchor pin being first in line with the direction of wheel rotation from the s-cam assembly as depicted in Exhibit 5.10. As noted earlier, the primary shoe typically experiences higher braking forces than the secondary shoe—and the relative magnitude and sensitivity of primary versus secondary anchor pin forces confirms this.

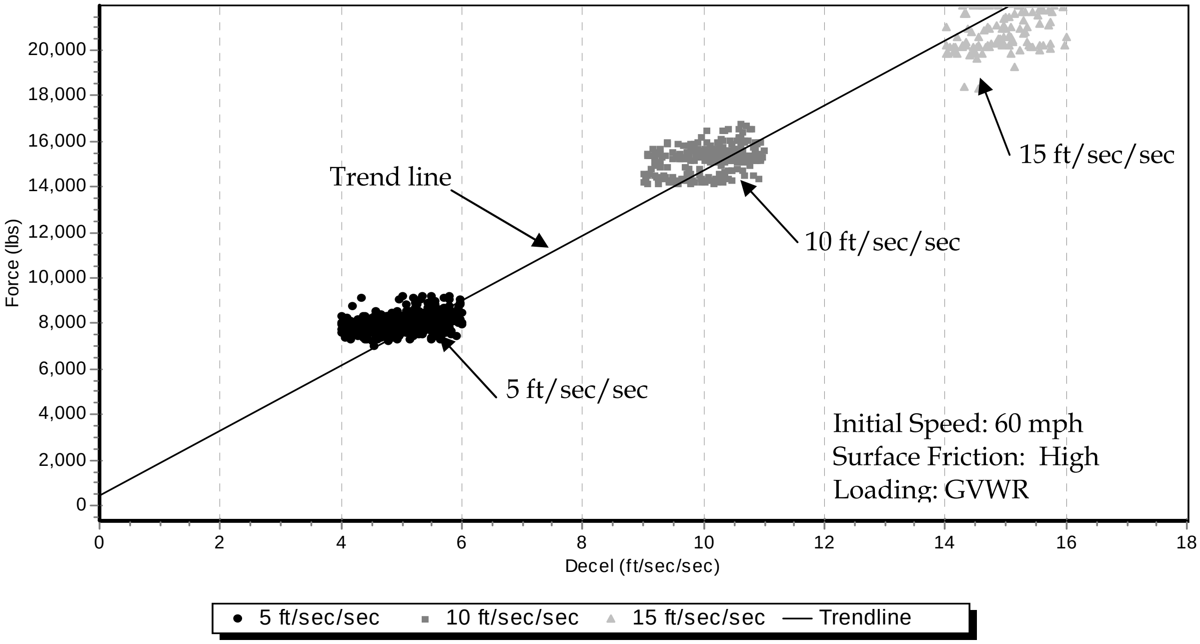
The primary anchor pin force during 5, 10, and 15 ft/sec/sec deceleration braking is plotted against time in Exhibit 5.11. The primary anchor pin force increased proportionally as the target deceleration rate increased.

Exhibit 5.11 –Primary Anchor Pin Force Measurement at Differing Deceleration Rates
(left intermediate brake assembly)



In Exhibit 5.12, primary anchor pin force is plotted directly against the deceleration rate of the vehicle (instead of versus time as in Exhibit 5.11) for a variety of test conditions at 5, 10, and 15 ft/sec/sec target deceleration rates.

Exhibit 5.12 – Primary Shoe Anchor Pin Force Correlation With Deceleration Rate



The trend line in Exhibit 5.12 shows a linear relationship between the deceleration rate of the vehicle and the primary anchor pin strain-gauge force, and that anchor pin force is a reliable predictor of vehicle braking performance.

5.3.2 Performance-Based Brake Tester Comparison

The previous section shows that there is a correlation between the primary anchor pin force and braking performance. To better understand the relationship between anchor pin strain-gauge forces and actual braking force, the test truck was placed on a performance based brake tester (PBBT) to measure the true braking force generated at the vehicle's wheels. Exhibits 5.13 and 5.14 plot the primary (bottom) and secondary (top) anchor pin force versus the PBBT brake force for the tractor's left-side and right-side intermediate axle brake assemblies, respectively.

Exhibit 5.13 – Anchor Pin Force vs. PBBT Brake Force
(left intermediate brake assembly)

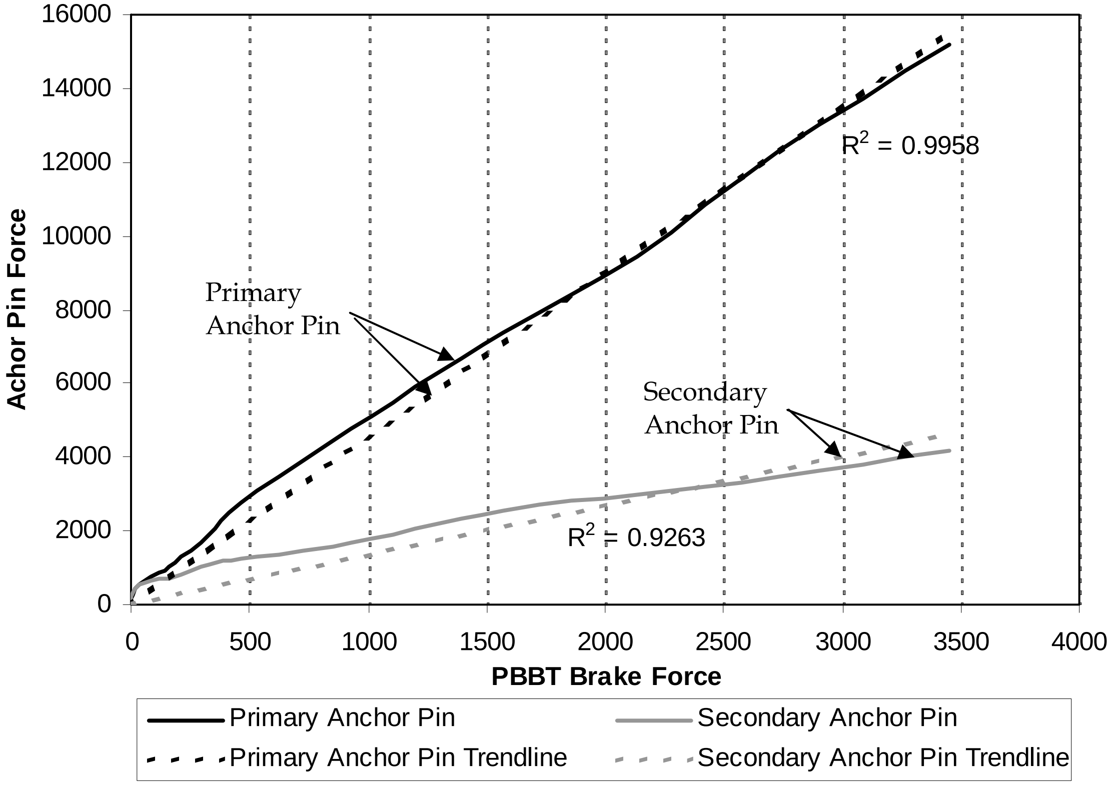
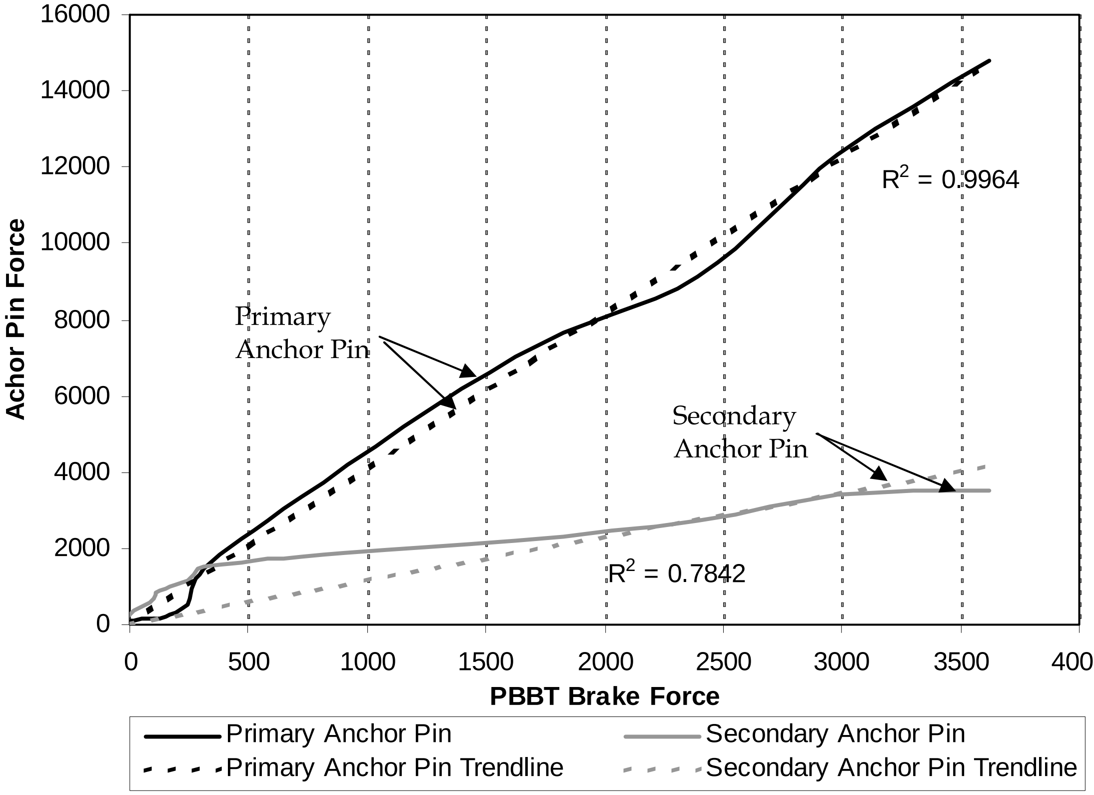


Exhibit 5.14 - Anchor Pin Force vs. PBBT Brake Force
(right intermediate brake assembly)



As shown in Exhibit 5.13, the primary anchor pin force has a more linear correlation with the actual (PBBT) brake force than does the secondary anchor pin force (a correlation coefficient of 0.9958 compared with 0.9263). For the right intermediate brake assembly, as shown in Exhibit 5.14, a correlation coefficient of 0.9964 for the primary anchor pin is compared with 0.7842 for the secondary pin. This indicates that the primary anchor pin force has a very linear correlation with the actual braking force recorded using the PBBT.

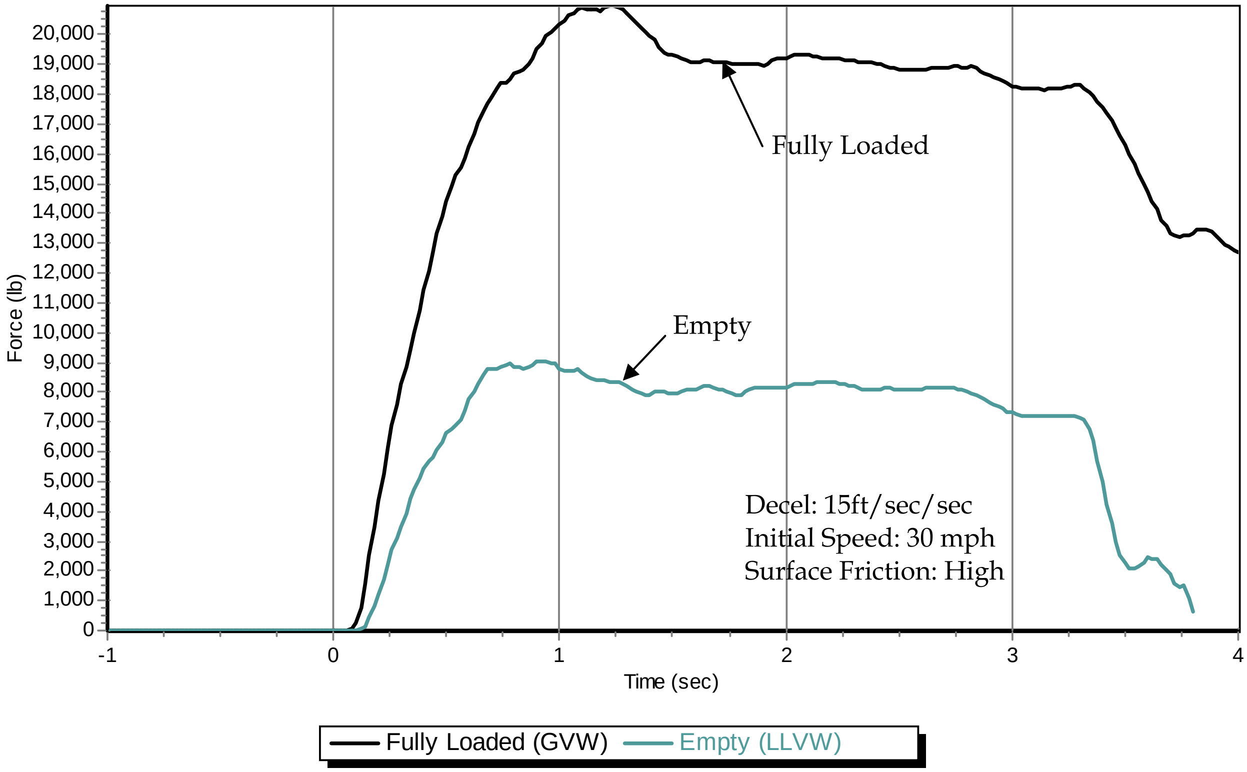
The previous exhibits show that primary anchor pin force is correlated closely with both the deceleration rate and the actual braking force (as measured by the PBBT) of the vehicle. Since the secondary anchor pin does not provide as precise, responsive, or proportional a measurement of braking performance, the remainder of this report will focus on showing only the output of the primary anchor pin strain gauges as a measure of braking force.

From a commercialization perspective, this observation has important implications—specifically, that it is necessary to instrument only a single anchor pin to accurately measure brake force.

5.3.3 Empty Versus Fully Loaded

In Exhibit 5.15, the primary anchor pin force during a hard braking event (15 ft/sec/sec) from 30 mph on dry pavement is compared for loaded versus unloaded conditions.

Exhibit 5.15 – Primary Anchor Pin Force With a Fully Loaded and Empty Vehicle
(left intermediate brake assembly)



The data shows that during hard braking (15 ft/sec/sec) with a full load (79,620 lbs) the measured force at the anchor pin is about 21,500 lbs. This compares with about 9,000 lbs when the vehicle is empty (LLVW 33,610 lbs)—or about 2.4 times as much braking force when loaded. This measured increase in force is nearly identical to the theoretical increase based on the equation Force=mass x acceleration, which indicates that the increased braking force should be proportional to the increase in mass: (79,620lbs/33,610 = 2.37)

5.3.4 Low- Versus High-Friction Surfaces

On a low-friction surface (wet pavement), the anchor pin force varies as the ABS system cycles the brake chamber pressure to prevent wheel lockup. Exhibit 5.16 depicts anchor pin force during a 15 ft/sec/sec deceleration on low- (wet) and high-friction (dry) surfaces.

Exhibit 5.16 – Primary Anchor Pin Force on a High- and Low-Friction Surface

(left intermediate brake assembly)

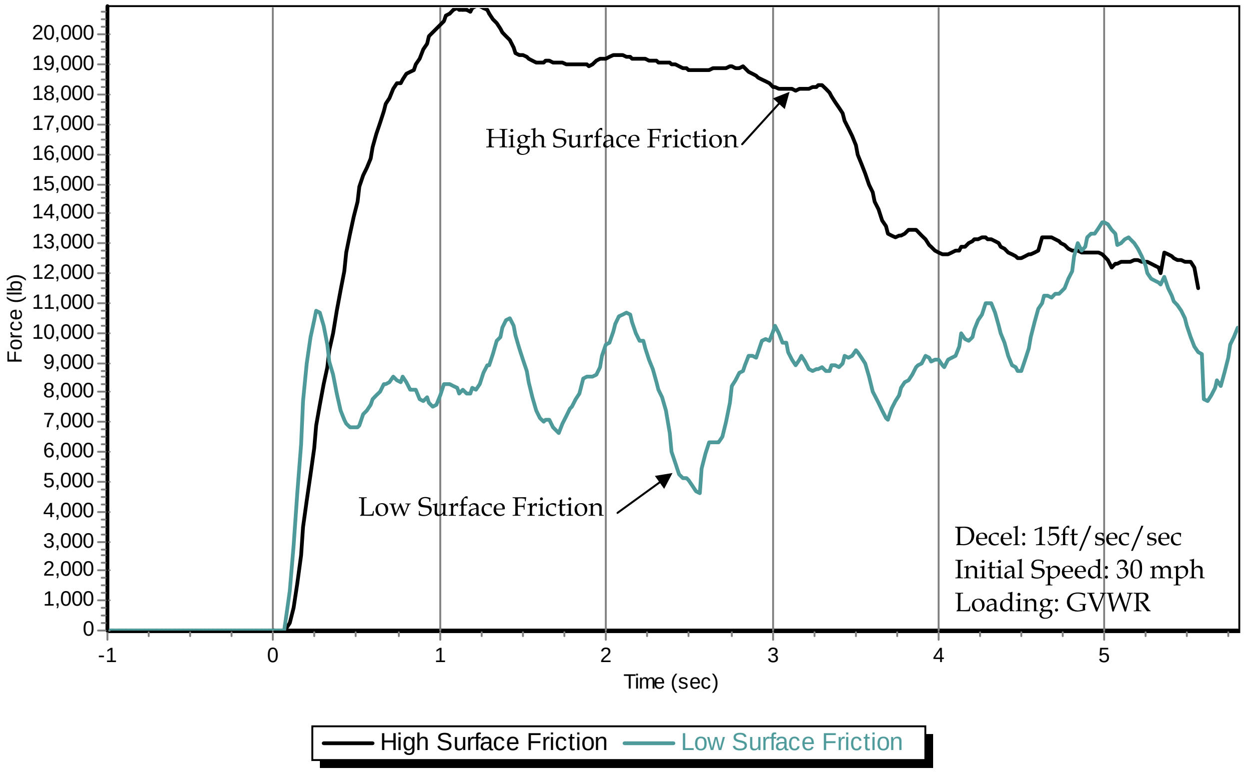


Exhibit 5.16 shows that on a low-friction surface, the anchor pin force is cycling corresponding to the activation of the ABS system. The ABS system releases application pressure to the left intermediate wheel to prevent wheel lockup and, as expected, the anchor pin force decreases. When the ABS reapplies application pressure, the anchor pin force increases. This pattern continues throughout the braking maneuver.

5.3.5 Out-of-Adjustment Brakes

Exhibits 5.17 and 5.18 compares anchor pin force during braking maneuvers at a 15 ft/sec/sec deceleration rate from 60 mph for a vehicle with:

- No brake defects (Code 0),
- Two brakes (left intermediate and right rear) out-of-adjustment by 2-1/8-inch stroke (Code 4), and
- Two brakes (left intermediate and right rear) out-of adjustment by 2-3/8-inch stroke (Code 2).

Exhibit 5.17 shows the anchor pin force on an out-of-adjusted brake assembly (left intermediate), while Exhibit 5.18 shows anchor pin force on a properly adjusted brake assembly (right intermediate) during the same series of braking events.

