Fleet Study of Brake Performance and Tire Pressure Sensors

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

July 2009

FOREWORD

This project is one of several performed under the provisions of Section 5117 of the Transportation Equity Act for the 21st Century (TEA-21). The primary objective of this project was to explore the overall effectiveness and customer acceptance of commercial vehicle brake performance and tire pressure monitoring systems in a field test setting. The work performed under the project included:

- Selecting brake performance and tire pressure monitoring systems that were representative of currently available products in the marketplace.
- Arranging for field testing of these systems with a commercial fleet, and in a normal "everyday" service environment.
- Developing data collection and analysis plans.
- Installing systems on test vehicles.
- Preparing for and conducting the field test.
- Analyzing the data and observations collected during the field test.
- Developing a report that summarizes the results of the analysis including observations and conclusions (this document).

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16. Abstract

The purpose of this project was to conduct a field study of brake performance and tire pressure monitoring systems on commercial heavy-duty vehicles operating under real world conditions. The study evaluated six systems in total—three brake performance and three tire pressure monitoring systems from various suppliers participating in the project. Transit bus platforms were selected for this field test because of the severe urban, stop/start duty cycle under which transit buses operate—an environment that accelerates both brake and tire wear thus allowing the sensor systems to be heavily "exercised" over the study period.

The test fleet included 12 test buses and 12 control buses. The buses were operated by the Washington Metropolitan Area Transit Authority in Washington, DC The test site was the Four Mile Run maintenance garage located in Arlington, Va. During the course of the 1-year field test, the buses averaged 129 miles per day, and the test fleet traveled a total of approximately 762,580 miles.

Four sources of data were used to evaluate the brake and tire monitoring systems: visual inspections, on-board self-diagnostic data, maintenance records, and technician interviews.

Both the tire and brake monitoring systems were found to hold up to the rigors of an urban city environment, and to provide fleet managers with data that can be used to improve vehicle safety and maintenance practices. The information provided by such systems allowed managers to better plan and anticipate maintenance actions, and to initiate preventative maintenance in order to prevent potentially severe failures. Key challenges associated with introduction of the sensor systems included: implementation of proper training for maintenance staff; consistent and correct use of data obtained from the systems; and, disciplined inspections and tracking of the sensor systems themselves to ensure they did not add to the overall vehicle maintenance requirements.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	Yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					AREA				
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	l	l	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
MASS					MASS				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lbs)	0.907	megagrams	Mg	Mg	megagrams	1.103	short tons (2000 lbs)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8 C + 32	Fahrenheit temperature	°F
ILLUMINATION					ILLUMINATION				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m2	cd/m2	cd/m2	candela/m2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS				
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

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

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LIST OF ACRONYMS

ABS	antilock braking system
AVM	Automatic Vehicle Monitoring
BPMS	brake performance monitoring system
CAN	controller area network
CMV	commercial motor vehicle
CNG	compressed natural gas
CV	commercial vehicle
DC	direct current
ECU	electronic control unit
F	Fahrenheit
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GVWR	gross vehicle weight rating
I/O	input/output
ID	identification
IVTM	Integrated Vehicle Tire Pressure Monitoring
LTCCS	Large Truck Crash Causation Study
MCMIS	Motor Carrier Management Information System
MCSAP	Motor Carrier Safety Assistance Program
NHTSA	National Highway Traffic Safety Administration
PBBT	Performance-Based Brake Tester
psi	pounds per square inch
RF	radio frequency
RFID	radio frequency identification
TEA-21	Transportation Equity Act for the 21st Century
TPMS	tire pressure monitoring system
TRC	Transportation Research Center
USDOT	U.S. Department of Transportation
VDC	volts direct current
WMATA	Washington Metropolitan Transit Authority

EXECUTIVE SUMMARY

PROJECT FUNDING

Under the provisions of Section 5117 of the Transportation Equity Act for the 21st Century of 1998 (TEA-21), Congress authorized the U.S. Department of Transportation (USDOT) 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 (CV Sensor Study). This study was completed as a Task Order under the CV Sensor Study.

PROJECT SUMMARY

The Report summarizes the findings from a field test of various brake and tire condition monitoring systems installed on heavy duty commercial motor vehicles (CMVs). Specifically, three different brake performance and three tire pressure monitoring systems were installed on 12 heavy duty commercial vehicles and operated for one year (one brake sensor system and one tire pressure monitoring system were installed on each test vehicle). Transit buses were chosen for the study because of the rather severe environment in which they operate relative to brake and tire wear conditions. The costs, benefits and overall performance of the brake and tire systems were compared with a similarly operated control fleet. The information from this project can be used by fleet managers (as well as by truck original equipment manufacturers and sensor system developers) to make important decisions related to the application, design, and use of such systems.

BACKGROUND AND RATIONALE FOR STUDYING BRAKE AND TIRE MONITORING SYSTEMS

Brake System Monitoring

The number of CMVs with defective brakes that are operating on highways is a situation that has plagued the industry for years. Commercial vehicle inspection data shows that about 19 percent of all inspected vehicles—nearly one in five—were found to have one or more brake defects.[*] In 2008, the Commercial Vehicle Safety Alliance Roadcheck 2008 conducted a 72-hour inspection of 67,931 vehicles in Canada, Mexico, and the United States and placed 23.9 percent of them out

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[*] The 1998 Motor Carrier Management Information System (MCMIS) Inspection File is operated and maintained by the Federal Motor Carrier Safety Administration (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. By 2008, the number of inspections had grown to more than 3 million.

of service because of various vehicle related defects and violations. Brake-related issues accounted for 52.6 percent of these vehicles being placed out of service.[†]

It is well understood that 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 on large trucks are not commonly pinpointed as the causative factors in crashes, when defects are found, they frequently involve malfunctioning or defective brakes. Deficient or out of adjustment brakes were a factor in 29.4 percent of the fatal crashes investigated in the Federal Motor Carriers Safety Administration (FMCSA) 2006 Large Truck Crash Causation Study (LTCCS).(1) Further, the study ranked brakes as the number one equipment-related causal factor associated in the investigated crashes. Optimally adjusted braking systems could help prevent or mitigate crashes even when the braking system itself is not the initial cause of the crash.

Tire Pressure Monitoring

Lack of proper tire pressure maintenance also impacts safety as well as fuel efficiency in CMVs. Research sponsored by the FMCSA indicates that a significant portion of fleet operators do not regularly perform tire pressure maintenance recommended by tire manufacturers.(2) For example, FMCSA research has shown:

- Approximately 7 percent of all CMV tires are under-inflated by 20 pounds per square inch (psi) or more. Only 44 percent (approximately) of all tires are within ±5 psi of their target pressure.
- Tire-related costs are the single largest maintenance expense for CMV fleet operators. National average tire-related costs per tractor-trailer are about 2 cents per mile, or about $2,500 for an annual 125,000-mile operation.
- Improper inflation increases total tire-related costs by approximately $600 to $800 annually per tractor-trailer combination.
- For the average fleet operator in the United States, improper tire inflation increases the annual procurement costs for both new and retreaded tires by about 10 to 13 percent.
- On average (and for a tractor-trailer), improper tire inflation reduces fuel economy by about 0.6 percent.
- Weakened and worn tires that result from improper inflation is likely responsible for about one road call per year per tractor-trailer combination.

Tire inflation and condition directly link to vehicle stability and handling—and thus, to overall safety. Properly maintained and performing tires aid drivers in preventing and mitigating crash situations, while also improving fuel efficiency.

Technologies that could substantially reduce the cost and effort associated with tire and brake maintenance, and improve the ability to detect problems early, would likely lead to a reduction in the number and severity of commercial-vehicle-related crashes. Such technologies would also

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[†] Roadcheck 2008 (conducted June 3–5, 2008) inspected 67,931 CMVs at roadside inspection sites across Canada, Mexico, and the United States using the Commercial Vehicle Safety Alliance inspection procedures (web site: www.cvsa.org).

reduce costs and downtime associated with brake and tire systems. To address these issues, numerous types of brake performance monitoring and tire pressure monitoring systems have emerged in the marketplace over the last decade. However, the market penetration for these systems has remained comparatively low.

Previous FMCSA-sponsored research(3, 4) documented the performance, accuracy, and overall adequacy of these systems in a controlled, test track environment. However, the performance of these systems operating in real-world service has not been well documented. Because fleet operators rely heavily on such data, this lack of credible information has likely limited the widespread deployment of such systems.

STUDY OBJECTIVE

Following the work of previous FMCSA-sponsored studies that assessed the performance of brake condition and tire pressure management systems in a controlled test-track environment, the primary objective of this research project was to document the performance, reliability, durability, and maintainability of leading-edge commercial vehicle brake performance and tire pressure monitoring systems in “real world” service. This study focused on examining the ability of brake performance monitoring systems (BPMSs) to detect abnormalities, defects, and/or misadjustments of the brake system, and for tire pressure monitoring systems (TPMSs) to detect tire pressure, temperature and air loss, in routine operational service environments.

The project examines the performance of these systems and their ability to withstand the rigors of CMV operation. The project also included a review of fleet maintenance managers acceptance of the systems, and if and how they influenced on-going maintenance practices. The purpose of the project was to assess the relative ability of different types of brake and tire pressure monitoring systems to perform as promised, rather than to compare the performance of various manufacturers’ products with each other.

Following are the specific objectives of the study:

- Assess the benefits of using an onboard BPMS.
- Assess the benefits of using a TPMS.
- Determine whether TPMS can improve vehicle fuel economy.
- Determine the maintainability, durability, and reliability of TPMS and BPMS operating in a non-controlled service environment.
- Determine the degree to which brake performance and tire pressure monitoring systems influence fleet maintenance practices.
- Determine whether audio and visual displays provide sufficient information for maintenance personnel to diagnose tire and brake problems.
- Determine whether the various sensors systems incorporate sufficient self-diagnostic features to allow for efficient maintenance (i.e., so that they do not create more problems than they solve).

An ancillary goal of the project was to assess the benefits of a performance-based brake tester (PBBT).

OVERVIEW OF PROGRAM APPROACH

The study team's approach to evaluating the brake and tire sensor systems focused on completing the following tasks:

- Identify a commercial fleet operator (or "host" fleet) with characteristics that would allow for effective and fair evaluation of the monitoring systems, including:
  - an operating environment and duty cycle that could be considered severe for brake and tire wear (so that the sensor systems could be adequately "exercised" during the observation period).
  - homogeneity of the fleet in terms of vehicle type, make and model (so that sensor systems could be installed on like-vehicles and eliminate the potential for the vehicles themselves to influence the evaluation).
  - consistency of operations within the fleet relative to: driver assignments, routes, mileage accumulation, and maintenance operations (so that these external factors would not influence sensor system evaluation, thus allowing for a valid comparison with each other, and with the performance of a "control" fleet).
  - perhaps most importantly, the host operator should be interested in evaluating tire and brake sensor systems for possible widespread application on their own fleet, and should be generally supportive of the field study.
- Select candidate brake and tire sensor systems based on previous test track experience and commercial availability.
- Develop a test plan focused on evaluating the reliability, maintainability, accuracy, costs, and benefits of the various systems.
- Install candidate sensor systems.
- Conduct the field test.
- Analyze the data to determine maintainability, reliability, and durability of the systems, as well as fuel economy and safety benefits.
- Document results in a final report.

The host fleet selected was the Washington Metropolitan Area Transit Authority (WMATA). WMATA operates approximately 1,500 buses in Washington, DC, 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 "exercising" the sensor systems). In addition, the fundamental brake and tire designs for transit buses are very similar to a conventional tractor, thus allowing the results of this study to be extended to heavy-duty (class 8) trucks.

The study team evaluated three brake performance and three 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 were operated in a similar manner and used for comparison. A maintenance garage located in Arlington, VA, was selected as the test site based on its availability of buses of a consistent age and operating environment, and because of the low turnover and experience of the maintenance staff. With the assistance of WMATA and system vendors, the study team retrofitted the candidate systems on the buses at the bus garage. The buses operated in an area covering approximately 300 square-miles south and west of Washington, DC. 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.

Over the course of the evaluation period, the sensor systems were inspected weekly. Also, the brake monitoring systems were capable of storing various brake system failures and abnormalities (as fault codes)—and this data was 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 PBBT. 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 to assist with the 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 sensor system 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 reduce the incidence of operators ceasing bus service because of information from the displays. *Note: limiting vehicle related information to the bus driver (such as diagnostic information, dash warning lights, and even fuel gauge readings) is common in the transit industry.*

SYSTEMS EVALUATED

Three different brake performance monitoring systems from different manufacturers were evaluated under this program, as were three different tire pressure monitoring systems. The BPMSs and TPMSs selected represent a range of technological approaches. Further, the characteristics of these specific systems were assessed under controlled test track conditions through prior research efforts completed under the CV Sensors Study project sponsored by FMCSA. The manufacturers and systems that participated in the field study are as follows.

BPMS

- **MGM eStroke** is an electronic brake stroke monitoring system that provides brake stroke status readings for pushrod-operated air brakes. A Hall-effect sensor mounted within the brake chamber is used measure brake stroke travel.
- **GeoDevelopment Brake Insight** is a brake stroke monitoring system similar to the MGM system in that it uses a Hall-effect sensor. It differs in that the sensor and related hardware are mounted outside the brake chamber.

- **StrainSert Brake Performance Monitoring** system uses strain gauges affixed to the anchor pins on the S-cam drum brake assembly to measure shear stresses that develop during a braking event. Earlier studies have confirmed that these shear stresses correlate closely with actual brake force. The anchor pin shear stress values are monitored on each brake assembly and readings can be compared among all assemblies to detect brake force imbalance and other abnormalities.

Each of these systems includes an electronic control unit (ECU) which receives data from sensors (either the Hall-effect sensor in the cases of the MGM and GeoDevelopment units, or from stain gauges in the Strainsert system) and analyzes the information. Each system also includes display units that provide diagnostic data to the vehicle operator and/or maintenance personnel. Detailed information on these systems can be found in Section 5.

TPMS

- **WABCO Integrated Vehicle Tire Pressure Monitoring (IVTM)** was developed in conjunction with Michelin and launched in the CMV industry in 2003. Each tire and wheel assembly is equipped with a sensor that attaches to the valve stem and is secured to the rim by two lug nuts. A pneumatic hose runs between the sensor and valve stem. Tire inflation pressure and temperature data is wirelessly transmitted to an ECU on board the vehicle.
- **HCI Tire-SafeGuard** consists of pressure and temperature sensors, a transmitter, and a driver’s display. The measurement sensor is strapped to the wheel hub inside the tire. Data is transmitted in a way similar to the WABCO system.
- **Michelin eTire** for commercial vehicles was introduced by Michelin North America in October 2002. The system includes a radio frequency (RF) transmitter, pressure and temperature sensors, and an antenna, all of which are encased in impact- and heat-resistant plastic. The passive pressure and temperature sensors (which do not require batteries) receive power via RF transmissions from an external reader device. The eTire unit mounts to the inside sidewall of the tire via a molded rubber dock that chemically cures to the tire’s sidewall. The system is designed to work with a tire pressure gate reader, but may also be used with a handheld reader.

Detailed information on the TPMS evaluated in the study may be found in Section 4.

TEST FLEET AND PLATFORM SELECTION

WMATA was selected as the host fleet based on fleet size, age of vehicles, operating environment, proximity to the project sponsor and study team, maintenance facilities and practices, experience with the candidate technology under evaluation, and willingness to participate.

The test platform was a 2005 Orion VII 40-foot, low-floor bus with a gross vehicle weight rating of 42,500 pounds. Although a transit fleet was selected for this field test, it is important to note that the brakes and tires used on buses and trucks are similar. Both use S-cam brakes manufactured by the same suppliers. The diameters of the brakes are the same, but the width of a bus drum brake is slightly wider for improved heat dissipation. The tires used on both platforms are radial ply in construction, operate at similar pressures, and are similar in size. Bus tires are tailored for durability, while truck tires are tailored for fuel efficiency. The TPMSs and BPMSs evaluated under this program were standard production units available in the CMV market.

SUMMARY OF RESULTS

This study should prove useful to fleet operators in evaluating the capabilities and limitations of alternative BPMS and TPMS technological approaches, and help fleets in developing performance/functional specifications of BPMS for future vehicle purchases. The information should also be useful to suppliers and commercial vehicle manufacturers that are developing new BPMSs and TPMSs.

Overall, both the onboard TPMSs and BPMSs provided information on the condition of the bus's brakes and tires that was useful for improving maintenance practices and detecting tire and brake abnormalities. This information had a significant impact on inspection practices, including enhancing the overall efficiency of operations. While no firm procurement commitments were made, at the end of the field study, WMATA maintenance managers indicated they will consider the adoption of one or more monitoring technologies for new vehicle procurements and/or the retrofit of existing buses.

Key observations related to the on-board monitoring systems are as follows:

TPMS

- TPMSs provided accurate tire inflation pressure data when compared to measured (tire-gauged) values.
- TPMS sensors were found to be consistent and reliable reporting tire inflation pressures. On average, the systems reported false positives (a false low-pressure reading) 6 percent of the time or false negatives (a missed low-pressure reading) 2 percent of the time. The more frequent issue was "no reads" resulting from missing sensors and sensors in the wrong wheel location.
- Keeping track of individual wheel/tire sensor units themselves was a significant challenge during the field test. This logistical challenge arose because of the high frequency of tire changes; the fact that sensor mounting locations were out of view of technicians; and, lack of fleet-wide training on system awareness and operation. Training was limited to the host depot, but occasionally tire and brake maintenance would occur at other depots. Training across the entire system would be required to prevent technicians from misplacing and inadvertently discarding sensors.
- The durability of two TPMS sensor designs was initially challenged by operating in transit service. Failures occurred with the wheel-mounted sensors two months into testing. Excessive heat build-up caused the sensor housing to become brittle, crack, and fail. The sensor manufacturer provided a design change that consisted of an isolating pad on the bottom side of the sensor that contacted the wheel rim. This simple solution prevented further failures. Failures also occurred with the sensors that adhere to the tire sidewall. Specifically, the plastic casings on these sensors were found to

crack within the first few months of operation. The cracked sensor casings were determined to be caused by a manufacturing batch defect. Replacement sensors were found to be significantly more durable.

- An improvement in adherence to targeted tire pressures was not found on the test fleet compared to the control fleet. (i.e., average observed tire pressures between the control and test fleets were roughly the same). This may be because WMATA takes a pro-active role in maintaining target inflation pressures to comply with the tire vendor's warranty. Average tire inflation pressure was 111 pounds per square inch (psi) for both the test and control fleets (target: 115 psi). Tire life and fuel economy were also similar in both fleets. This was likely the case because, as noted earlier, the real time display of tire pressure readings was purposefully not made available to drivers, but only to maintenance personnel and technicians. Drivers could therefore not act immediately on such information to correct any tire pressure problems that may have been detected. In most CMV fleets, such real time information would be provided to drivers, and drivers would have the opportunity to act on the information as needed (e.g., adding air to tires at the next convenient time if low pressure was detected), thereby improving the average tire life and fuel economy of the fleet.
- Two tire blowouts could have been prevented during the course of the field test had the TPMS displays been visible to the bus operators. To maximize safety and operational benefits, system data needs to be available to the driver in real time (as well as being made available to maintenance staff).
- Technicians preferred the wheel-mount tire pressure sensors for two reasons:
  - They were easier to install.
  - Tires could be changed without removing or disconnecting the system.

Conversely, the technicians found valve-stem-mounted sensors difficult to connect to the inner tires on a set of dual-tire assembly. This issue may be unique to buses because the wheels and tires are surrounded by the structure of the vehicle. Tire-mounted sensors required more time to install (versus wheel or valve-stem mounted systems) because of the required tire surface preparations.

BPMSs

- Onboard BPMS were found to influence WMATA's inspection practices favorably. WMATA inspects its buses every 3,000 and 6,000 miles. With more than 200 buses operating out of each maintenance facility, these inspections require a significant amount of time. For the 3,000-mile inspection, WMATA has begun relying on the BPMS to assess the brakes. This reduces inspection times and allows more buses to be inspected within a given period.
- The durability of BPMS sensors was excellent in a rigorous urban transit operating environment. A single sensor failure occurred during the roughly 1 million miles traveled by the 12 test buses. Most maintenance actions 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 serial databus and WiFi transmitter capable of wirelessly transmitting various diagnostic data 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 e-mailed to maintenance supervisors. The eStroke systems evaluated under this program were integrated into this wireless data transfer system on-board the buses. The study team found that buses with eStroke 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 eStroke 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. This issue was corrected by the vehicle and brake manufacturers under the terms of their warranties.
- Based on interviews, the alerts from the BPMSs provided technicians with useful information to quantify driver complaints and reduce their frequency. Complaints with brakes are time consuming to troubleshoot because they require performing an inspection on a lift. Technicians commented that BPMSs 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 BPMSs 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 BPMSs provided 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 build confidence with the data generated from these monitoring systems. WMATA experienced this learning process with the systems evaluated under this program. WMATA and the study team worked with 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. For example, overstroke alarms were not always attributed to a defective brake. A majority of cases were found to be caused by either high operating brake temperatures, or because of the particular brake setup on the Orion VII test buses. Specifically, the axle design on the Orion VII buses is such that the 0.50-inch reserve stroke is utilized in normal brake operation—and because the brake stroke was operating at its limit in normal operations, numerous "false positive" overstroke alarms were detected.
- Based on the result of the field study, WMATA has confidence in brake performance monitoring systems and plans to specify their use in all of the buses they purchase in the future.

