COMMERCIAL VEHICLE SAFETY TECHNOLOGIES: APPLICATIONS FOR BRAKE PERFORMANCE MONITORING

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ABSTRACT

A brake system deficiency is the most common reason for a commercial motor vehicle (CMV) to be cited for a regulatory violation and to be taken out-of-service during a roadside inspection. As part of a major safety technology project intended to assess the state of the practice and potential contributions of advanced sensor systems, the Federal Motor Carrier Safety Administration (FMCSA) sponsored two studies on CMV brakes and related controls. The first study compared the performance of six types of brake systems and component sensors in a controlled, test-track environment under both nominal operating conditions and conditions where brake faults were deliberately introduced. The results indicated that all types of sensors tested (two different Hall-effect stroke sensors, anchor pins instrumented with strain gauges, embedded thermocouples, ABS wheel-speed sensors, linear potentiometers, and a pressure transducer) provided useful information on brake performance status. However, their accuracy and fault-detection properties varied considerably, influencing their potential use in operational settings. The second study assessed the performance and maintainability of brake monitoring devices in an urban transit fleet. Twelve test and 12 control transit buses were fitted with 3 brake performance monitoring (BPM) systems. The buses accumulated more than 1.2 million kilometers in aggregate, during a 12-month test period. In operational use, it was demonstrated that commercially available sensors can be used to improve the effectiveness and efficiency of brake performance system assessment and thereby reduce the risk of crashes attributable to poor brake performance. These studies provide new information directly comparing the performance of BPM systems in controlled and operational settings. Both study results are limited to the particular systems and applications tested. Study data are available from the FMCSA.

INTRODUCTION

Under Section 5117 of the Transportation Equity Act for the 21st Century of 1998, 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." A comprehensive technology scan, as well as numerous interviews with key industry stakeholders such as truck manufacturers, fleet operators, suppliers, and regulators, identified a variety of research areas. They included the design, functionality, and effectiveness of BPM systems for CMV applications.

Commercial vehicle braking system design and operation is directly linked to stopping distance and handling and, thus, to overall safety. Properly maintained and performing brakes are critical in preventing and mitigating crash situations. Although vehicle defects in large trucks are not commonly pinpointed as the causative factor in crashes, vehicle defects, when found, frequently involve malfunctioning or defective brakes.

For years, the CMV industry has been plagued by the significant number of trucks and buses operating on the highway with brake defects, despite attempts by many different groups to address the problem. CMV inspection data show that about 19 percent of all inspected vehicles (nearly one in five) have one or more brake defects. In June 2008, during a 72-hour intensive inspection initiative sponsored by the Commercial Vehicle Safety Alliance, 67,931 vehicles in Canada, Mexico, and the United States were inspected. Various vehicle-related defects and violations resulted in 23.9 percent of the vehicles examined being placed out-of-service and prohibited from operation until the defects were remedied. Slightly more than half of these out-of-service vehicles (52.6 percent) were cited for brake-related issues.

Optimally adjusted braking systems can help prevent or reduce the severity of CMV-involved crashes, even when the braking system is not the initial cause of the crash. Brake sensors, acting independently or as part of a coordinated system on a CMV, can measure dynamically and continuously the actual braking force at each wheel. Brake sensors can provide a warning to the driver, maintenance personnel, and roadside safety officials if the vehicle's braking ability is degraded to an unsafe level. In addition, brake sensors can provide information to aid in diagnosing the specific deficiencies. Brake sensors also can be integrated into a CMV's electronically controlled brake system in a "closed-loop" fashion to balance the braking action at each wheel. This will improve service life and provide additional input for controlling braking action at each wheel during crash avoidance maneuvers.

COMPARATIVE CONTROLLED TESTING OF BRAKE SENSORS

The first study documented the performance and operational characteristics of leading-edge technological approaches to monitoring CMV brake systems. It focused on comparing and contrasting the ability of the various sensors to detect abnormalities, defects, and maladjustments of the brake system. Multiple systems were installed on a tractor-trailer combination vehicle so they could be tested concurrently and under the same test conditions. A test matrix was developed to encompass a variety of controlled braking maneuvers, including low to high deceleration rates executed on dry and wet pavement, on level and graded surfaces, and with the CMV lightly laden and loaded to its gross vehicle weight rating (GVWR). All tests were performed on a test-track.

The study sought to answer questions concerning the performance of specific sensors and measures, including 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 antilock brake system (ABS) wheel-speed sensors be used to determine wheel slip? Can the relationship of wheel slip to brake force be used to detect brake system defects?
- Air chamber stroke sensing systems — How accurate and reliable are they? What defects can they detect? What malfunctions might they fail to detect? Is it important to monitor brake stroke continuously, or is measurement of over/under stroke sufficient?
- Deceleration measurements — Although comparing deceleration with air brake pressure input to determine total brake force can be used to detect brake defects, 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?
- On-board brake temperature measurement — Relatively low-cost thermocouples can readily be affixed to brake system components. How reliably and quickly could they detect brake system defects?

Baseline performance and sensor outputs were first established with all wheel/brake assemblies on the vehicle optimally adjusted and with no defects. The test vehicle, equipped with a new set of brake linings, was subject to Federal Motor Vehicle Safety Standard (FMVSS) 121 S6.1.8 (brake burnishing procedures). Braking performance of the vehicle was verified using a roller dynamometer performance-based brake tester (PBBT) to compare the brake force measurements from the various sensors to a reference standard.

The following sections describe the BPM systems and other instrumentation, the test vehicle, the test program, and the results.

Instrumentation

StrainSert Anchor Pin Strain Gauges. In 1998-1999, the National Highway Traffic Safety Administration funded a Small Business Innovative Research project to evaluate the use of strain-gauged pins to provide an indication of brake performance. A grant was awarded to StrainSert, West Conshohocken, Pennsylvania, which produces strain-gauged pins for various commercial measurement applications. For the evaluation, anchor pins were 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.