Exhibit 5.17 – Anchor Pin Force Measured on Out-of-Adjustment Brake Assembly
(left intermediate brake assembly)

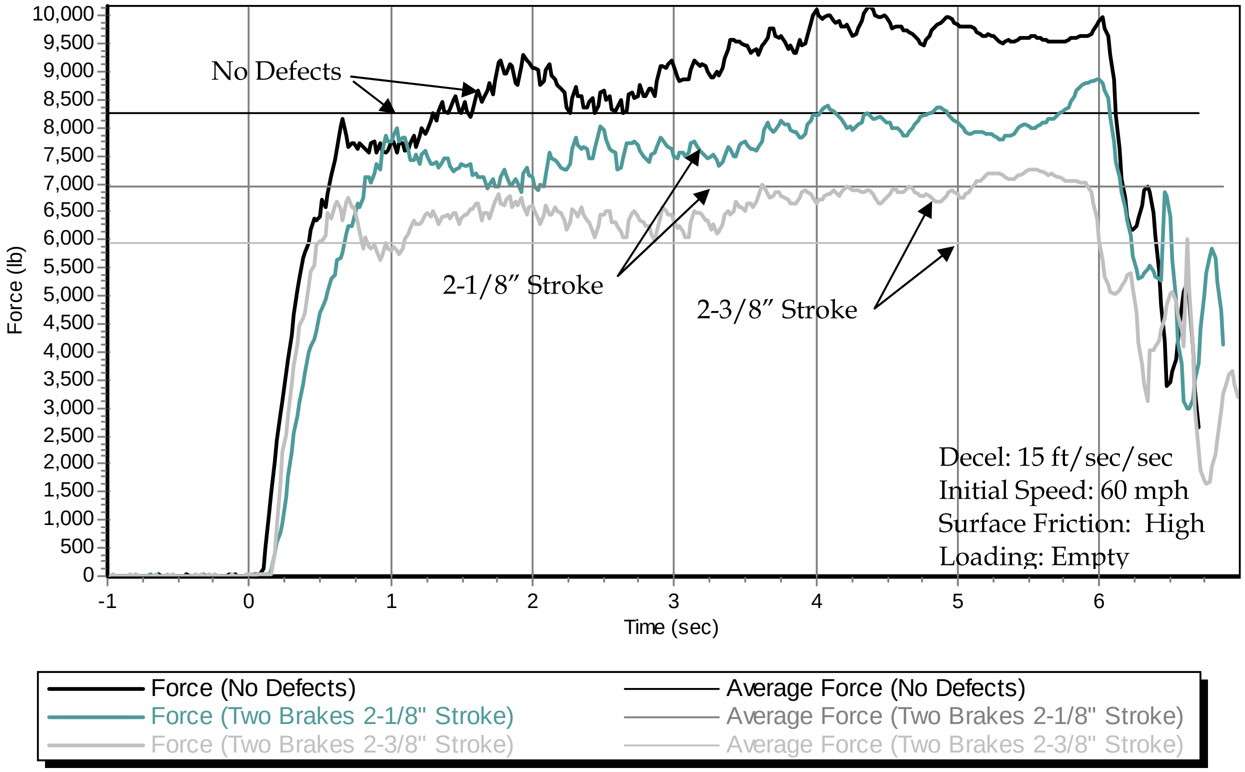
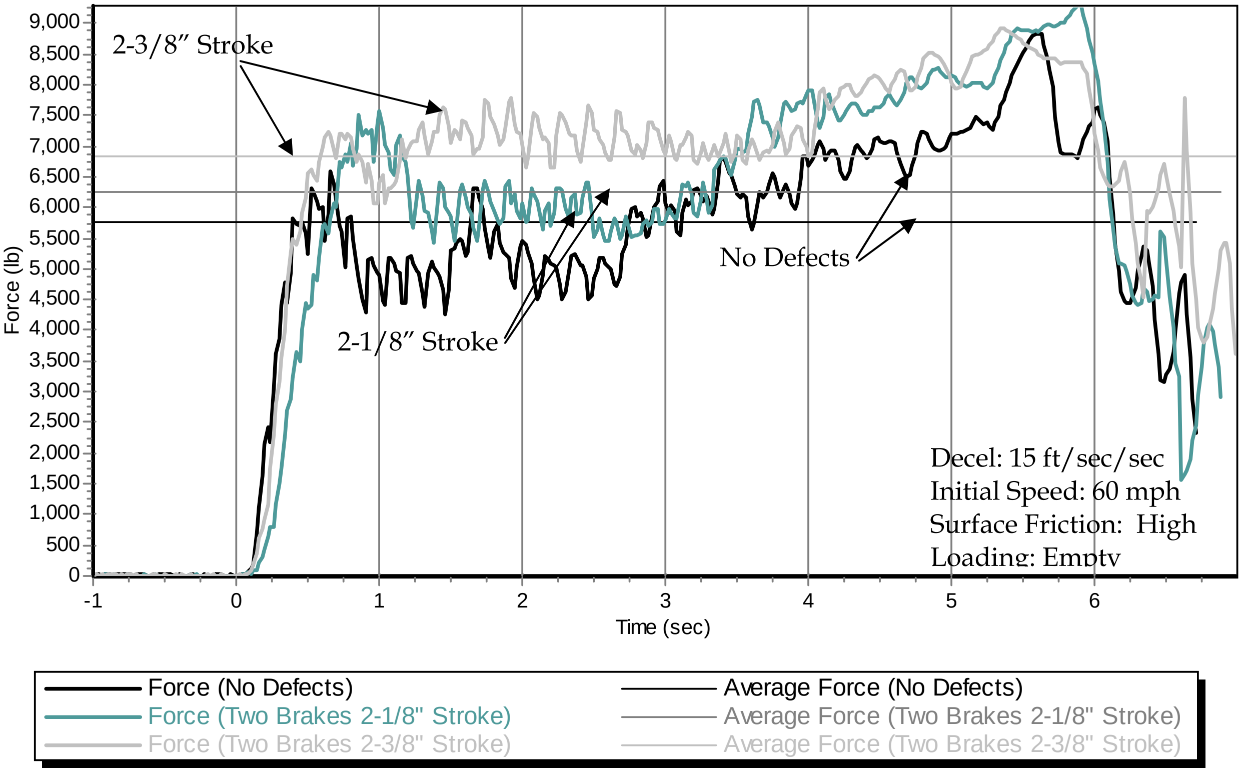


Exhibit 5.17 shows that there is a decrease in average stopping force generated by the out-of-adjustment brakes. However, as shown in Exhibit 5.18, in order for the vehicle/driver to maintain the same (desired) deceleration rate, the braking forces required on the remaining, correctly adjusted, brakes increases.

Exhibit 5.18 – Anchor Pin Force Measured on Properly Adjusted Brake Assembly
(right intermediate brake assembly)

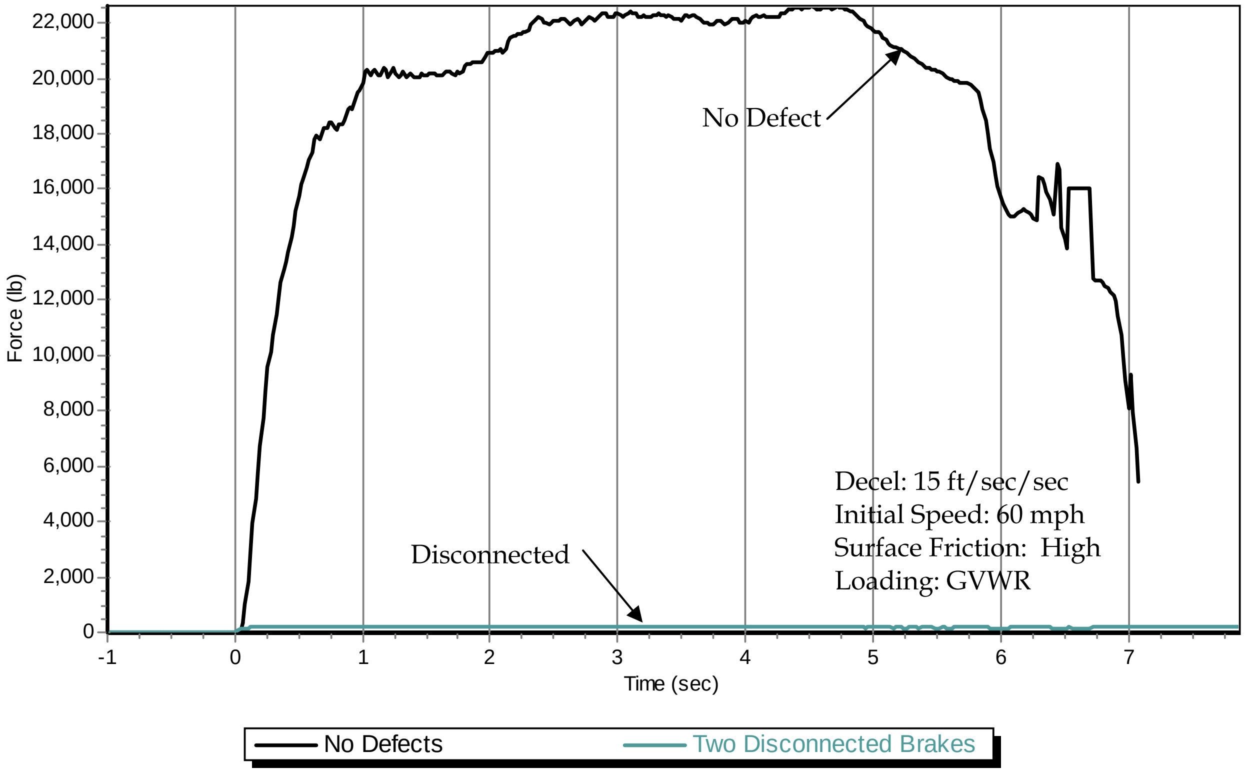


Exhibits 5.17 and 5.18 illustrate that anchor pin strain gauges can provide valuable information to determine if brakes are properly adjusted based on the forces generated from each brake assembly. For example, the output forces from each wheel assembly could be electronically averaged and compared (by an onboard ECU) during varied braking maneuvers to determine if one or more brakes were out of adjustment. If the vehicle were equipped with an electronically controlled braking system (ECBS), this information could be used effectively to increase the control pressure at an individual brake assembly to compensate for the out-of-adjustment condition (or for that matter, any other condition that might be causing the braking forces to be lower or different than desired). In Exhibits 5.17 and 5.18, the control pressure and deceleration rate vary only slightly for each of these three test runs; 39 psi control pressure and 13.5 ft/sec/sec deceleration rate for no defects, 34 psi control pressure and 12.88 ft/sec/sec deceleration rate for two brakes out-of-adjustment 2-1/8 inches, and 33 psi control pressure and 14.03 ft/sec/sec deceleration rate for two brakes 2-3/8 inches out-of-adjustment. Therefore, it

is likely that small variations in control pressure and/or deceleration rate would be largely undetectable by the driver during unbalanced braking conditions on two brake assemblies.

Exhibit 5.19 shows the left intermediate primary anchor pin force for 15 ft/sec/sec braking maneuvers from 60 mph with no brake defects and when two brakes (including the left intermediate) were disconnected (Code 7).

Exhibit 5.19 – Comparison of Primary Anchor Pin Force of a Properly Adjusted and Disconnected Brake
(left intermediate brake assembly)

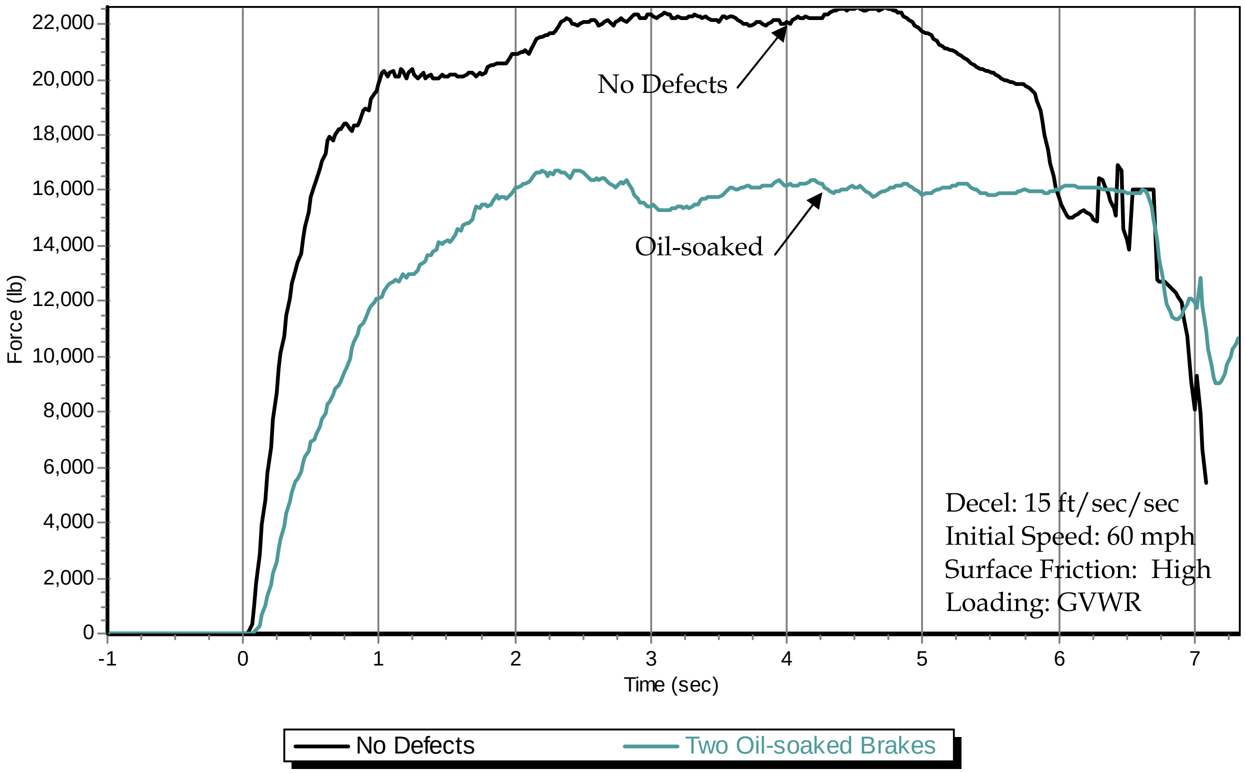


As depicted in Exhibit 5.19, when a brake was disconnected (i.e. when at maximum stroke the brake shoe does not contact the brake drum) little force was generated on the anchor pin. During the average braking maneuver with two brakes disconnected, as in Exhibit 5.19, the driver was only able to maintain an average 10.5 ft/sec/sec deceleration rate (he was unable to achieve the 15 ft/sec/sec target deceleration rate) and the average control pressure increased to 98psi. This is compared with an average deceleration rate of 13.5 ft/sec/sec and average control pressure of 87 psi for the same average braking maneuver with no brake defects. In this situation, it is therefore likely that the disconnected brakes would be detectable by the driver during the braking maneuver.

5.3.6 Oil-soaked Brake Linings

In addition to detecting disconnected and out-of-adjustment brakes, anchor pin strain gauges also show that braking force is reduced with oil-soaked brake linings. Exhibit 5.209 shows anchor pin force for a 15 ft/sec/sec braking maneuver from 60 mph with no brake defects and with two oil-soaked linings, i.e., Code 6 (including the left intermediate brake linings).

Exhibit 5.20 –Primary Anchor Pin Force with Oil-Soaked Brakes
(left intermediate brake assembly)



As shown in Exhibit 5.20, the force generated by the oil-soaked brake lining was significantly less than that of normal (dry) brakes. One might expect that the frictional force (force due to the friction between the brake shoe lining and the drum) would decrease due to the oil, while the non-friction (or "normal") force on the anchor pin (due to the pressure exerted by the brake shoe on the brake drum which is perpendicular to the frictional force) would remain the same or perhaps increase if or when the driver increased brake control pressure in an attempt to maintain desired deceleration rates.

As reviewed in Section 2.2, although the anchor pin strain gauges provide force in two perpendicular directions (X and Y), until now we have been basing our assessment of this technology's capabilities for detecting brake performance only on the **resultant force** of the two strain gauges. However, differentiating between oil-soaked brakes and out-of-adjustment brakes is possible by observing the **relative change** in force between the X and Y direction strain gauges. The orientation of the strain gauge in the "X" direction was intended to measure and isolate the rotational friction forces between the drum and the shoe, whereas the "Y" direction strain gauge was offset 90 degrees in an attempt to isolate the mechanical (non-friction) force generated by the outward movement of the shoe against the drum. In reality, the forces at the anchor pin are likely complex and each strain gauge is affected by both types of forces (mechanical and frictional)… but hopefully to different degrees.

Exhibit 5.21 depicts the X and Y primary anchor pin force for the left intermediate brake assembly under the following conditions:

- Code 0- all brake assemblies properly adjusted (Code 0),
- Code 4- two brake assemblies (left intermediate and right rear) out-of-adjustment 2-1/8", and
- Code 6- two oil-soaked brake assemblies (left intermediate and right rear).

Exhibit 5.21 – X and Y Anchor Pin Forces
(left intermediate brake assembly)

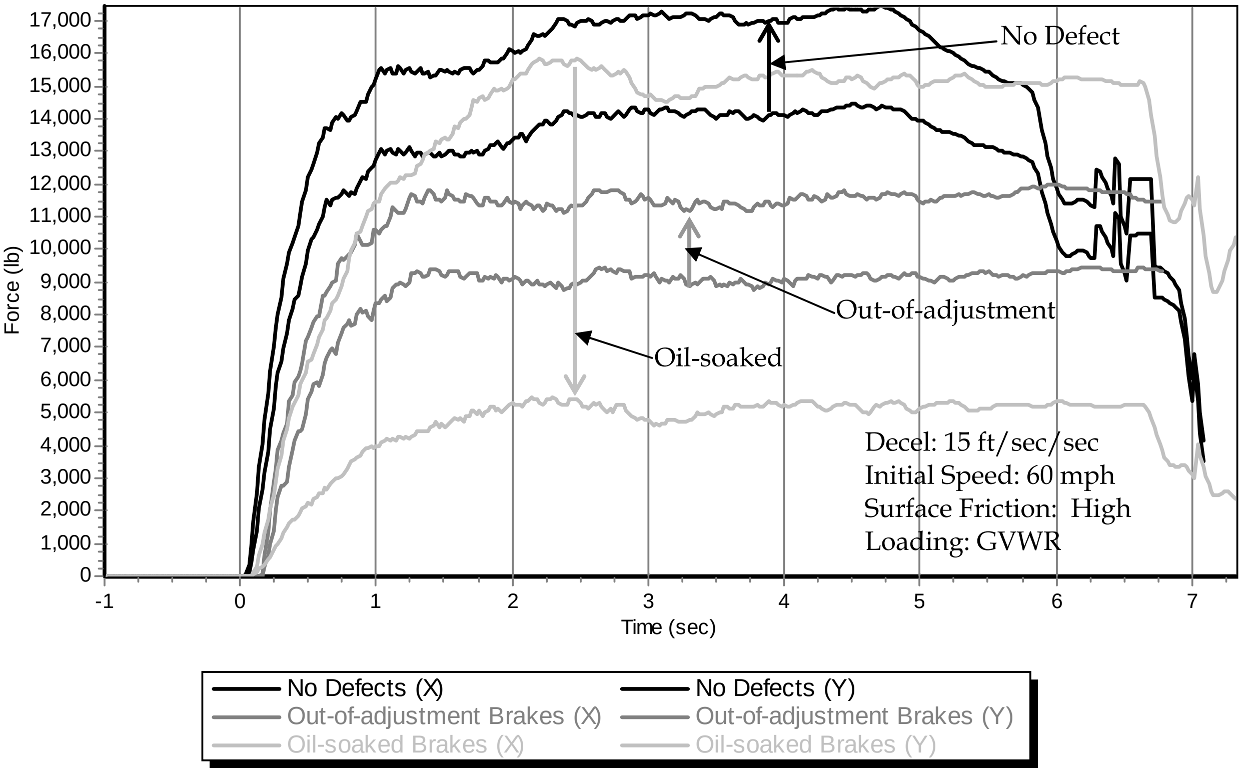


Exhibit 5.21 shows that for properly adjusted brakes (red), as well as out-of-adjustment brakes (blue), the Y direction forces were about 2,000 to 3,000 pounds less than the X-direction strain gauge. This might be expected, since the relative rotational friction forces for a given applied braking pressure remain high with dry brakes. However, with oil-soaked brake shoe linings, the coefficient of friction was reduced and the rotation friction forces (X direction) decreased significantly, while the force in the Y direction (outward mechanical force) actually **increases** as the driver increases brake pressure in an attempt to maintain the desired deceleration rate. With oil-soaked brakes, the Y direction forces are actually much **higher** than the X-direction forces. This information could be used by an onboard ECU to indicate to the driver and maintenance staff if the detected defect in the brake assembly (and associated reduction in brake performance) was caused by an oil-soaked lining as opposed to an out-of-adjustment condition.

Summary-Strain gauges. The previous exhibits show that the anchor pin strain gauges, specifically those located on the primary anchor pin, correctly and accurately identified out-of-adjustment brake assemblies and disconnected brakes. In addition, using the relative forces from the two (X- and Y-direction) strain gauges located in each anchor pin, it was possible to correctly determine when there was an oil-soaked brake shoe lining. The anchor pin strain gauges also provided a high-resolution image of true braking force that could be used to determine and adjust (through a system such as ECBS) unbalanced braking conditions.