ROADMAP TO REPORT

Section 1 provides background information on FMCSA's Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program (the program under which this project was sponsored). It also provides details on the rationale for this research effort, its objectives, and the approach used to evaluate TPMSs and BPMSs.

Section 2 provides a description of the field test. This section includes information on the host fleet, the vehicle platform, and the technologies evaluated.

Section 3 describes the sources of data used to evaluate the technologies. These sources include system data, maintenance records, vehicle inspections, and maintenance interviews.

Section 4 focuses on the activities related to the evaluation of the TPMSs. It details the work involved in installing the systems, presents analyses of data collected during the field test, and provides key observations and conclusions of the study.

Section 5 focuses on the activities related to the evaluation of the BPMSs. It details the work involved in installing the systems, presents analyses of data collected during the field test, and provides key observations and conclusions of the study

1. INTRODUCTION AND BACKGROUND

1.1 COMMERCIAL VEHICLE SAFETY TECHNOLOGY DIAGNOSTICS AND PERFORMANCE ENHANCEMENT PROGRAM

The purpose of the Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program (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 on 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 focuses 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 commercial motor vehicle (CMV) safety and assessing their cost savings potential and/or operational benefits, thus helping to create market demand and encourage commercialization.

To help identify possible research areas, the following tasks were completed:

- An extensive literature search of relevant technical journals and databases.
- Individual interviews and discussions with representatives from truck and trailer manufacturers, fleet operators, owner operators, and industry suppliers, as well as staff at the National Highway Traffic Safety Administration (NHTSA), Federal Motor Carrier Safety Administration (FMCSA), and Federal Highway Administration (FHWA) who are involved in commercial vehicle safety research.
- 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 CAN).
- Cost, benefits, and implementation issues associated with event data recorders.
- Active suspensions systems.
- Advanced vehicle diagnostic and prognostic tools.
- Issues related to implementation of "Smart Copilot" onboard systems.

The focus of this report is on the first, second and seventh research areas on the list—brakes and related controls, tire inflation and condition monitoring systems, and advanced vehicle diagnostic and prognostic tools.

In prior tasks under the CV Sensors Study contract, FMCSA completed comprehensive evaluations of brake performance and tire pressure monitoring systems on a closed test track. The primary objective of that work (Task Order #3, completed in November 2003, Report FMCSA-PSV-04-002; and Task Order #8, completed in July 2006, Report FMCSA-PSV-07-001) was to document the performance and operational characteristics of leading-edge commercial vehicle brake performance and tire pressure monitoring systems. Baseline performance characterization of the systems were performed according to "scripted" test matrices and under controlled-test-track environments. In contrast, this study focused on a more naturalistic field study of brake performance and tire pressure monitoring systems.

1.2 BACKGROUND AND RATIONALE FOR THIS RESEARCH EFFORT

Brake and tire deficiencies are the two most common vehicle-related deficiencies cited in commercial vehicle roadside inspections. It is well understood that an improperly adjusted or maintained braking system can compromise stopping distance, handling, and overall safety. Likewise, worn and improperly maintained tires can also impair vehicle handling and braking—particularly during evasive or emergency type of maneuvers. Sensor systems that could provide an early warning to drivers and/or maintenance personnel of possible problems with brakes or tires would help reduce the incidence of such deficiencies and lead to an overall improvement in commercial vehicle safety.

As noted, previous task orders under this contract, specifically Task Orders 3(3) and 8(4), provided comprehensive baseline assessments of a variety of state-of-the-art brake and tire pressure monitoring systems and tire pressure management systems. However, the maintenance, reliability and overall customer acceptance of these systems was not evaluated—and hence, a more real world testing of the systems was deemed appropriate.

An urban transit bus fleet was chosen to evaluate the durability and reliability of the brake performance and tire pressure monitoring systems. The vehicles in an urban bus fleet are subjected to some of the most severe service conditions encountered by CMVs. Inter-city transit buses generally operate at moderate-to-low speeds, have high axle weights, and make frequent stops. These factors effectively accelerate wear and tear on both brakes and tires—as well as on the sensor systems involved in this field study.

It is also important to note that the foundation brakes and tires used on these vehicles are similar to those used on many long-haul trucks and motor coaches—and therefore the results of this field study should be useful to mangers of these fleets as well.

Additional factors favoring the use of a transit fleet for evaluating the various sensor systems was consistency of operating and maintenance practices, tight control and tracking of driver assignments, as well having a sizeable fleet of essentially identical vehicles. These conditions minimized the influence of such "externalities" on the durability, reliability and performance of the sensors systems.

1.3 RESEARCH OBJECTIVES

The primary objective of this research study was to document the performance, reliability, durability, and maintainability of leading-edge commercial vehicle brake performance and tire pressure monitoring systems in real-world service. Three different brake performance monitoring systems from different manufacturers were evaluated under this program, as were three different tire pressure monitoring systems. The brake performance monitoring system (BPMS) and tire pressure monitoring system (TPMS) selected represent a range of technological approaches. The study focused on examining the ability of brake performance monitoring system sensors to detect abnormalities, defects, and/or misadjustments of the brake system and for the TPMSs to detect tire pressure, temperature, and air leakage rates in a non-controlled service environment.

The study team examined the performance of these systems and their ability to withstand the rigors of revenue-service operation. The study also included a review of fleet maintenance personnel acceptance of the systems and if/how the systems influenced brake and tire maintenance practices.

This study should prove useful to fleet operators in evaluating the capabilities and limitations of alternative BPMS and TPMS approaches and in determining specifications for future truck purchases. The information should also be useful to suppliers and commercial vehicle manufacturers that are developing new BPMSs and TPMSs.

Following are the specific objectives of the study:

- Assess the benefits of using an onboard BPMS.
- Assess the benefits of using a TPMS.
- Determine whether TPMS can improve vehicle fuel economy.
- Determine the maintainability, durability, and reliability of TPMS operating in a non-controlled service environment.
- Determine the maintainability, durability, and reliability of BPMS operating in a non-controlled service environment.
- Determine the degree to which brake performance and tire pressure monitoring systems influence fleet maintenance practices.
- Determine whether audio and visual displays provide sufficient information for maintenance personnel to diagnose tire and brake problems.
- Determine whether the various sensors systems incorporate sufficient self-diagnostic features to allow for efficient maintenance (i.e. so that they do not create more problems than they solve).

An ancillary goal of the project was to assess the benefits of a performance-based brake tester.

1.4 OVERVIEW OF APPROACH

The study team's approach to evaluating the brake and tire sensor systems focused on completing the following tasks:

- Identify a commercial fleet operator (or "host" fleet) with characteristics that would allow for effective and fair evaluation of systems and technologies, including:
  - an operating environment and duty cycle that could be considered severe for brake and tire wear (so that the sensor systems could be adequately "exercised" during the observation period).
  - homogeneity of the fleet in term of vehicle type, make and model (so that sensor systems could be installed on like-vehicles and eliminate the potential for the vehicles themselves to influence the evaluation).
  - consistency of operations within the fleet relative to: driver assignments; routes, mileage accumulation, and maintenance operations (so that these externalities would not influence sensor system evaluation, thus allowing for a valid comparison with each other, and with the performance of a "control" fleet).
  - perhaps most importantly, the host operator should be interested in evaluating tire and brake sensor systems for possible widespread application on their own fleet, and should be generally supportive of the field study.
- Select candidate brake and tire sensor systems based on previous test track experience and commercial availability.
- Develop a test plan focused on evaluating the reliability, maintainability, accuracy, costs, and benefits of the various systems.
- Install candidate sensor systems.
- Conduct the field test.
- Analyze the data to determine maintainability, reliability, and durability of the systems, as well as fuel economy and safety benefits.
- Document results in a final report.

The host fleet selected was the Washington Metropolitan Area Transit Authority (WMATA). WMATA operates approximately 1,500 buses in Washington, DC. 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 a conventional tractor, thus allowing the results of this study to be extended to heavy-duty (class 8) trucks.

The study team evaluated three brake performance and three 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 were operated in a similar manner and used for comparison. A maintenance garage located in Arlington, VA, was selected as the test site based on its availability of buses of a consistent age and operating environment, and because of the low turnover and experience of the maintenance staff. With the assistance of WMATA and 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, DC. 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.

Over the course of the evaluation period, the systems were inspected weekly, and system data was 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 performance-based brake tester. 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 to assist with the 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 reduce the incidence of operators ceasing bus service because of information from the displays. *Note: limiting vehicle related information to the bus driver, (such as diagnostic information, dash warning lights and even fuel gauge readings) is common in the transit industry*.

2. DESCRIPTION OF THE FIELD TEST

2.1 HOST FLEET

A very critical step in conducting the field test was to identify a fleet suitable for field testing BPMSs and TPMSs. Several potential host fleet operators were evaluated. The key factors considered in selecting an appropriate test fleet included the following:

- **Service Environment/duty cycle.** An environment which accelerates the "wear and tear" on the sensor systems was favored in order to maximize the potential for uncovering (or amplifying) operational pros and cons of the various systems. Further, for practical considerations related to data collection, a fleet that operated within a limited geographic area and utilized a single maintenance facility was preferred. Urban pickup/delivery, vocational, and transit fleets were therefore targeted. These types of fleets would simplify data collection and provide a severe operating environment for brakes and tires.
- **Vehicle Type.** Because this study focused on sensor systems applicable to commercial vehicles, a fleet of heavy-duty trucks such as class 7/8 tractor trailers, heavy-duty vocational trucks, or urban transit buses were considered.
- **Fleet Location.** A fleet operating in the Washington, DC, area, close to the study team and sponsor (FMCSA) was preferred in order to minimize program costs.
- **Vehicle Age.** All else being equal, a fleet with newer vehicles was preferred so as to minimize the potential for breakdowns and maintenance problems with other vehicle systems (which would limit mileage accumulation during the study period).
- **Maintenance Facilities and Practices.** Candidate fleets were evaluated to determine whether their facilities and maintenance systems were sufficient for supporting the program. A fleet with a modern and reliable electronic maintenance management system was required so that maintenance actions could be recorded (in particular, labor hours and parts replacement related to the brake and tire systems).
- **Experience with Candidate Technologies.** Previous experience with the systems was seen as an asset for planning, training, and conducting the test. In considering candidate fleets, maintenance employees were asked about their familiarity with the sensor systems under evaluation.
- **New Technology Test Experience.** Fleets whose employees had previous experience with pilot testing new technologies were sought.
- **Willing Participant.** A fleet's commitment to participate in the program was critical to program success.

The search identified several potential host fleets and included package delivery, beverage delivery, refuse collection, and transit fleets operating in the greater Washington DC metropolitan area. WMATA was selected on the basis of the fleet criteria defined above.

WMATA operates approximately 1,500 buses out of 10 maintenance depots in and around Washington, DC, Maryland, and Virginia. Each bus averages roughly 30,000 miles annually, or about 120 miles per day. The bus fleet is primarily made up of standard 40-foot urban transit buses with a 12-year service life. The fleet included buses manufactured by Orion, New Flyer, NABI, and Flxible. In addition to the standard buses, WMATA also operates a smaller number of 30-foot and 60-foot articulated models. Currently, 70 percent of the fleet is fueled with diesel, but the remaining buses operate on compressed natural gas (CNG). WMATA also operates about 50 hybrid electric buses. The average age of WMATA's fleet is 7.6 years. All preventative maintenance and repairs are performed in-house.

2.2 VEHICLE PLATFORM

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 CNG. All 12 buses are operated out of WMATA's Four-Mile Run maintenance garage. The buses were selected because they were new, operated in a combination of urban and suburban service, and had CNG propulsion/fueling systems. The selection of CNG-fueled vehicles reduced the chance that they could be reassigned to another garage since only 2 of the 10 garages can accommodate the maintenance and fueling requirements of CNG buses. In addition, the new CNG buses were already equipped with one of the brake performance monitoring systems under evaluation—specifically, the MGM eStroke. After a series of pilot tests in 2007, WMATA began ordering new buses with the MGM's eStroke system. Further, using a system manufactured by Clever Devices,(5) brake performance data (from the eStroke system) as well as engine and transmission fault codes, are offloaded wirelessly to a central server located at the maintenance garage.

Each bus's gross vehicle weight rating (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 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 1 provides a full vehicle specification.

Table 1. Transit Bus Specifications

General		
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)	42,540	
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**
Curb Weight, 30,990 pounds	11,000	19,990
GVWR, 42,540 pounds	14,780	27,760

2.3 TECHNOLOGIES UNDER EVALUATION

The brake performance and tire pressure monitoring systems selected for this study were chosen on the basis of two main criteria: documented successful performance under controlled testing, and commercial availability. Previous research sponsored by the FMCSA (Task Orders 3(3) and 8(4) under the "Sensors Study" program) assessed the accuracy and reliability of BPMSs and TPMSs respectively under controlled conditions, and essentially provided important baseline characterization data about the products prior to conducting the field study. A brief review of the work completed under these task orders is presented in the following sections.

2.3.1 Brake Performance Monitoring Systems

Task Order 3, *Onboard Sensors for Determining Brake System Performance*,(3) documented the performance of leading-edge technological approaches to monitoring commercial vehicle braking systems. The study focused on various sensors and their ability to detect abnormalities, defects, and misadjustments of the braking system.

Brake monitoring systems were tested on a closed test track at Transportation Research Center (TRC) in East Liberty, Ohio, in the 2001–2002 time frame. The brake monitoring systems were installed on a conventional tractor-trailer and included the following technologies.[‡]

- Brake chamber stroke sensors.
- Anchor pin strain gauges.
- Wheel-speed sensors.
- Brake shoe thermocouples.

The systems were evaluated under a variety of braking maneuvers including low-to-high deceleration rates on dry and wet pavement, on level and graded (sloped and super-elevated) surfaces, and under no-load and fully loaded conditions. Each brake assembly was optimally adjusted to establish baseline performance criteria. The test matrix included deliberately "staged" faults or defects on brake assemblies. The sensor outputs were examined to determine their ability to detect brake defects under various braking conditions.

Brake Chamber Stroke sensors. Brake stroke monitoring systems examined included the MGM eStroke and Spectra Brake Inspector. Both systems were able to detect brake deficiencies. Following are the key observations and conclusions on these systems:

- System accuracy varies depending on the load, deceleration rate, and type of brake deficiency. The systems had the most difficulty detecting brake deficiencies when the trailer was unloaded and when braking was at low deceleration rates; however, the manufacturers noted that these systems are designed to primarily detect overstroke conditions during hard-braking applications (rather than precise stroke measurement during light decelerations).
- In-cab displays featured indicator lights for each brake assembly and provided the driver with valuable real-time data on the overall condition of the vehicle's braking system.
- Brake stroke monitoring cannot differentiate between out-of-adjustment brakes and oil-soaked shoe linings. During testing, the linear potentiometers recorded oil-soaked shoe linings as an overstroke condition.
- The resolution and accuracy of stroke sensors make them well-suited for detecting brake maintenance needs and potential brake safety issues.

[‡] An additional brake performance monitoring system from NorCorp Systems was also briefly evaluated. This system attempted to correlate brake system control pressure with vehicle deceleration rate in order to determine if the brakes were working properly. Software problems however prevented complete testing of this system.

Based largely on the observations above, two brake stroke monitoring systems were selected for the fleet test—MGM eStroke and GeoDevelopment Brake Insight. The MGM eStroke brake monitoring system featuring its brake chamber mounted sensor was selected for the fleet test because of its performance at TRC and its commercial availability. The Brake Insight system was selected because WMATA had previously evaluated the Spectra system and was interested in comparing it with a similar product from GeoDevelopment. Both the GeoDevelopment and Spectra systems have a similar design and use a sensor that mounts externally to the brake chamber. Furthermore, the GeoDevelopment system offered a shoe lining wear sensor, which WMATA was interested in evaluating.

Anchor Pin Strain Gauges. Task Order 3 also examined instrumented drum brake anchor pins manufactured by StrainSert. Each anchor pin is fitted with two strain gauges oriented 90 degrees apart. One of the strain gauges is mounted normal to the direction of rotation, 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 other 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. The anchor pin strain gauges performed well during track testing and were considered for field testing for the following reasons:

- Track testing demonstrated a highly predictable relationship between force data generated by the 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 brakes, disconnected brakes, 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 to application on 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 instrumented anchor pins can differentiate between an out-of-adjustment brake and a brake with oil-soaked shoe linings.
- The instrumented anchor pins performed reliably throughout the testing.

At that time of testing (2002), StrainSert had only recently developed the instrumented anchor pins and had not yet incorporated them into a complete and commercially available brake monitoring system. Therefore, the anchor pins were connected directly to a data acquisition system, and their outputs were later analyzed using a custom database tool. StrainSert has since made progress in developing a complete brake monitoring package. The system includes the anchor pins, electronic control unit (ECU), display unit, and software package with user-adjustable brake force and alarm thresholds.

Wheel speed sensing. 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. During braking (particularly hard braking) individual wheel/tire assemblies actually experience a very minor degree of skidding which causes the truck to slow down. The working hypothesis was that if a particular brake assembly was not functioning properly (due to out of adjustment brakes, worn brakes, or any other defect), then that wheel would be rotating slightly faster than the other wheel/tire assemblies which were braking normally (and therefore experiencing a slight degree of skidding). These differences in individual wheel speeds (during a braking event) could then be compared to determine if one or more brake assemblies was malfunctioning.

Unfortunately, the wheel-speed sensor system tested during Task Order 3 was sufficiently accurate to only detect grossly out-of-adjustment and/or disconnected brakes. Wheel-speed sensors do not provide sufficient accuracy to detect brakes that are marginally out of adjustment (i.e., 2 1/8 inches or less). Additionally wheel-speed sensors cannot differentiate between out-of-adjustment brakes and oil-soaked linings.

Brake Shoe Thermocouples. As part of the Task Order 3 work, thermocouples were mounted at varying depths within the shoe linings to test their sensitivity for determining brake deficiencies. These tests showed that 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.

Of the four brake monitoring technologies tested, brake chamber stroke sensors and anchor pin strain gauges proved to be the most viable candidates for continued testing in the field. Specifically, the following brake performance monitoring systems were made part of the field study at WMATA:

- The eStroke system, by MGM Brakes.(6)
- The Brake Insight, by GeoDevelopment.(7)
- The StrainSert Anchor Pin System.(8)

2.3.2 Tire Pressure Monitoring Systems

Task Order 8, *Tire Pressure Monitoring and Maintenance Systems Performance*,(4) documented the performance, accuracy, and operational characteristics of leading-edge approaches to commercial vehicle tire pressure monitoring and maintenance systems. The study focused on the various TPMS sensors and their ability to provide accurate tire pressure readings, detect slow and rapid changes in tire pressure, and maintain tire pressure under adverse conditions.

Task Order #8 evaluated a variety of tire pressure monitoring and automatic inflation systems under controlled conditions on a closed test track at Transportation Research Center, Inc. (TRC) in East Liberty, Ohio, in the 2005 to 2006 time frame. The TPMSs were installed on a conventional tractor-trailer combination and on a motor coach, and they included the following types of systems:

- Tire equalizers to balance pressures between tires in a dual installation.
- Tire pressure monitors to keep track of the pressure in each tire.
- Tire pressure maintenance systems to maintain tire pressure at desired levels.

The tire pressure monitoring and maintenance systems were evaluated under a variety of staged test conditions such as slow leaks, fast leaks, single tire incidents and multi-tire incidents. These tests were completed to determine threshold warning levels, failure modes, and general system operation. Only tire pressure *monitoring* systems, not tire pressure *maintenance* systems, were viewed as viable candidates for the fleet field test—primarily because pressure maintenance systems would need to tap into the secondary air supply, which WMATA was not interested in doing because the buses were new and under warranty.

Based on the results from testing under Task Order #8, and on consultation with WMATA bus operations and maintenance staff, it was determined to evaluate the following types of tire pressure monitoring systems as part of the field study:

- A valve-stem-mounted system.
- A wheel-mounted system.
- A tire-mounted TPMS.