The StrainSert pins are designed to be interchangeable with conventional anchor pins and are held in place using a simple keeper plate. 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 Figure 1 for a diagram of an S-cam brake assembly and Figure 2 for a photograph of the StrainSert anchor pins installation.) 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, more wear) than the secondary shoe. Likewise, the primary anchor pin should encounter higher forces.

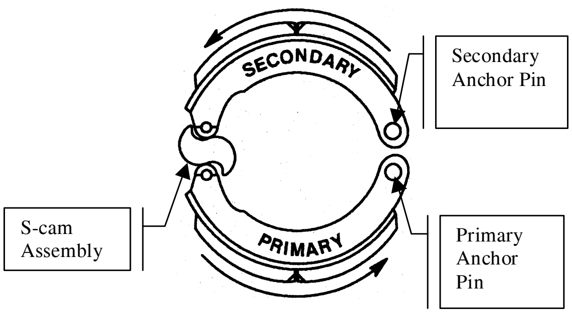

Figure 1. Left Intermediate Axle Brake Shoe.

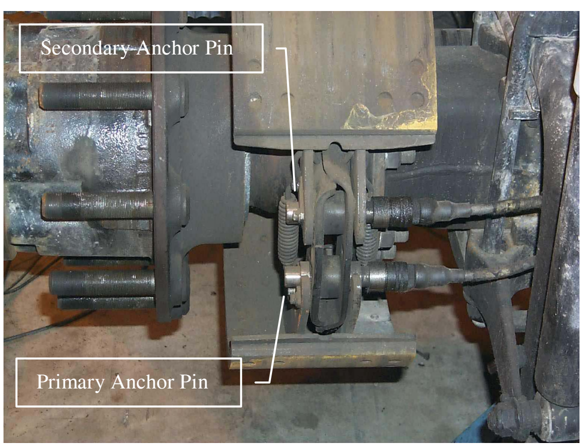

Figure 2. StrainSert Anchor Pins.

For the evaluation, each anchor pin was fitted with two strain gauges oriented 90 degrees apart, roughly in the "X" and "Y" direction. One of the strain gauges was mounted normal to the direction of rotation (the "Y" direction) and was intended predominantly to measure the mechanical non-friction, normal force exerted by the movement of the brake shoe as it moves against the drum. The "X" axis strain gauge was offset 90 degrees from normal and was intended primarily to measure the rotational friction force between the drum and the lining. The StrainSert anchor pins could 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.

<u>MGM E-Stroke</u>. MGM Brakes of Charlotte, North Carolina, the leading supplier of brake chambers (70 percent of the market), provided the study team with a commercial production electronic-stroke monitoring system or E-Stroke 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. The E-Stroke system is illustrated in Figure 3. A communication module processes this voltage change and determines the status of the brake system. The communication module is capable of detecting normal stroke, 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 require replacement of the standard brake chambers. Although the E-Stroke system is designed as a pre-trip inspection tool, the system continuously monitors the status of the brake system and can provide a visual indication of a stroke-related fault on a cab-mounted display.

Figure 3. MGM E-Stroke System.

<u>Spectra Products Brake Inspector</u>. Spectra Products, Inc., of Etobicoke, Ontario, provided Brake Inspector, another commercial production brake chamber stroke sensor system. This system, shown in Figure 4, is similar to the MGM system in function, using a single Hall-effect sensor, but the sensor hardware is mounted outside the brake chamber. Therefore, unlike the MGM E-Stroke system, the Spectra Brake Inspector 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 Brake Inspector is also designed as a pre-trip brake status indicator, as well as a real-time brake-stroke status monitor. Spectra also includes a mechanical measurement indicator which is mounted on a clevis pin and provides a visual means to check the brakes in the event of a power or display failure.

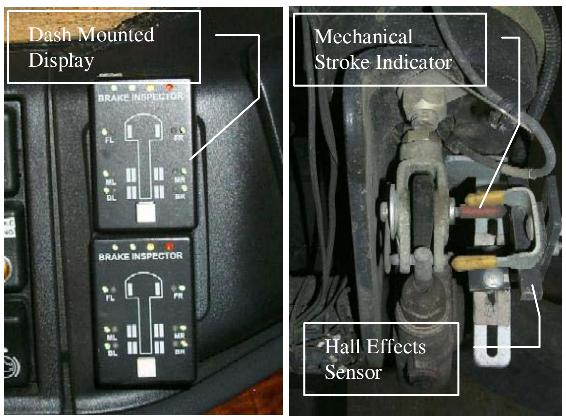

Figure 4. Spectra Brake Inspector.

Thermocouples. Standard Type J thermocouples were included in the instrumentation suite to determine whether they could be used reliably to detect brake defects, as well as to provide a temperature reference for evaluating the other sensors and systems. Temperature is an indication of brake adjustment status. Disconnected or backed-off brakes run cooler than properly adjusted brakes, while dragging brakes run hotter. The thermocouples were mounted at varying depths within the shoe lining to test their sensitivity in determining brake deficiencies.

ABS Wheel-Speed Sensors. Wheel-speed sensors are a standard component of ABS systems used on heavy-duty trucks and buses. The variable-reluctance sensor is the most common type of wheel-speed sensor used in the industry. It uses 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. 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.

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 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 affects the rotational speed of that wheel compared with other wheels. If the braking force is low on a given wheel assembly, the wheel will tend to rotate a fraction faster than the other wheels. Conversely, if the braking force is high, the wheel will rotate slightly slower.

Linear Potentiometers. The linear potentiometers used in the evaluation (model number JP73213) were manufactured by Penny and Giles Controls, Ltd. These laboratory grade, special-purpose linear potentiometer sensors were mounted to the brake chamber push rods to measure their linear displacement during braking. Measurement of brake chamber stroke provides an indication of the driver's input to the air brake system. 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.