5.4

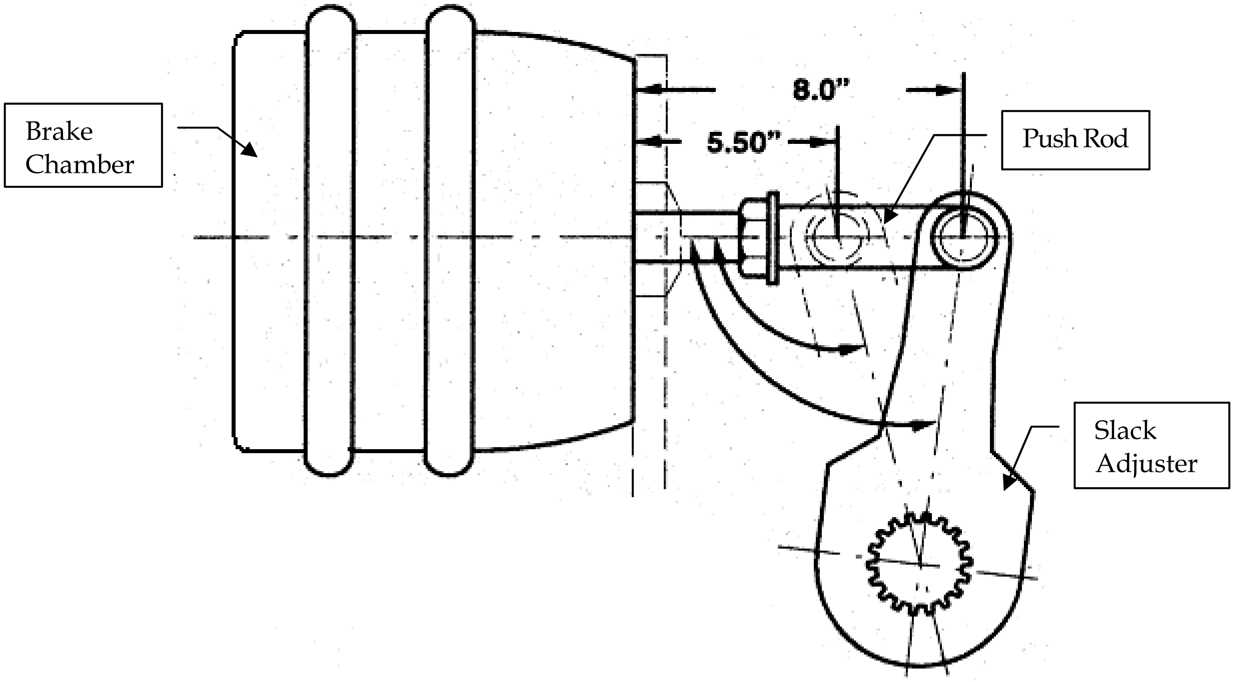
5.5 STROKE SENSORS

Brake chamber stroke is the distance that the brake chamber diaphragm moves the push rod that connects to the slack adjuster. This movement is shown in Exhibit 5.22, with the maximum brake chamber stroke equal to 2.5 inches.

Three brake chamber stroke sensors/sensor packages were installed in the vehicle and tested during this project:

- Linear potentiometers (a general-purpose sensor) mounted externally to the brake chamber on the left-side and right-side intermediate brake assemblies,
- A brake chamber stroke sensor package mounted externally to all of the brake assemblies and trailer (Spectra Brake Inspector), and
- A stroke sensor system mounted internally to the brake chamber on all of the brake assemblies on the tractor and trailer (MGM E-Stroke).

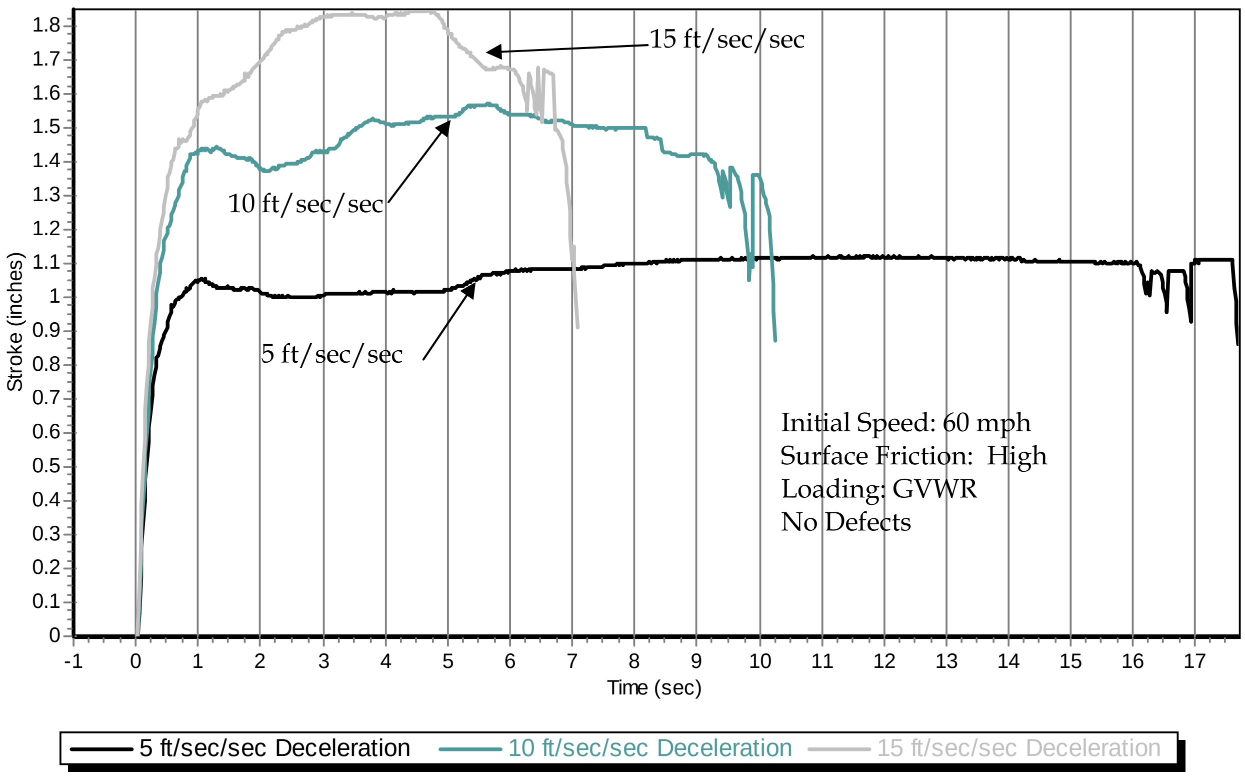
Exhibit 5.22 – Brake Chamber Stroke Diagram



The linear potentiometers were the only brake stroke sensors connected to the DAS. The Spectra and MGM sensor packages required the driver to manually record the data shown on the system's illuminated displays.

An example of the data collected from the linear potentiometers is shown in Exhibit 5.23. The left intermediate brake chamber stroke, as measured using the analog linear potentiometers, is plotted for three deceleration rates of 5, 10, and 15 ft/sec/sec from 60 mph. The average brake chamber stroke for the 5 ft/sec/sec stop is approximately 1 inch, compared with 1.4 inches and 1.7 inches for the 10- and 15-ft/sec/sec stops, respectively.

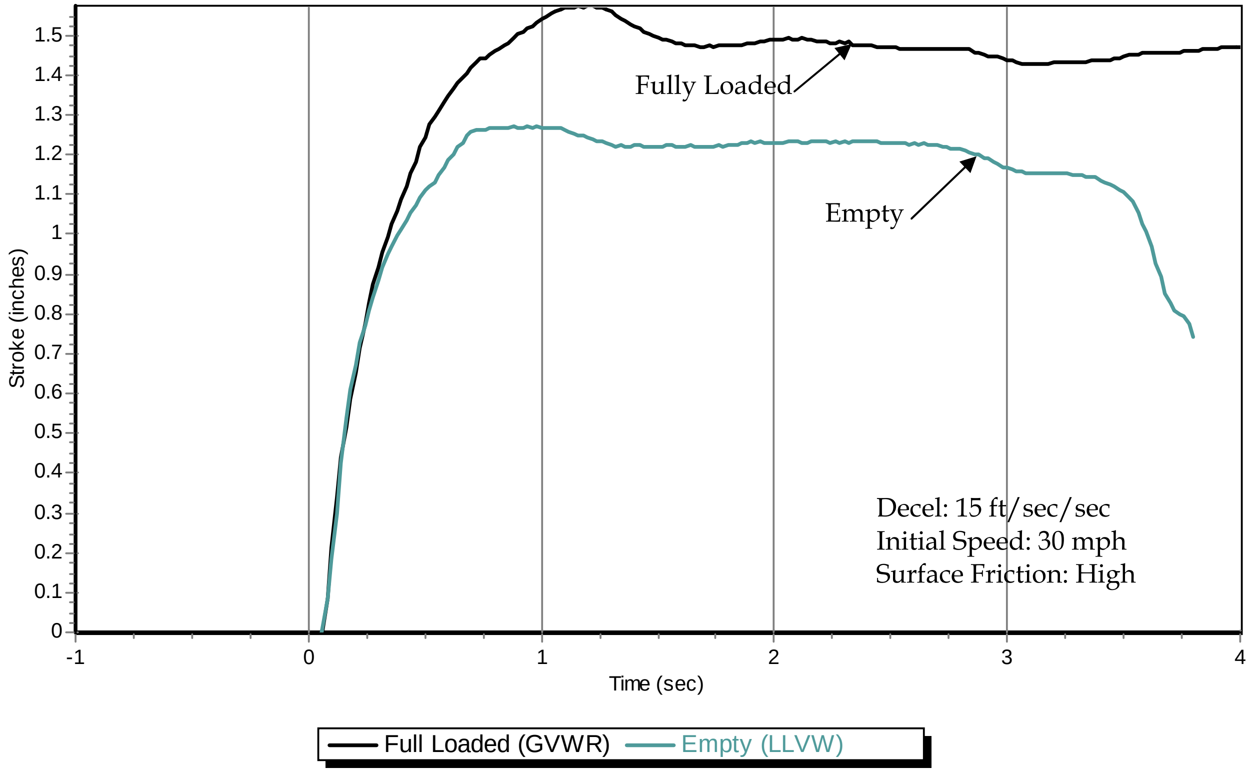
Exhibit 5.23 – Brake Chamber Stroke at Various Deceleration Rates
(left intermediate wheel assembly)



5.5.1 Empty Versus Fully Loaded

Exhibit 5.24 depicts brake chamber stroke during a 15 ft/sec/sec deceleration from 30 mph for a fully loaded (79,620 lbs maximum GCW) and an empty (33,610 lbs) vehicle.

Exhibit 5.24 - Brake Chamber Stroke on an Empty and Fully Loaded Truck
(left intermediate wheel assembly)



Decel: 15 ft/sec/sec
Initial Speed: 30 mph
Surface Friction: High

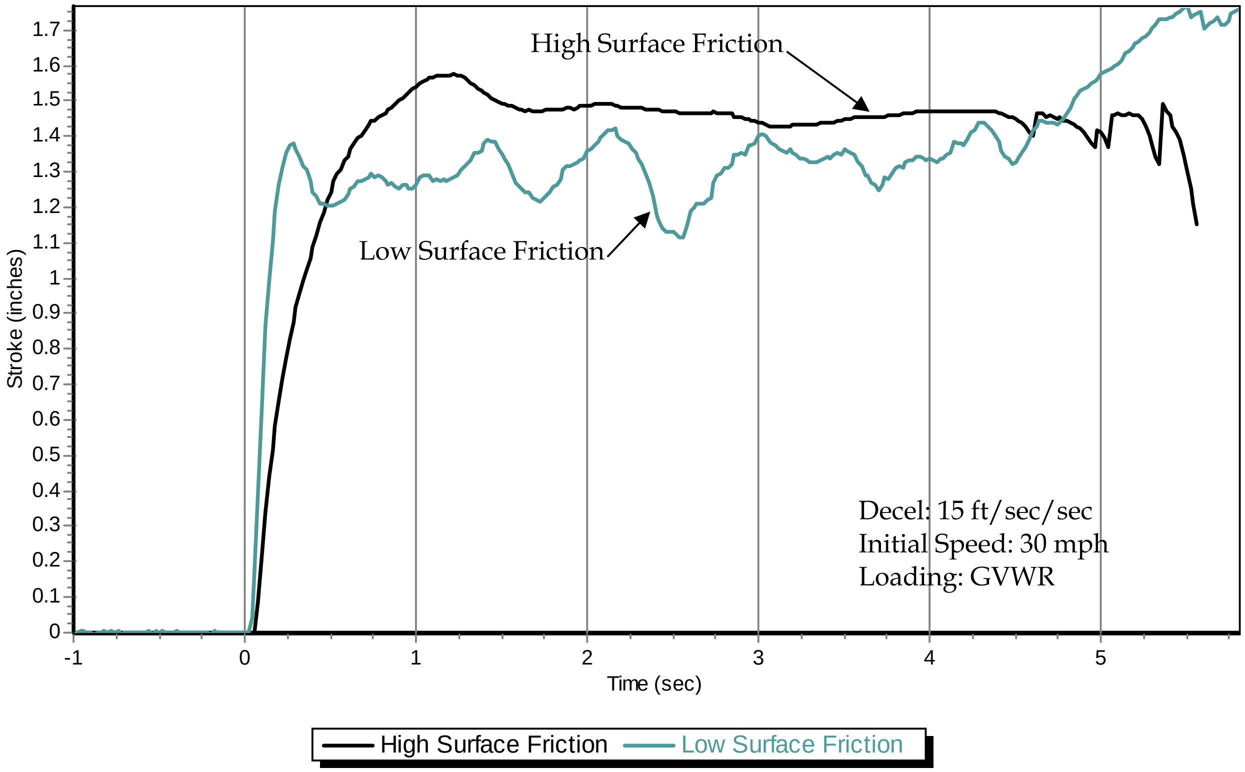
Exhibit 5.24 shows that there was an increase in brake chamber stroke (of approximately 0.3 inches) as a result of the increase in weight of the vehicle, from 33,610 lbs total for an empty vehicle to 79,620 lbs for a fully loaded (maximum GCW) vehicle.

For this same series of tests, the anchor pin strain gauges registered an increase in braking force of about 120% from the empty to loaded conditions (see Exhibit 5.15), whereas stroke measurement increased by approximately 25%. This indicates that the stroke measurement provides a comparatively insensitive, low-resolution estimate of true braking force.

5.5.2 Low- Versus High-Friction Surface

To examine how surface friction and ABS activation affect brake chamber stroke, Exhibit 5.25 depicts brake chamber stroke during a 15 ft/sec/sec deceleration on both high (dry) and low(wet) friction surfaces.

Exhibit 5.25 - Brake Chamber Stroke on a Low- and High-Friction Surface
(left intermediate wheel assembly)



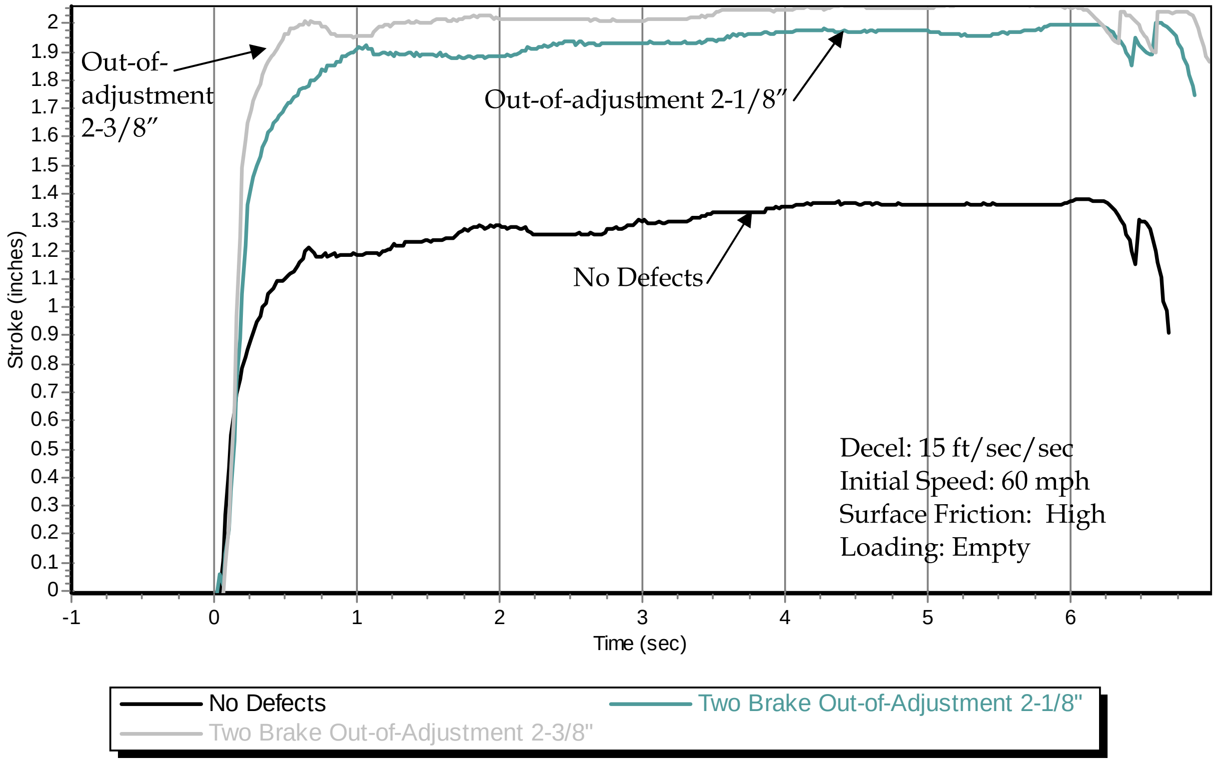
As the ABS system detected a decrease in wheel speed, the ABS pressure modulator valves released brake pressure in an effort to prevent wheel lockup. This then caused the brake chamber stroke to decrease, which resulted in less braking force at the affected wheel. After the wheel speed increased, the ABS system then returned the brake pressure to normal until the wheel speed decreased again and the cycle repeated. During the low-friction surface braking maneuver, the ABS was cycling the brake pressure to prevent wheel lockup, thus producing the fluctuations in brake chamber stroke that are shown in Exhibit 5.26.

5.5.3 Out-of-Adjustment Brakes

Exhibit 5.26 shows the left intermediate brake chamber stroke when:

- All of the brake assembles are adjusted properly (Code 0, no defects);
- Left intermediate and right rear brake assemblies are out-of-adjustment 2-1/8 inches (Code 4); and
- Left intermediate and right rear brake assemblies are out-of-adjustment 2-3/8 inches (Code 2).

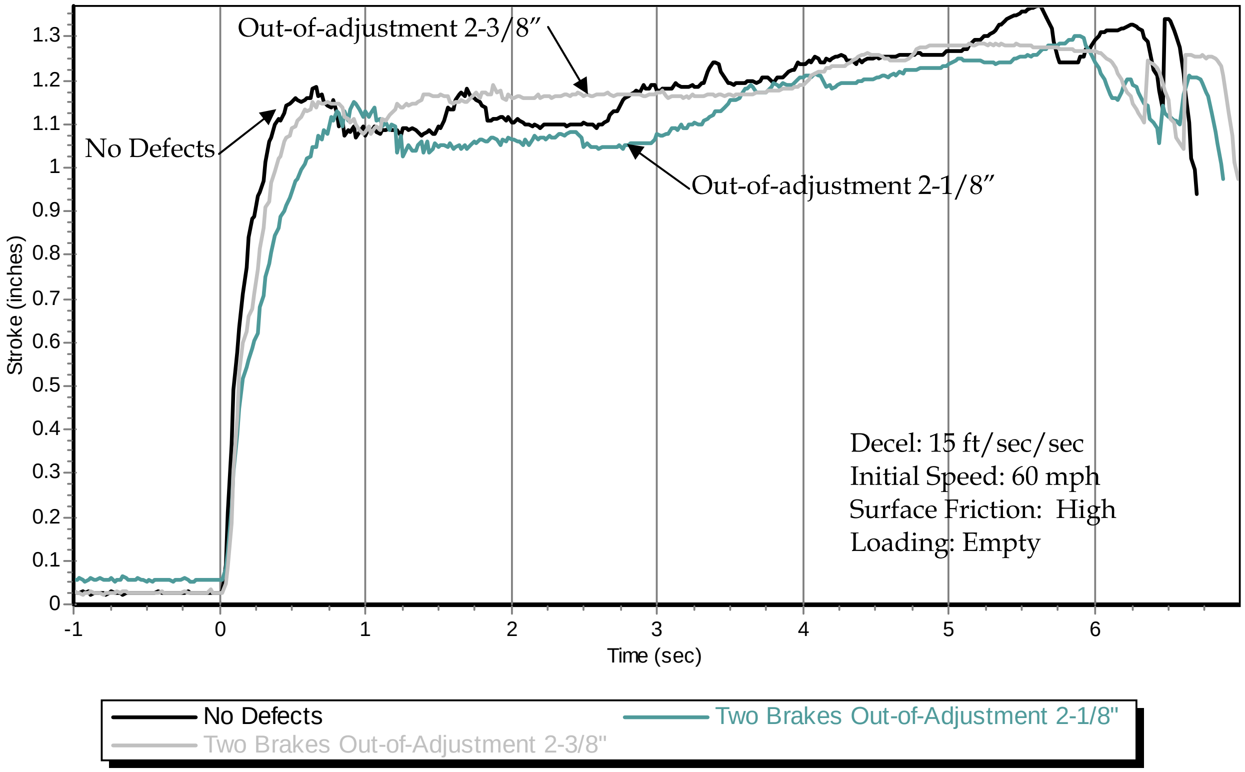
Exhibit 5.26 –Brake Chamber Stroke with Out-of-Adjustment Brakes
(left intermediate wheel assembly)



With no brake defects, the brake chamber stroke was approximately 1.3 inches on average during the braking maneuver. With two brakes out-of-adjustment 2-1/8 and 2-3/8 inches, Exhibit 5.26 shows that the brake chamber stroke increased to 1.9 and 2.0 inches, respectively (on average), during the braking maneuver. This significant increase in brake chamber stroke would likely be detectable by a stroke sensing system, yielding an accurate determination that the brakes were out of adjustment.