Specifically, the three systems selected for the field test were manufactured by WABCO, HCI, and Michelin and are described as follows:

WABCO IVTM System. WABCO's IVTM system, developed in conjunction with Michelin, was launched in the CMV industry in 2003. Each tire and wheel assembly is equipped with a sensor that attaches to the valve stem and is secured to the rim by two lug nuts. A pneumatic hose runs between the sensor and valve stem.(9)

HCI Tire-SafeGuard. HCI Corporation manufactures the Tire-SafeGuard TPMS. The system consists of pressure and temperature sensors, a transmitter, and a driver's display. The measurement sensor is strapped to the wheel inside the tire.(10)

Michelin eTire. Michelin North America introduced its eTire system for commercial vehicles in October 2002. The sensor includes a radio frequency (RF) transmitter, pressure and temperature sensors, and an antenna, which are encased in impact- and heat-resistant plastic. The sensor mounts to the inside sidewall of the tire via a molded rubber dock that chemically cures to the tire's sidewall. It should be noted that the system is designed to be used with a tire pressure gate reader. For the purpose of this test, a Michelin-supplied handheld tire pressure reader was used.(11)

2.4 FLEET TEST PLAN

Based on the project's overall objectives, and on available resources, 12 buses were selected for testing the candidate systems during a 1-year period. Because there were three unique brake performance systems, and three unique tire pressure monitoring systems to be evaluated, the test buses were divided into three groups of four buses each, with each group receiving a different combination of a particular tire pressure monitoring and brake performance monitoring system. Twelve identical buses operating from the same facility were used as a control group. Table 2 provides information on sensor system pairings and bus identification (ID) numbers. It should be noted that the test buses came pre-equipped from the factory with MGM's eStroke system.

Table 2. Bus ID and Sensor System Pairing

Bus Numbers	BPMS	TPMS
2501–2504 (4 buses)	MGM eStroke	WABCO IVTM
2505–2508 (4 buses)	GeoDevelopment Brake Insight	HCI Tire-SafeGuard
2509–2512 (4 buses)	StrainSert Brake Performance Monitoring	Michelin eTire
2513–2524 (12 buses)	Control Group	Control Group

During the 1-year test period, WMATA operated the test buses as part of its normal scheduled fleet. WMATA also recorded maintenance data such as fuel usage, accumulated mileage, and preventive maintenance inspection results. The data collection methods and data sources are discussed further in Section 3.

2.5 SCHEDULE

Program planning started in fall 2005. During this time, the study team secured the participation of the host fleet and the vendors of the sensor systems. In April 2006, the installations of the candidate systems began. The study team worked closely with WMATA maintenance technicians and system vendors to ensure that each system was installed properly and that it would not interfere with other systems on the bus. The installations were staggered throughout the summer of 2006 because of scheduling challenges with vendor representatives and component availability.

The field test data collection effort covered the period from November 2006 through November 2007. During this time, the vehicles were inspected weekly. In addition, a Performance Based Brake Tester (PBBT), supplied by Link Radlinski,(12) was used to test each bus once a month to verify braking system performance and operation. At the conclusion of the test phase, all testing hardware was removed from the vehicles.

3. DATA COLLECTION

3.1 DATA SOURCES

Six sources of data were used to perform an assessment of the reliability, durability, and maintainability of the BPMSs and TPMSs under evaluation:

- Weekly inspections.
- Maintenance records.
- BPMS and TPMS data.
- PBBT data.
- Maintenance staff interviews.
- Study team observations.

3.1.1 Weekly Inspections

Buses were withheld from service once per week to inspect the sensor systems, brakes, and tires. WMATA technicians performed the inspections with the assistance of the study team. The study team developed data collection forms to assist with the inspections and capture the findings. While weekly inspection of the test buses was completed very consistently, bus availability and technician time constraints limited the amount of inspections performed on the control buses.

The following information was recorded weekly from the test buses, (the weekly brake and tire data collection forms are provided in Appendix A):

- Bus mileage.
- Tire temperature at the time of inspection (hot or cold).
- Ambient temperature.
- Weather conditions.
- Tire pressures as they appear on display.
- Tire pressures measured with gauge.
- Tire condition (damaged, scuffed, and so forth).
- Brake monitoring display status.
- Mounting/physical condition of sensors.

Buses were driven to an area that WMATA had designated for study activities and inspected individually. Figure 1 shows several test buses undergoing weekly program inspections.

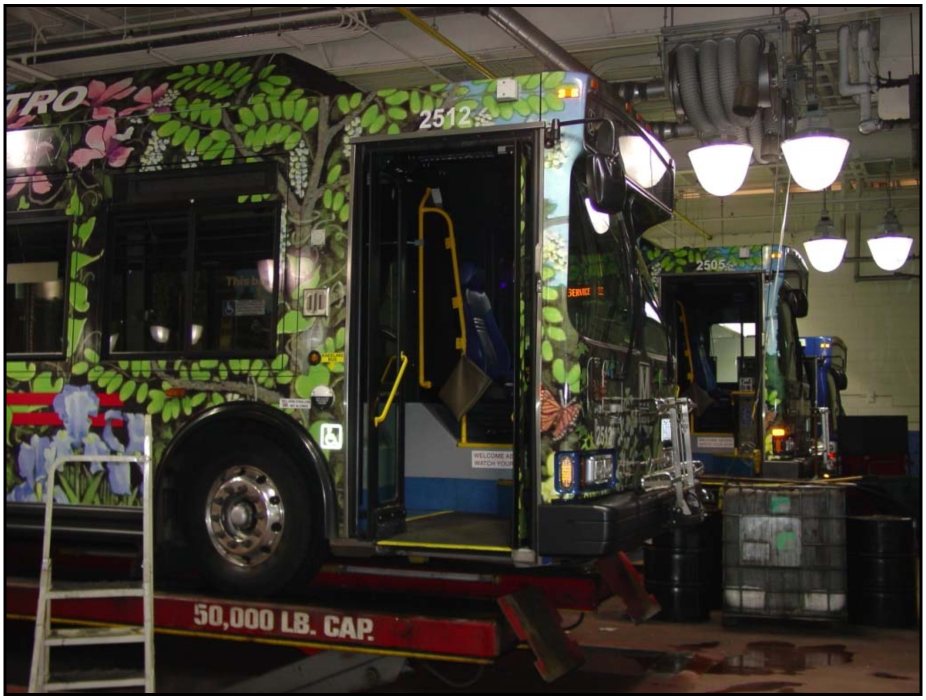


Figure 1. Buses on Lifts During an Inspection

The technician first recorded the bus's ID number and mileage. The technician would then use the display/control units of each system, to record the tire pressures as well as any alarms, warnings, or faults generated by either the TPMS or the brake monitoring system. Once the system displays were checked and system status recorded, the bus was elevated approximately three feet to conduct the manual tire pressure measurements and the brake system inspections. Tire pressure in each of the bus's tires with a checked using a manual tire pressure gauge, and readings were recorded on the tire data collection form (see Appendix A). While measuring tire pressures, the technician also visually inspected the tire for damage or unusual wear.

It should be noted that all but two of the brake and tire monitoring system display units were mounted in the input/output (I/O) cabinet just behind the driver's seat, per WMATA's request The MGM e-Stroke display was also mounted directly behind the driver's seat but outside the I/O cabinet (eTire's system did not have an on-board display). This was done to purposely limit the availability of vehicle diagnostic information to the operator, thereby preventing the potential for drivers to misinterpret the information and issue unwarranted road-calls. The eTire system used a handheld radio frequency identification (RFID) reader to obtain the pressure readings from the sensor tags located in each tire.

Next, the bus lift was raised higher so that a technician could walk under the bus to inspect the brake lining thickness at each brake assembly, and also measure the pushrod stroke at the brake chambers. To measure the brake stroke, one technician sat on the driver's seat inside the bus while a second technician held a tape measure up to the brake chamber near the pushrod. The technician inside the bus stepped on the brake pedal, and the technician outside the bus measured the brake stroke travel (in inches) and recorded the information on the data collection form (see Appendix A).

In addition to the inspection data above, the technician also recorded whether the system accurately detected a low-pressure warning or a malfunctioning brake, and whether the system reported a legitimate fault or a false alarm.

The study team collected the completed forms from the supervisor on a weekly basis and entered the data into a database created specifically for the study.

3.1.2 Maintenance Records

WMATA, like most large fleets, maintains a database to track and monitor vehicle maintenance. WMATA uses the MAXIMO(13) database to track vehicle mileage, fuel consumption, and all maintenance activities such as brake and tire replacements.

The MAXIMO database was used to gather a variety of information related to the test and control buses including: fuel usage, mileage accumulation, failures with the BPMS and TPMS, and maintenance actions related to brakes and tires (see Sections 4.2 and 5.3 for more details and data analyses results).

3.1.3 Brake Performance and Tire Pressure Monitoring System Data

All of the brake performance monitoring systems involved in the field test incorporated the capability to record various diagnostic and sensor data within the ECUs of each system. The tire pressure monitoring systems on the other hand did not include data recording capability. The WABCO IVTM system featured a J1939 connection, however the system was not integrated with the automatic vehicle monitoring (AVM) system on the bus because of program funding and time constraints. Tire Safeguard did not offer a downloading feature, and the eTire system did not have an onboard vehicle storage or display.

The Brake Insight brake monitoring system was capable of storing brake alarms, warnings, and faults. These alarms were recorded along with a date and time stamp and a description of the problem. The system reported on problems with the brakes or with the system itself. For example, brake problem descriptions included brake overstroke, dragging brake, brake out of adjustment, high brake temperature, and worn shoe lining. An example of a system problem includes sensor out of alignment, communication failure, failed sensor, low voltage reading, and missing sensor. The system was capable of storing 2,700 lines of data. The data could be exported via a RS-232 connection located on the faceplate of the display unit.

MGM’s eStroke brake monitoring system was also capable of recording data. The type of data recorded was similar to the information recorded by the Brake Insight system minus the high temperature and worn shoe lining information. The eStroke system was integrated into the AVM system on the bus and capable of wirelessly off loading data to a central server located at the bus garage. The server would automatically send emails to the maintenance personnel and study team on the status of the bus’s brakes. The work required to integrate the eStroke system with the AVM was completed by MGM and the AVM system manufacturer, Clever Devices, as part of the bus procurement contract between WMATA and Orion.

The StrainSert system also recorded brake alarms, warnings, and faults, however, it did not provide a fault description. The system identified the faulty brake and provided anchor pin force versus time data to assist maintenance personnel with determining the fault. The system was capable of storing 100 heavy braking events. StrainSert defined heavy brake events as those exceeding 1,800 pounds of force on the S-cam anchor pin. The events are downloadable via an Ethernet cable.

3.1.4 Performance Based Brake Testing (PBBT) Data

The Link Radlinski Model 20200 Portable Roller Brake Tester, also known as a PBBT, was incorporated into the program to help evaluate the performance of the BPMS and to assess the benefit of off-board brake systems relative to onboard systems. PBBTs are well regarded in the industry for their ability to detecting brake deficiencies and are used in manufacturing plant, fleet maintenance garages, and vehicle inspection facilities. A detailed description of the PBBT used for this study can be found in Section 5.1.4.

Buses were tested on the PBBT roughly once per month. The baseline brake testing of the 24 buses, performed in October 2006, took several days and was spread over a 3-week period. WMATA and the study team became more efficient in coordinating the logistics involved in testing the program buses over time, ultimately being able to test 24 buses in a single day.

The results obtained from PBBT testing were analyzed and compared with the data collected by the sensors from each bus. This data was used for evaluating the durability and accuracy of the systems. It was also used for assessing whether the current maintenance intervals are appropriate or if new maintenance practices could reduce operating costs (See Section 5.2).

3.1.5 Maintenance Staff Interviews

The maintenance technicians and supervisors were interviewed informally throughout the test period and formally at test completion. The intent of the interviews was to gather information about their experiences with maintaining the systems, the ease of the data presentation, and the usefulness of the information (See Sections 4.2.7 and, 5.2.6 for more details and data analyses results).

3.1.6 Study Team Observations

The study team worked closely with WMATA maintenance technicians to accurately document and diagnose malfunctions and failures related to the BPMSs and TPMSs under evaluation. The study team recorded in a journal the issues related to the test systems throughout the fleet test. The journal was a valuable resource for analyzing the durability, reliability, and maintainability of the brake and tire sensor systems. This analysis is discussed further in Section 4.2 and 5.3.

3.2 META DATA

This section provides general information on the data collected during the field test, including where the buses were operated, total miles traveled, and total maintenance actions performed. Specifically, the section provides information on the following:

- Vehicle operation, including vehicle miles traveled.
- Total data forms collected.
- Total maintenance actions recorded.
- Total equipment failures.

The test buses operated in an area covering approximately 300 square miles south and west of Washington, DC (see Figure 2). The majority of miles were accumulated in an urban environment with minimal highway driving. The buses averaged 16 miles per hour in revenue service and approximately 129 miles per day. The test fleet accumulated 762,580 miles during the course of the field test.

Figure 2. Operating Area from Four-Mile Run Maintenance Garage

Data was collected approximately once a week during the data collection phase of the program, resulting in a total of 1,210 tire and brake data forms—619 for tire data and 591 for brake data. In addition to the information collected on the weekly forms, the control and test vehicles were tested on the PBBT about once per month, for a total of 200 PBBT records.

Maintenance records were gathered for all brake and tire maintenance inspections from November 2006 to November 2007. A total of 248 maintenance records were identified during this period. Of the maintenance actions identified, 124 were tire-related items. Of the tire-related incidents, 24 records were generated for changing tires based on accumulated mileage, and 12 records were generated for replacing tires that had been penetrated by a foreign object. The remaining actions, 124 items, were brake related. As part of the brake actions, 25 brake overhauls were completed.

During the test, 10 road calls required support equipment to respond. Nine of the road calls were tire related; two of those were because of extensive tire damage and are discussed in more detail in Section 4. The tenth road call was in response to accident damage. A refuse truck hit bus number 2504 at the front-right corner. The accident was unrelated to the field test equipment under evaluation and was instead the result of refuse truck driver error.

Sections 4 and 5 provide detailed results on the TPMSs and BPMSs evaluated under this field test.

4. TIRE PRESSURE MONITORING SYSTEM FIELD TEST RESULTS

4.1 TPMS TEST ARTICLE DESCRIPTIONS AND INSTALLATION

Installation of the three TPMSs equipment began in April 2006. All installations were performed at WMATA's Four-Mile Run bus maintenance facility in Arlington, VA. The study team worked closely with WMATA maintenance technicians and system vendors to ensure that each system was installed properly on the buses and that it would not interfere with other systems on the bus. The installations were staggered throughout summer 2006 because of scheduling challenges with vendor representatives and component availability. The IVTM equipment was the first system installed. The eTire installation occurred in June 2006, and the Tire-SafeGuard installation occurred in August 2006. The display units for the IVTM and Tire-SafeGuard systems were installed inside the I/O cabinet located behind the driver's seat and out of view of the driver (The eTire system was not designed to interact with the driver, and does not include an onboard display unit).

4.1.1 WABCO IVTM

4.1.1.1 General Description

WABCO's IVTM system,(9) developed in conjunction with Michelin, was launched in the CMV industry in 2003. The IVTM system consists of the following three main components, which are shown in Figure 3:

- Tire pressure sensor wheel module (left).
- Display unit (center).
- ECU (right).

Figure 3. WABCO IVTM Components

Each tire and wheel assembly is equipped with a sensor unit which contains a pressure transducer and a transmitter. Power for the sensor unit is supplied from a built-in lithium battery with a 5-year service life. The sensor unit is secured to the wheel rim at a location adjacent to the valve stem using the two closest lug nuts. A pneumatic hose runs between the sensor and valve stem (Figure 4).

Figure 4. WABCO IVTM Sensor Unit Mounting

The valve-stem mounted sensors continually check tire pressure and transmit a pressure reading to an ECU (i.e., a receiver/processor) via an RF signal every 15 minutes. The ECU is generally mounted on the tractor (or vehicle) chassis halfway between the front and rear axles. It contains a built-in antenna to receive the pressure data from the tire pressure sensor units. If the sensor detects a loss of pressure (below a pre-determined level), the system increases the transmission frequency to once every 30 seconds. The radio frequency signal is 433 MHz. The ECU is hardwired into the vehicle's 24V power supply circuit.

The centralized location of the ECU among the tires being monitored (roughly equidistant between the 4 wheel locations on the tractor) eliminates the need for additional antennas housed within the sensors. If the vehicle is equipped with a trailer, a second (separate) ECU is located at a centralized point between the tires on the trailer chassis and is used to collect inflation pressure data from the trailer tires. This data is then re-transmitted to the "main" ECU on the tractor.

The main (tractor-based) ECU is hardwired to a display unit which is designed to sit on the dashboard, (although it could be located elsewhere—and in fact was located out of view of the bus driver as noted earlier).

The dashboard-mounted display unit warns the driver visually and acoustically of low tire pressures. A yellow lamp indicates a slow rate of pressure loss or slight decrease in pressure; a red lamp indicates extremely low pressure. The yellow and red lights are located at the lower edge of the display. Using an on-screen menu, the position of any instrumented tire can be selected by the driver and its inflation pressure can be queried. If all tires are within an appropriate inflation pressure range, the display is blank. If any of the tires have low pressure, the display screen shows the location of the tire and its pressure. Figure 5 shows (for example) a low pressure reading of 5.9 bar (85 psi) on the right-rear tag axle tire.

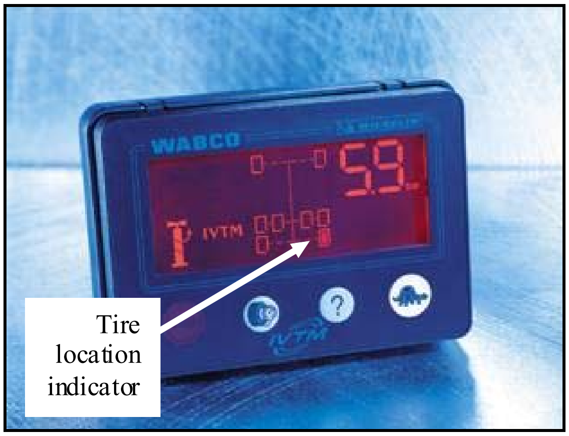


Figure 5. WABCO IVTM System

4.1.1.2 *Installation*

The WABCO IVTM TPMS was installed on bus numbers 2501, 2502, 2503, and 2504. WABCO provided a service engineer to lead the installation.

The buses used in this field test had six tires—single tires on the steer axle and dual tires on the drive axle—thus requiring a total of six sensor units to be installed.

To install the sensor unit, the pneumatic hose should first be connected to the sensor module and then connected to the tire’s valve stem. With the hose already connected to the valve stem, the sensor unit can be slipped over the wheel lugs and secured in place with the cap nuts. Attaching the sensor unit to the valve stem with the short hose before securing it to the wheel proved to be the quickest way to mount the wheel module to the steer tires. Figure 6 illustrates the wheel module installation process on a steer tire.

Figure 6. Wheel Module Installation on a Steer Tire

On the rear wheels, the procedure varies slightly from that used on the front wheels. Connecting the hose to the inner tire posed some challenges on the rear wheels; on transit buses, these tires are set back inside a wheel well, which limits access to the inner dual tire. Also, the gap between the dual tires is insufficient to place a hand between them to connect the hose to the inner tire’s valve stem. (Note: WMATA did not use valve-stem extensions on its buses' inner dual tires, which would have simplified the wheel module installation on the rear axle.)

To create access to the inner tire's valve stem, WABCO recommends loosening all 10 cap nuts on the outer rear wheel and removing only the two cap nuts nearest the valve stem on each tire. Loosening all of the cap nuts allowed the outer wheel to separate from the inner wheel. This creates a gap wide enough to reach a hand in-between the inner and outer rear tires without having to remove a wheel from the bus. Figure 7 shows the tight gap between dual tires and the cap nuts being loosened and removed from the rear wheel lugs.

Figure 7. Wheel Gap and Cap Nut Removal on a Rear Wheel

Notice in Figure 7 that the engineer removed the cap nuts from the 3 o'clock and the 9 o'clock positions on the rear wheel. The valve stems on this dual tire assembly are positioned 180 degrees out of phase with each other. It is necessary to mount the wheel modules 180 degrees out of phase to avoid affecting the balance of the tires.