Pressure Transducer. A low-cost pressure transducer from Texas Instruments (part number 84HP062T00150GSOC) was installed on the test vehicle to assist in evaluating the other sensor packages. Control pressure can provide an accurate measurement of the driver's input into the air brake system via the treadle valve and 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.

Test Vehicle

The test vehicle was a new 2001 Volvo VNL 64T Series tractor, 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 caused by the use of older equipment. The flatbed semi-trailer design allowed 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, semi-trailer, and brake hardware are provided in Table 1, found at the end of this paper.

The test vehicle was equipped with the brake sensor packages and general-purpose sensors, which were installed 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. Figure 5 shows the locations of the various sensors.

The test matrix included introducing pre-planned faults or defects on selected brake assemblies and repeating various braking maneuvers. Because the major objective of this test program was to evaluate the ability of the various sensor technologies to detect brake problems, 10 different brake deficiency scenarios were examined, ranging in severity from no deficiencies to 4 fully disconnected brakes. To maintain the stroke adjustment, the automatic adjustment feature of the slack adjuster was disabled on the affected brakes. Defects examined included various levels of out-of-adjustment brakes, disconnected brakes, and oil-soaked brakes. To simplify the analysis, no more than one deficiency was introduced to any given wheel or axle.

Data from the sensor packages were recorded using an onboard personal-computer-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) transmitted to the vehicle's SAE J1939 high-speed electronic network. The data was then processed off-board using conventional database and engineering plotting tools.

Test Program

The test program was designed to subject various types of brake performance sensors and systems to a comprehensive series of brake tests under a variety of operating conditions 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 defects were systematically introduced to determine the sensors' abilities to detect problems with respect to dry and wet road 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.

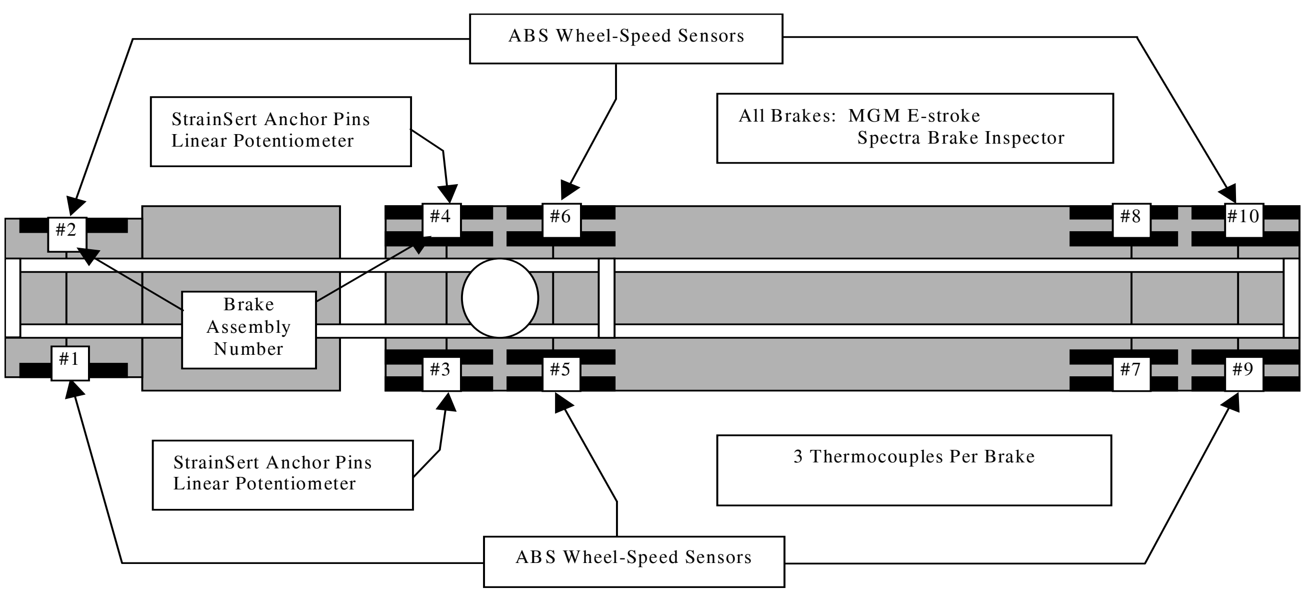

Figure 5. Sensor Locations.

In addition to the controlled deceleration tests, the brake sensor packages were subjected to simulated road tests to model the duty cycle that a vehicle would follow during extended mountain 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 industry-recognized, Jennerstown mountain test procedure was administered on a flat, closed test track. 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 brake temperatures (IBTs) between 150° F and 200° F. In an effort to account for any degradation in baseline brake performance resulting from 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 PBBT was incorporated into the program to assist in evaluating the performance of the instrumented anchor pins against true service brake force. The PBBT used in this study was a roller chassis dynamometer-based system, capable of evaluating air brake systems on trucks and buses. PBBTs are commercially available and assist vehicle manufacturers and fleet operators by dynamically measuring the rolling resistance, brake threshold pressure, service brake force, parking brake force, and anti-lock braking systems (sensors, valves, and wiring).

Brake Burnish. The test vehicle, equipped with a new set of brake linings, was subject 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 ft/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.

Data Collection Process. A Link data acquisition system (DAS) received information from 59 individual channels at a frequency of 50 hertz. Six of those channels were digital and were broadcast from the SAE J1939 network. A contact switch mounted to the brake treadle valve activated the DAS. Data were 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 on the dashboard of the truck. The average braking event lasted about 3to 8seconds and generated approximately 17,000 data points (59 channels x 6 seconds x 50 data points per second). The data were downloaded to a compact disk at the completion of each day of testing. In total, the testing program generated approximately 375 megabytes of data.

The operator was responsible for manually recording the test identification number and other specific information, including environmental conditions, IBT, average control pressure, stopping distance, and the time required to stop the vehicle. The operator was also responsible for monitoring and documenting data generated from three sensor packages. These self-contained systems were not connected directly to the Link DAS, as they did not have signal output suitable for recording.