During the discussion of strain gauges in subsection 5.3.5, it was determined that when one or more brake assemblies are out of adjustment, then the remaining correctly adjusted brakes exhibit an increase in braking force as the driver tries to maintain a given deceleration rate. Therefore, it might be expected that an increase in stroke could be measured on the correctly adjusted brake assemblies during braking tests with some of the brakes out of adjustment (i.e. Codes 2 and 4). This, however, was not the case. Exhibit 5.27 shows the right intermediate brake chamber stroke, which is adjusted correctly, during the same braking maneuvers as in Exhibit 5.26.

Exhibit 5.27 – Brake Chamber Stroke Measured on Properly Adjusted Brake Assembly (right intermediate) with Left Intermediate Brake Out-of-Adjustment

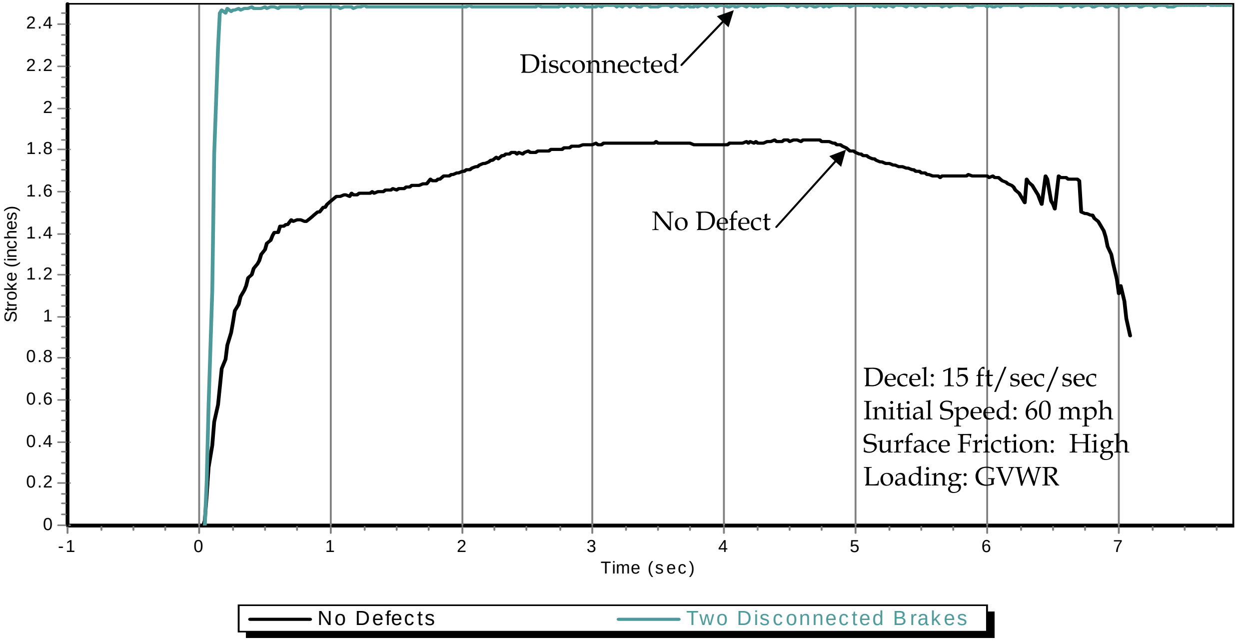


In Exhibit 5.27, the average stroke was 1.17 inches for the braking maneuvers with no defects, 1.10 inches for two brakes out-of-adjustment 2-1/8 inches, and 1.16 inches for two brakes out-of-adjustment 2-3/8 inches. Therefore, stroke sensors would likely not provide the resolution necessary to correctly determine brake balance during conditions where other brake assemblies are out-of-adjustment. This evidence supports the notion that brake stroke travel is a comparatively insensitive measurement of braking force.

Exhibit 5.28 and 5.29 depict the left and right intermediate brake chamber stroke, respectively, during braking maneuvers when all of the brake assemblies were adjusted properly and when there were two disconnected brake assemblies (Code 7). As shown in Exhibit 5.28, the brake chamber quickly reached maximum stroke, 2.5 inches, and maintained this level throughout the maneuver (thus generating no braking force).

Exhibit 5.28 – Brake Stroke Travel With and Without Disconnected Brakes

(left intermediate wheel assembly)

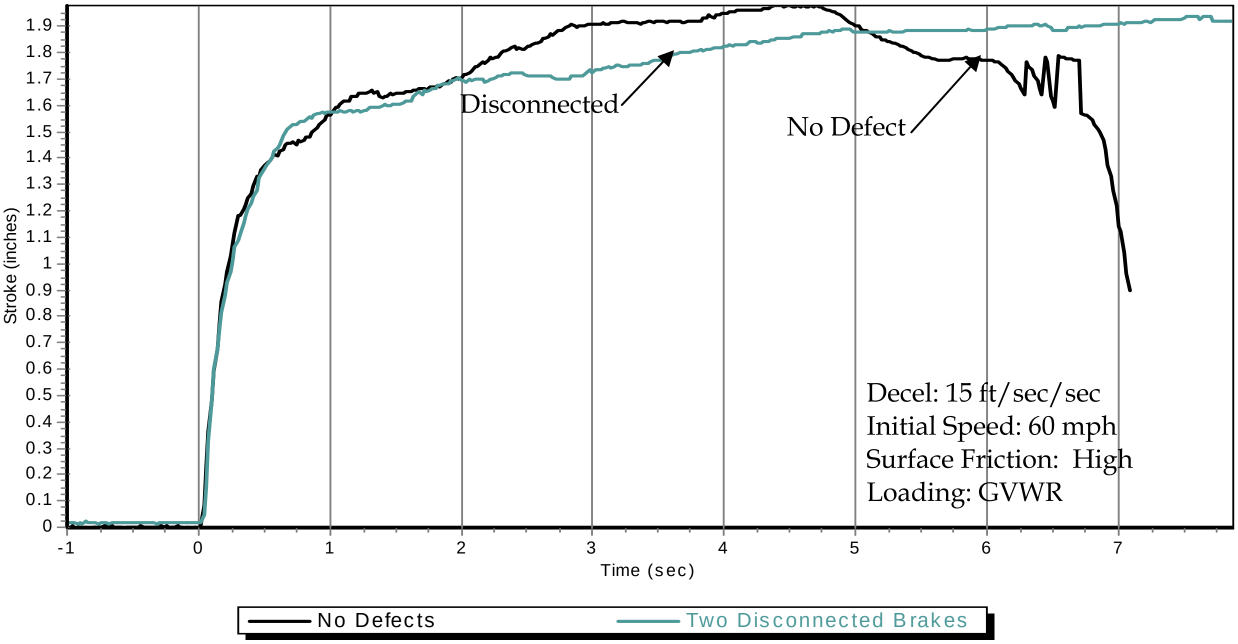


Decel: 15 ft/sec/sec
Initial Speed: 60 mph
Surface Friction: High
Loading: GVWR

In Exhibit 5.29, the properly adjusted (right intermediate) brake chamber stroke varied slightly when two brakes were disconnected. The average stroke on the right intermediate brake assembly was 1.70 inches when there were no brake defects and 1.72 inches when two brakes were disconnected.

Exhibit 5.29 – Brake Stroke Travel of Properly Adjusted Brake Assembly During Testing with Two (other) Disconnected Brakes

(right intermediate brake assembly)

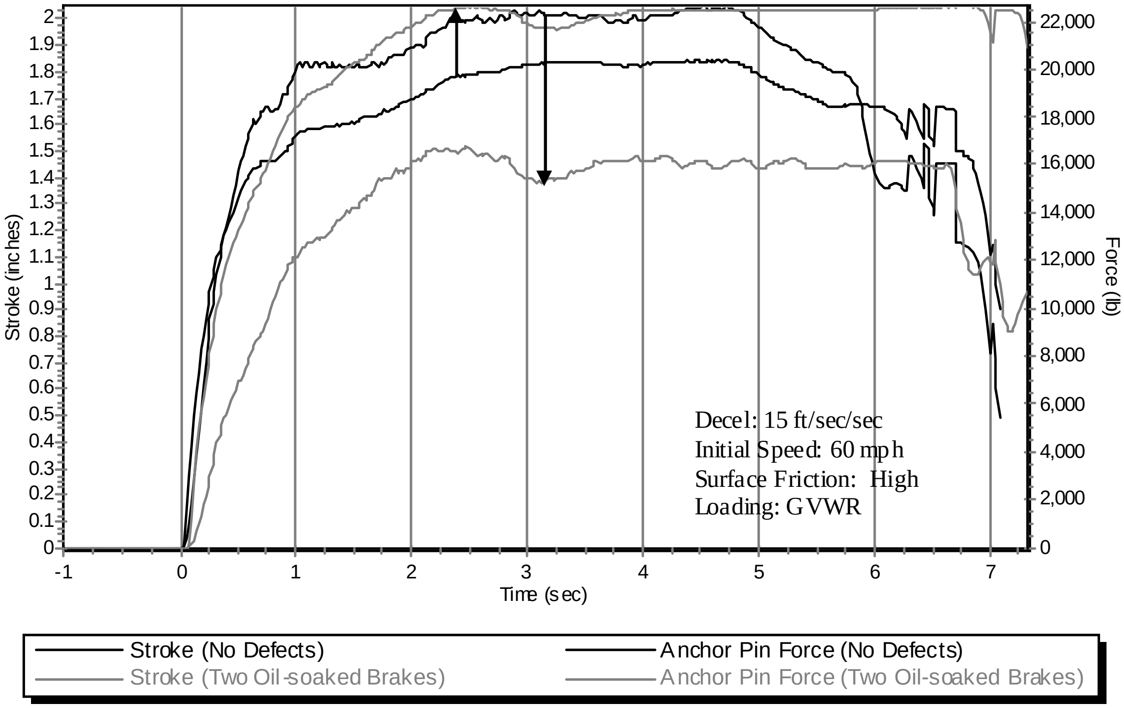


Decel: 15 ft/sec/sec
Initial Speed: 60 mph
Surface Friction: High
Loading: GVWR

5.5.4 Oil-Soaked Brake Linings

Exhibit 5.30 depicts the left intermediate brake chamber stroke (as well as anchor pin force) for a 15ft/sec/sec deceleration from 60 mph with all brake assemblies properly adjusted and with two oil-soaked brake assemblies (the left intermediate and right rear).

Exhibit 5.30 – Brake Chamber Stroke with Two Oil-Soaked Brakes
(left intermediate brake assembly)



Decel: 15 ft/sec/sec
Initial Speed: 60 mph
Surface Friction: High
Loading: GVWR

Exhibit 5.30 shows that oil-soaked brakes increased brake chamber stroke but decreased anchor pin force generated by the brake assembly. In this instance, stroke travel was a misleading indication of actual braking force.

Summary-Brake Stroke monitoring. The previous exhibits show that stroke sensing, particularly with high-accuracy linear potentiometers as used in this testing program, are suitable for detecting brake defects (e.g., out-of-adjustment, disconnected, and oil-soaked brakes) in much the same manner as anchor pin strain gauges. However, stroke measurement is likely not accurate enough to be suitable for use in brake balancing applications that might leverage the precise wheel-by-wheel braking control capability of electronically control braking systems. With such a system, it would be necessary to know the degree to which braking ability at each wheel assembly was affected by various defects. As shown, stroke measurement does not yield such precise measurement of braking force—and in some instances may be misleading.

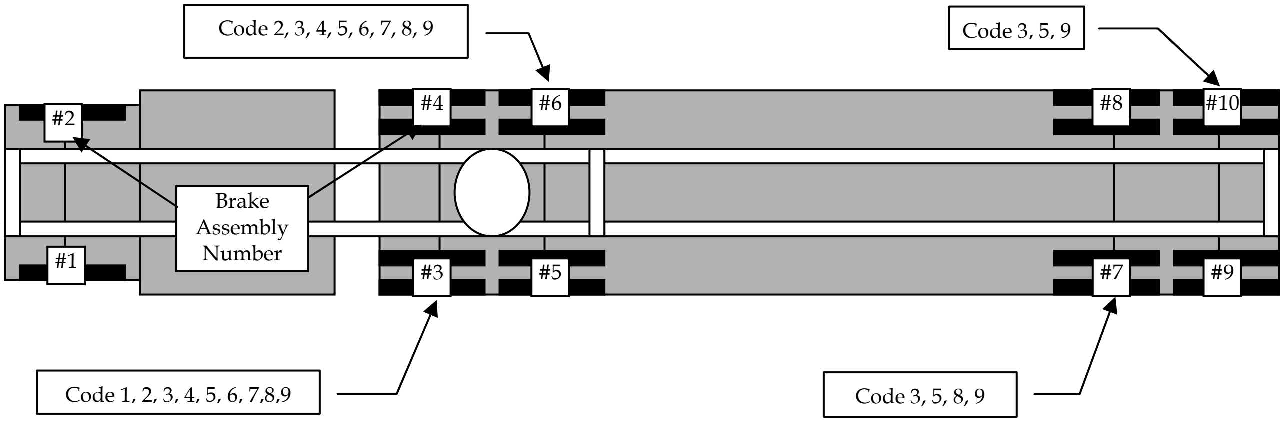
5.5.5 MGM Internal Brake Chamber Stroke Monitoring

Exhibits 5.31 and 5.32 describe specific defect codes and show their locations on the vehicle. Exhibit 5.33 presents a tabulation of the output (or indicator light status) of the MGM stroke measurement system under various test maneuvers with induced defect Codes 0 through 9. It should be noted that the MGM E-stroke system is intended to be primarily used while the vehicle is at rest or in a "static" condition to assist with pre-trip inspections. However, the system does operate continuously and is capable of monitor brake system status "real-time". The results presented in this section are of the systems ability to detect brake problems during "real-time" operation.

Exhibit 5.31 - Brake Deficiency Codes

Code	Description	Wheel Location (s)	CVSA Defect Quantification	Out of Service
0	None (all brakes correctly adjusted, baseline)		None	No
1	1 brake out of adjustment: 2 3/8 inches stroke	# 3	10% defective	No
2	2 brakes out of adjustment: 2 3/8 inches stoke	# 3, 6	20% defective	Yes
3	4 brakes out of adjustment: 2 3/8 inches stroke	# 3, 6, 7, 10	40% defective	Yes
4	2 brakes out of adjustment: 2 1/8 inches stroke	# 3, 6	10% defective	No
5	4 brakes out of adjustment: 2 1/8 inches stroke	# 3, 6, 7, 10	20% defective	Yes
6	2 brakes oil soaked	# 3, 6	20% defective	Yes
7	2 brakes disconnected	# 3, 6	20% defective	Yes
8	3 brakes disconnected	# 3, 6, 7	30% defective	Yes
9	4 brakes disconnected	# 3, 6, 7, 10	40% defective	Yes

Exhibit 5.32 – Brake Deficiency Codes and Affected Wheels



The MGM E-Stroke system included an orange indicator light on the dash panel to signal an over-stroke condition in the brake chambers. Highlighted in bold on the chart are all of the instances where the sensors **incorrectly** indicated the brake condition.

Exhibit 5.33 – MGM Internal Brake Chamber Stroke Measurement System Output

Code	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Location(s)	**None**	**#3**	**#3, 6**	**#3, 6, 7,10**	**#3, 6**	**#3, 6, 7,10**	**#3, 6**	**#7, 10**	**#3, 6, 7**	**#3, 6, 7, 10**
Defect	**None**	**2-3/8″**	**2-3/8″**	**2-3/8″**	**2-1/8″**	**2-1/8″**	**Oil-Soak**	**Discon.**	**Discon.**	**Discon.**
30 Mph, Loaded, Dry Surface										
5 ft/sec/sec	No Light	orange	orange	orange	▨	orange	▨	▨	orange	orange
10 ft/sec/sec	No Light	orange	orange	orange	▨	orange	▨	▨	orange	orange
15 ft/sec/sec	No Light	orange	orange	orange	▨	orange	▨	▨	orange	orange
30 Mph, Unloaded, Dry Surface										
5 ft/sec/sec	No Light	**No Light**	orange	orange	**No Light**	**No Light**	▨	orange	orange	orange
10 ft/sec/sec	No Light	**No Light**	orange	orange	**No Light**	**No Light**	▨	orange	orange	orange
15 ft/sec/sec	No Light	orange	orange	orange	**No Light**	orange	▨	orange	orange	orange
60 Mph, Loaded, Dry Surface										
5 ft/sec/sec	No Light	orange	orange	orange	▨	orange	▨	▨	orange	orange
10 ft/sec/sec	No Light	orange	orange	orange	▨	orange	▨	▨	orange	orange
15 ft/sec/sec	**orange**	orange	orange	orange	▨	orange	▨	▨	▨	▨
60 Mph, Unloaded, Dry Surface										
5 ft/sec/sec	No Light	**No Light**	orange	orange	**No Light**	**No Light**	▨	**No Light**	orange	orange
10 ft/sec/sec	No Light	**No Light**	orange	orange	**No Light**	orange	▨	orange	orange	orange
15 ft/sec/sec	No Light	orange	orange	orange	orange	orange	▨	orange	▨	orange

▨ Indicates data not recorded and/or system not operating during test

Bold text indicates a faulty reading

The MGM E-Stroke system is designed to provide the operator with a method for determining quick and accurate brake stroke status. It is intended for use during pre-trip "walk-around" inspections, however, it was found to be very accurate during heavy braking applications (fully loaded vehicle and/or high deceleration rates). The system had the most difficulty detecting brake problems during low deceleration rate braking maneuver conducted with an empty trailer(a situation where the lowest braking force, and therefore lowest change in brake chamber stroke, was required). With a fully loaded vehicle, there was only one case where the system incorrectly determined that there was a fault in the brake system (a false positive): a hard 15 ft/sec/sec deceleration from 60 mph.

The MGM E-Stroke system did included an indicator box that displayed which brake assemblies experienced a brake problem. However, this indicator assembly was located outside the vehicle and therefore was not available to the test driver to record detailed information. The indicator box is not intended for use while driving; it is intended for pre-trip inspections only.

5.5.6 Spectra External Brake Chamber Stroke Monitoring

Exhibit 5.34 presents the output of the Spectra external brake chamber stroke measurement system during several testing maneuvers with defect Codes 0 through 9. The Spectra system included a complete dash panel mounted indicator display showing the status of each brake assembly (a device that was mounted externally to the cab for the MGM E-Stroke system). It should be noted that the Spectra system is intended to be primarily used while the vehicle is at rest or in a "static" condition to assist with pre-trip inspections. However, the system does operate continuously and is capable of monitor brake system status "real-time". The results presented in this section are of the systems ability to detect brake problems during "real-time" operation. Highlighted in bold are the instances and locations where the sensors incorrectly indicated the brake condition.