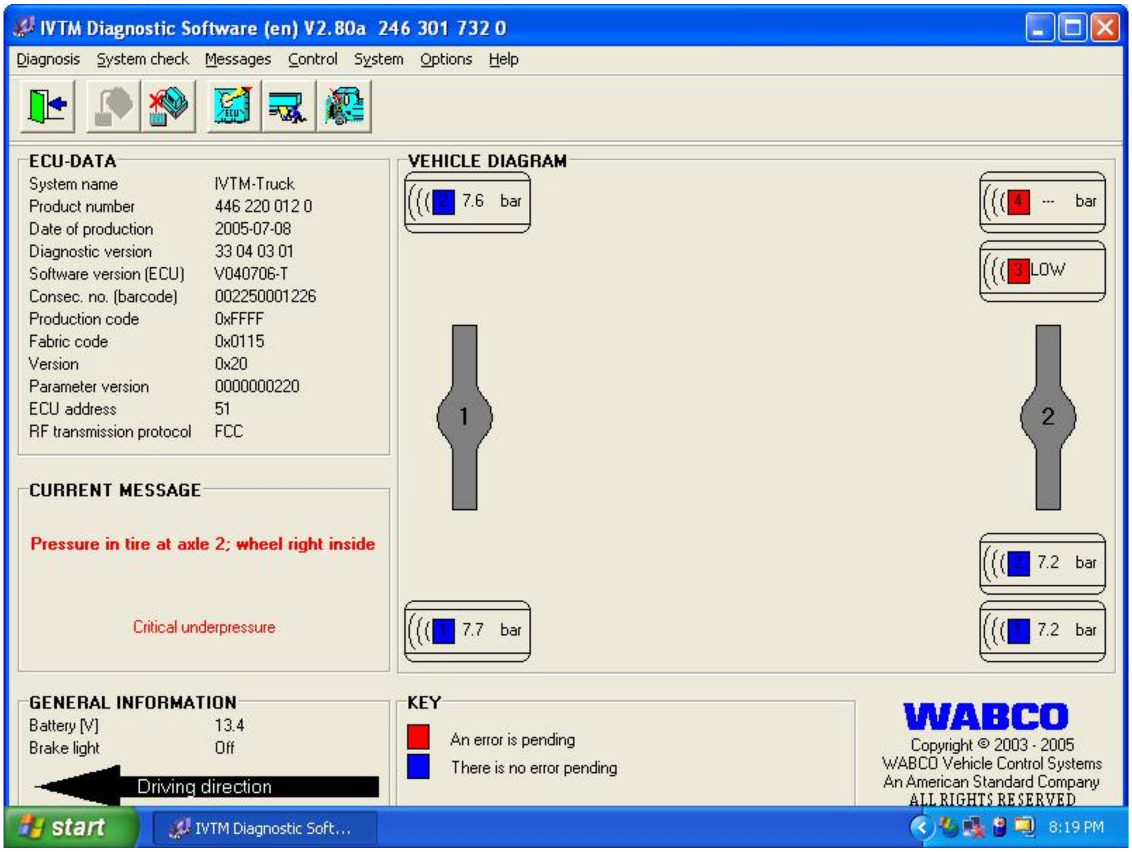
The IVTM ECU and display were both installed inside the bus's passenger compartment and hidden from view of the driver and passengers. Figure 8 illustrates the mounting locations for the ECU and the display unit. The ECU was mounted to a support beam above the lighting track on the street side of the bus. The ECU mounting location is hidden behind an access panel. It was important to install the system's ECU in a location near the center of the bus to enable the best possible signal reception broadcast from the sensor modules at the wheel ends. The ECU was electrically protected by a 5-ampere circuit breaker and hardwired to a terminal strip in the I/O cabinet located behind the driver's seat.

Figure 8. WABCO ECU and Display Unit Locations

After all of the IVTM hardware components were installed, the system was programmed in accordance with the manufacturer's instructions. The IVTM ECU was equipped with a diagnostic data port that could be accessed with a laptop, so that an engineer could communicate with the ECU via WABCO's IVTM diagnostic software. Figure 9 depicts the main diagnostic screen.

The diagnostic screen shows tire pressure readings and system messages. Each wheel module was hard-coded with a unique ID number which represented a specific wheel positions on the bus. The screen is currently indicating low tire pressure readings for the curbside rear dual tires, (red colored icons).

The WABCO IVTM installation required 2-1/2 days to equip all four buses with the system. (Note: The WABCO IVTM system typically can be installed on a six-wheeled vehicle in 1.5 hours by a trained professional.) The WABCO field engineer, a study team engineer, and a WMATA maintenance technician performed the installations.



ECU-DATA

System name	IVTM-Truck
Product number	446 220 012 0
Date of production	2005-07-08
Diagnostic version	33 04 03 01
Software version (ECU)	V040706-T
Consec. no. (barcode)	002250001226
Production code	0xFFFF
Fabric code	0x0115
Version	0x20
Parameter version	0000000220
ECU address	51
RF transmission protocol	FCC

CURRENT MESSAGE

Pressure in tire at axle 2; wheel right inside

Critical underpressure

GENERAL INFORMATION

Battery [V]	13.4
Brake light	Off

Driving direction

KEY

🟥 An error is pending

🟦 There is no error pending

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An American Standard Company
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Figure 9. IVTM Diagnostic Software Screenshot

4.1.2 HCI Tire-SafeGuard

4.1.2.1 General Description

HCI Corporation(10) manufactures the Tire-SafeGuard TPMS which consists of the following components:

- Wheel module (the tire condition sensing unit that is affixed to the wheel hub.)
- Relay antennas (which relay RF signals from the wheel modules to the ECU).
- ECU (which processes data transmitted from the wheel modules).
- Driver display unit (which displays tire condition information to the driver).

Figure 10 shows two wheel modules (top left), a wheel module secured to a wheel by a hose clamp (top right), the ECU and display unit (bottom left), and one of three antennas (bottom right).

Figure 10. HCI Tire-SafeGuard Components

The wheel module includes an integrated pressure-temperature transducer, an RF transmitter, and internal battery (with an estimated life of more than 5 years) to supply power for the unit. The wheel module (or sensor unit) is strapped to the hub of the wheel inside the tire. The sensor's transmitter automatically switches on when the vehicle is moving faster than 15 miles per hour. It transmits RF signals (which include pressure, temperature, and wheel position data) to a nearby antenna unit, which is hardwired (using coaxial cable) to the system's ECU/receiver unit. The data is processed by the ECU and the tire condition information (and/or warnings as appropriate) are then sent to the driver's display unit.

The system monitors tire pressure continuously even when the vehicle is parked. The system alerts drivers of low-pressure situations by providing the location, temperature, and pressure readings via display icons and an audible signal. Figure 11 shows the wheel-mounted sensor (right) and driver's display (left). The display pictured is showing a right-front tire pressure of 112 psi and temperature of 89 degrees Fahrenheit (F). The pressure warning threshold is adjustable by the user and can be set from 18 to 130 psi. The display can be connected to any 12 volts DC (VDC) power source on the vehicle. It is 3-1/2 inches by 1-1/8 inches by 5/8 inches in size and weighs 1.5 ounces. The system has been on the market since 1991.

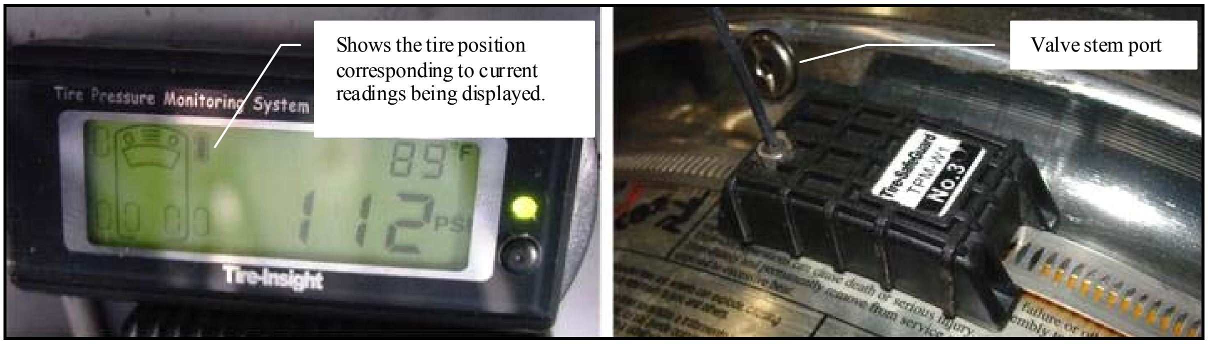


Figure 11. HCI Tire-SafeGuard TPMS

4.1.2.2 Installation

The Tire-SafeGuard TPMS was installed on bus numbers 2505, 2506, 2507, and 2508.

A study team engineer and a WMATA maintenance technician installed the Tire-SafeGuard system by following the instruction manual provided with each system. A wheel module sensor was installed on every wheel of the bus. With the tire removed from the wheel, the sensor is strapped to the wheel at the lowest point of the drop center well using a hose clamp. Once the sensor is securely strapped to the wheel, the tire is remounted to the wheel and inflated. The top right photo in shows a tire pressure sensor strapped to a wheel. Notice that the wheel sensor is mounted next to the wheel's valve stem port. The choice of the mounting location near the valve stem port helps prevent damage to the sensor unit when changing the tire. During previous test track work at TRC, it was discovered that the paddle arm on tire-changing machines frequently contacted and damaged sensors. With the wheel sensor mounted near the valve-stem port on each wheel, the tire changer knows the approximate location of the sensor inside of the tire and can avoid contacting it with the paddle arm.

The Tire-SafeGuard system requires three antennas—one at the front of the bus (to pick up RF signals from the steer tires) and one near each of the left and right rear dual tire assemblies. Figure 12 shows the two styles of antennas that were installed. These antennas are connected to the ECU via coaxial cable.

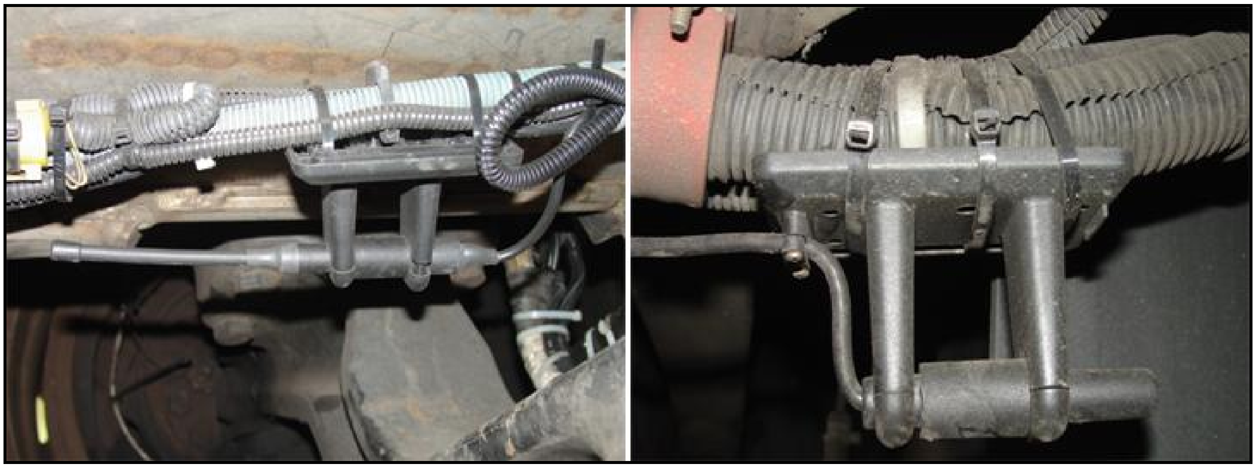


Figure 12. HCI Tire-SafeGuard Antennas

Once all of the hardware was installed on the bus, the system was programmed and calibrated using the display unit. The display unit has two buttons that can be pressed and held to activate the system's setup modes. The engineer performing the installation first entered the "warning threshold setup" and set the warning threshold tire pressure at 103 psi (~10 percent below the 115 psi set tire pressure). The engineer then entered the manual setup screen of the "tire setup select mode." The tire setup select mode allowed the engineer to "train" the tire pressure sensors to specific wheel locations. While in manual mode, the engineer trained one sensor at a time to a specific wheel position, beginning with the right steer tire. The engineer released 3 pounds of pressure from the right steer tire until the display screen indicated that the system recognized the sensor located in the right steer tire. The engineer then repeated this process on the remaining tires in the following order, as specified by the operator's manual—right rear outer tire, right rear inner tire, left rear inner tire, left rear outer tire, and left steer tire.

The Tire-SafeGuard installation required 2-1/2 days to equip four buses with the system. A study team engineer and a WMATA maintenance technician performed the installation.

4.1.3 Michelin eTire

4.1.3.1 General Description

Michelin North America(11) introduced its eTire system for commercial vehicles in October 2002. The eTire system consists of the following components:

- Tire condition sensor unit (an integrated transducer unit with multiple sensors, unique ID code, and RF transmitter).
- Tire sensor unit docking fixture (SensorDock).
- eTire location label.
- Vehicle ID tag (similar in design to the tire condition sensor unit, but does not incorporate any sensors).
- Portable handheld tag reader (a fixed position gate reader system can also be used).
- BIBTRACK (an internet based software application, hosted by Michelin, for assisting fleets with tire maintenance and tracking needs).

eTire Sensor Unit. The "heart" of the system is the eTire sensor. This sensor unit contains pressure and temperature sensors (pressure readings are temperature compensated), an RF transmitter, and an antenna—all encased in impact- and heat-resistant plastic. The unit measures 4 inches by 1.5 inches and weighs less than an ounce (see Figure 13).

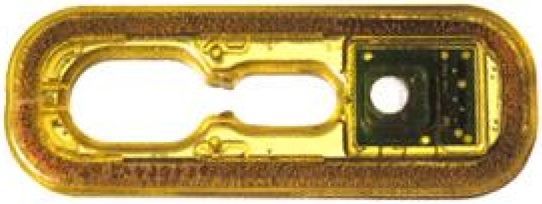


Figure 13. eTire Sensor Unit

The eTire sensor unit inside the tire is differentiated from the HCI or WABCO units in that it does not require a battery to supply power for transmitting the tire condition data. Rather, the sensor unit receives just enough power via RF signals from the reader so that it can reflect a signal back to the reader containing tire condition data. Specifically, the eTire sensor reports the current tire temperature, pressure, and a factory programmed sensor ID which can be correlated to a particular tire position.

SensorDock. The sensor unit attaches to the truck tire inner sidewall using a docking type station called the SensorDock, (Figure 14, left). The SensorDock, which itself is molded rubber, attached to the inside sidewall through a chemical curing process similar to the process used to repair tires. The eTire kit includes a variety of tools and adhesives to attach the SensorDock to the tire, (Figure 14, right).

Figure 14. eTire SensorDock and Installation Kit

To install the sensor, the unit is slipped over a knob on the rubber dock and locked into place. Once installed, the sensors remain attached to the tire throughout the entire life of the tire including retread processes. At the end of the tire's useful life, the sensor can be removed and reattached to a new truck tire with a new SensorDock.

eTire Location Label. The eTire sensors are read (or queried) using external transceivers (see next section). The handheld reader requires the operator to wave the device over the exact location of the sensor. Michelin has made finding the location of the sensor easier by providing an eTire label that is installed on the outside of the tire at the location of the eTire sensor, (see Figure 15)

Figure 15. eTire Location Label

Vehicle ID Tag. The eTire system also includes a RFID vehicle ID tag which is similar in design to a tire sensor unit expect that it does not contain any sensors. The vehicle ID tag is coded with a unique identifier that is assigned to a particular vehicle. It can be mounted in a variety of locations, but on the test buses, was mounted inside an access panel on the front of the bus.

Tag Readers. Two options are available to read the sensors—a handheld reader, or a gate reader. The handheld sensor tag reader uses RFID technology to read and record the tire pressure in each tire (see Figure 16).

Figure 16. eTire Handheld Tag Reader

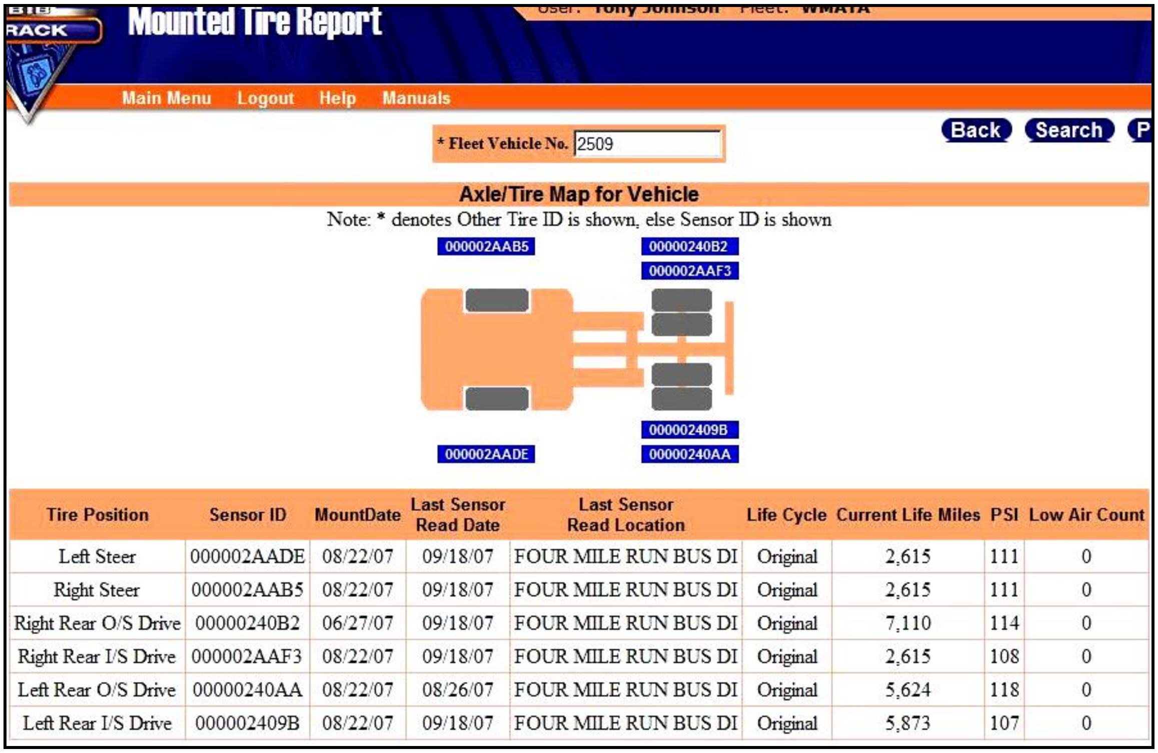
In order to read and store tire pressures using the handheld reader, the handheld reader first must be "waved" passed the vehicle ID tag located at the front of the bus. The vehicle ID tag enables the eTire system to associate individual tires to a particular vehicle. Once the handheld reader has identified the vehicle, the reader is then used to detect tire pressures and is waved passed the eTire location labels on each tire. The reader must be waved as close to the surface of the tire as possible until a sensor is detected and its associated tire pressure is displayed on the screen. A technician could use the handheld reader to record tire condition data from multiple vehicles. The tire condition data (sensor ID, pressure) and associated vehicle ID is then downloaded from the handheld reader to a laptop computer via a printer cable connected to a docking station. Michelin supplied the necessary software with the eTire system to install and run the BIBTRACK™ application, a software program which allows tire condition data to be transferred from the handheld reader to the BIBTRACK online database.

The eTire sensor units affixed to each tire can also be read using a gate reader in a more time efficient manner—and indeed this method is preferred if a location and other operational logistics support such an arrangement. A gate reader, as installed at a refuse facility near Indianapolis, IN, is shown in Figure 17.

Figure 17. eTire Gate Reader

The gate reader requires the vehicle to be traveling less than 5 miles per hour to receive the information from all of the tires, including the inside duals. The gate reader is equipped with wired and wireless options for connecting to the internet. If the gate reader is used, it can be connected directly to the BIBTRACK application and data is automatically transferred from the gate reader to the BIBTRACK system.

BIBTRACK Software Application. The eTire system is not designed to provide tire condition data directly to drivers, and in fact does not include a driver's display option. Rather, the system is designed to collect tire condition data in a comprehensive fashion from vehicles in a fleet, and then make the data available for viewing and analysis on a Michelin hosted website application. BIBTRACK is the Michelin website that tracks tires and provides recommended actions for problem tires. The website stores up-to-date information on a fleet's tires, tracks tire costs, and monitors inventories. The screenshot in Figure 18 shows the "Mounted Tire Report" for bus number 2509 from the BIBTRACK system. This report provides the user with a snapshot of tire data, which includes sensor/tire position, the date the tire was mounted, the date of the last tire pressure scan, tire mileage, tire pressures, and the number of low-pressure readings.