The data generated from the brake test program were 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 graphing capability was extremely useful in identifying trends in the data.

Results

Anchor Pin Strain Gauges. The track testing showed a highly predictable relationship between force data generated by instrumented (strain-gauged) anchor pins and the vehicle's deceleration rate. Instrumented anchor pins could accurately detect brake deficiencies in specific (individual) wheel assemblies, including out-of-adjustment, disconnected, and/or oil-soaked brake shoe linings. They also could measure the effect of an out-of-adjustment brake on the other (properly adjusted) brakes on a vehicle. Finally, as shown in Figure 6, data from instrumented anchor pins can be resolved into "X" (friction force) and "Y" (normal force) components and, thus, could point to causes for performance decrements. Notably, they could differentiate between an out-of-adjustment brake and a brake with oil-soaked brake shoe linings because an oil-soaked brake shoe lining generates less force in the "X" direction.

Figure 7 shows that primary anchor pin force was closely correlated with both the deceleration rate and the actual braking force (as measured by the PBBT) of the vehicle. This observation has important implications from a commercialization perspective since it would be necessary to instrument only a single anchor pin to accurately measure brake force.

Figure 8 shows that for properly adjusted brakes, as well as out-of-adjustment brakes, 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 increased as the driver applied brake pressure in an attempt to maintain the desired deceleration rate. With oil-soaked brake shoe linings, the Y direction forces were actually much higher than the X direction forces. This information could indicate to the driver and maintenance staff that the detected defect in the brake assembly (and associated reduction in brake performance) was caused by an oil-soaked brake shoe lining as opposed to an out-of-adjustment condition.

Stroke Sensors. The accuracy of the readings from the sensor systems varied, depending on the load, deceleration rate, and type of brake deficiency. Both commercial systems tested (MGM E-Stroke and Spectra Products Brake Inspector) had the most difficulty detecting brake deficiencies with the trailer unloaded and at low deceleration rates. The manufacturers of both systems state that they are intended to detect overstroke conditions during hard braking. Additionally, stroke measurement obtained from the systems tested 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 controlled braking systems. Unlike the instrumented anchor pins, brake stroke monitoring could not differentiate between out-of-adjustment brakes and oil-soaked brake shoe linings. This is illustrated in Figure 9. Oil-soaked brake shoe linings caused the linear potentiometers to record an overstroke condition.

Brake Shoe Thermocouples. Because of the unpredictable variations in initial brake temperature, the comparatively slow response time of thermocouples, and their inherent general inaccuracies, the ability of brake shoe thermocouples to detect and differentiate brake deficiencies during discrete braking events was found to be very limited. In general, the simulated mountain tests showed that brake lining thermocouples were 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 brake shoe linings. It is likely that brake assembly temperature would need to be compared across axles in order to determine brake defects, as typical braking temperatures differ for front, intermediate, and rear tractor axles, depending on the load.

Wheel-Speed Sensors. Wheel-speed sensors were sufficiently accurate to detect grossly out-of-adjustment and disconnected brakes. However, they were not accurate enough to detect brakes that were 1/8-inch or less beyond the readjustment limit. Although they were able to detect performance decrements stemming from oil-soaked brake shoe linings, they were not able to differentiate between out-of-adjustment brakes and oil-soaked linings. Finally, wheel-speed data broadcast on the J1939 network was significantly less accurate than data from actual ABS wheel-speed sensors; but it was still able to detect grossly out-of-adjustment, disconnected, and poorly performing brakes. See Figure 10. The advantage of utilizing wheel speed as a means of diagnosing brake performance is that sensors are already on-board all CMVs equipped with ABS.

Figure 10 shows that the left front and right front relative wheel speeds were symmetric around zero because the average of the absolute left side and right side speeds was equal to the front axle speed. The relative speeds of the rear wheels differed 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 illustrated 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 milliseconds) is evident from the roughly 0.1-second steps in the data traces.

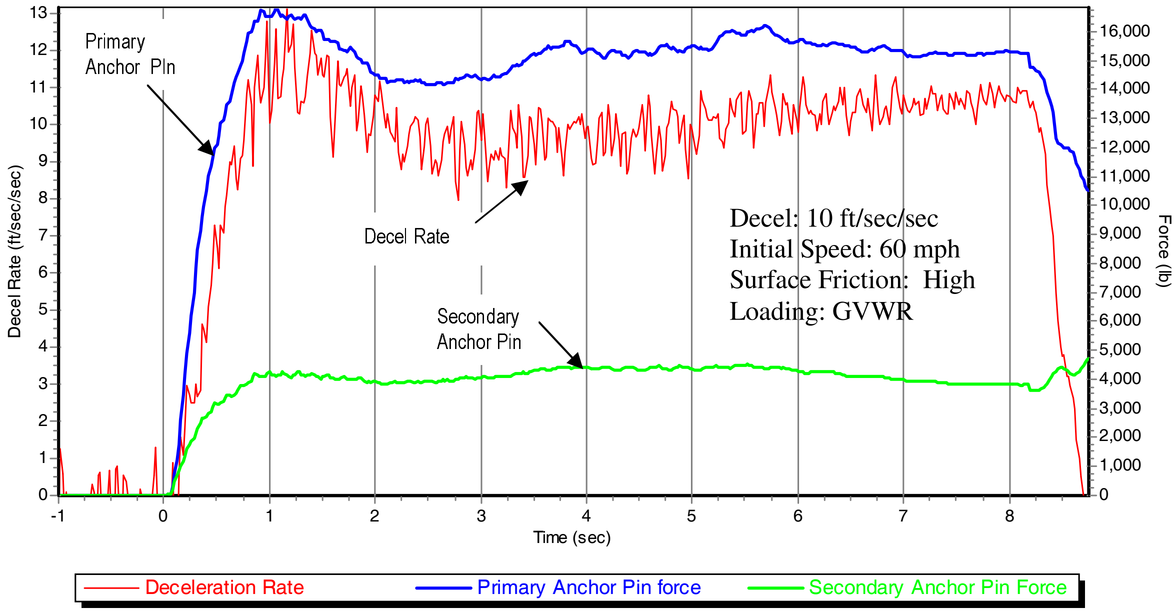

Figure 6. Primary and Secondary Anchor Pin Force During Moderate Deceleration.