Exhibit 5.34 – Spectra External Brake Chamber Stroke Measurement System Output

Code	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Location(s)	**None**	**#3**	**#3, 6**	**#3, 6, 7,10**	**#3, 6**	**#3, 6, 7,10**	**#3, 6**	**#7, 10**	**#3, 6, 7**	**#3, 6, 7, 10**
Defect		**2-3/8″**	**2-3/8″**	**2-3/8″**	**2-1/8″**	**2-1/8″**	**Oil-soak**	**Discon.**	**Discon.**	**Discon.**
30 Mph, Loaded, Dry Pavement										
5 ft/sec^2	All Green	**#3, 5**	#3, 6	**#3, #6, #7**	▨	**#3**	▨	▨	#3, 6, 7	#3, 6, 7, 10
10 ft/sec^2	All Green	**#3, 5**	#3, 6	**#3, 6, 7**	▨	**#3, 6, 7**	▨	▨	**#3, 6, 7, 9, 10**	**#3, 6, 7, 9, 10**
15 ft/sec^2	**#9**	**#3, 5**	#3, 6	**#3, 6, 7, 9**	▨	**#3, 6, 7**	▨	▨	**All but #1, 2, 5**	**All but #1, 2, 5**
30 Mph, Unloaded, Dry Pavement										
5 ft/sec^2	All Green	**All Green**	**#6**	**#6, 7, 10**	**All Green**	**All Green**	▨	#7, 10	**#6, 7, 10**	#3, 6, 7, 10
10 ft/sec^2	All Green	#3	#3, 6	#3, 6, 7, 10	**#2**	**#10**	▨	#7, 10	**#6, 7, 10**	#3, 6, 7, 10
15 ft/sec^2	All Green	#3	#3, 6	#3, 6, 7, 10	**#2, 3, 6**	#3, 6, 7, 10	▨	#7, 10	**#6, 7, 10**	#3, 6, 7, 10
60 Mph, Loaded, Dry Pavement										
5 ft/sec^2	**#5**	#3	#3, 6	**#3, 6, 7**	▨	**#3, 6, 7**	▨	▨	**#3, 6, 7**	**All but #1,2,4,5**
10 ft/sec^2	**#9**	**#9**	#3, 6	**#3, 6, 7**	▨	**#3, 6, 7, 9**	▨	▨	**All but #2, 4, 5**	**All but #5**
15 ft/sec^2	**All but #6**	**All but #1,2,6**	#3, 6	**#3, 6, 7, 9**	▨	**#3, 6, 7, 9**	▨	▨	▨	▨
60 Mph, Unloaded, Dry Pavement										
5 ft/sec^2	All Green	**All Green**	**#6**	#3, 6, 7, 10	All Green	**All Green**	▨	#7, 10	**#6, 7, 10**	#3, 6, 7, 10
10 ft/sec^2	All Green	#3	#3, 6	#3, 6, 7, 10	#2	#3, 6, 7, 10	▨	#7, 10	**#6, 7, 10**	#3, 6, 7, 10
15 ft/sec^2	**#5**	#3	#3, 6	#3, 6, 7, 10	#2, 3, 6	#3, 6, 7, 10	▨	#7, 10	▨	**#1,2,3,6,7, 10**

▨ Indicates data not recorded and/or system not operating during test

Bold text indicates incorrect reading

The Spectra system is intended for use during pre-trip “walk-around” inspections, however, it was found to be accurate during heavy braking applications (fully loaded vehicle and/or high deceleration rates). During most of the test runs, the system correctly reported that there was an over-stroke condition on at least one brake assembly. The exceptions were 5 ft/sec/sec decelerations with an unloaded vehicle (a similar result as with the MGM E-Stroke system).

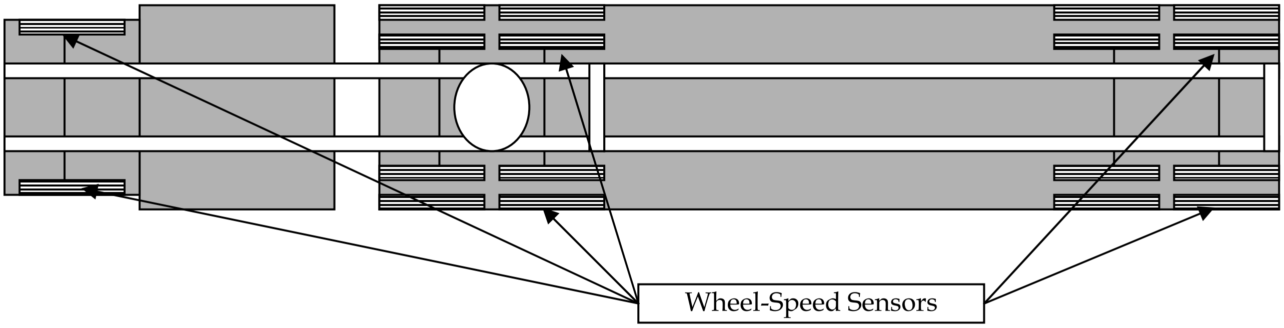
There were also several cases in which the system either (1) reported some of the over-stroke conditions but not all, or (2) reported an over-stroke condition on brakes that were adjusted properly (a false positive). For example, Code 1 from 30 mph with a fully loaded vehicle at 5, 10, and 15 ft/sec/sec deceleration rates reported both brake #3 and brake #5 as having a malfunction when only brake #3 was out-of-adjustment. Also, there were several test runs of Code 8 under various conditions where brake #3 was not reported as having a malfunction.

5.6 WHEEL-SPEED SENSORS

5.6.1 Wheel-Speed Sensing Technologies

ABS Wheel Sensors. As noted, the ABS system installed on the tractor utilizes four wheel speed sensors and four pressure modulator valves to activate the ABS (referred to commonly as a 4S/4M system). Exhibit 5.35 shows the locations of both the tractor and trailer wheel-speed sensors.

Exhibit 5.35 – Wheel-Speed Sensor Locations

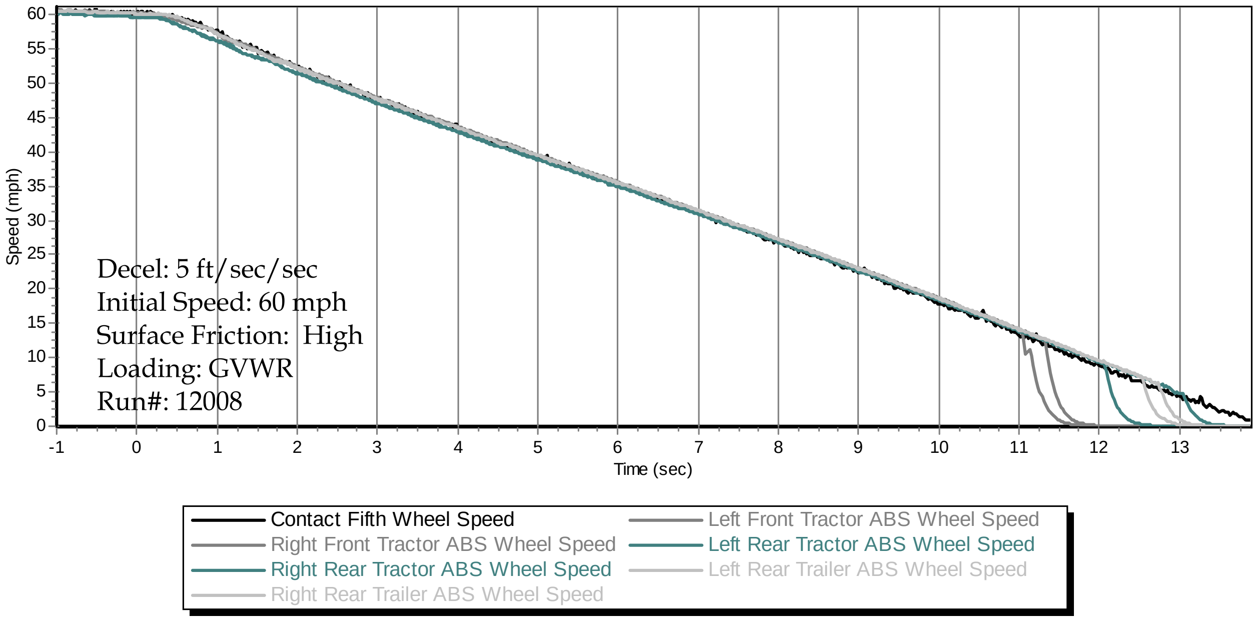


On the tractor, a single modulator valve for the left and right side controlled both the intermediate and rear axle brakes, and wheel-speed sensors were located only on the rear axle. Brake manufactures typically forego wheel-speed sensors (and associated modular valves) for both drive axles, since in practice the wheel speeds of these two axles (on the same side) are nearly identical.

In addition, the trailer ABS assembly had a right and left wheel speed sensor on the rear trailer axle, and a right and left pressure modulator valve, which controlled the ABS activation, on both the front and rear brake assemblies. In total, the trailer ABS system had two speed sensors and two modulator valves (a 2S/2M system).

Exhibit 5.36 shows the output of the tractor and trailer ABS wheel-speed sensors, along with the contact fifth wheel, for a single deceleration from 60 mph at 5 ft/sec/sec.

Exhibit 5.36 – ABS Wheel-Speed Sensors



As shown in Exhibit 5.36, all of the wheel-speed sensors follow closely with the actual vehicle speed (from the contact fifth wheel) throughout the duration of the braking maneuver, except at low speeds (<15 mph), where the wheel speeds fall off quickly as the contact fifth wheel speed continues at the same deceleration rate. This is due not to inaccuracies in the wheel-speed sensors but rather to limitations in the data logging equipment. Since the ABS use variable-reluctance sensors to measure wheel speed from a toothed ring located on the wheel assembly, the sensor outputs a signal with a varying frequency corresponding to the speed of the vehicle. A low frequency indicates a low speed and a higher frequency indicates a higher speed. Low frequencies (< 200 Hz), corresponding to less than 15 mph, were difficult for the data logger to detect.

Exhibits 5.37 and 5.38 show the tractor and trailer ABS wheel-speed sensors, respectively, during a braking maneuver that required ABS activation and a 15ft/sec/sec deceleration from 30 mph on a low-friction surface. The speed of the contact fifth wheel is shown for reference.

Exhibit 5.37 – Tractor ABS Wheel Speed Sensors During Wheel Lockup

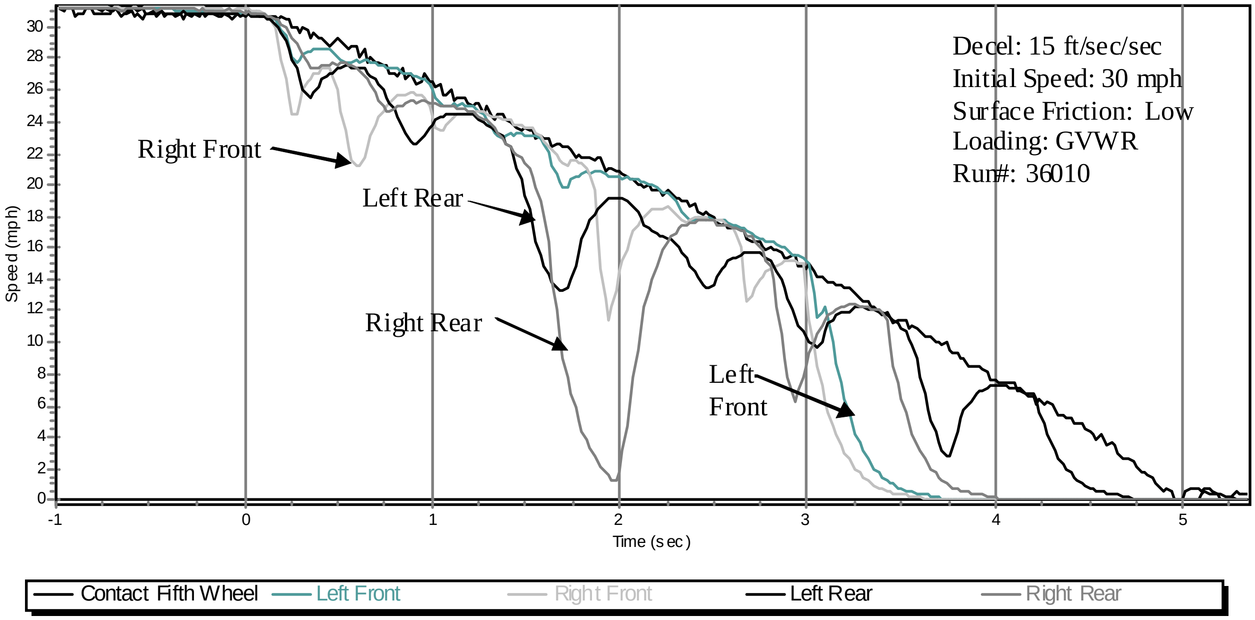
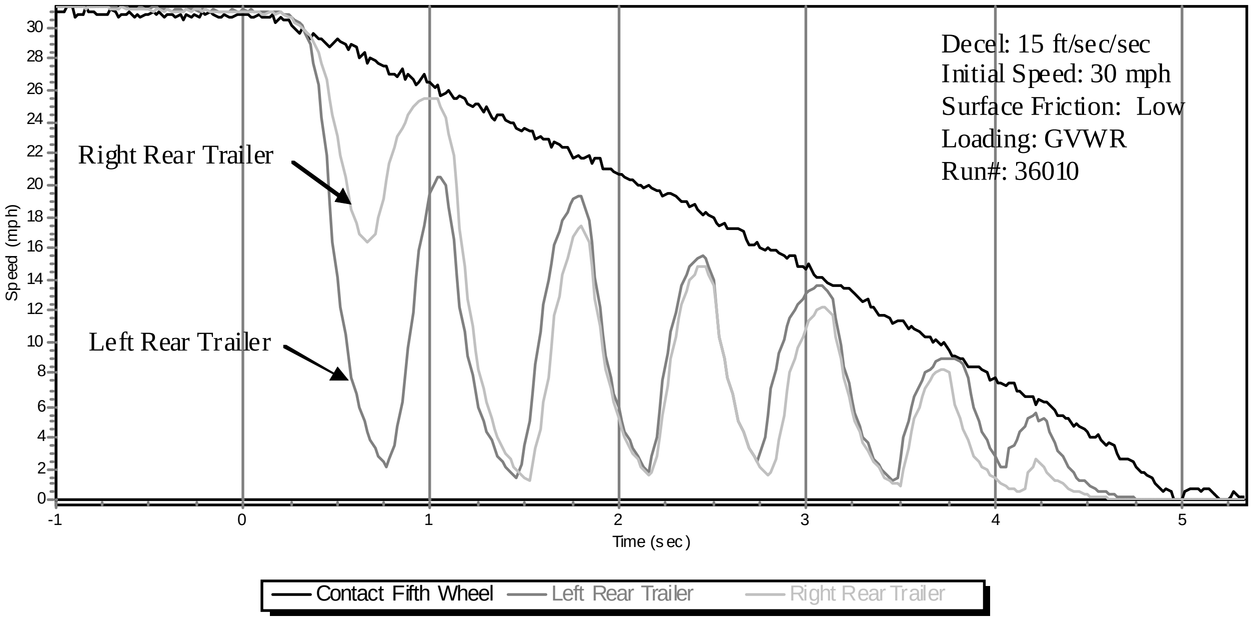


Exhibit 5.38 – Trailer ABS Wheel Speed Sensors During Wheel Lockup



In Exhibits 5.37 and 5.38, the wheel-speed sensors show each wheel beginning to lock momentarily before the ABS releases brake pressure and the wheel releases. Pressure is then reapplied and the wheel begins to lock again. In Exhibit 5.37, the trailer ABS system appears to not have as tight a control loop as the tractor ABS system in Exhibit 5.37. The trailer wheels are allowed to lock considerably more than the tractor wheels, as shown by the larger decrease in wheel speed before the ABS releases brake pressure. The trailer wheels actually slow to speeds around 2 mph before the ABS takes effect.

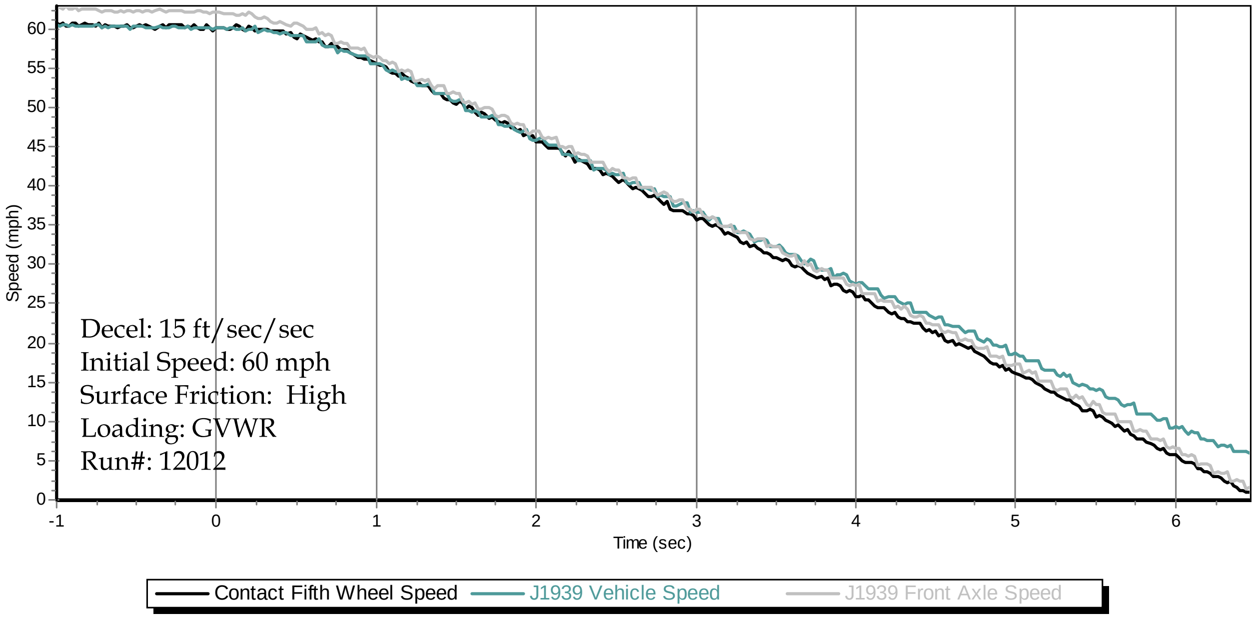
J1939 Vehicle and Wheel Speed Data. Wheel and vehicle speed data definitions are specified as part of the J1939 network standard. The ABS and transmission ECUs monitor "raw" speed data directly from wheel-speed sensors and transmission tailshaft rpm sensors, respectively. ECUs use the unfiltered data for "internal" processing purposes to control ABS functions and transmission shifting functions. The ABS and transmission ECUs also broadcast filtered or modified versions of the data onto the J1939 network in a fashion consistent with the J1939 data definition requirements. Specifically, six data elements related to vehicle speed are available on the J1939 network. (All six were recorded by the onboard DAS for all test runs.) The data elements are:

1. Average speed of the vehicle as calculated from the tailshaft speed;
2. Front axle speed (average speed of the front two wheels) as calculated from the front left-side and right-side wheel-speed sensors;
3. Relative wheel speed of the left front wheel as compared to the average front axle speed;
4. Relative wheel speed of the right front wheel as compared to the average front axle speed;
5. Relative wheel speed of the left rear wheel as compared to the average front axle speed; and
6. Relative wheel speed of the right rear wheel as compared to the average front axle speed.

The J1939 average vehicle speed broadcast by the transmission ECU has a resolution of 0.0024 mph from 0 to 156 mph. The front axle speed, which was the average of the front left and right wheel speeds, was also broadcast over the J1939 by the ABS ECU with a resolution of 0.0024 mph from 0 to 156 mph. Relative wheel speeds for the front and rear, left-side and right-side wheels were the difference between the front axle average wheel speed and the actual speed of the wheel, and were broadcast by the ABS ECU with a resolution of 0.04 mph from –4.8 to +4.8 mph. The relative wheel speeds broadcast by the ABS ECU have a significantly lower resolution (0.04 mph) than those of the vehicle speed (0.0024 mph) or the front axle speed (0.0024 mph). This is a result of the message size restraints of the J1939 network, as all of the ABS ECU wheel speeds must fit into a single standard size J1939 message (8 bytes).

Exhibit 5.39 presents data from a typical 15ft/sec/sec deceleration from 60 mph with a fully loaded (maximum GCW) trailer. The J1939 vehicle speed and J1939 front axle speed is compared with the speed of the contact fifth wheel.

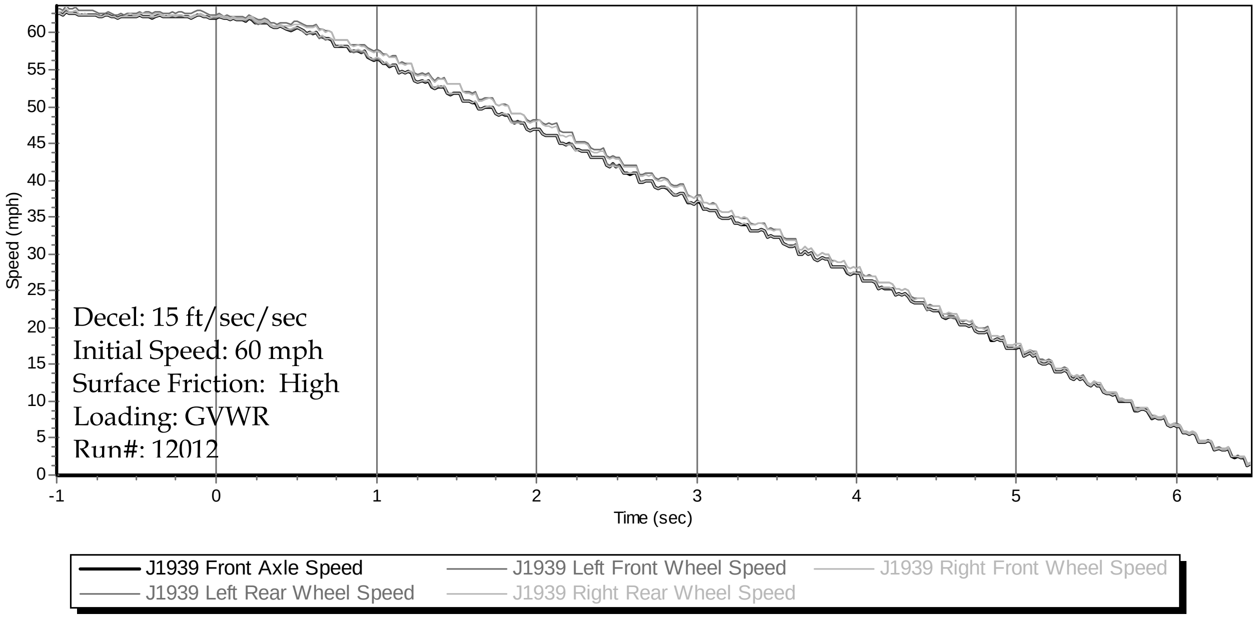
Exhibit 5.39 – J1939 Vehicle and Front Axle Speed Versus Speed of Contact Fifth Wheel



In Exhibit 5.39, the J1939 front axle speed closely follows that of the contact fifth wheel, whereas the J1939 vehicle speed varies significantly from that of the contact fifth wheel at low speeds. This is likely due to a decrease in transmission tailshaft speed sensor accuracy at low speeds (Hall-effect sensors in general are not accurate at low speeds).