* Fleet Vehicle No. 2509

Axle/Tire Map for Vehicle

Note: * denotes Other Tire ID is shown, else Sensor ID is shown

Tire Position	Sensor ID	MountDate	Last Sensor Read Date	Last Sensor Read Location	Life Cycle	Current Life Miles	PSI	Low Air Count
Left Steer	000002AADE	08/22/07	09/18/07	FOUR MILE RUN BUS DI	Original	2,615	111	0
Right Steer	000002AAB5	08/22/07	09/18/07	FOUR MILE RUN BUS DI	Original	2,615	111	0
Right Rear O/S Drive	00000240B2	06/27/07	09/18/07	FOUR MILE RUN BUS DI	Original	7,110	114	0
Right Rear I/S Drive	000002AAF3	08/22/07	09/18/07	FOUR MILE RUN BUS DI	Original	2,615	108	0
Left Rear O/S Drive	00000240AA	08/22/07	08/26/07	FOUR MILE RUN BUS DI	Original	5,624	118	0
Left Rear I/S Drive	000002409B	08/22/07	09/18/07	FOUR MILE RUN BUS DI	Original	5,873	107	0

Figure 18. BIBTRACK Screenshot

Access to BIBTRACK is included with the purchase of the eTire system. A fleet manager must create a username and password to access his fleet's tire data in BIBTRACK—this only takes a few minutes to set up. Once logged in, the fleet manager can access tire reports and modify his fleet's profile (number of vehicles, tire type, and tire inventory). In addition to BIBTRACK's secure website, the handheld and gate readers have ID numbers that are assigned to a particular facility which ensures that fleet managers can only view data from tire sensors scanned at their own facilities.

4.1.3.2 Installation

The Michelin eTire system was installed on WMATA bus numbers 2509, 2510, 2511, and 2512. Michelin provided a sales engineer and a service engineer to lead the installation.

The eTire installation at WMATA's Four-Mile Run bus maintenance facility began with training the study team and technicians on installing a sensor dock to the inside sidewall of a tire. The procedure includes scraping the inside wall of the tire to remove the ridges left behind by the tire mold process, buffing the inside wall smooth using a grinder, adhering the sensor dock to the tire wall using vulcanized paste, and installing the sensor onto the sensor dock using a soapy-water mix to reduce friction between the two surfaces. The Michelin engineer demonstrated the installation procedure on one tire and then observed the tire technician and the study team engineer as they took turns installing the sensor dock on other tires. Figure 19 shows the tire technician smoothing a small area of the inside sidewall of the tire (left), applying vulcanizing paste to the sensor dock (middle), and installing the eTire sensor over the sensor dock (right). The sensors were installed near the valve stem to make them easier to locate with the handheld reader.

Figure 19. Michelin eTire Sensor Dock Installation Process

After the initial sensor dock installation training, the WMATA tire technician installed sensor docks and sensors in new tires that would eventually be mounted on the test buses. The sensors were installed in 24 new tires in a little more than 8 hours. The sensor-equipped tires were marked with chalk to identify them, and they were set aside in the garage’s tire bay until they could be mounted onto the test buses.

Following the eTire sensor installation training, the Michelin engineers trained the study team engineer to use the handheld reader and BIBTRACK software.

After all of the eTire-equipped tires were installed on the test buses, the study team engineer used the handheld reader to scan each tire into inventory and to assign the tire to a specific wheel position on the bus. This data was then uploaded to BIBTRACK.

Because the study focused on a small number of buses, and because of physical space limitations at WMATA, the installation of a drive-by gate reader was not practical. To this extent, the eTire system was not used to its full potential. According to Michelin, much of the cost savings potential of the eTire system is gained by eliminating the driver or maintenance technician labor hours needed to physically check tire pressures.

4.1.4 Control Vehicles

To facilitate the evaluation of the TPMSs, data related to tire condition, maintenance and cost was also monitored for a group of buses that did not utilize any type of tire monitoring system (i.e., standard buses). These buses were the same make and model as the test buses and included bus numbers: 2513–2524. The buses were operated out of the Four Mile Run facility, and used in a similar service environment as the test fleet.

4.2 TEST RESULTS

Data was collected from the test fleet and control vehicles over a 14-month period, from September 2006 to November 2007. During the first months, the vehicles and their newly installed equipment were validated and confirmed to be working properly (this period essentially represented a “shakedown” period for the equipment as well as for data collection procedures). Full data collection began in November 2006. Data was collected approximately once a week during the test period. Throughout the course of the test, a total of 619 tire data forms were collected. Data collected for both the test and control buses included tire-related maintenance records and manually measured tire pressures. The data collected from the test buses also included TPMS measurements of inflation pressures, system display messages, system data downloads, and visual tire inspections.

A total of 124 tire-related maintenance records were generated from the 24 test and control buses during the field test. To gain additional insight regarding "normal" tire related maintenance and cost, a total of 185 tire maintenance records were gathered and analyzed for the 24 test and control buses from March 2006 through January 2008 and provide a comparison of pre-test, test, and post test tire-related maintenance records. Sixty of the 124 records were generated for tires changed due to normal tire wear because of accumulated mileage, and 22 records were generated for tires changed due to penetration by a foreign object. A total of 257 TPMS sensor issues, which were not tire issues, were recorded during the test period. The issues were categorized as: missing sensor, no sensor output, disconnected sensor, equipment failure, and incorrect installation. Many of the TPMS sensor issues were addressed and resolved by the TPMS manufacturers and are discussed in Sections 4.2.3 and 4.2.4.

Detailed test results are presented in this section and are organized as follows:

- Performance.
- Reliability.
- Maintainability.
- Durability.
- Functionality.
- Maintenance analysis.
- Technician interviews.

4.2.1 System Accuracy

The accuracy of TPMSs is defined as the ability of the system to provide a true assessment of the tire pressure as compared to a manually gauged assessment.

To evaluate the performance (or accuracy) of the TPMSs, manual tire pressure measurement readings were taken once a week on each bus and then compared with pressures as reported by the TPMSs at the time of the manual measurement. Each bus was inspected approximately 56 times throughout the course of the test, resulting in a total of 3,714 tires inspected. Occasionally, certain buses were unavailable for a weekly inspection because a test bus was mistakenly put into service or a bus was removed from service and awaiting maintenance. Not all of the inspections yielded valid comparisons because of problems with the TPMSs themselves, or in a few instances, because of problems associated with manually checking the tires.

Of the total inspections completed, 77 percent provided valid numeric tire pressure readings for both the manual and the system readings. Table 3 shows the overall results of weekly tire pressure inspections in terms of valid readings as well as reasons for invalid manual or system tire pressure readings.

Table 3. Comparison of Tire Pressure Data Points

Data Points	Validity	N	%
Successfully Recorded	Valid	2,850	76.7%
TPMS Problem	Invalid	654	17.6%
Low Pressure, No Numeric Value	Invalid	71	1.9%
Tire/ Valve stem issues	Invalid	139	3.8%
Total Data Points	**All**	**3,714**	**100.0%**

The sensors themselves presented the largest challenge in recording tire pressure readings. In 17.6 percent of the inspections, the sensors could not be read because they failed, were missing, or were mounted to tire positions other than those to which they were assigned. The issue of sensor failures was addressed early in the fleet test, but missing and improperly assigned sensors continued to be an issue throughout the test period. In 1.9 percent of the inspections, the system recorded a "Low" pressure reading, which by design of a particular display unit prevents the measured pressure reading from being displayed.

The final 3.8 percent of tire inspection "problems" were due to a flat tire, slow leak, or valve stem related issue. These valve stem issues include problems with the valve stem itself, access to the valve stem, and human error. A majority of the valve stem related issues were noted with the inner dual tire on the rear axle. The data collection forms stated the valve stem was "out of reach," and a tire pressure measurement could not be obtained. The reason for this was traced to a particular stick pressure gauge that one technician used to measure tire inflation pressures. This gauge had an angled chuck that did not line up properly with the valve stem on the rear inner tires. The angled chuck pressure gauge was replaced with a straight foot chuck pressure gauge that included a 30-degree reverse angle, so that the inflation pressure could be measured at all tire positions.

Table 4 presents the results of the manually checked tire pressure readings. A total of 3,534 manual tire pressure readings were obtained (Note: 41 manual tire pressure readings were left blank on some inspection forms, however, those data points were invalid due to TPMS problem). As shown, 80 percent of tires measured were within 5 psi of, or greater than, the 115 psi target inflation pressure.

Table 4. Manually Gauged Tire Pressure Inflation Results from Weekly Inspections

Tire Pressure (psi)	# of Measurements	Percent (%)
>115	1,342	38%
115–110	1,496	42%
109–105	517	15%
104–100	136	3%
99–95	19	1%
< 95	24	1%
Total # of Valid Measurements	**3,534**	**100%**

Table 5 compares the tire pressure readings from the TPMSs with the manually measured readings. Technicians recorded manual tire pressure readings using standard-issue pressure gauges. Although these were high-quality gauges, they were not specifically calibrated for the purposes of this field test. The gauges were capable of reading pressures from 10 to 160 psi in 2 psi increments. As shown in Table 5, about 91 percent of the time, the physically measured and sensor system readings were within 5 psi of each other—and 97 percent of the time, they were within 10 psi.

Table 5. Comparison of Tire Pressure Reading: TPMS versus Manually Gauged Readings

Tire Pressure Difference	Number	Percent of Total
No difference	367	12.9%
< 5 psi	2,230	78.2%
> 5 psi	253	8.9%
> 10 psi	87	-
> 15 psi	45	-
> 20 psi	36	-
> 25 psi	29	-
> 100 psi	11	-
Total # of Measurements	**3,058**	**100.0%**

Table 6 presents the tire pressure differential data for each TPMS participating in the field study. As shown, the percentage of readings showing "no difference" between the manually measured and the TPMS measured pressures ranged from 9.1 percent (eTire) to 16.9 percent (WABCO). The TPMSs were within 5 psi of the manually measured readings: 94.5 percent of the time (WABCO); 87 percent of the time (Tire SafeGuard); and 93 percent of the time (eTire).

Table 6. Tire Pressure Differential by System, Raw Data

Pressure Difference	Total #	Total %	WABCO IVTM #	WABCO IVTM %	Tire-Safe Guard #	Tire Safe Guard %	eTire #	eTire %
No difference	367	12.9%	175	16.9%	132	11.4%	60	9.1%
< 5 psi	2,230	78.2%	803	77.6%	874	75.6%	553	83.9%
Within 5 psi		91.1%		94.5%		87%		93%
Between 5 psi and 10 psi	166	5.8%	32	3.1%	90	7.8%	44	6.7%
Within 10 psi		96.9%		97.6%		94.8%		99.7%
Between 10 psi and 15 psi	42	1.5%	11	1.1%	30	2.6%	1	0.2%
Between 15 psi and 20 psi	9	0.3%	3	0.3%	6	0.5%	0	0.0%
Between 20 psi and 25 psi	7	0.2%	3	0.3%	4	0.3%	0	0.0%
Between 25 psi and 100 psi	18	0.6%	6	0.6%	12	1.0%	0	0.0%
> 100 psi	11	0.4%	2	0.2%	8	0.7%	1	0.2%

To assess the ability of TPMS improve average tire inflation pressures (and thus reduce tire wear and improve fuel economy), the tire inflation data collected from the test buses was compared to the data collected from the control buses. It should be noted that the bus maintenance facility had limited resources and only assigned two technicians to inspect buses during one shift each week, which limited the number of buses that were inspected. A priority was placed on inspecting all 12 of the test buses and as many of the control buses as possible in the time allotted. Control fleet tire pressure data was augmented with data collected and recorded by the Goodyear representative. Table 7 shows the average tire pressures between the test and control fleets.

Table 7. Average Tire Inflation Pressure

Fleet	Front Left	Front Right	Rear Inside Left	Rear Inside Right	Rear Outside Left	Rear Outside Right
Test Fleet	112.8	112.9	111.7	111.4	110.1	110.2
Control Fleet	112.0	111.3	111.3	111.1	110.0	111.7

As shown in Table 7, the comparison of inflation pressures for the test fleet and the control fleet indicated a minimal difference between them. The overall averages for the test and control fleets were 111.5 psi and 111.2 psi, respectively. The study team found that the similarity of inflation pressures between the two fleets was influenced by WMATA's active role in maintaining tire pressure as part of its tire contract with Goodyear. Goodyear is under contract to measure the inflation pressure of each tire once per month and add air when the measured pressure is below 111 psi (at the time the field test began, WMATA technicians were responsible for maintaining tire inflation levels). Another factor influencing test results is the location of the system displays. The TPMS display was not visible to the driver, so corrective action was not taken daily as part of a pre-trip inspection as would be the case with a typical for-hire trucking fleet.

Because differences in average tire inflation pressures between the test and control fleets were minimal, and since the test and control fleets operate similar routes, differences in fuel economy between the fleets were also minimal. As shown in Table 8, the fuel economy of the control fleet was slightly better than the test fleet prior to initiating the field test, and this relationship remained stable throughout the field test (test fleet fuel economy did not improve). For reasons unrelated to tire pressures, both the test and control fleets experienced a slight increase in fuel economy during the field test period.

Table 8. Fleet Fuel Economy

Test Fleet Period	Test Fleet Mileage	Test Fleet Fuel Consumption (diesel equivalent)	Test Fleet MPG	Control Fleet Period	Control Fleet Mileage	Control Fleet Fuel Consumption (diesel equivalent)	Control Fleet MPG
Pre-Test	343,865	110,223	3.12	Pre-Test	342,751	107,773	3.18
Test	375,939	111,761	3.36	Test	391,041	111,604	3.50
Total	**719,804**	**221,984**	**3.24**	**Total**	**733,792**	**219,377**	**3.34**

4.2.2 Reliability

For fleet operators, technicians, and supervisors to rely on TPMSs for tire inflation maintenance, they must have confidence in the system and the information it presents. In short, the information presented by the display units must be reliable, and system reliability is essential for encouraging the use of TPMS equipment in commercial vehicles. For TPMSs, this means that the system correctly and consistently reports whenever a tire is under (or over) inflated; and that the system does not report an over/under inflation problem when in fact inflation pressure is within targeted limits. If the TPMS does not detect/report an improper inflation condition (when such a condition does indeed exist), it is termed a “false negative.” If the TPMS incorrectly reports a tire inflation problem when none exist then it is called a “false positive.”

The reliability of the TPMSs was determined by comparing the information presented on driver/operator displays (i.e., warnings, or lack thereof) to the measured (manually gauged) tire pressures. A TPMS display status was identified as *valid* (or correct) if:

- The TPMS did not display an alert for a low-pressure condition *and* the manual tire pressure reading showed actual pressure to indeed be within 10 percent of target (target pressure was 115 psi); or,
- The system did warn the operator of a low-tire condition and the manual reading did indeed show that the tires were under-inflated by 10 percent or more.

Alternatively, *invalid* (or incorrect) display status readings were divided into three categories:

- **False Positive.** The TPMS reported a low tire pressure (≤ 103 psi), when the actual condition observed was a normal tire pressure (> 103 psi).
- **False Negative.** The TPMS reported a normal tire pressure (> 103 psi), when the actual condition observed was a low tire pressure (≤ 103 psi).
- **No Read.** The TPMS reported no reading of tire pressure. The cause of the condition could be related to issues such as a missing sensor, an improper sensor threshold setting, or a special condition (e.g., flat tire).

Excessive false-positive readings may cause the user to discount true (or real) tire warnings. A false-negative reading results in an undetected unsafe condition, which can lead to loss of vehicle control, damage, and injury. Similar to false positives, excessive no-read conditions can diminish confidence in the performance of the TPMS.

An analysis of all three system in total showed that the TPMS displays were valid 75 percent of the time (i.e., for 75 percent of the inspections, the display status matched actual conditions). As shown in Table 9, no-read conditions (17 percent) accounted for the largest percentage of invalid display status readings. False-positive and false-negative conditions accounted for less than 10 percent of the total invalid display status readings.

Table 9. Incidences of Invalid Display Reading

Type of Reading	Data Points	Percentage
False Positive	227	6%
False Negative	61	2%
No Read	635	17%
Total	**953**	**25%**

System reliability varied considerably among the three TPMSs under test. An assessment of the individual systems found the Tire-SafeGuard system had the most reliable performance, with a valid display status reading in 90.9 percent of the tire inspections, as shown in Table 10. The poorest performing system, eTire, provided valid tire pressure display status in about 53% of the tire inspections.

Table 10. Overall TPMS Reliability Results

System	Valid	Invalid
WABCO IVTM	82.0%	18.0%
Tire-SafeGuard	90.9%	9.1%
eTire	53.2%	46.8%

The eTire system was found to have an extensive number of no-read conditions during the tire inspections. As shown in Table 11, the eTire system could not report the tire pressure in 44 percent of the tire inspections. The majority of these failures were traced to a manufacturing defect, with the sensor causing the casing to be brittle and fail prematurely upon impact. The failure conditions are further explained in Section 4.2.4.

Table 11. TPMS Reliability by System Type

System	False Positive	False Negative	No Read	Total Percent
WABCO IVTM	10.4%	1.5%	6.1%	18.0%
Tire-SafeGuard	6.8%	2.3%	0.0%	9.1%
eTire	1.3%	1.1%	44.4%	46.8%

In Figure 20, the distribution of valid and invalid tire assessments is shown for each system. Discounting the high failure rate of the eTire equipment, the largest contributor to invalid display status readings for each system was the presence of false-positive conditions.

Another measure of reliability of TPMSs was whether the sensor systems were deemed to be “operational” during visual inspections and system checks by WMATA technicians and/or study team staff. The status of the sensor was identified as “operational” if a tire pressure reading was obtained at the control unit. If a sensor could not read the tire pressure, it was deemed “non-operational.” A sensor may be non-operational for several reasons, including communication failures, disconnected components, missing components, and broken components. An analysis of the entire field test showed the sensors were operational during 83.6 percent of the visual inspections.

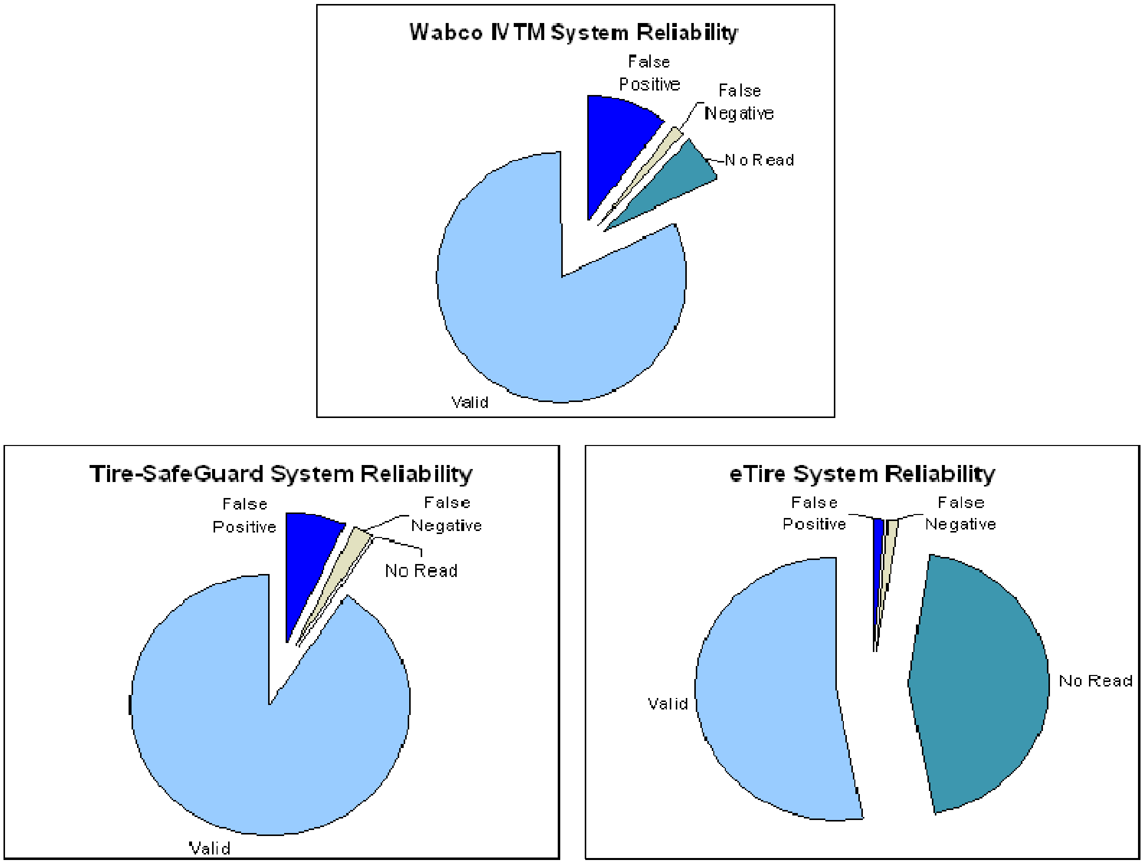


Figure 20. Individual System Reliability Charts

Operational reliability (sometimes referred to as system availability) varied among the three installed systems. Tire-SafeGuard had the most reliable sensors. As shown in Table 12, the sensors were operational during 98.2 percent of the visual inspections. The poorest performing system, eTire, was fully operational in only 64.1 percent of the visual inspections. A manufacturing flaw, discussed later in Section 4.2.4, was identified in the eTire sensors, resulting in low system reliability. Other sensor failures were caused by component batch manufacturing issues, improper sensor installation, and sensor material fatigue.