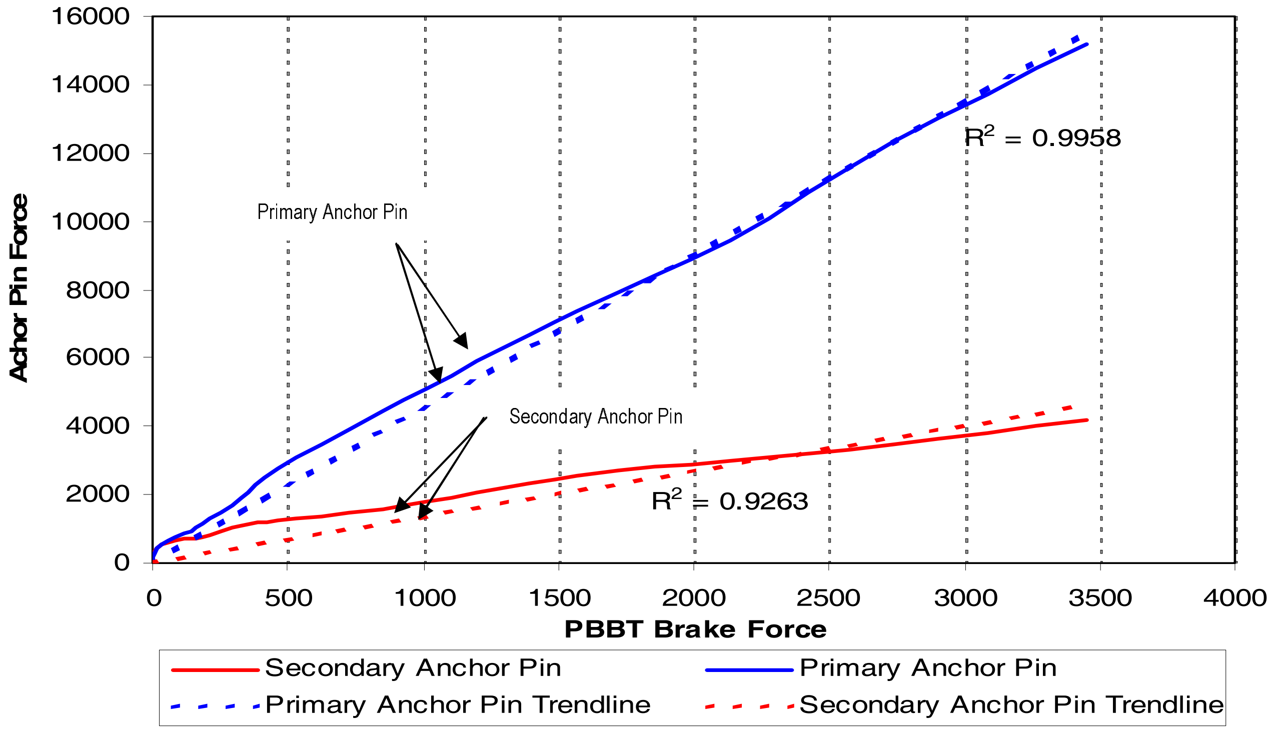

Figure 7. Anchor Pin Force vs. PBBT Brake Force.