In Exhibit 5.40, the J1939 relative wheel speeds for all four wheels have been converted to absolute wheel speeds by adding each relative wheel speed to the J1939 front axle wheel speed per the J1939 message specification (in a post-processing operation completed by the authors) and plotted against the J1939 front axle speed.

Exhibit 5.40 – Absolute J1939 Wheel Speeds Versus J1939 Front Axle Speed



As expected, when the vehicle is on a high-friction surface and wheel lockup is not an issue, the J1939 relative wheel speeds are similar to the J1939 front axle speed because they are all calculated from wheel-speed sensor data from the ABS ECU. In fact, this data correlates closely with the speed of the contact fifth wheel as reported in Exhibit 5.39.

In Exhibit 5.41, the right front wheel speed (as measured directly from the ABS wheel speed sensor) is shown along with the J1939 calculated right front wheel speed.

Exhibit 5.41 - Right Front ABS Wheel-Speed Sensor Versus Absolute Right Front J1939 Wheel Speed

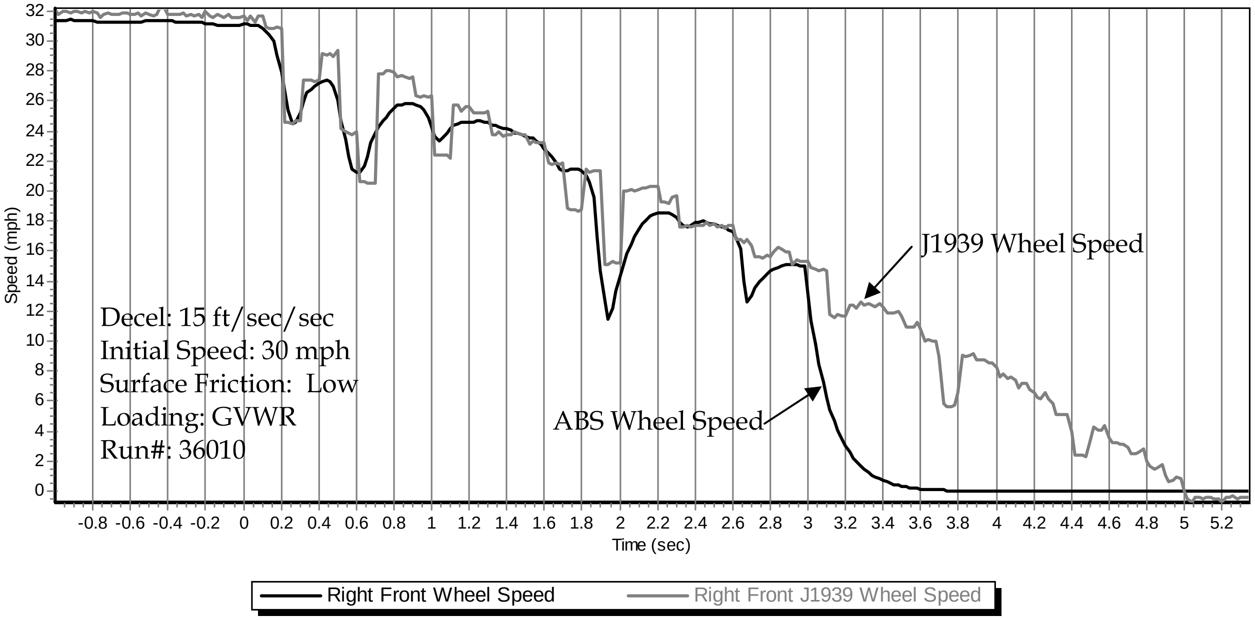
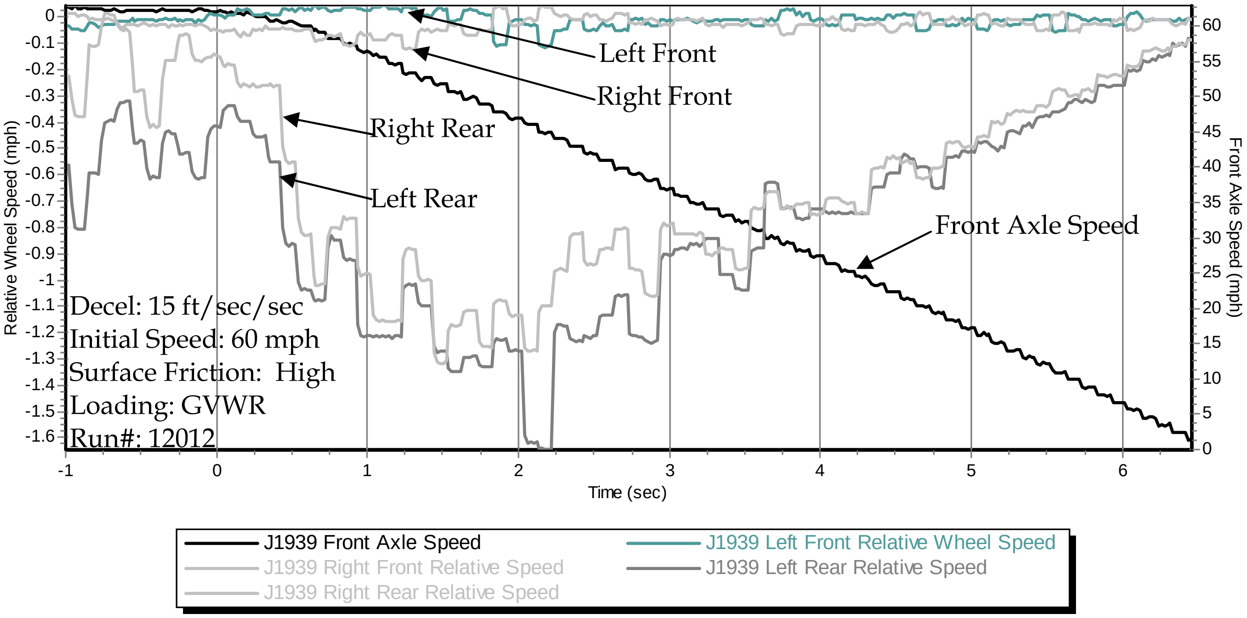


Exhibit 5.41 shows that a significant amount of information is lost in the J1939 wheel speed data as a result of the frequency (10 times per second) and resolution (0.04mph) limitations of the J1939 wheel speed broadcast message. To more closely examine J1939 wheel speed data, Exhibit 5.42 shows the relative wheel speed (the difference from the front axle wheel speed) for the left-side and right-side front and rear wheels compared with front axle speed.

Exhibit 5.42 –Wheel Speeds Relative to the Front Axle Speed with Properly Adjusted Brakes



In Exhibit 5.42, the left front and right front relative speeds are symmetric around 0 because the average of the absolute left-side and right-side speeds is equal to the front axle speed. In Exhibit 5.42, the relative speeds of the rear wheels differ from the front axle speed by as much as 1.6 mph during this braking maneuver.

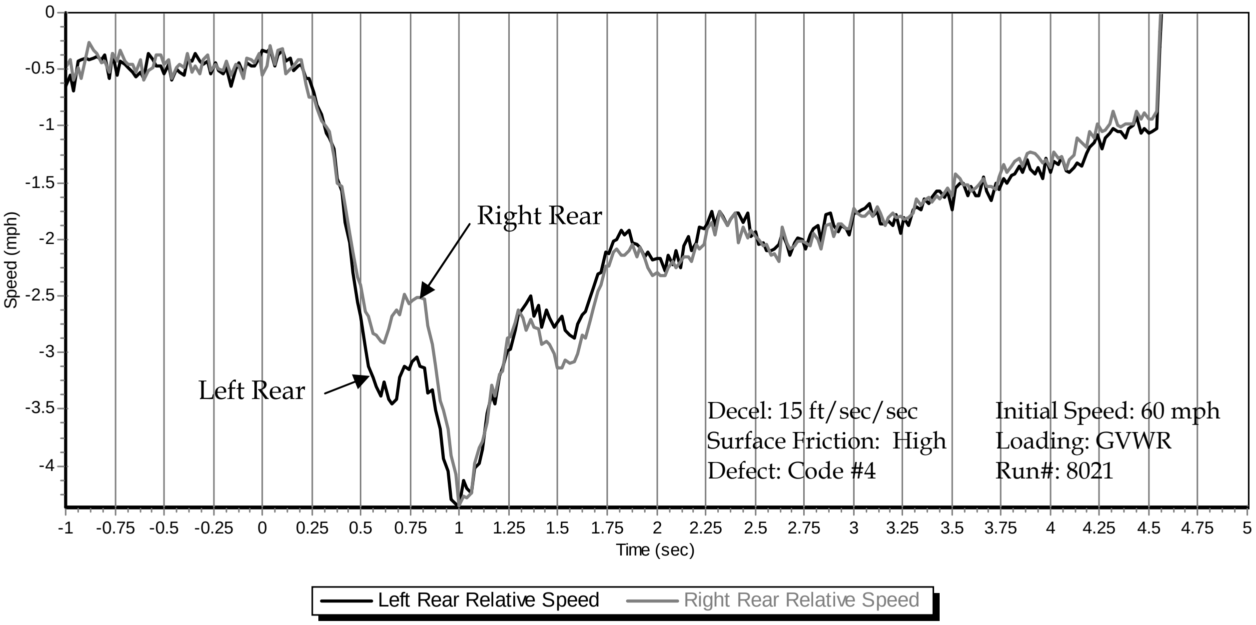
The low resolution of the relative wheel speed data (0.04 mph) is evident in Exhibit 5.42 by the abrupt transitions from one wheel speed to another in 0.04 mph increments. The transmission frequency of the J1939 wheel speed message (100 ms) is evident from the roughly 0.1-second steps in the chart. (This is not always the case, however, due to the data logging system not always being synchronized with the J1939 transmissions, and because of delays on the J1939 data bus).

5.6.2 Use of Wheel-Speed Sensors to Detect Out-of-Adjustment Brakes

Using direct ABS wheel speed sensor data, Exhibits 5.43 through 5.45 show the relative left-rear and right-rear wheel speeds (as calculated by averaging the front axle wheel-speed sensors and subtracting the left- and right-rear wheel speeds, respectively) when the left-intermediate and right-rear brake assembles were:

- Out-of-adjustment by 2-1/8 inches (Code 4),
- Out-of-adjustment by 2-3/8 inches (Code 2), and
- Disconnected (Code 7).

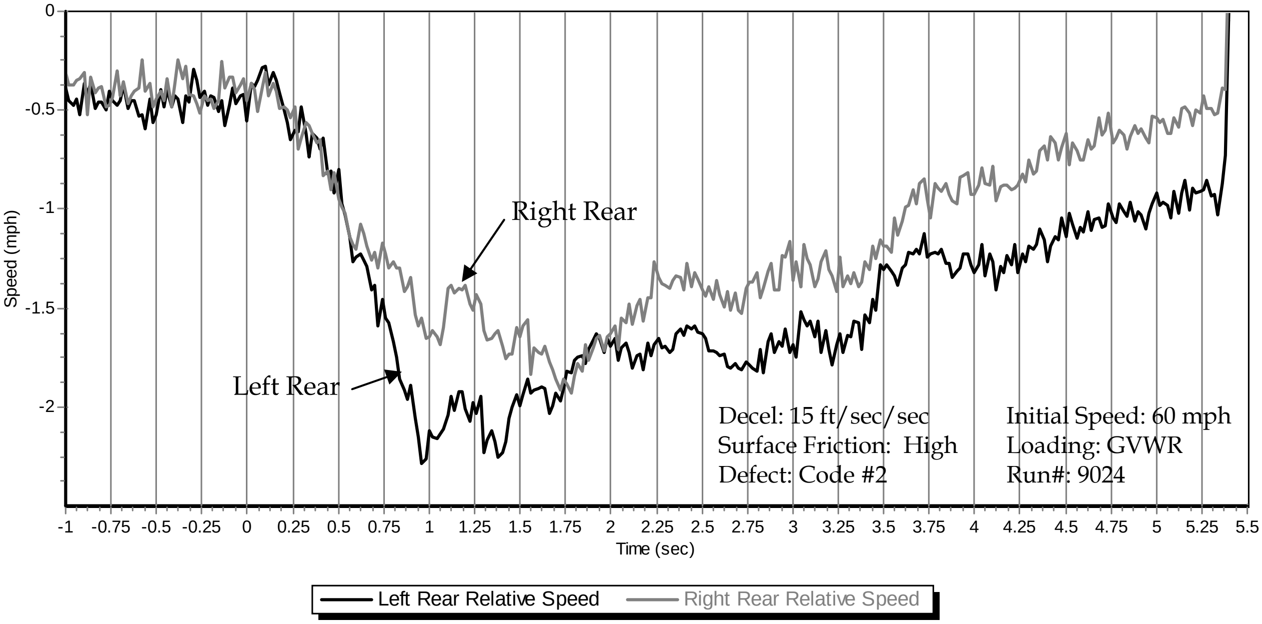
Exhibit 5.43 – Wheel Speeds Relative to Front Axle Speed with 2-1/8 Inches Out-of-Adjustment Brakes



With the left intermediate and right rear brake 2-1/8 inches out-of-adjustment (Exhibit 5.43), there is little variation in relative wheel speeds between the left and right wheel assemblies. This slight variation would make it difficult to detect a brake assembly that is only 2-1/8 inches out-of-adjustment.

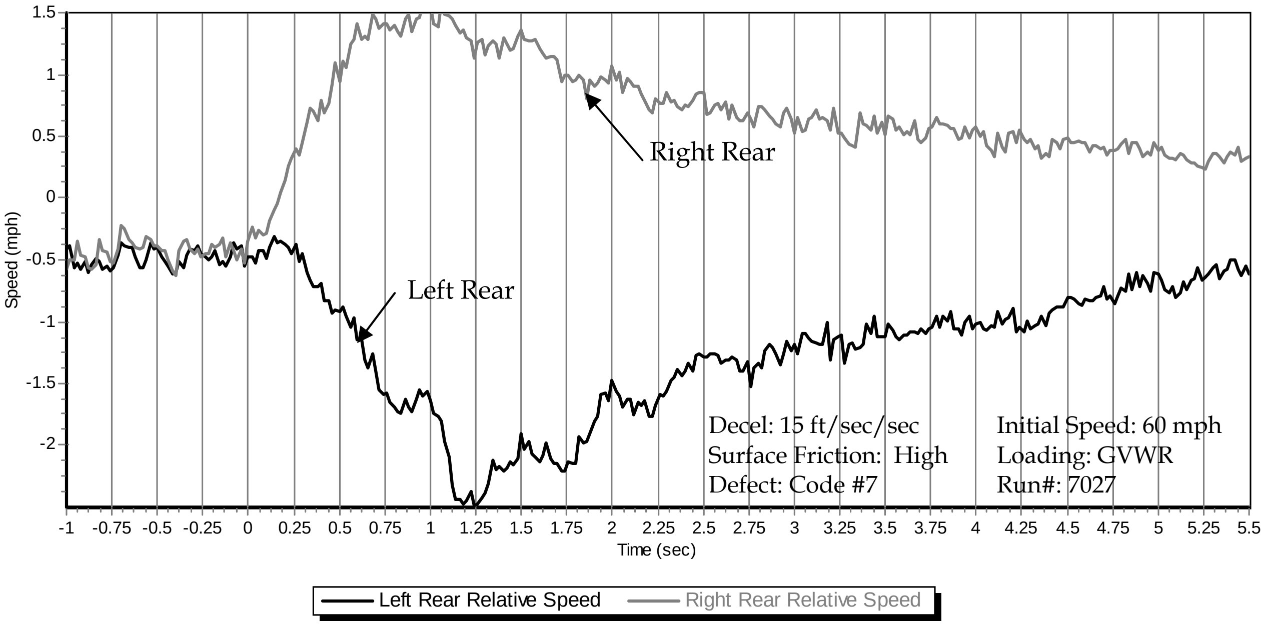
However, at 2-3/8 inches out-of-adjustment (Exhibit 5.44), the relative speed of the right rear assembly (one of the two brakes that are out-of-adjustment) during braking is noticeably faster than that of the left rear relative speed (a wheel that is properly adjusted).

Exhibit 5.44 - Wheel Speeds Relative to Front Axle Speed with 2-3/8 Inches Out-of-Adjustment Brakes



When the right rear brake is disconnected, the relative speed of the right rear wheel is actually slightly faster (by about 1.5 mph) than the actual vehicle speed, indicating that there is no braking action on that wheel and it is just rolling along with the vehicle, as shown in the data in Exhibit 5.45.

Exhibit 5.45 - Wheel Speeds Relative to Front Axle Speed with Disconnected Brakes

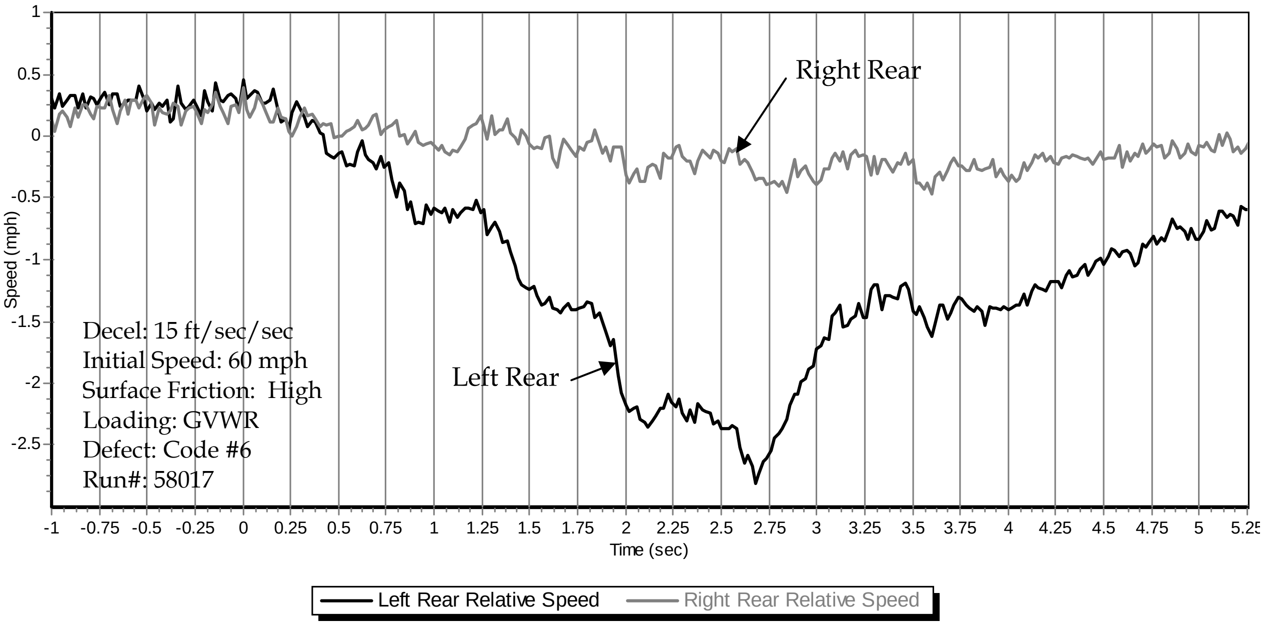


Exhibits 5.43 through 5.45 show that as brakes become more out-of-adjustment, from 2-1/8 to 2-3/8 inches and then eventually disconnected, the ABS relative wheel-speed data can be used to discriminate between brakes that are in and out of adjustment. In other words, the ABS relative wheel speed data has sufficient resolution to determine whether a wheel is out-of-adjustment, at least for levels 2-3/8 inches out-of-adjustment and greater.

5.6.3 Use of Wheel-Speed Sensors to Detect Oil-Soaked Brakes

Exhibit 5.46 shows that the ABS wheel-speed sensors have sufficient resolution to adequately detect an oil-soaked brake assembly. There is a noticeable variation between the relative speed of the right rear brake (which is oil-soaked) and the left rear brake (which is operating normally). The speed variation depends on the amount of oil on the brake assembly.