Table 12. Sensor Condition, by TPMS

Sensor Condition	WABCO IVTM	Tire-SafeGuard	eTire
Operational	89.0%	98.2%	64.1%
Non-Operational	11.0%	1.8%	35.9%

4.2.3 Maintainability

Maintainability pertains to the maintenance efforts necessary to keep the TPMSs in working order. This section focuses on the human interaction with the TPMSs and the steps taken to ensure that all sensors and system hardware were fully functional. Maintainability issues contributed to nearly one-half of the system malfunctions or failures during the field test. These maintenance shortfalls include missing sensors, improper sensor tracking, improper sensor installation, and improper sensor handling.

4.2.3.1 Sensor Tracking

A major challenge during the field test was keeping track of TPMS sensors. The eTire system sensors presented a particular challenge because of the location of the sensor. Unlike the other systems evaluated, the eTire sensor was located on the inside of the tire's sidewall out of the technician's view—even after the tire itself was removed from the wheel rim. The study team found that if the technician was unaware of the presence of the sensor, there was a good chance that it would be discarded during tire changes. This was a problem throughout the test period because of technician reassignments, in-field (emergency) tire repairs, and miscommunications. The problem persisted even after increasing the training provided to technicians.

As an example, during one weekly inspection, test engineers learned of an initiative to replace the steer tires on the bus fleet at the Four-Mile Run facility because of a warranty issue with premature wear. During weekly inspections, two test buses (number 2511 and number 2512) were found to have missing eTire sensors in the front steer tires. The eTire-equipped tires had been removed from the bus and discarded.

In another example, the rear tires on bus number 2512 were replaced because of damage, and the sensors were not transferred to the new tires. This time, however, the oversight was discovered, and the sensors were recovered before the tires were discarded.

Keeping track of the eTire sensors was a constant challenge for both the study team engineers and WMATA technicians throughout the field test. By the end of the test period (after just 14 months of testing), more than half of the eTire sensors on the four test buses had been misplaced. It was recognized that transit bus service presented unique challenges to maintaining a TPMS. These challenges include the fact that numerous technicians may service any particular bus, and that buses experience a relatively high frequency of tire changes per year compared to over the road tractor-trailer combinations. At times, the Four-Mile Run garage had five overlapping maintenance shifts, and occasionally technicians would be reassigned to work at a different bus garage; therefore, it was difficult to ensure that all technicians at the Four-Mile Run garage had working knowledge of the TPMS installed on the 12 test buses.

The HCI's Tire-SafeGuard system had a similar, but less severe problem with tracking sensors. The sensor tracking problem was mostly attributed to the sensor module's mounted location inside the tire which was not clearly visible to maintenance technicians, (although unlike the eTire sensor, the Tire-SafeGuard sensor was plainly visible once a tire was removed from the wheel rim). Again, not all technicians were aware that they were dismounting tires from a bus equipped with TPMS.

Tires missing their sensors were sometimes discovered during the weekly system inspection. Most of Tire-SafeGuard tire pressure sensors were eventually recovered from tires removed from the test buses once the tire was removed from the rim (thereby exposing the sensor).

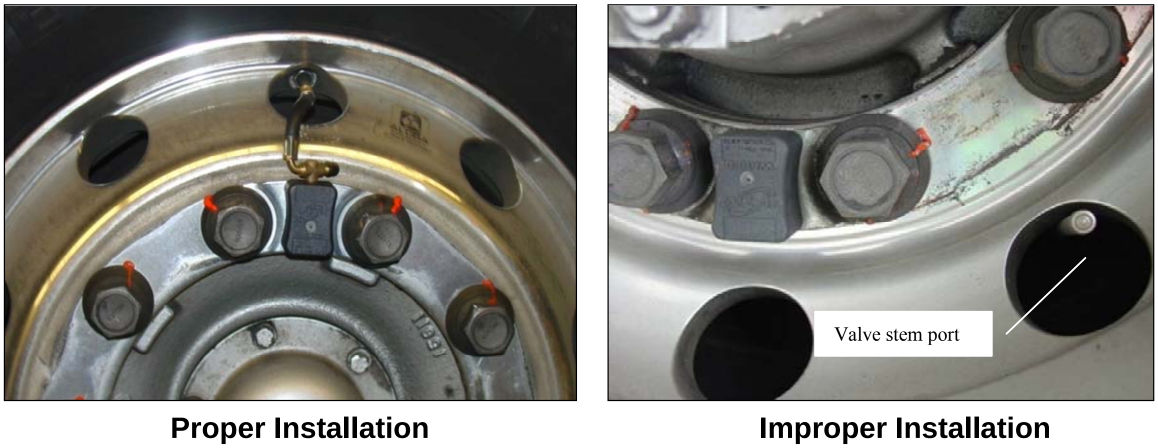
The Tire-SafeGuard sensors, once remounted on a bus, needed to be retrained to match their wheel location in the ECU. This was not necessary if the wheel and sensor was removed from a bus, fitted with a new tire, and remounted to the same wheel location on the bus. However, the remounting of a wheel sensor to exactly the same position on the same bus was rare. Often, the new sensor module would remain unassigned (not recognized by the ECU) until the replaced tire was identified during the weekly inspections. To retrain new sensors to specific wheel positions, a technician must first hold down the setup button on the system display unit until the system enters "Tire Setup Mode." Once in setup mode, the technician must release 3 psi of air out of the right front steer tire. Releasing 3 psi from the tire triggers the sensor module to transmit a signal which the ECU receives and associates with the tire position. Once the ECU recognizes a tire position, the display cues the technician to move to another tire position and release air from that tire. The steps are repeated for the remaining tire positions until the system recognizes all of the sensor modules on the vehicle. Once the retraining is complete, the technician refills the tires to the proper inflation pressure.

In contrast, WABCO's IVTM system had just three recorded instances of missing sensors. In all three instances, the tires failed in service and were replaced by field technicians during a road call. Unfortunately, the sensors that were removed from the damaged tires were not remounted to the new tires and were lost. The sensors were lost because the sensors are retained by lug nuts, which must be removed along with the sensor before changing the tire.

4.2.3.2 Sensor Replacement

Another challenge with maintaining TPMS during the fleet study was ensuring that tire pressure sensors were re-installed properly when tires were replaced. The WABCO IVTM wheel module was improperly installed (or installed in the wrong wheel positions) on test buses several times during the fleet study.

For example, proper and improper installations of WABCO's IVTM wheel module are shown in Figure 21. For proper installation (left side of figure), the module is installed between the wheel lug nuts that are to the immediate left and right of the valve stem. A hose attaches the wheel module to the tire's valve stem. The hose on the wheel module end has a Schrader valve, which allows a technician to manually check the tire pressure or add air pressure to the tire without disconnecting the hose from the valve stem.



Proper Installation **Improper Installation**

Figure 21. Proper and Improper IVTM Module Installation

The improper installation (right side) shows the wheel module attached to the two lugs to the left of the valve stem, rather than directly below it. As a result, the hose required to connect the module to the valve stem was too short, rendering the system useless.

Another example of an improper installation is shown in Figure 22. The hose that connected the wheel module to the tire valve stem was improperly connected on two different tires on a particular bus. On both tires, one end of the hose was connected to the Schrader valve at the hose's other end, instead of the tire's valve stem.

Figure 22. Improper IVTM Hose Connections

In some instances, problems with the IVTM system occurred because a sensor unit had been re-installed on a different wheel during routine tire changes.

One example occurred on bus number 2503. On this bus, the IVTM display denoted that a wheel module was missing on the right-rear inner tire. Upon inspection, a technician noticed that a wheel module was mounted and properly connected to the right-rear inner tire. However, there was no wheel module mounted on the right-steer wheel. The technician compared the serial number written on the wheel module on the right-rear inner tire to the serial numbers programmed in the ECU, which revealed that the module installed at the right-rear inner tire belonged at the right-steer tire location.

In another example, the same bus as in the previous example (number 2503) experienced a flat tire at the right-rear inner location. The technicians replaced the tires and reinstalled the modules. In the process, the two wheel modules that were programmed to the right-rear tires were mixed up and installed with the sensor programmed to the outer tire attached to the inner tire and vise versa. The error was identified the following morning, and the IVTM ECU was reprogrammed to reflect the change.

4.2.3.3 Maintenance Damage

Additional TPMS maintainability issues were noted during routine tire maintenance. In one example, the hose that connects the IVTM sensor unit to the tire's valve-stem was damaged during a tire change, as was the tire's valve stem. It was unclear what specific actions/events caused this damage.

In another situation, an IVTM wheel module was removed from service because of a reported leak at the right-rear inner tire. The technician reported a hissing noise at the valve stem. By removing the IVTM connecting hose, the noise was eliminated. The module was tested by connecting the hose to a different tire, but the failure could not be replicated. The module was reinstalled on the tire with no further failure reports. Another challenge with the IVTM system is properly installing the sensor on the inner dual tire. The location of the inner tire valve stems makes it difficult to ensure the module has been properly installed.

4.2.4 Durability

Durability pertains to the ability of the TPMS components to withstand the wear and tear experienced in normal operating service. Most durability concerns identified during the fleet study were attributed to manufacturing defects or minor design deficiency. Manufacturing defects led to a need for numerous sensor replacements throughout the fleet test. Durability issues were communicated to the manufacturers, and damaged or defective parts were shipped to manufacturers for analysis. The manufacturers addressed their systems' durability issues and provided design improvements or new installation instructions to combat future failures.

4.2.4.1 eTire Durability Issues

The eTire system had the most prevalent durability issue among the TPMSs tested during the fleet test. Damaged eTire sensors were initially identified in November 2006. Maintenance technicians noticed that the eTire system's handheld sensor reader did not detect sensors in several tires on bus numbers 2509, 2510, 2511, and 2512. A closer look revealed that 14 tires contained sensors that did not communicate with the handheld reader. The tires were removed for inspection. In each tire, the sensor unit had separated from the SensorDock mounted onto the inside sidewall of the tire. In only one case did the SensorDock separate from the tire wall itself. Figure 23 shows one of the sensors discovered in the inspection.

Figure 23. Damaged eTire Sensors

As shown in Figure 23, the sensors were found broken into numerous pieces. The failed components were returned to the manufacturer for analysis. To continue the field test, new sensors were installed in each of the 14 tires. To secure the sensors to the sensor dock until a failure analysis could determine the cause of the separation, an inner liner sealant was used to lubricate the sensor before it was installed on the sensor dock as recommended by the manufacturer. When dry, the sealant helps secure the sensor to the dock.

In January 2007 an eTire representative visited the maintenance facility to determine the cause of the sensors cracking and detaching from the sensor dock. During the inspection of the four eTire-equipped buses, a broken sensor was located in the left steer tire of bus number 2512. The sensor appeared to have broken free of the SensorDock, which was still mounted to the tire sidewall. The failure mode of the sensor appeared to mimic the findings in November 2006. Under further inspection, the right steer tire was removed. In this instance, the sensor was attached to the SensorDock, but it appeared to have a small crack in the casing (Figure 24). The crack was located on the thin plastic casing in direct contact with the mushroom-shaped mounting knob on the sensor dock. While interviewing the technicians directly responsible for installing and maintaining the systems, it was noted that several other sensors had exhibited similar failure modes. The failed components were returned to Michelin for a full analysis.

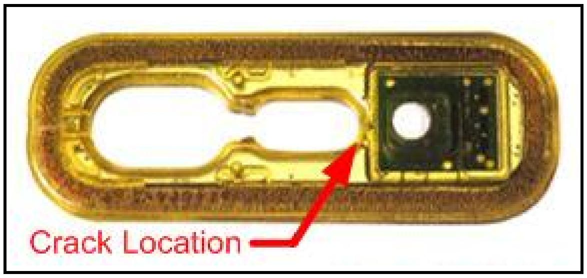


Figure 24. Cracked eTire Sensor, Bus Number 2512

The manufacturer initially believed the sensors failed due to improper installation of the SensorDock and sensor tag. However, while at the maintenance facility, the eTire representative was able to determine that the eTire installation methods were followed properly by observing the tire technician install a new SensorDock and sensor unit in a new tire. When comparing the failed sensor units found in the left steer tire to those found in the right steer, identical surface cracks were identified in each sensor casing. Other damaged sensors that had been collected up to this point exhibited identical failure modes. All of the damaged sensors were collected and inspected by Michelin.

Michelin determined that each of the damaged sensors had the same batch number printed on them. The discovery led to a determination that a manufacturing flaw existed with these sensors. Figure 25 shows an eTire sensor with the batch number written in the upper right portion of the sensor. The original sensors installed at the beginning of the test had a batch number of 0-122691.

The eTire sensors that replaced the faulty sensors came from batch number 0-122831 and did not exhibit failures during future inspections. The sensors from the batch number exhibiting the manufacturing defect were segregated from inventory and removed from the test site.

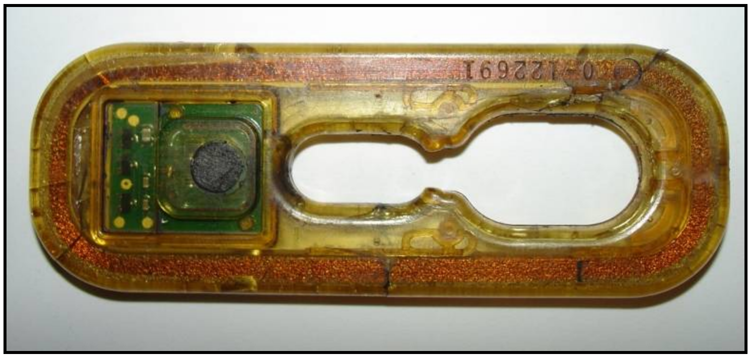


Figure 25. Batch Number of Failed eTire Sensors

In May 2007 additional damaged sensors were identified during the replacement of the rear tires of bus number 2512 (see Figure 26 and Figure 27). Each of the four sensors exhibited similar patterns of cracking and damage as the other eTire sensors. Despite the visible damage to the sensor casing, three of the four sensors were still functional. These four sensors were found to be from the same defective manufacturing batch identified earlier by the eTire representative.

Figure 26. Damaged eTire Sensor, Bus Number 2512

Figure 27. Cracked eTire Sensors, Bus Number 2512

Throughout the test, eTire sensors with batch number 0-122691 continued to experience a high failure rate. All of the failed sensors identified up to this point in the test were part of the first batch of eTire sensors. Of the 48 sensors ordered as part of the initial installation, an estimated 75 percent failed because of the identified manufacturing defect.

In response, Michelin provided an additional 24 sensors that were used to complete a fleet-wide replacement of the sensors on eTire-equipped buses. After the new batch of sensors was installed, the sensor failure rate reduced significantly. Only a handful of failed sensors were identified after the fleet-wide sensor replacement, and their batch numbers did not match those of the faulty manufacturing batch. The durability of the eTire sensors improved after the fleet-wide sensor replacement; however, eTire sensors continued to be lost during tire replacements because of challenges associated with keeping technicians trained on the system—and with other logistics issues discussed previously.

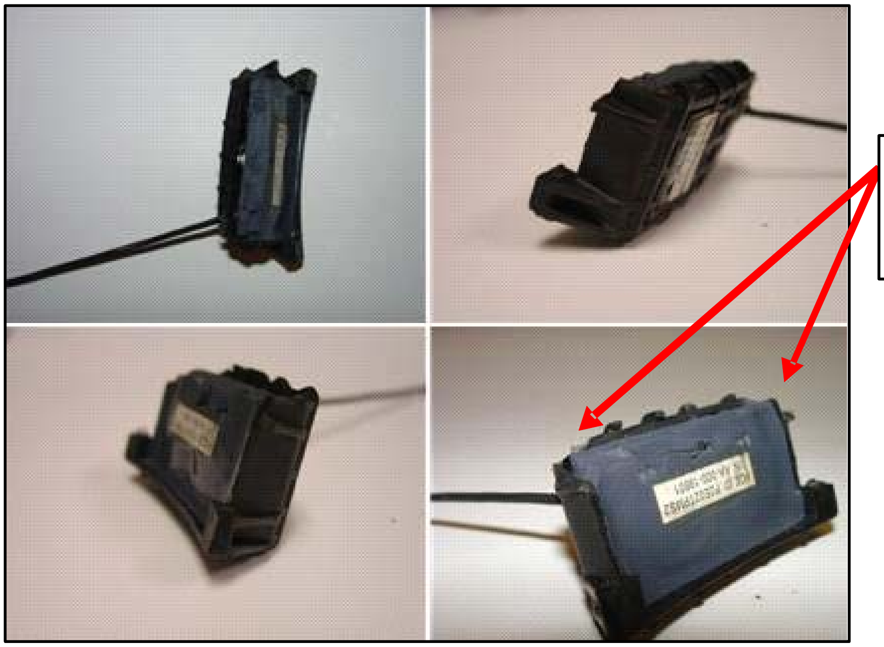
4.2.4.2 Tire-SafeGuard Durability Issues

Two durability failures occurred with the Tire-SafeGuard system. The first failure was identified in September 2006 when two sensors installed on bus number 2508 could not be detected. According to the system display, the steer tire sensors were experiencing significantly different temperature and pressure readings compared to the rear tires. To test the system, air was manually released from each of the steer tires, but no tire pressure change was indicated on the display. To establish communication with these sensors, a new antenna was tested in place of the existing antenna, and an effort was made to reprogram the sensors. These attempts failed to result in communication with the sensors.

Because of the failed troubleshooting attempts, the steer tires of bus number 2508 were removed and inspected. Upon removing the tires from the wheel rim, several small fragments of metal were discovered in each tire. The sensors removed from the tires exhibited unusual wear and abrasion on the outer casing. Upon further investigation, it was determined that the excess metal strapping used to retain the sensor was not removed before the wheel was reinstalled. The excess metal appeared to have broken free of the metal band while the bus was in service, fracturing into smaller pieces while moving freely within the tire and ultimately damaging the sensors. As Figure 28 shows, the metal fragments were part of the metal strap used to retain the sensors to the wheel.

Figure 28. Tire-SafeGuard Band Fragments and Damaged Sensors, Bus Number 2508

The second failure was identified in January 2007. During an analysis of tire data on bus number 2506, it was noted that the readings of the right rear inner tire had retained a consistent value of 128 psi and 111 degrees Fahrenheit over several weeks of data collection. These values were significantly higher than other tire readings on the same bus, which averaged 110 psi and 55 degrees Fahrenheit. The right rear wheels were removed from bus number 2506 to determine the condition of the suspect sensors. Upon removal of the tire from the wheel rim, the sensor was no longer attached to the rim. The sensor appeared to have broken free of the metal band intended to secure it to the rim (see Figure 29).



Missing Edge on Damaged Sensor Module

Figure 29. Damaged Tire-SafeGuard Sensor, Bus Number 2506—Right Rear Inner Tire

The sensor module experienced significant damage to its underside. A large piece of plastic had broken away from the bottom and one side of the sensor. The broken plastic had originally assisted in forming the open slots on the underside of the sensor used to secure it to the wheel rim. Initial investigations identified improper installation, heat-induced plastic fatigue, or heat-induced metal expansion as possible failure modes.

In July 2007 five additional damaged sensors were identified. Four of the damaged sensors were removed from bus number 2507. Unlike the earlier failure, the damaged sensors were still secured to the wheel rim by the metal strap. As Figure 30 and Figure 31 show, the sensors exhibited casing cracks and casing failures (i.e., plastic casing was broken and missing). In each of the failed sensors, the failure location was identified at the underside of the sensors. Large portions of the plastic casing were missing from the underside of the sensor. In addition, two of the sensor casings had split open completely. The sensors were replaced, and the manufacturer conducted an analysis to determine the cause of the problem.

Figure 30. Additional Damaged Tire-SafeGuard Sensors

Figure 31. Additional Damaged Tire-SafeGuard Sensors

At the end of July 2007, Tire-SafeGuard issued a product improvement notice to the study team, along with a shipment of new wheel sensors. The revised wheel module sensor units included “foot pads” that would adhere to the underside of the sensor. Each sensor was affixed with two of the foot pads to provide improved heat distribution for the plastic sensor housing. The product improvement was intended to prevent the sensor from splitting or cracking while in service. After this product improvement, no further failures were identified during the field test.