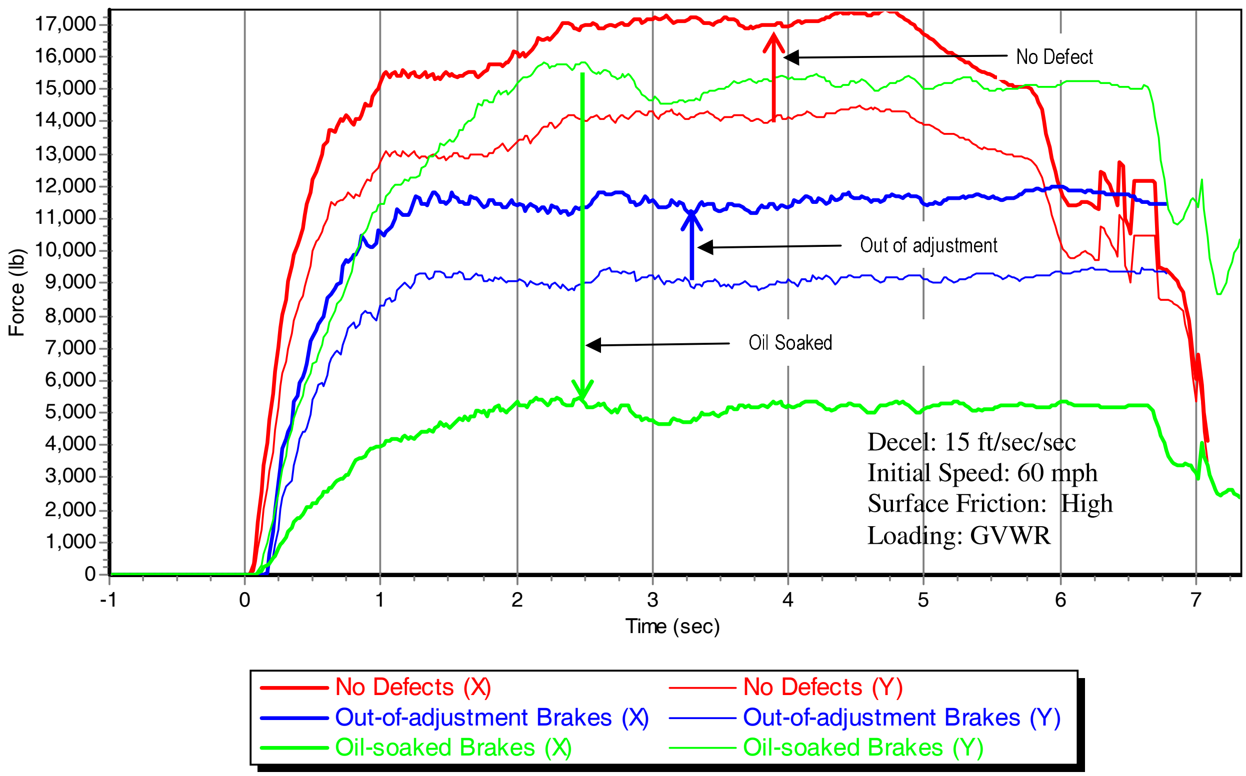

Figure 8. X and Y Anchor Pin Forces, Left Intermediate Brake Assembly, Under Various Defect Conditions.

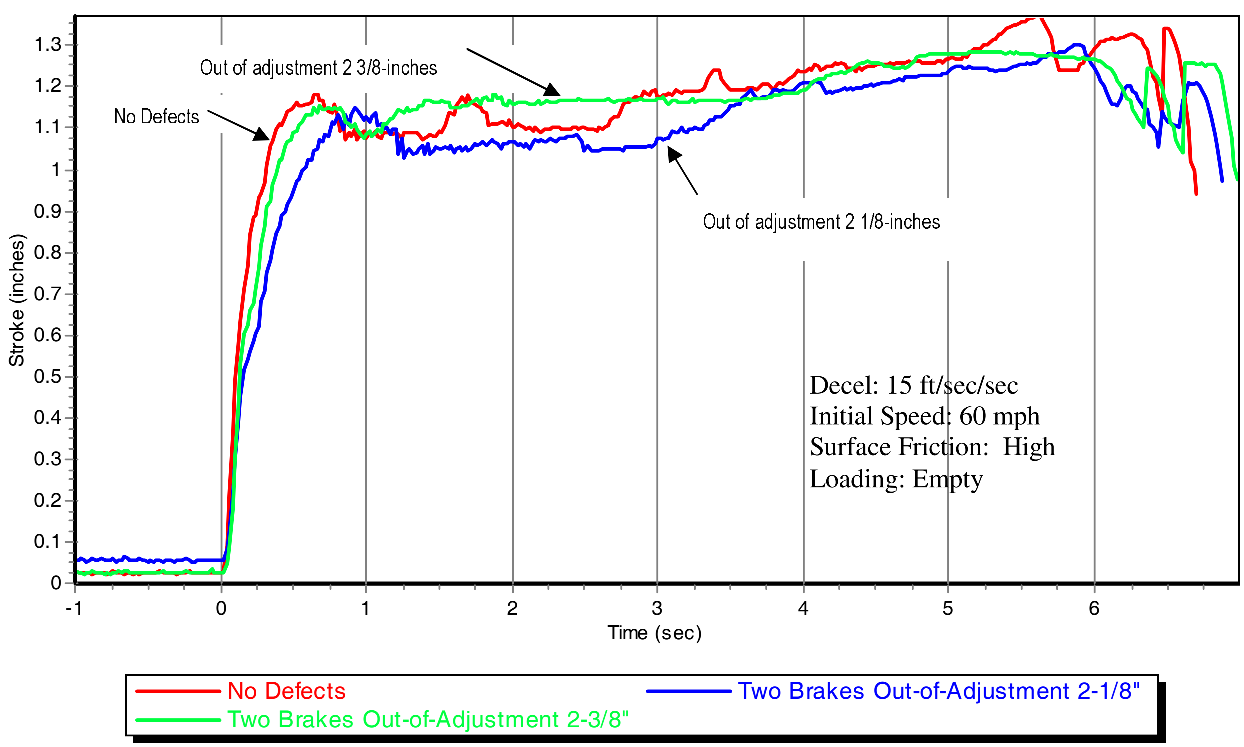

Figure 9. Brake Chamber Stroke Measured on Properly Adjusted Brake Assembly (Right-Intermediate) with Left Intermediate Brake Out-of-Adjustment.