Exhibit 5.46 – Wheel Speeds Relative to Front Axle Speed with Oil-Soaked Brakes



5.6.4 J1939 Wheel-Speed Sensing of Brake Defects

The previous section showed that measuring and comparing individual wheel speeds (using direct wheel-speed sensor data) is a valid and reliable method for detecting various brake performance issues. Acquiring this data, however, requires accessing the proprietary, certified, and essentially self-contained ABS systems from the brake manufacturers. While this was safely and reliably accomplished as part of this special brake sensor testing project, it would involve significant coordination between brake manufacturers and truck OEMs if such a concept were to move into a production environment. This is primarily due to the market requirement that multiple combinations of brake systems, engines, and transmissions from different suppliers be specified and integrated into truck platforms from all North American truck OEMs.

The J1939 network specification and associated data definition set was developed to address this compatibility obstacle in integrating electronic systems from different manufacturers. It would be desirable, therefore, to use wheel-speed data broadcast on the J1939 network to detect brake performance issues—as opposed to direct measurement by the ABS wheel-speed sensors. However, the J1939 wheel-speed data yields lower-resolution data and lower-frequency image of relative wheel speed, since the information is limited to the message size constraints of the J1939 protocol. Like Exhibits 5.42 through 5.45, Exhibits 5.47 through 5.50 depict the results of an examination of wheel speed as a means of detecting out-of-adjustment, disconnected, and oil-soaked brakes, but these new exhibits rely on J1939 data rather than on the ABS data.

Exhibit 5.47 – J1939 Wheel Speeds Relative to Front Axle Speed with 2-1/8 Inches Out-of-Adjustment Brakes

(right rear out-of-adjustment)

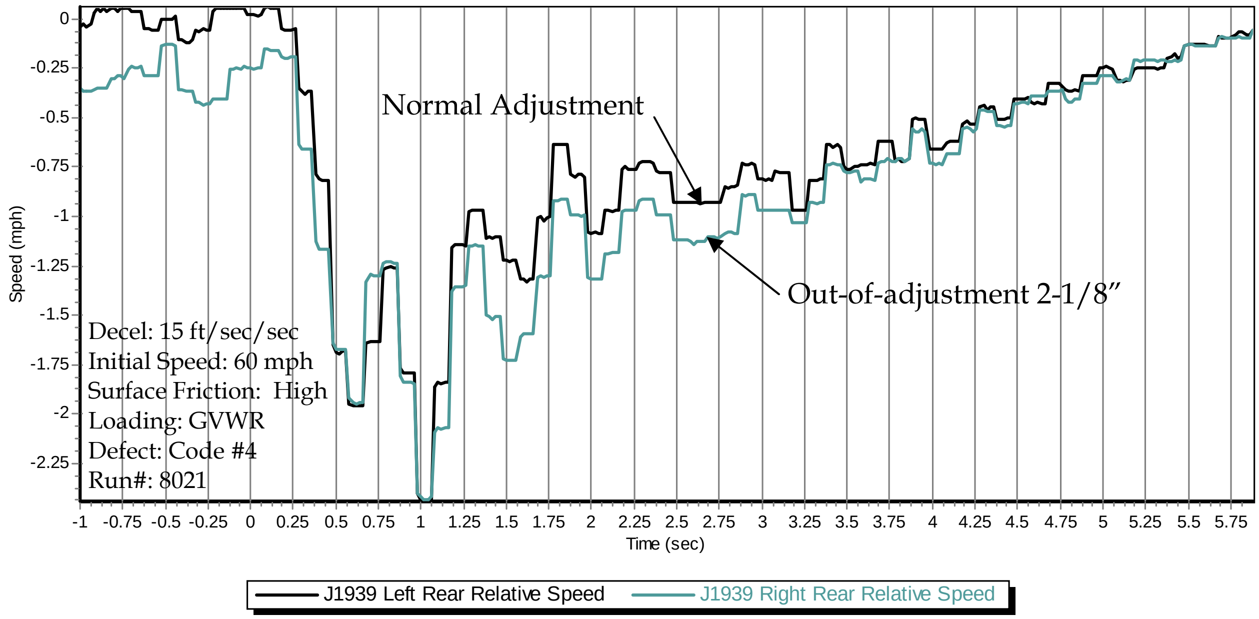


Exhibit 5.48 – J1939 Wheel Speeds Relative to J1939 Front Axle Speed with 2-3/8 Inches Out-of-Adjustment Brakes

(right rear out-of-adjustment)

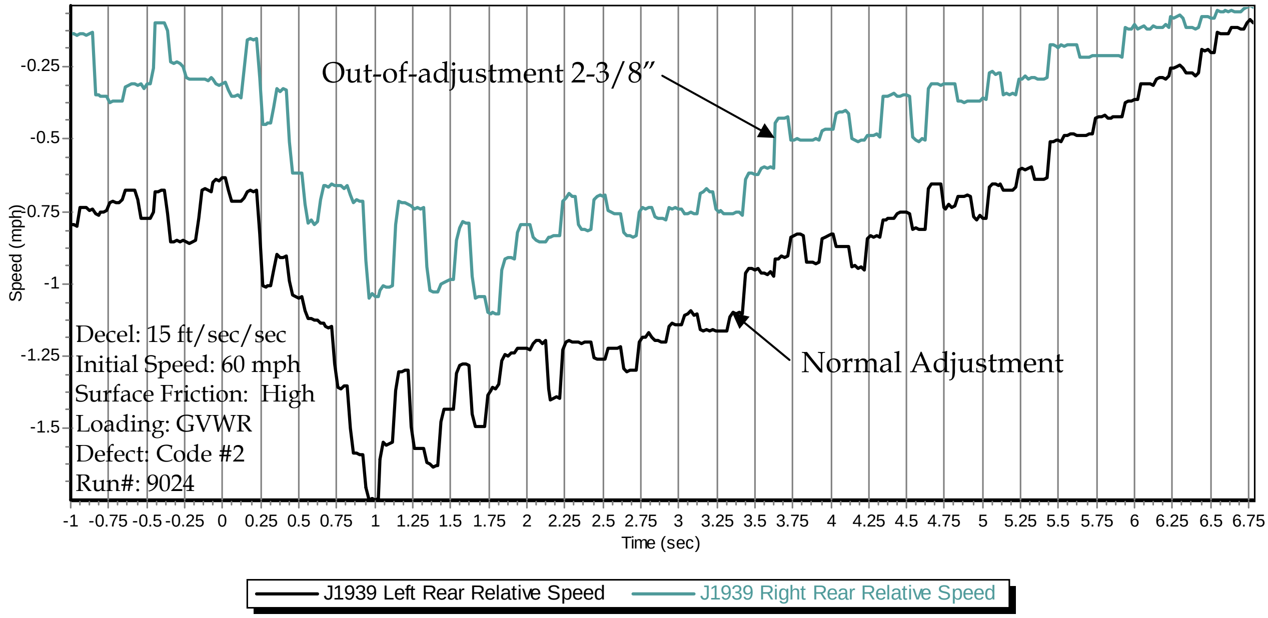


Exhibit 5.49 – J1939 Wheel Speeds Relative to J1939 Front Axle Speed with Disconnected Brakes

(right rear disconnected)

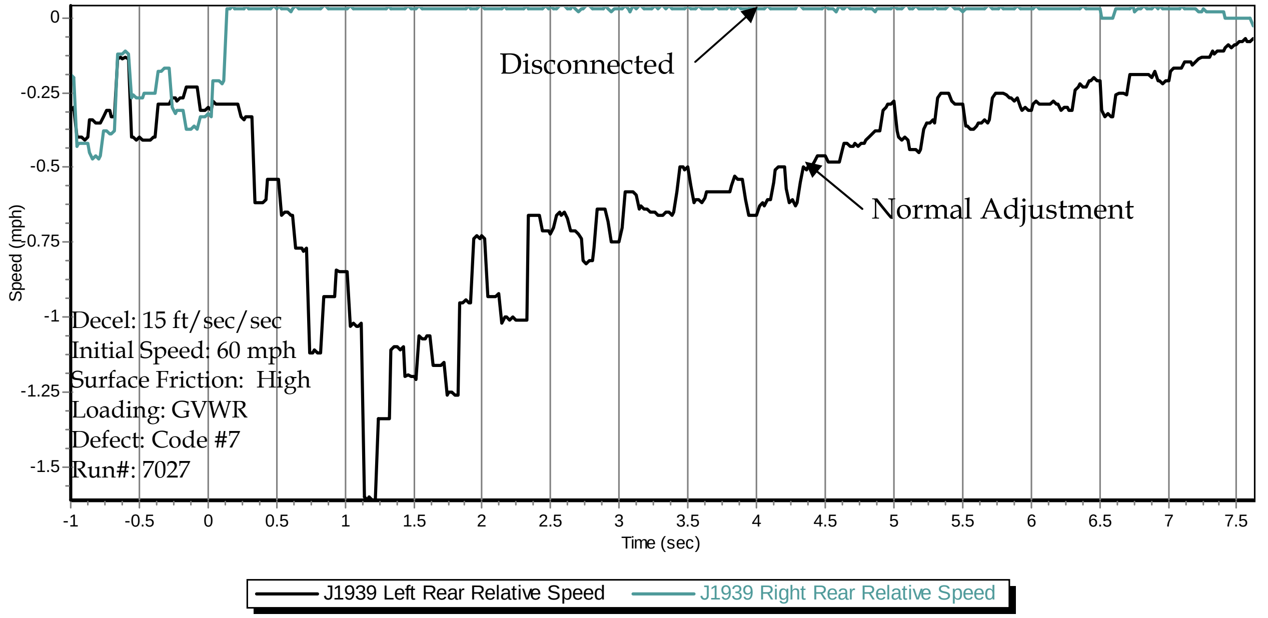
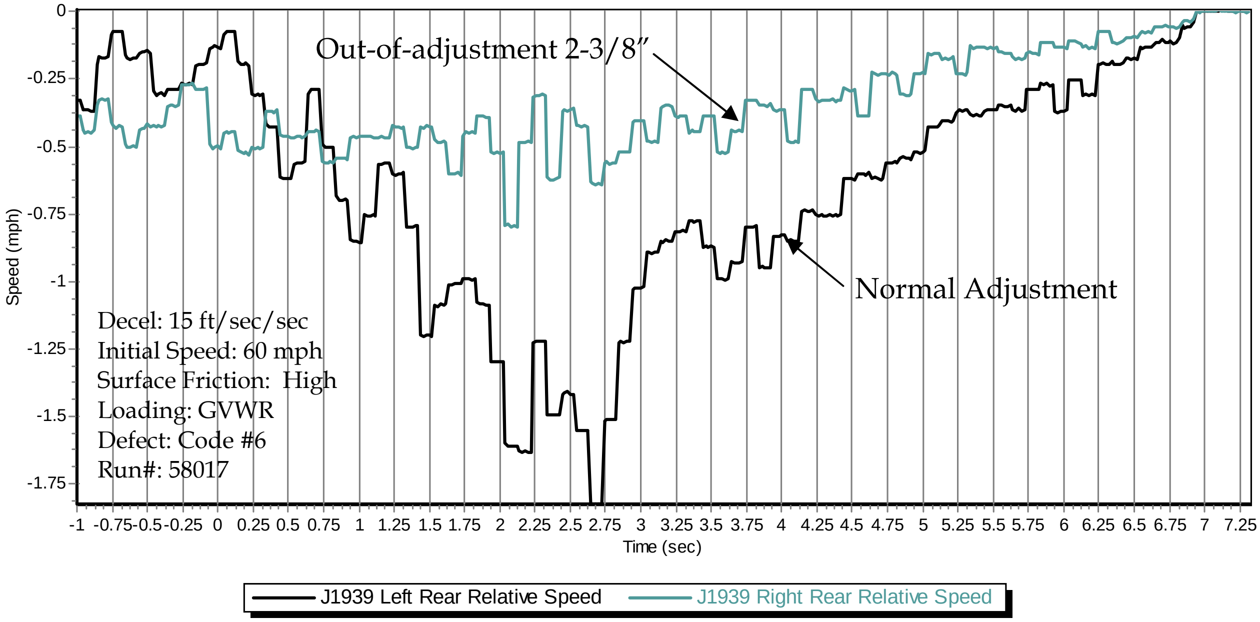


Exhibit 5.50 – J1939 Wheel Speeds Relative to J1939 Front Axle Speed with Oil-Soaked Brakes

(right rear oil-soaked)



As these exhibits show, the resolution of the J1939 wheel speed message would appear to be sufficient to detect brakes that are significantly out-of-adjustment (2- 3/8 inches), disconnected, and/or oil-soaked. However, as was the case with direct wheel speed measurement, the J1939 speed data cannot be used to detect moderately (2-1/8 inches) out-of-adjustment brakes.

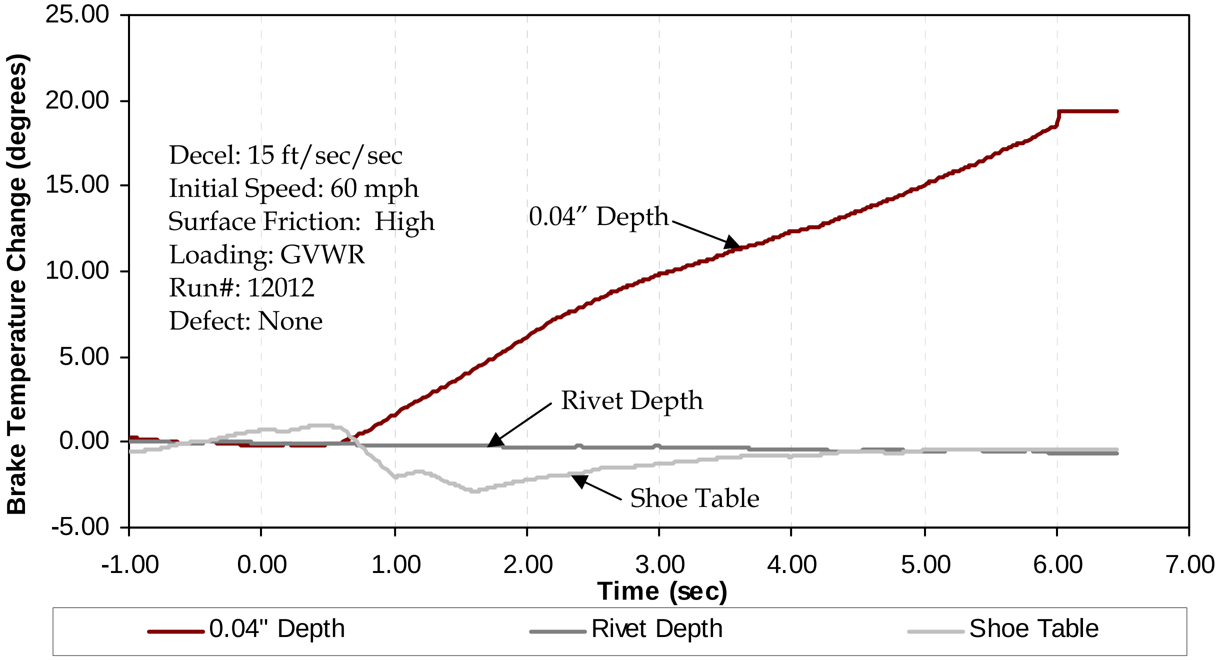
5.7 BRAKE SHOE THERMOCOUPLES

Three J-type thermocouples were located on the primary brake shoe in each of the 10 tractor-trailer brake assemblies:

- At 0.04 inches from the surface of the brake shoe lining;
- At the depth of the brake shoe rivet (0.25 inches from the back of the shoe; or 0.592 inches from the surface of the brake shoe lining on the tractor drive axle and trailer axle brake assemblies; and 0.44 inches from the surface of the brake shoe lining on the steer axle brake assemblies); and
- Welded onto the bottom of the shoe table.

The temperature was recorded for one second prior to and throughout each braking maneuver. Since each brake assembly had a slightly different initial temperature (before each braking maneuver) the data was converted from absolute temperatures to the change in temperature relative to the average initial brake temperature for the one second before the braking event (this is most commonly referred to as the delta temperature or delta T during the braking event). Exhibit 5.51 shows the left rear tractor brake temperature change for a 15 ft/sec/sec deceleration from 60 mph.

Exhibit 5.51 – Brake Lining Delta T with Properly Adjusted Brakes
(left rear tractor brake assembly)



In Exhibit 5.51, the thermocouple located 0.04 inches from the surface of the lining showed an increase in brake temperature of approximately 20° F, while the rivet depth and shoe table thermocouples showed no increase in brake temperature. In fact, this is the case during all of the individual braking maneuvers performed, and is likely due to the large thermal mass of the brake shoe and lining which, during these relatively short discrete braking maneuvers, effectively dissipates the heat .

Exhibit 5.52 shows the changes in temperature readings from the 0.04-inch depth thermocouples located on all of the tractor brake assemblies during the same 15ft/sec/sec stop from 60 mph.

Exhibit 5.52 - Tractor Brake Delta Ts with Properly Adjusted Brakes

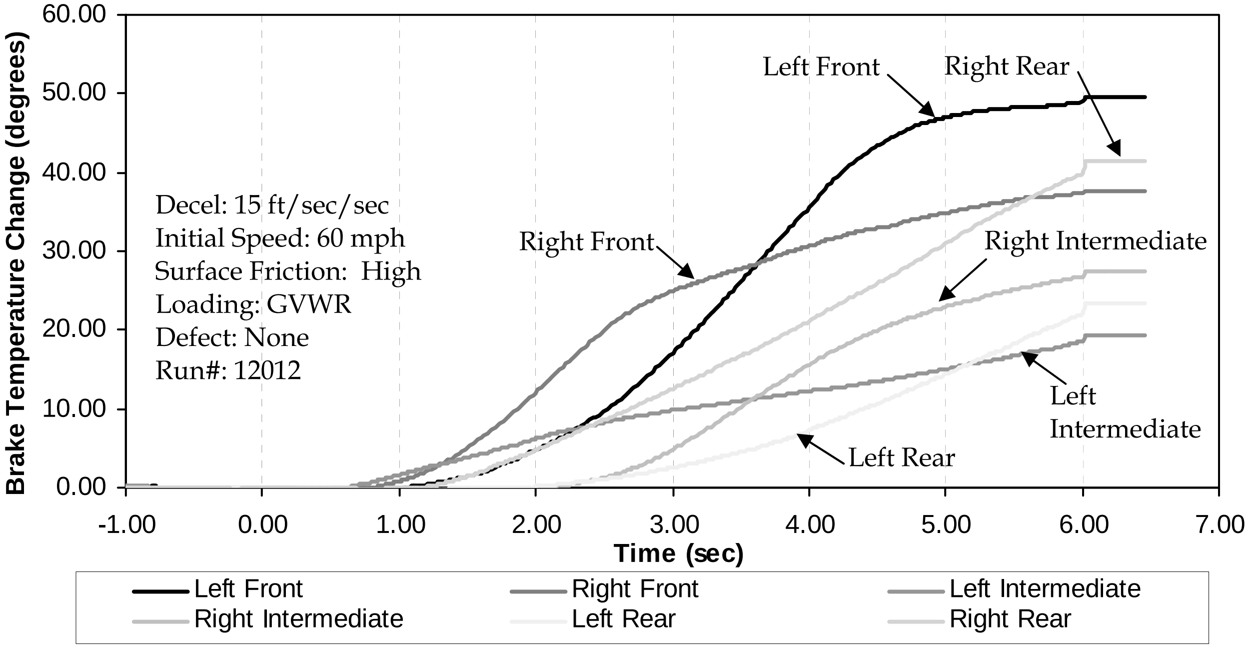


Exhibit 5.52 shows that, even when properly adjusted, brake lining temperature varied significantly between brake assemblies. During a 6-second hard braking maneuver (15ft/sec/sec from 60 mph) with properly adjusted brake assemblies, some brake shoe temperatures increased as much as 50° F (left front in the example above) while other brake shoe temperatures increased as little as 20° F (left rear in the example above).

A subsequent examination of brake temperatures at various wheel locations was conducted under several conditions including out-of-adjustment brakes, disconnected brakes, and oil-soaked brakes. The initial hypothesis was that the brake assemblies that were out-of-adjustment, disconnected, or oil-soaked would experience a significantly lower increase in temperature during braking maneuvers (due to reduced friction). Data from these discrete braking tests however was inconclusive (with the exception of the disconnected brake tests, which, as expected, showed little to no increase in temperature).

On some test runs (under various load, speed, and deceleration conditions) the brake assemblies that were out-of-adjustment or oil-soaked experienced roughly the same increase in temperature as the properly adjusted brake assemblies. In other test runs, the brakes with induced defects behaved as expected. In a few instances, the temperatures of the "defective" brake assemblies were actually higher then those of the properly adjusted brake assemblies. Further, no pattern to the relative temperature changes in defective versus properly adjusted brakes could be attributed to certain categories of test conditions such as speed, load, or deceleration rate.