4.2.4.3 WABCO IVTM Durability Issues

The WABCO IVTM tire pressure monitoring system did not experience any durability issues during the fleet study. There were reported cases of missing sensors or improper hose connections as noted in Section 4.2.3, but its valve-stem mounted wheel modules and other hardware components completed the field test without failure.

4.2.5 Maintenance Records

Tire-related maintenance actions were gathered from the fleet’s maintenance database (MAXIMO). The records collected identified tire-replacement actions, TPMS hardware replacements, and bus recovery actions caused by a tire failure while in service. The review of the MAXIMO data aimed to identify repeated TPMS and tire issues, reduced road calls resulting from system installation, and extended tire life resulting from system installation.

Overall, 124 tire failures were recorded in MAXIMO during the field test (see Table 13). The failures were divided into seven categories—flat tire, foreign object, low pressure, mileage-based, road call, TPMS failure, and worn tires. The most records were generated for “mileage-based” tire changes, with 60 records total. The vehicles’ tires were replaced because they reached the scheduled replacement mileage. The “worn tires” category (17 total records) designated tire changes that were necessary because of an observed worn condition rather than having reached their expected mileage life. These tires may have experienced increased wear for reasons other than normal wear, and had to be changed before the scheduled maintenance task.

Table 13. Tire-Related MAXIMO Records

Tire Failure Category	Test Fleet	Control Fleet	Total
Flat Tire	6	1	7
Foreign Object	12	10	22
Low Pressure	3	1	4
Mileage Based	24	36	60
Road Call	6	3	9
TPMS Failure	5	0	5
Worn Tire	7	10	17
Total	**63**	**61**	**124**

The category with the second most maintenance records, “foreign object,” identified maintenance actions caused by a foreign object piercing the tire. Under these records, the tires were replaced as part of an unscheduled maintenance service. The “flat tire” category had seven records. A review of the database for these failures did not note the cause of the flat tire. The failures were likely caused by unreported foreign objects or slow leaks at the rim or valve stem. Clarification was not provided in the maintenance record.

The remaining categories accounted for less than 15 percent of the maintenance records:

- **Low Pressure (2.5 percent).** A tire was reported to have a low pressure—much lower compared to the other five bus tires. Of the four instances, only a single instance was reported as a failure. In this instance, a leak was identified at the valve stem. The remaining records had no maintenance actions.
- **Road Call (7 percent)**. The maintenance records identified nine road calls during the field test. For test vehicles, the TPMS was not queried to verify that it identified the fault causing the road call. Two of these instances occurred on Interstate 395 and caused excessive tire damage. Section 4.2.6 provides further information.
- **TPMS Failure (5 percent).** A TPMS failure was identified as any record generated by the TPMS itself. In general, the faults were generated because of faulty tire sensors or incorrectly installed hardware. In two instances, an inspection by the mechanic identified a faulty sensor (one eTire and one Tire-SafeGuard) that had to be replaced. In the remaining three instances, the IVTM air hose was either missing or improperly installed but did not result in road calls. Section 4.2.3 further discusses these failures and the resulting corrective action.

As the analysis of the MAXIMO data shows, the test and control fleets experienced a similar number of tire failures throughout the course of the test—and it is inconclusive (or unlikely) that the TPMS systems helped reduced these catastrophic type tire failures.

In addition to the five reported TPMS failures by WMATA, the study team kept records on the number of sensors replaced during the course of the field test. As shown in Table 14, 73 spare sensors were used to support the program.

Table 14. Sensors Replaced

Sensor Type	Number of Sensors Initially Installed	Number of Sensors Replaced
IVTM	24	3
Tire-SafeGuard	24	18
eTire	24	52
Total	**72**	**73**

Three IVTM sensors were replaced during the test period. One sensor developed a leak. It was removed from the bus and returned to WABCO for analysis. The other two sensors were misplaced during a roadside tire replacement.

Eighteen Tire-SafeGuard system sensors were replaced during the test period. Two sensors were damaged as a result of faulty installation and six sensors suffered heat damage. HCI Corporation equipped the replacement sensors with an insulator pad. The remaining 10 sensors were misplaced during tire changes.

Fifty-two eTire sensors were replaced. Forty sensors were identified as having a manufacturing defect as discussed previously. The remaining 12 sensors were misplaced during tire replacements.

4.2.6 Isolated Events

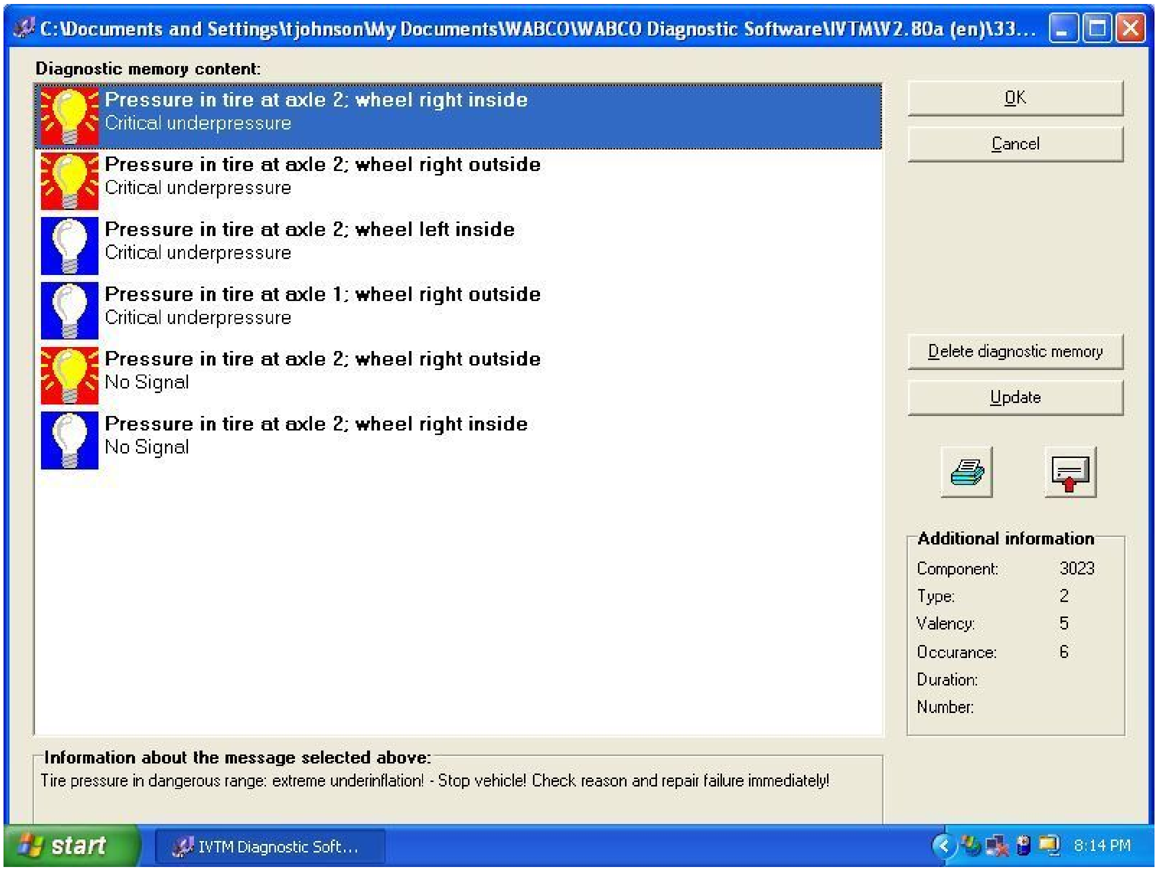
Throughout the course of the field test, several isolated tire and TPMS equipment failures were apparent. However, they were not directly attributable to a TPMS failure, technician failure, or system functionality issue. Each of these failures offered important insights to the operation of the TPMSs.

4.2.6.1 Tire Blowout

One incident occurred on July 18, 2007. While traveling on I-395 in Virginia, both right rear tires on bus number 2503 went flat. The outer tire, shown on the right in Figure 32, seemed to experience a small puncture from a foreign object, causing it to lose air. The inner tire, shown on the left in Figure 32, appeared to fail shortly after the outer tire failure and sustained the most extensive damage. The photograph indicates that the failure likely occurred at the 2 o'clock position on the outer tire. At this position, a piece of rubber was identified as missing from the tire, possibly after contacting a piece of construction debris. In the interviews, technicians identified construction debris, such as concrete rebar, as a common cause of tire failures on buses maintained at the Four-Mile Run facility.

Figure 32. Damaged Tires From Bus Number 2503

Bus number 2503 was equipped with the IVTM system, which can store tire fault information. After connecting a laptop to the IVTM ECU, six separate faults were identified. The system detected low and critically low tire pressure at both right rear tire locations, (see Figure 33). The system detected that the right rear tires were extremely under-inflated and indicated that the tire pressures were at a "critical under-pressure" level. If the display had been in the driver's clear view instead of in an inaccessible cabinet, one can reasonably assume that (1) the system would have notified the driver of the dangerous tire conditions before the tire blowout occurred and (2) the driver would have been able to pull to the side of the road safely. It should be noted that the IVTM system does not store date or time stamps (however, the latest IVTM software does now include date and time stamp information on system messages). Therefore, the low and critically low tire pressure warnings detected by the system cannot be associated with certainty to the July 18 tire failure.



Diagnostic memory content:

Pressure in tire at axle 2; wheel right inside
Critical underpressure

Pressure in tire at axle 2; wheel right outside
Critical underpressure

Pressure in tire at axle 2; wheel left inside
Critical underpressure

Pressure in tire at axle 1; wheel right outside
Critical underpressure

Pressure in tire at axle 2; wheel right outside
No Signal

Pressure in tire at axle 2; wheel right inside
No Signal

Additional information

Component: 3023
Type: 2
Valency: 5
Occurance: 6
Duration:
Number:

Information about the message selected above:

Tire pressure in dangerous range: extreme underinflation! - Stop vehicle! Check reason and repair failure immediately!

Figure 33. IVTM Fault History for Bus Number 2503

4.2.6.2 *Sensor Module Air Leak*

Another unique failure involved an IVTM wheel module. A technician reported a leak at the right rear outer tire's valve stem. Removing the wheel module eliminated the source of the leak. An effort was made to troubleshoot the source of the air leak. First, a new hose was attached to the module and valve stem, but the leak was still present. During troubleshooting, it was determined that the wheel module itself was causing the leak. The wheel module was removed from service and returned to the manufacturer.

4.2.6.3 *Cracked Antenna on eTire Handheld Tag Reader*

A routine inspection on June 10, 2007, revealed a damaged eTire handheld sensor reader. The reader was unable to locate or read sensor tags inside the tires of bus number 2509, nor was it able to detect or read the vehicle ID sensor tag located at the front of the vehicle. A technician attempted to troubleshoot the handheld reader. First, the reader was returned to the cradle dock to ensure upload of the latest software to the reader. The software update did not correct the issue. Inspecting the case of the reader revealed a crack near the reader's antenna. As shown in Figure 34, the crack in the casing appeared to damage the internal antenna. Through the casing crack, the internal antenna coil was severed from the reader. The damaged reader was returned to Michelin's local service representative and a new reader was shipped to the Four-Mile Run facility on June 27, 2007. Therefore, system tire pressures on the eTire equipped buses could not be recorded during the weekly inspections on June 10, June 17, and June 24, 2007. The new handheld reader was placed into service the week of July 1, 2007.

Figure 34. Damaged eTire Handheld Reader

4.2.7 Technician Interviews

Informal discussions took place with technicians and mechanics throughout the study period, and formal interviews were conducted at the end of the field test. The participants believed that, overall, TPMSs could benefit the fleet. They stressed the need for accurate tire pressure information and their preference for tire pressure monitoring through communication with an AVM system (i.e., the Clever Devices WiFi based diagnostic system). In an ideal situation, the AVM system would alert the maintenance staff of under inflated tires in the fleet, reducing the need for manually measuring tire pressures. The technicians' comments related to the individual TPMSs are as follows.

4.2.7.1 WABCO IVTM

Overall, the participants were satisfied with the operation of the IVTM. They identified three main areas of concern—sensor hose condition, propensity for misplacing sensors, and sensor installation.

During the inspection of the sensor units, the technicians said they found that the hose connected to the units was, on occasion, either damaged or leaking air. The failure was noted most often at the right front steer tire of the bus. The buses at WMATA encounter street curbs and the guide rail in the bus wash rack more frequently at this wheel location than other wheel locations. As a result, any equipment installed external to the wheel at this wheel location is prone to damage. The failure of the equipment was resolved by disconnecting the hose from the valve stem if a leak was identified. The action was taken to eliminate the risk of a complete loss of pressure (although such a solution eliminated the ability to sense tire pressure at the right front steer tire.

In several cases, sensor units were found missing from tires after road call incidents to replace a flat tire. Shop supervisors speculated that the technicians responsible for the road call might have forgotten to reinstall the sensor units when replacing the tire, leaving the sensor units on the roadside. Alternatively, the particular technician responding to such a road call may not have been properly trained and/or been aware of the IVTM sensors.

Technicians commented that installing the wheel modules at the rear dual wheel assemblies was difficult because of the wheel well orientation and the small gap between the rear dual wheels. The limited accessibility made it difficult to attach the wheel module’s hose to the inner valve stem. To increase the accessibility of the valve stem, the technicians had to increase the gap between the dual tires and access the valve stem from under the bus while the bus was slightly elevated on a post lift. The first action required the technicians to loosen or remove all of the lugs on the wheel assembly to increase the gap between the wheels. With the lug nuts loosened, the technician then lay on his side on the floor and reached his arm under the wheel well and into the gap between the tires to attach the hose to the inner tire’s valve stem.

4.2.7.2 HCI Tire-SafeGuard

Although each of the three TPMSs tested in the study had pros and cons, the maintenance technicians preferred the HCI Tire-SafeGuard system. The technicians noted the ease of installation and the detailed installation procedures. The wheel-mounted tire pressure sensor required only a screwdriver to mount the sensor to the wheel rim. To protect the wheel sensor from damage during tire replacement, the installation procedures advised mounting the sensor near the valve stem port on the wheel. The procedure provided the technicians with the approximate mounting location so they could avoid damaging the sensor with the tire removal tools.

However, because the Tire-SafeGuard tire pressure sensors are located inside the tire, their presence and status were difficult to track. A technician could not tell that a tire was equipped with the sensor simply by looking at the tire. As a result, the sensors could be lost during tire replacement. In some instances, technicians unknowingly replaced Tire-SafeGuard-equipped tire and wheel combinations with standard tire and wheel combinations. The buses returned to service and the missing sensors went undetected until the next weekly system inspection (by study team staff). Technicians commented that if a sensor was absent from a tire location, the system display only indicated a loss of sensor communication at that location. Tracking the sensors and sensor-equipped tires increased the technicians’ workload.

4.2.7.3 Michelin eTire

Technicians found the most problems with the eTire TPMS during the fleet study. The problems reflect issues with the durability of the eTire sensors (see section 4.2.4), sensor tracking, and use of the handheld sensor reader.

Technicians commented that they preferred sensors that attach to the wheel instead of the tire. They mentioned that the high frequency of tire changes on buses increased the chances of misplacing sensors—particularly with a system such as eTire where the sensor is attached to the tire rather than the wheel rim (the implication being that tires are wear items that are discarded, but rims are not). Technicians also discussed the challenges of mounting the sensor in a consistent location so that it could be easily read using a handheld unit. Early in the test program, technicians sometimes mounted sensors on the wrong side wall. Procedures were developed to ensure a consistent mounting location. These were not issues encountered with the other systems.

The technicians found the eTire handheld reader difficult and time consuming to use. To read the eTire sensor tags mounted to the inside sidewall of the tire, technicians had to hold the handheld reader within inches of the tire sidewall and move the reader slowly until it detected a sensor. Moving the reader between the dual tires on the rear axle was especially difficult because of the wheel well and close proximity of the dual tires. Also, the reader would often “time out” if it did not locate a sensor within 10 to 15 seconds.

In addition, the handheld reader needed to be returned to its docking station to ensure it was fully charged for its next use. In should be noted that the handheld unit is designed for “spot checks” of tire pressure condition, and that Michelin recommends the use of a drive-by gate reader as the preferred method to read a vehicle’s tire pressure. In this scenario, a bus would drive between two gates that automatically detect and download tire pressures at each of the tires. When presented with this option, technicians believed the gate reader would be a great improvement over the handheld reader. The gate reader was not used in this study because of funding constraints and the infrastructure modifications required to properly mount and power the gate reader.

Tires equipped with the eTire sensors were also difficult to track since sensor units are not easily visible. Technicians noted that the eTire sensors would be easier to track if the entire bus fleet utilized the tire pressure monitoring system.

4.3 OBSERVATIONS AND CONCLUSIONS

TPMS sensors were found to be consistent and reliable in reporting tire inflation pressures when compared to measured (tire-gauged) values. On average, the systems reported false positives (a false low-pressure reading) 6 percent of the time or false negatives (a missed, or undetected low-pressure reading) 2 percent of the time. The more frequent issue was “no reads” resulting from missing sensors, failed sensors, or sensors in the wrong wheel locations.

Keeping track of individual wheel/tire sensor units themselves was a significant challenge during the field test. This logistical challenge arose because of the high frequency of tire changes; the fact that sensor mounting locations were out of view of technicians; and lack of fleet-wide training on system awareness and operation. Training was limited to the host depot, but occasionally tire and brake maintenance would occur at other depots. It is recommended that training across the entire system be required to prevent technicians from misplacing and inadvertently discarding sensors.

The durability of two TPMS sensor designs was initially challenged by the operating conditions experienced in transit service. Failures occurred with the wheel-mounted sensors two months into testing. Excessive heat build-up caused the sensor housing to become brittle, crack, and fail. The sensor manufacturer provided a design change that consisted of an isolating pad on the bottom side of the sensor that contacted the wheel rim. This simple solution prevented further failures from occurring. Failures also occurred with the sensors that adhere to the tire sidewall early in the test program. The plastic casings on these sensors developed cracks during testing. The cracked sensor casings were determined to be caused by a manufacturing batch defect. Replacement sensors were found to be significantly more durable.

An improvement in adherence to targeted tire pressures was not found on the test fleet compared to the control fleet (i.e., average observed tire pressures between the control and test fleets was roughly the same). This may be because WMATA takes a pro-active role in maintaining target inflation pressures to comply with the tire vendor's warranty. Average tire inflation pressure was 111 psi for both the test and control fleets (target: 115 psi). Tire life and fuel economy were also similar in both fleets. This was likely the case because, as noted earlier, the real time display of tire pressure readings was purposefully not made available to drivers, but only to maintenance personnel and technicians. Drivers could therefore not act immediately on such information to correct any tire pressure problems that may have been detected. In most commercial truck fleets, such real time information would be provided to drivers, and drivers would have the opportunity to act on the information as needed (for example, adding air to tires at the next convenient time if low pressure was detected), thereby improving the average tire life and fuel economy of the fleet.

Two tire blowouts could have been prevented during the course of the field test had the TPMS displays been visible to the bus operators. To maximize safety and operational benefits, it is recommended that system data be made available to the driver in real time (as well as being made available to maintenance staff).

Technicians preferred the wheel-mount tire pressure sensors for two reasons: they were easier to install and tires could be changed without removing or disconnecting the system. Conversely, the technicians found valve-stem-mounted sensors difficult to connect to the inner tires on a set of duals. This issue may be unique to buses because the wheels and tires are surrounded by the structure of the vehicle. Tire-mounted sensors required more time to install (versus wheel or valve-stem mounted systems) because of the required tire surface preparations.

5. BRAKE PERFORMANCE MONITORING SYSTEM FIELD TEST RESULTS

5.1 BPMSS UNDER EVALUATION

The systems selected for this field evaluation program were chosen because they represented a range of technological approaches for assessing brake performance, and because each was examined under controlled test track conditions in prior studies sponsored by the FMCSA. The systems participating in the field trial included:

- MGM eStroke.
- GeoDevelopment Brake Insight.
- StrainSert Brake Performance Monitoring.
- Link Radlinski Model 20200 Portable Roller Brake Tester.

5.1.1 MGM eStroke

5.1.1.1 General Description

The eStroke, by MGM Brakes, is an electronic brake stroke monitoring system that provides brake stroke status readings for pushrod-operated air brakes. The eStroke system consists of a Hall-effect sensor that moves in parallel with the brake actuator piston rod to induce a voltage that is proportional to linear movement. The output from the Hall-effect sensor (i.e., the voltage change) is sent to an integrated ECU/display unit where it is correlated to brake stroke position.