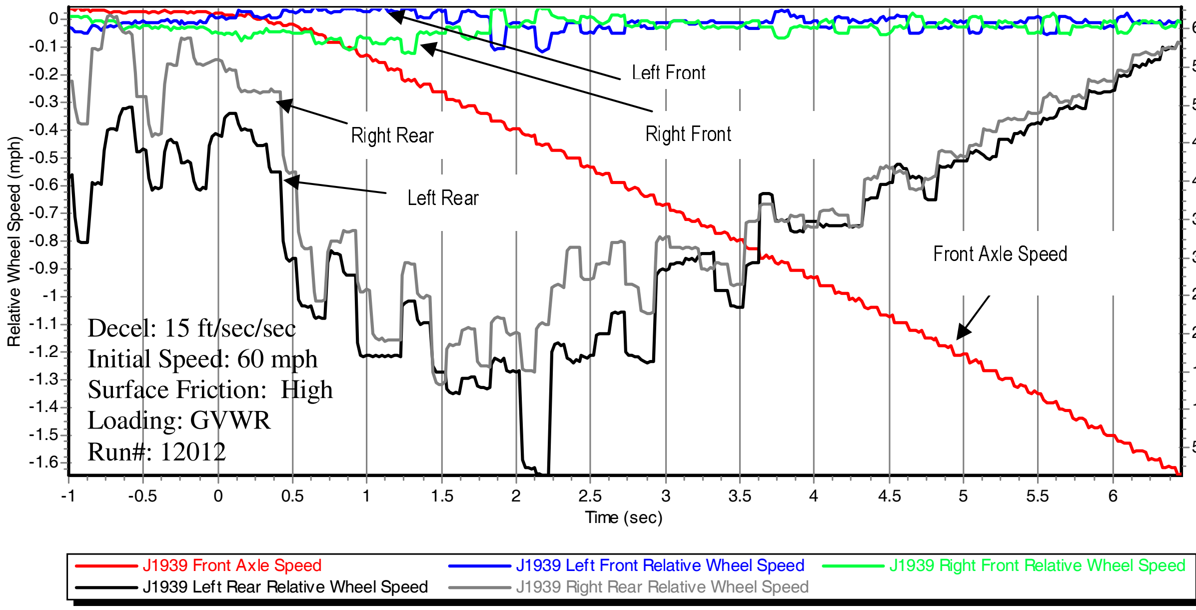

Figure 10. Wheel Speeds Relative to the Front Axle Speed with Properly-Adjusted Brakes.

BRAKE PERFORMANCE FIELD OPERATIONAL TEST

The second study focused upon documenting and evaluating several leading-edge BPM systems in a fleet setting. The study team sought to identify a commercial fleet operator (or host fleet) with characteristics that would allow for effective and fair evaluation of systems and technologies. These criteria included: an operating environment and duty cycle that could be considered severe for brake and tire wear; homogeneity of the fleet in terms of vehicle type, make, and model; consistency of operations within the fleet relative to driver assignments, routes, mileage accumulation, and maintenance operations; and a strong commitment by the host fleet to evaluating these systems in a controlled study for possible implementation in its own fleet.

The host fleet selected was the Washington Metropolitan Area Transit Authority (WMATA). WMATA operates approximately 1,500 buses in Washington, D.C. and the surrounding metropolitan area. Transit bus platforms were selected for this field test because their severe urban, stop/start duty cycle leads to accelerated brake and tire wear (thus challenging the sensor systems). In addition, the fundamental brake and tire designs are very similar to those on a conventional tractor, thus allowing the results of this study to be extended to heavy-duty (class 8) trucks.

The test fleet consisted of 12 Orion VII series, 2005 model year, urban transit buses. The buses are a “low floor” design, 40 feet long and 102 inches wide, and operate on compressed natural gas. Each bus’s GVWR is 42,540 pounds. The passenger capacity is 41 seated and 36 standing passengers for a total of 77 passengers. The curb weight of the buses is 30,990 pounds. The 16,500-pound front and 28,600-pound capacity rear axles are manufactured by Rockwell. Four S-cam Meritor brake assemblies are mounted on each wheel end. Front brakes measured 16-1/2 inches by 6 inches, and the rear brakes measure approximately 16-1/2 inches by 8-5/8 inches. Table 2 provides a full vehicle specification and can be found at the end of this paper.

The study team evaluated 3 BPM systems (as well as the 3 tire pressure monitoring systems) on 12 heavy-duty urban transit buses in revenue service for a period of one year. A control fleet of 12 identical buses was operated in a similar manner and used for comparison. A maintenance garage located in Arlington, Virginia was selected as the test site, based on the availability of buses of a consistent age and operating environment and on the experience and low turnover of the maintenance staff. With the assistance of WMATA and BPM system vendors, the study team retrofitted the candidate systems on the buses at the garage. The buses operated in an area covering approximately 300 square-miles south and west of Washington, D.C. The majority of miles were accumulated in an urban environment with minimal high-speed highway travel. The buses averaged 16 miles per hour in revenue service and were driven an average of 129 miles per day.

WMATA staff recorded all maintenance and fueling activities and entered the data into a maintenance management database. This information was made available to the study team for evaluation. At the conclusion of the test, maintenance staff were interviewed about their experience operating and maintaining the systems. Other than the standard data-recording capabilities of the candidate systems, no additional (or special-purpose) data-logging devices were added to the vehicles. The system status displays were located out of the drivers' view per the request of WMATA fleet managers. The study team and WMATA technicians were responsible for monitoring the systems' display status. This was done to limit driver distraction, as well as to reduce the incidence of operators halting a bus because of information from the displays. In the transit industry, it is common to limit the vehicle-related information available to the bus driver to basic items, such as vehicle speed, brake reservoir pressure, and dash-mounted warning lamps.

Three different BPM systems were evaluated under this program, as were three different tire pressure monitoring systems. The BPM systems selected (MGM E-Stroke, GeoDevelopment Brake Insight, and Strainsert) represented a range of technological approaches. The Strainsert and E-Stroke systems had been assessed in the controlled tests described earlier in this paper. The Brake Insight system uses a Hall-effect sensor mounted outside the brake chamber. The E-Stroke system was factory-installed on all of the buses but was the primary system under test in four buses. The Brake Insight and Strainsert systems were each installed on 4 buses, and 12 additional buses served as the study controls.

Project planning began in the autumn of 2005. Sensor system installation took place in the spring and summer of 2006, to accommodate the schedules of the fleet and the suppliers' field engineers. Data were collected for 12 months (November 2006 through November 2007). Over the course of the evaluation period, the systems were inspected weekly, and system data were downloaded as part of the test program. Additional data were collected in conjunction with WMATA's various maintenance inspections, which included a safety inspection every 3,000 miles and a comprehensive preventative maintenance inspection every 6,000 miles. In addition to the inspections, brake system performance was evaluated once per month using a roller-dynamometer PBBT.

The buses were placed on lifts for brake inspections, as shown in Figure 11. This enabled technicians to walk under the bus to inspect the brake lining thickness at each brake assembly and to measure brake pushrod stroke. The applied-stroke method was used. One technician would apply the brakes while at the driver's seat, and a second technician, outside the bus, would measure the brake stroke travel (in inches) and record it on the brake data collection form.

Figure 11. Test Bus on Platform Lift.