After a thorough examination of the temperature data, it was concluded that brake temperatures during discrete braking events cannot be reliably used to detect various types of brake defects. It is likely that inherent variations in thermocouple accuracy due to exact positioning, wire length, and fabrication, as well as complex thermal inertia phenomenon within the brake assembly, contribute to the difficulty of utilizing spot-check temperature measuring during these events. This does not, however, preclude the use of temperature and heat data to detect brake performance issues during real-world repetitive and continuous braking applications, as discussed in the next section.

5.7.1 Thermocouple Response During Simulated Mountain Tests

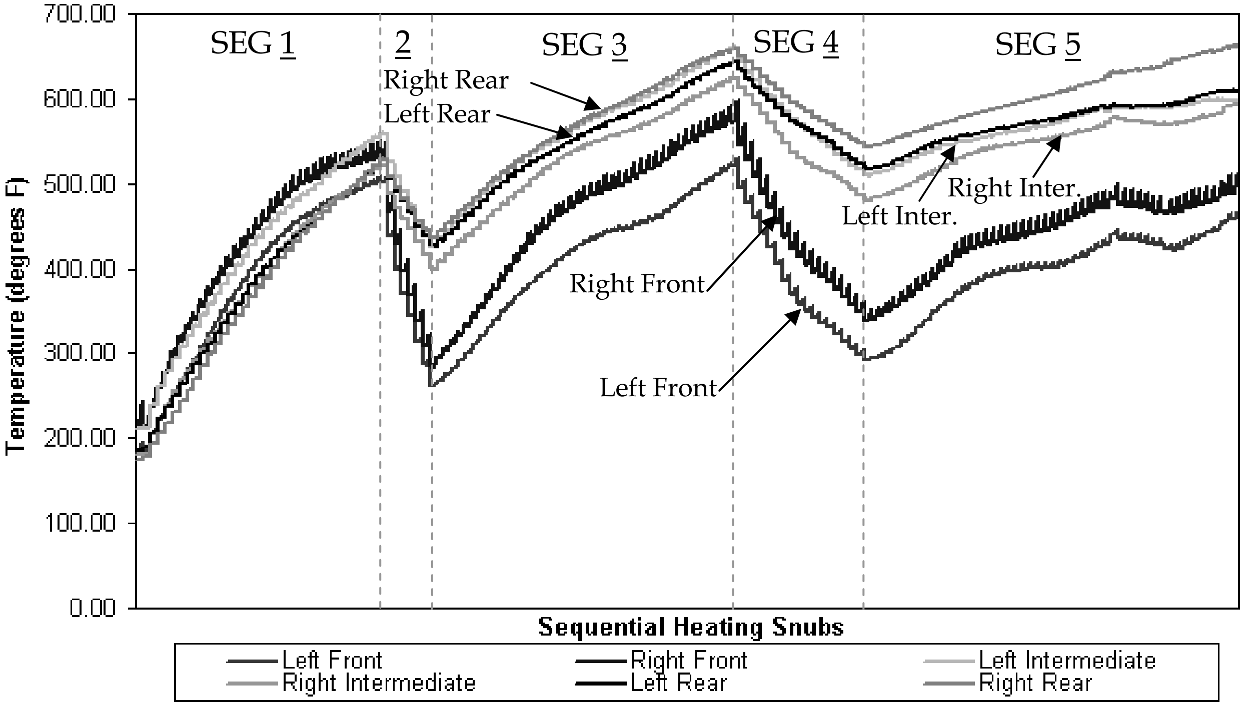
Temperatures on all brake assemblies were monitored during the Jennerstown simulated mountain test. The Jennerstown test is divided into five segments that are executed sequentially. During each segment, a series of brake snubs from 34 mph to 19 mph were repeated. The number of snubs and cycle time between snubs define the five segments. The Jennerstown matrix description is shown in Exhibit 5.53.

Exhibit 5.53 – Simulated Mountain Test

Segment	# of Snubs	Decel. Rate (ft/sec/sec)	Snub Speed (mph)	Defects (Code 0-9)	Cycle Time (sec)
Initial Brake Temperature (IBT) 150 to 200° F					
1	34	7.4	34 to 19	C0-C9	30
2	7	7.4	34 to 19	C0-C9	125
3	42	7.4	34 to 19	C0-C9	20
4	18	7.4	34 to 19	C0-C9	70
5	57	7.4	34 to 19	C0-C9	40

Exhibit 5.54 shows brake lining temperature for each tractor brake assembly during the simulated mountain test, with all brakes adjusted properly.

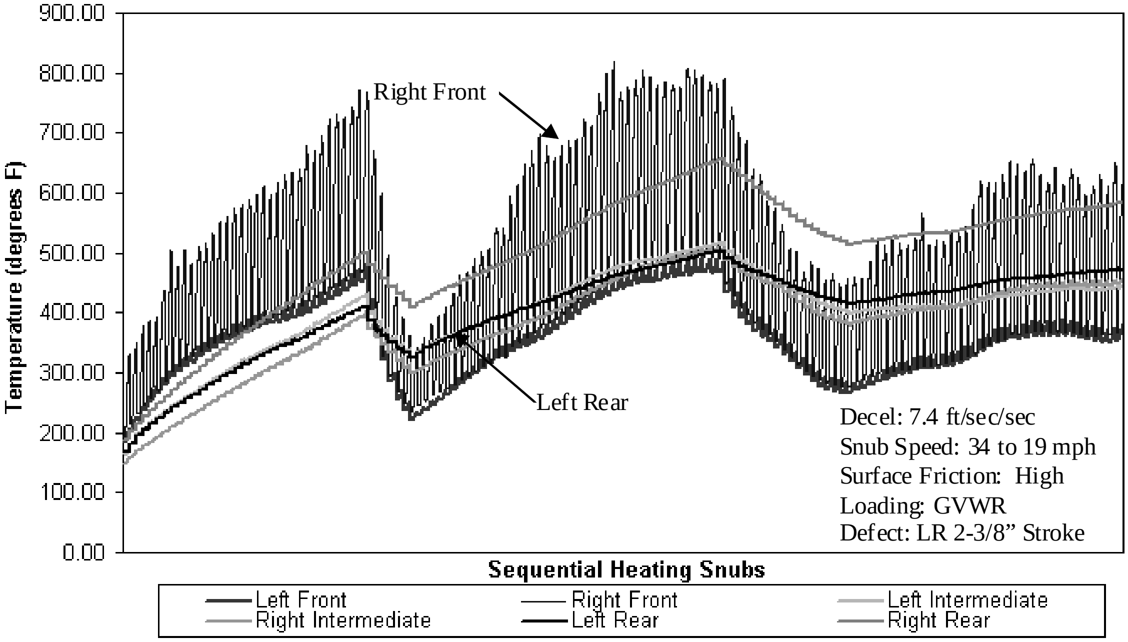
Exhibit 5.54 – Simulated Mountain Heating Snubs with No Brake Defects



As expected, when the cycle time between heating snubs increased, the brake temperature began to decrease as the brakes were given longer time to cool between each snub. In general, the front brake assemblies accumulated less heat than the rear brake assemblies throughout the heating snubs. This is likely a result of the front brake assemblies being proportioned to provide less braking force than the rear brake assemblies (i.e. the front brakes are significantly smaller and have less of a load than the drive axle brakes). In addition, undisturbed airflow toward the front of the tractor can allow for quicker cooling of the front brake assemblies.

Exhibit 5.55 depicts tractor brake lining temperatures during simulated mountain heating snubs when one brake (left rear) is out-of-adjustment 2-3/8 inches.

Exhibit 5.55 – Simulated Mountain Heating Snubs with Left Rear Brake Out-of-Adjustment 2-3/8 Inches

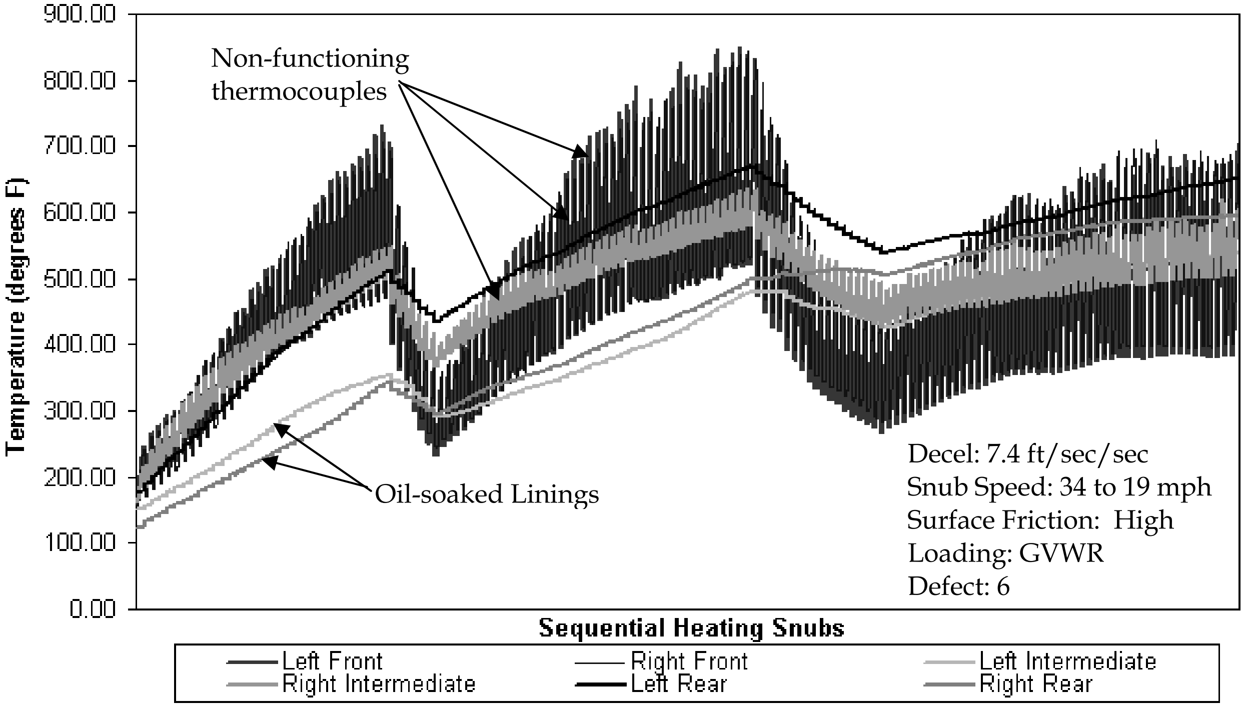


Two observations can be made from Exhibit 5.55:

- The right front thermocouple shows a much quicker and higher increase in brake temperature along with a very rapid decrease in brake temperature during each cycle, which is likely a result of an error with the thermocouple or thermocouple placement (i.e. the lining might have worn significantly, causing the thermocouple to be exposed on the surface and therefore come in contact with the drum).
- The left rear brake assembly shows a significant decrease in brake temperature compared with that in Exhibit 5.54. This suggests that by comparing relative brake temperatures between brake assemblies on the same axle during extended braking activities, it may be possible to detect out-of-adjustment brakes using brake lining thermocouples.

Exhibit 5.56 depicts tractor brake lining temperatures during simulated mountain heating snubs when two brakes are oil-soaked.

Exhibit 5.56 – Jennerstown Test with Two Brakes Oil-Soaked
(left intermediate and right rear)



Decel: 7.4 ft/sec/sec
Snub Speed: 34 to 19 mph
Surface Friction: High
Loading: GVWR
Defect: 6

Several observations can be made from Exhibit 5.56:

- The oil-soaked brake linings (left intermediate and right rear) initially showed less heat build-up than the non-oil-soaked brake linings, clearly indicating issues with those brake assemblies.
- Toward the end of the simulated mountain test, the oil-soaked linings began to show regular temperature changes, indicating that the lining friction was returning to normal, perhaps after most of the oil had vaporized.
- The left front, right front, and right intermediate brake lining thermocouples appeared to not be functioning properly. This may have been due to brake lining wear, which caused the thermocouples to be exposed to the surface of the lining. This test was performed toward the end of the test program, after significant brake wear was likely.

In general, the simulated mountain tests showed that brake lining thermocouples are effective at determining brake defects during extended braking maneuvers. Given enough time and heat build-up, clear patterns emerge with out-of-adjustment, disconnected, and oil-soaked brakes. It is likely that brake assembly temperature would need to be compared across axles in order to determine brake defects, as typical braking temperatures differs for front, intermediate, and rear tractor axles, and depends on load.

6. OBSERVATIONS AND CONCLUSIONS

This chapter outlines the key observations and conclusions presented in previous chapters regarding the performance and operational characteristics of the various sensor packages and their ability to detect abnormalities, defects, and/or out-of-adjustment brake systems. This section also introduces potential applications for brake sensors in advanced ABSs and ECBSs.

6.1 ANCHOR PIN STRAIN GAUGES

Pre-production instrumented anchor pins (interchangeable with conventional S-cam anchor pins) fitted with strain gauges capable of measuring the shear stresses applied to anchor pins of a drum brake assemblies used on heavy-duty S-cam brakes. The following are some key observations and conclusions on the instrumented anchor pins, and the monitoring of brake shoe force:

- Track testing shows that a highly predictable relationship exists between force data generated by instrumented (strain-gauged) anchor pins and the vehicle’s deceleration rate. Instrumented anchor pin force is therefore an accurate measurement of a vehicle’s braking performance.

- Testing conducted using the PBBT (chassis dynamometer) confirmed a linear relationship between the instrumented anchor pin force and the force measured between the tire and roller interface (defined as true brake force). The PBBT testing data also showed that the **primary** anchor pin provides a better correlation between pin force and true brake force—and a higher-resolution output than the secondary anchor pin.

- Instrumented anchor pins can accurately detect brake deficiencies in specific individual wheel assemblies--including out-of-adjustment, disconnected, and/or oil-soaked shoe linings. Their sensitivity is such that they can also measure the effect of an out-of-adjustment brake on the other (properly adjusted) brakes on a vehicle. This capability lends itself for application to advanced brake balancing control schemes that might be possible with ECBSs.

- Instrumented anchor pins can accurately detect even low brake forces. By resolving the resultant force into the “X” (friction force) and “Y” (normal force) directions, the instrument anchor pins can differentiate between an out-of-adjustment brake and a brake with oil-soaked shoe linings. This capability could likely be leveraged to improve diagnostic efficiency and overall brake maintenance planning.

- The instrumented anchor pins performed reliably and with a resolution that is sufficient for potential use in brake balancing system.

6.2 STROKE SENSORS

The test truck was equipped with two commercially available stroke sensor packages and a pair of linear potentiometers mounted on the intermediate drive axle. Key observations and conclusions on the commercial sensors, and on the utility of monitoring stroke sensing in general, are as follows:

- Commercial brake chamber stroke sensor packages can detect brake deficiencies and are very effective as a pre-trip brake inspection aid. Their "real-time" accuracy varies depending on the load, deceleration rate, and type of brake deficiency. Both commercial systems tested had the most difficulty detecting brake deficiencies with the trailer unloaded and at low deceleration rates.

- In-cab displays featuring indicator lights for all 10 brakes provide the driver with valuable real-time data on the overall condition of the vehicle's braking system. Displays mounted outside the cab are intended for pre-trip inspection purposes only.

- Commercial stroke sensor packages and stroke monitoring in general can alert the driver to potential problems with brakes. However, unlike the instrumented anchor pins, they cannot differentiate between out-of-adjustment brakes and oil-soaked shoe linings. For example, with an oil-soaked shoe linings, the linear potentiometers recorded an over-stroke condition.

- The resolution and accuracy of stroke sensors is best suited for use in detecting brake maintenance needs and potential brake safety issues, but is probably not appropriate for use in brake balancing systems.

6.3 WHEEL-SPEED SENSORS

ABS wheel-speed sensors can be used to measure individual wheel-slip by comparing the calculated speed of each wheel against the calculated average for all wheels—or against some other "actual" speed reference such as a transmission signal or a contactless fifth wheel that measures ground speed. The J1939 wheel speed message is also a viable option for determining wheel-slip. Some key observations and conclusions regarding wheel-speed sensing are:

- In general, ABS wheel-speed sensors are highly accurate and track closely with “actual” vehicle speed as measured by an instrumented fifth wheel.

- Wheel-speed data broadcast on the J1939 network had a significantly lower resolution than that of the actual ABS wheel-speed sensors. On the network, wheel-speed data resolution is artificially limited due to message size limitations and low sampling frequencies.

- The transmission tailshaft speed sensor loses accuracy at low vehicle speeds.

- The resolution of wheel-speed sensors is sufficient to detect grossly out-of-adjustment and disconnected brakes. Wheel-speed sensors do not provide sufficient resolution to detect brakes that are out-of-adjustment 2-1/8 inches or less.

- Wheel-speed sensors have sufficient resolution to detect a problem due to oil-soaked brake linings. Their accuracy depends on the extent of the contamination. However, unlike instrumented anchor pins, wheel-speed sensors cannot differentiate between out-of-adjustment brakes and oil-soaked linings.

- Although the resolution of wheel-speed sensor data broadcast over the J1939 network is limited, it is sufficient to detect grossly out-of-adjustment, disconnected, and poorly performing brakes.

6.4 BRAKE SHOE THERMOCOUPLES

Thermocouples, mounted at varying depths within the shoe lining, were evaluated to determine whether they could reliably be used to detect brake defects. The thermocouples were also used to assist in evaluating the other sensor "packages". The following are some key observations related to thermocouple temperature measurement of brake shoes and linings:

- Of the three thermocouple depths used, only the thermocouple closest to the brake drum (0.04 inches) recorded a significant rise in temperature during discrete braking maneuvers.

- The response time of thermocouples in general is not sufficient to detect brake problems during discrete braking events.

- Because of unpredictable variations in initial brake temperature, the comparatively slow response time of thermocouples, and the general inaccuracies inherent with thermocouples, their ability to detect and differentiate brake deficiencies during discrete braking events is very limited.

- During the simulated mountain testing, temperature patterns were detected and used to identify various brake deficiencies. Brake shoe thermocouples were used to record the maximum temperature down a grade, which could be reported to the driver.

- The proximity that thermocouples must have to the shoe lining surface to detect dragging or disconnected brakes may prevent them from being used in commercial applications, where it may not be practical to embed them directly in the lining.

6.5 GENERAL BRAKE PERFORMANCE AND TEST OBSERVATIONS

Observations and conclusions about brake system performance and about the testing in general are as follows:

- A delay of 0.085 seconds was recorded between the time the driver depressed the brake pedal and force was generated at the instrumented anchor pins.

- Minor changes in control pressure were measured between tests with no brake defects versus with two brakes out-of-adjustment by 2-3/8 inches during a high-deceleration brake event. These control pressure fluctuations are likely to be undetectable by a driver. Even using pressure sensors, it would likely be difficult to differentiate from other “normal” fluctuations in control pressure that might be introduced by variations in road surface, tire condition, loads, and driver reactions.

- ABS control loop algorithms used on the tractor were significantly tighter than those used on the trailer

- On a highly reflective, low-friction surface, the optical non-contact fifth wheel had difficulty detecting the vehicle speed. A similar situation would likely occur on wet or icy roads and could occur on roads where there is a large buildup of road oil.

6.6 POTENTIAL SENSOR APPLICATIONS

This section presents potential applications for the commercial use of instrumented anchor pins, as well as expanded uses of commercial stroke-sensing technology.

- **Brake Balance Systems** – The instrumented anchor pins accurately detected brake deficiencies and provided sufficient resolution to measure the increase in work done by the remaining brakes on a vehicle. This would make them ideal for use in brake balance application in conjunction with advanced "brake-by-wire" technologies. In this application, brake pressure could be tailored to individual brakes based upon brake force output readings. The benefits include increased brake life due to improved brake lining wear, and the ability to perform minor brake adjustments in real time.

- **Wireless Transfer of Brake Data** – Companies in the transportation industry market products capable of wirelessly transferring maintenance data from the vehicle to a central data processing computer in a maintenance yard. These systems are currently configured to wirelessly transfer engine and transmission fault codes, for example, from the vehicle's network. The information generated from the commercial stroke sensor packages and instrumented anchor pins could be broadcast to the vehicle's network and similarly transferred to the maintenance yard. The data could assist in improving vehicle brake safety, scheduling brake work, and tailoring brake rebuild schedules.

- **Improving Regenerative Braking in Hybrid Applications** – Many hybrid propulsion manufacturers currently use an open-loop approach in combining regenerative braking and friction braking. Basically, the initial application of the brake treadle valve is regenerative. Exceeding a preset limit energizes the friction brakes. This open-loop control methodology results in an arbitrary amount of regenerative braking force being applied, and less-than-optimal energy captured during a braking event.

  Instrumented anchor pins can measure the beginning of a friction-braking application and its applied force. By factoring in this data, regenerative braking algorithms could be closed-loop in nature. A closed-loop regenerative braking system, while still isolated from the service brakes, will optimize the braking energy recovered as well as reduced emissions, improve brake wear, and improve fuel economy.