Results

• Onboard BPM systems were found to influence favorably WMATA's inspection practices. WMATA inspects buses every 3,000 and 6,000 miles. With over 200 buses operating out of a maintenance facility, these inspections require a significant amount of time. For the 3,000-mile inspection, WMATA has begun relying on the BPM systems to assess the brakes. This reduces inspection times and allows more buses to be inspected within a given period.
• The durability of BPM system sensors was excellent in a rigorous urban transit-operating environment. Only one sensor failure occurred during the 12-month test period. Maintenance actions on the sensors were few and were limited to broken wires, loose connectors, and sensor adjustments.
• In transit service, information from onboard monitoring systems needs to reach maintenance personnel in a timely fashion to be useful. WMATA's buses are equipped with a controller area network (CAN) databus and WiFi transmitter capable of wirelessly transmitting alarms from the bus to a server housed at the maintenance garage. Each time the bus returns to the garage, this data is off-loaded

and emailed to maintenance supervisors. The E-Stroke systems evaluated under this program were integrated into this CAN network. The study team found that buses with E-Stroke alarms were inspected and problems corrected in a timely fashion (on the same or the next day). On buses with monitoring systems that only communicated via in-vehicle display, a week or more could elapse before brake problems were addressed.

• MGM's E-Stroke system proved useful in the early detection of a manufacturing issue in the alignment between the brake chamber and slack adjuster on the test buses. The vehicle and brake manufacturers corrected this issue under the terms of their warranties.

• The WMATA technicians interviewed noted that the BPM system alerts provided them with useful information to quantify driver complaints and reduce their frequency. Complaints about brakes are time consuming to troubleshoot because they require performing an inspection on a lift. Technicians commented that the BPM systems reduced the number of driver complaints and provided real-time information they could use to decide whether the bus should be withheld from service.

• The BPM systems evaluated under this program were not able to detect worn brake linings in need of replacement. All but one of the test buses underwent a rear brake overhaul at roughly 70,000 to 80,000 miles into the field test. In the weeks and days leading up to the rear brake overhauls, none of the monitoring systems triggered an alarm indicating poor brake performance or excessive stroke travel. It should be noted that the Brake Insight system featured a wire-loop lining wear sensor embedded in the shoe lining. Unfortunately, the sensor embedded into the lining was placed at a depth lower than the minimum thickness used by WMATA to replace shoe linings.

• Onboard BPM systems provide a new source of information enabling technicians to identify and address brake issues. As with any new data source, a learning period is required to understand, interpret, and be confident with the data generated by these monitoring systems. WMATA experienced this learning process with the systems evaluated under this program. WMATA and the study team worked with BPM system vendors to tailor algorithms (and warning thresholds) for WMATA's transit vehicles to minimize false positives and improve the overall reliability of the information. Among the algorithms so modified were those relating to the base foundation brake setup, which was found to operate close to adjustment limits. The foundation brake setup coupled with the operating environment, which cycled the brakes frequently, caused hot brake conditions and resulted in overstroke alarms.

• Based on the results of the field study, as well as its previous independent testing, WMATA has confidence in BPM systems and plans to specify their use in all of the buses that WMATA purchases in the future.

CONCLUSIONS

Results from controlled track tests illustrated several key differences among the BPM systems. 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. 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. Instrumented anchor pins sensitivity, on the other hand, 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 advanced braking systems. Finally, the resolution of wheel-speed sensors is sufficient to detect grossly out-of-adjustment and disconnected brakes. As these sensors are already included on new trucks as a component of ABS, they could be utilized to provide a low-cost approach to identifying brake adjustment problems.

In the brake performance field test, BPM systems provided information on the condition of the bus's brakes that was useful for improving maintenance practices and detecting brake abnormalities. This information had a significant impact on inspection practices and enhanced the overall efficiency of operations. While no firm procurement commitments were made, WMATA maintenance managers indicated at the end of the field study that they would consider the adoption of one or more monitoring technologies for new vehicle procurements and the retrofit of existing buses.

REFERENCES

Kreeb, R. M., B.T. Nicosia, D. Skorupski, and R. Radlinski, "On-Board Sensors for Determining Brake System Performance." Report FMCSA-PSV-04-001, December 2003.

Van Order, D., D. Skorupski, R. Stinebiser, and R. Kreeb, "Fleet Study of Brake Performance and Tire Pressure Sensors." Performed under Contract DTFH61-99-C-00025, Task Order 9, July 2005 – July 2008. Report forthcoming from FMCSA.

Table 1.
Track Test Vehicle Specifications

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

Table 2.

Transit Bus Specification

TRANSIT BUS		
Bus Model	Orion VII	
Serial Number	4V4NC9JH91N317953	
Model Year	2005	
Engine	Cummins C8.3 Gas Plus	
Transmission	Voith D864.3E	
Front Suspension	Air	
Rear Suspension	Air	
Wheelbase (inches)	286 inches	
ABS	WABCO 4S4M	
GVWR (pounds)	42,560	
BRAKES		
	Front	**Rear**
Manufacturer	ArvinMeritor	ArvinMeritor
Type	S-Cam Drum	S-Cam Drum
Size (inches)	16.5 x 6	16.5 x 8.63
Lining	Meritor A3222F2296	Meritor A3222F2294
Slack Adjusters	Haldex, 5-Notch Adjustment	Haldex, 5-Notch Adjustment
Chamber Type	MGM E-Stroke Type 24 Long	MGM E-Stroke Type 30 Long
Drum	Dayton-Walther 85123561002	Webb 64051B
TIRES		
	Front	**Rear**
Manufacturer	Goodyear	Goodyear
Make/Type	City Tire	City Tire
Size	305/70 R22.5	305/70 R22.5
Pressure (psi)	115	115

WEIGHT DISTRIBUTION			
	Front Axle	**Rear Axle**	**Total**
Curb Weight, pounds	11,000	19,990	30,990
GVWR, pounds	14,780	27,760	42,540