By monitoring brake stroke travel and position, the system can detect overstroke, dragging brake, and/or a nonfunctioning brake actuator. The system must be calibrated during installation for brake systems having different maximum actuator travel in order to properly determine what degree of travel constitutes “overstroke,” dragging brakes, etc.

The Hall-effect sensor itself is contained within the air brake chamber thereby eliminating packaging interference with chassis and suspension components. This “internal chamber” design also serves to protect the sensor components from exposure to the harsh environmental conditions in the wheel end area. Figure 35 shows the MGM brake chamber.

Figure 35. MGM Brake Chamber and Display

The ECU/display unit was located in a control box directly behind the driver's seat. The display, shown in Figure 36, consists of five lights. One light identifies the functional status of the overall system, (if the light is red, the system is not operating properly). The four remaining lights identify the status of the brake assembly at each wheel-end. Unless a green light is present at a particular wheel-end, one of the following conditions had occurred:

- **Overstroke.** If the light at a particular wheel-end location rapidly blinks red.
- **Dragging Brake.** If the light at a particular wheel-end location slowly blinks red.
- **Brake Actuator Not Functioning.** If the light at a particular wheel-end location alternates between red and green.
- **Sensor Fault.** If the light at a particular wheel-end location blinks orange.

As noted in Section 3, the eStroke brake monitoring system is capable of storing brake alarms, warnings, and faults. These events are recorded by the ECU/display unit along with a date and time stamp and a description of the fault(s) detected. The system reports on problems with the brakes or with the system itself. For example, brake problem descriptions (fault codes) include brake overstroke, dragging brake, or brake actuator not working. Examples of system fault codes include: sensor out of alignment; communication failure; failed sensor; low voltage reading; and missing sensor. The system is capable of storing over 2000 separate incidents (or fault codes). The data can be exported onto the vehicle's SAE J1587 or J1939 electronic databus which can then be displayed on "smart" dashboards or transmitted to off-board vehicle monitoring devices.

Figure 36. eStroke System Display

For this field test, the eStroke system data output (i.e., fault code reports) was linked to the AVM system on the bus (supplied by Clever Devices). The AVM system was capable of wirelessly off loading data to a central server located at the bus garage. The server would then automatically send emails to the maintenance personnel and study team on the status of the bus's brakes as reported by the eStroke system.

5.1.1.2 Installation

The MGM eStroke system was factory installed at Orion Bus Industries manufacturing facilities in Mississauga, Ontario, Canada. The work required to integrate the eStroke system with the AVM was completed by MGM and the AVM system manufacturer, Clever Devices, as part of the bus procurement contract between WMATA and Orion.

5.1.2 GeoDevelopment Brake Insight

5.1.2.1 General Description

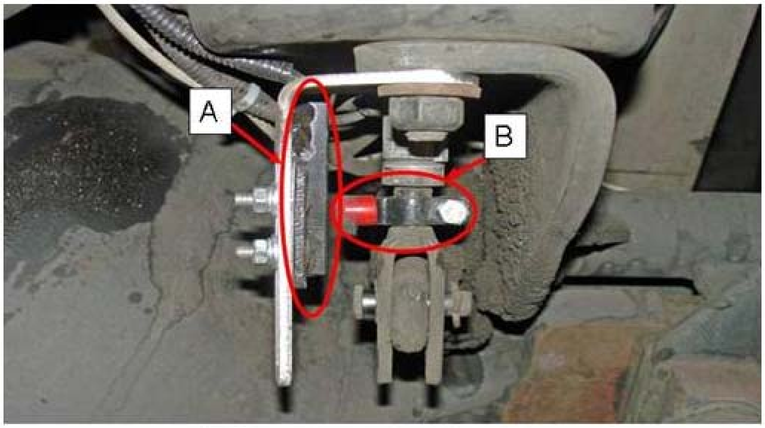
The Brake Insight system, by GeoDevelopment,[§] is a brake stroke monitoring system that is similar to the MGM eStroke in that it uses a Hall-effect sensor to measure brake stroke travel and positioning. The difference is that the sensor and related hardware are mounted *outside* (or external to) the brake chamber. The Brake Insight system consists of the following main components:

- Wheel-end sensors (to electronically monitor brake stroke travel).
- Thermocouples and lining wear sensors.
- S-box control unit (ECU).
- Display unit.

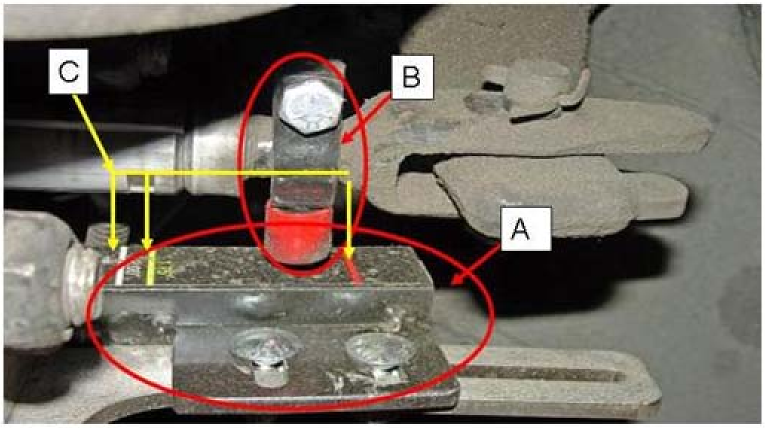
[§] GeoDevelopment, distributed by Truck Trailer Transit, 1601 Theodore Street, Detroit, MI 48211; www.tttonline.com.

Wheel-end sensors. The wheel-end sensors (shown in Figure 37), consist of (A) a Hall-effect sensor, (B) a magnetic clevis pin (which links the push rod from the brake chamber to the S-cam brake lever assembly), and (C) visual indictors of brake stroke. Similar to the eStroke system, the Hall-effect sensor for the Brake Insight system has a magnet (i.e., the clevis pin) that moves in parallel with the actuator piston rod to induce a voltage change in the sensor. Brake Insight has an electronic control module (called the S-box) that processes the voltage change and determines the travel and position of the push rod. The Brake Insight system is capable of detecting normal stroke, overstroke, dragging brake, and a nonfunctioning brake actuator based on brake stroke travel.

The outside casing of the Hall-effect sensor unit is also scribed with precisely placed markings (visual indicators) which can be used to determine the relative position of the pushrod, ("C" in Figure 37). The markings are calibrated in a manner that would allow a technician to quickly determine an over or understroke condition during a conventional (manual) brake actuation test. Using the magnetic clevis pin as a pointer, the indicators provide a visual means to check the brakes in the event of a power or display failure.



Side View of Hall-effect Sensor and Magnetic Clevis Pin



Top View of Hall-effect Sensor, Magnetic Clevis Pin, and Visual Indicators

Figure 37. Brake Insight Components

Each brake stroke actuator sensor is mounted on a bracket that allows the unit to be adjusted for various brake chamber designs and stroke lengths (from 1.75 inches to 3.0 inches). Figure 38 shows a wheel-end sensor before mounting on a brake chamber. The two bolts that secure the sensor to the bracket can be loosened, and the sensor can slide along the bracket to line up with the magnet on the pushrod.

Figure 38. Brake Insight Wheel-End Sensor and Mounting Bracket

Lining Wear and Brake Temperature Sensors. Unique to the Brake Insight system is the application of shoe lining wear and temperature sensors (Figure 39). These sensors are integrated into the system and help signal normal maintenance requirements (prognostics), as well as to detect potential brake system problems. The information from these sensors can augment the information from the brake stroke sensor to diagnose potential brake system issues.

The shoe lining wear sensor is simply a metal plug with a set of electrical contacts affixed on the surface. The plug is then embedded in the shoe lining at a depth indicative of end-of-life wear. When the lining wears to this depth, the metal contacts on the plug become short-circuited, sending a signal to the ECU indicating the shoe linings have reach the end of their useful life. A thermocouple is also integrated into the sensor plug, and the output is continuously monitored by the ECU to detect excessively high brake temperature. For the WMATA application, when a temperature of 685 degrees F is reached, the ECU sends a high temperature warning signal to the Display unit.

The left photo (Figure 39) shows the wear side of the sensor, and the center photo shows the mounting hardware where the thermocouple connects to the wear sensor and shoe. A single cable is connected to the sensor unit (right photo) to route information to the ECU (S-box). This cable contains three leads (one for the thermocouple and two for the lining wear sensor).

Figure 39. Lining Wear Sensor Installed in Brake Shoe

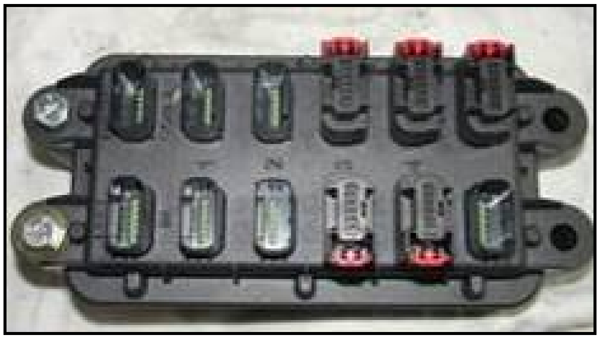


Figure 40. Brake Insight ECU (S-box)

S-box ECU. The brake stroke actuator sensors and the lining wear/temperature sensor units at each wheel-end were hardwired to the S-box control unit (or ECU, see Figure 40). The Brake Insight monitoring system is designed to store fault codes associated with various brake system abnormalities and events, as well as fault codes associated with the system itself (self diagnostic codes). The various fault codes are recorded along with a date and time stamp and a description of the problem or issue. For example, brake problem descriptions included brake overstroke, dragging brake, brake out of adjustment, brake out of service, high brake temperature, and worn shoe lining. There are unique fault codes to identify each wheel-end (i.e. for each sensor unit installed on the vehicle) and for each type of occurrence. Examples of a "system" problem include sensor out of alignment, communication failure, failed sensor, low voltage reading, and/or missing sensor. The system is capable of storing 2,700 fault codes. The data could be exported via a RS-232 connection located on the faceplate of the display unit.

Display Unit. The S-box is hardwired to the Display unit (Figure 41) which was located in the I/O box behind the driver's seat. The Display can be programmed to operate in "Driver Mode," or in "Maintenance Mode." In Driver mode the software will display only critical faults to the driver as defined by the customer. In maintenance mode all fault conditions are displayed.

Figure 41. Brake Insight Display Unit

5.1.2.2 Installation

The GeoDevelopment Brake Insight system was installed on WMATA bus numbers 2505, 2506, 2507, and 2508. Truck Trailer Transit Inc., a distributor of Brake Insight, provided three service technicians to lead the installation. The factory technicians began by installing the magnetic clevis pins on the pushrods extending from the brake chambers. Normally, the original clevis pins that link the pushrod to the slack adjuster are removed and replaced with the magnetic pins. However, the clevis pins used with the MGM brake chambers on the WMATA buses were welded in place and could not be removed. To overcome this issue, the technician installed a pipe clamp with a magnetic end on the pushrod near the existing clevis pin. Once the magnets were installed on the pushrods, the technicians mounted the wheel-end sensors to the brake chambers using the supplied brackets.

Cabling was routed from the sensors mounted at each brake chamber along the underside of the bus to the S-box located just forward of the front driver’s side wheel well. The S-box was mounted to the underside of the bus, near the air reservoir, and protected from road debris. Figure 42 shows the location of the S-box, display unit, and wheel-end sensors.

Figure 42. Brake Insight Component Mounting Locations

To install the lining wear/brake temperature sensor units, all of the wheels and brake drums were first removed from the test bus. Next, the four S-cam drum brakes were disassembled as if performing a scheduled brake job. Using a drill press, a guide hole was drilled through the brake shoe from the metal side of the shoe. Then, the technician flipped the shoe over and drilled through the brake lining and shoe with a 5/8-inch hole saw. The lining wear/temperature sensor unit was then mounted in the hole in the brake shoe.

5.1.3 StrainSert Brake Performance Monitoring

5.1.3.1 General Description.

The StrainSert brake monitoring system consists of the following main components:

- Instrumented brake anchor pins.
- ECU.
- Display unit.

Instrumented Anchor Pins. The StrainSert system uses strain gauges affixed to the anchor pins on the S-cam drum brake assembly to measure shear stresses that develop during a braking event. Earlier studies have confirmed that these shear stresses correlate closely with actual brake force.

Each anchor pin is fitted with two strain gauges oriented 90 degrees apart. One of the strain gauges is mounted normal to the direction of rotation, 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 other 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 system consists of four anchor pins, (one for each brake assembly) which are mounted on the primary shoe, (Figure 43). The output from the sensors are routed to an electronic control unit. The anchor pin shear stress values are monitored and compared with the values of the other brakes and with empirical data. Values exceeding preset thresholds (either absolute values, or differential values among sensors) are flagged as “faults”, and an appropriate alert signal is sent to a display unit.

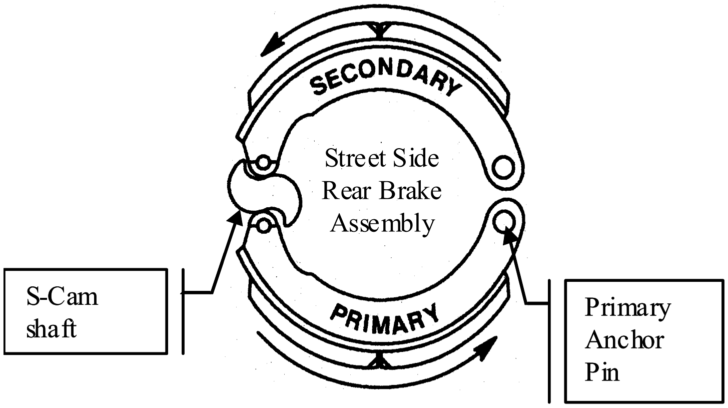


Figure 43. S-Cam Brake Assembly Diagram

Figure 44 shows an instrumented anchor pin uninstalled (left and center photos), and installed in a brake assembly (right photo).

Figure 44. StrainSert Anchor Pin

Notice the grease fitting on the anchor pin in the top left photo. The grease fitting on the original anchor pin was relocated from the center of the pin to the connector end to accommodate the addition of the strain gauges.

ECU and Display. Sensor units are hardwired to an ECU, which is then connected to a Display Unit (Figure 45). The various threshold warning parameters and fault code algorithms are customized for specific applications by an authorized technician (see Installation, next section.) The system is designed to detect out-of-adjustment brakes, dragging brakes, oil-soaked linings, and disconnected shoe linings.

Figure 45. StrainSert ECU and Display Unit

5.1.3.2 Installation

The StrainSert Brake Monitoring System was installed on WMATA bus numbers 2509, 2510, 2511, and 2512. StrainSert provided three service engineers to lead the installation and configure the systems.

StrainSert custom manufactured the brake anchor pins to replace those used in the Orion VII buses. To install the instrumented anchor pins all of the wheels and brake drums were removed from the test bus. Next, the four S-cam drum brakes were dissembled as if performing a scheduled brake job. The stock anchor pins were replaced with the StrainSert units and the brakes were then reassembled.

Figure 46 illustrates the mounting locations for the ECU, display unit, and brake anchor pins. The ECU was mounted to a support beam above the lighting track on the street side of the bus.

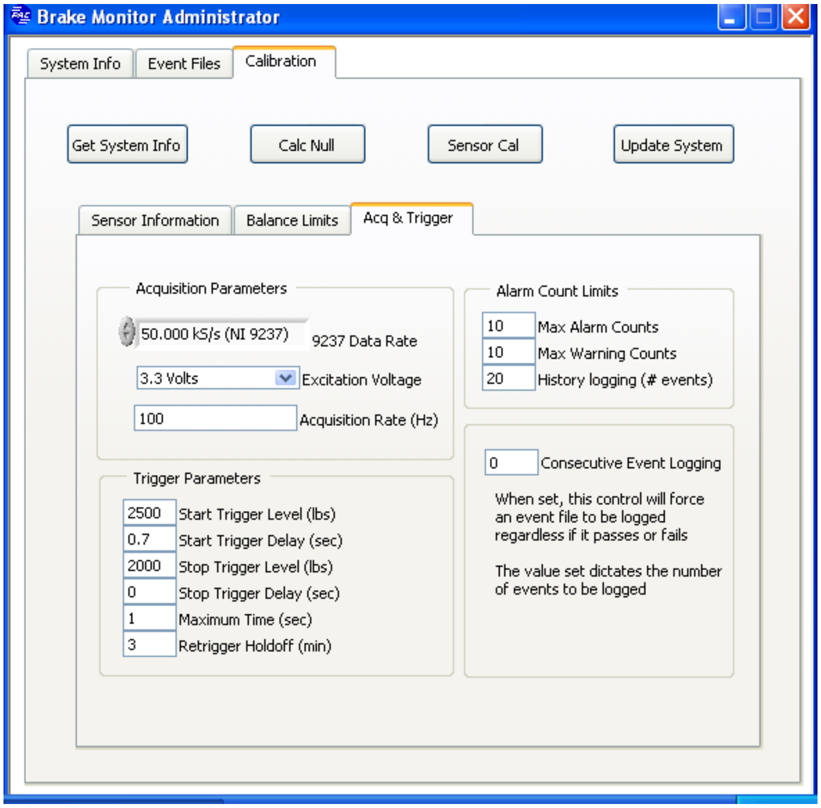
Figure 46. StrainSert Component Mounting Locations

The display unit was installed inside the I/O cabinet located behind the driver's seat and out of view of the driver.

An eight-conductor shielded cable connected each instrumented anchor pin to the ECU. The shielded cables were routed from each brake assembly along the underside of the bus to an electrical compartment below the driver's side window. The cables were secured to the bus's wire harnesses and hoses with zip ties. The cables were then pulled into the I/O cabinet behind the driver's seat and into the cable tray behind the lighting track in which the ECU was mounted.

Once all of the system hardware was installed on the bus, the system was calibrated. A StrainSert engineer connected a laptop to the Ethernet port on the front of the display unit. The laptop provided a user interface to communicate directly with the ECU. The engineer set trigger parameters and warning thresholds for the system using the programming menu depicted in Figure 47.

The "trigger parameters" shown at the bottom left portion of Figure 47 represent the brake force values at which the system would start and stop monitoring a braking event. In this example, the "start trigger level" was set at 2,500 foot pounds to ensure the system would begin monitoring only if the brakes were applied with intent to stop the vehicle—not if the driver was simply riding the brakes. In this example, the system captures brake force readings in 1-second intervals and stops monitoring braking force when the force drops below 2,000 foot pounds.



Acquisition Parameters

50.000 kS/s (NI 9237) 9237 Data Rate
3.3 Volts Excitation Voltage
100 Acquisition Rate (Hz)

Trigger Parameters

2500 Start Trigger Level (lbs)
0.7 Start Trigger Delay (sec)
2000 Stop Trigger Level (lbs)
0 Stop Trigger Delay (sec)
1 Maximum Time (sec)
3 Retrigger Holdoff (min)

Alarm Count Limits

10 Max Alarm Counts
10 Max Warning Counts
20 History logging (# events)

0 Consecutive Event Logging

When set, this control will force an event file to be logged regardless if it passes or fails

The value set dictates the number of events to be logged

Figure 47. StrainSert Calibration Software Screenshot

The brake balance parameter (not shown in Figure 47) establishes the threshold at which a brake warning or alarm would trigger. The brake balance parameter compares the braking force of the left brake and the right brake on each axle. If the difference is greater than 30 percent, a "warning" is logged by the system. If the difference is greater than 40 percent, the system logs an "alarm." An alert message is sent to the Display unit only after the system generates a minimum number of warnings or alarms. A user-defined "alarm count limits" parameter is used to set the number of warnings or alarms required for the system to generate an alert. For the screen shot shown in Figure 47, the Alarm Count Limits parameter was set to send an alert to the display unit after generating either 10 system warnings or 10 system alarms.

5.1.4 PBBT

The Link Radlinski Model 20200 portable Performance Based Brake Tester (Figure 48), also known as a PBBT, was incorporated into the program to serve as a reference measurement tool for evaluating the accuracy of the on-board brake performance monitoring systems, and more generally to assess the pros and cons of off-board brake system testing relative to integrated onboard BPMS. This roller dynamometer-based system, with two 11 kW three-phase drive motors with mechanical brakes, can dynamically measure the rolling resistance; brake threshold pressure; service brake force; parking brake force; and antilock braking systems (ABS) sensors, valves, and wiring. The PBBT provides an industry-accepted reference measurement of brake performance. Basically, the vehicle's front or rear wheels are positioned on top of the roller dynamometer. An electronic alpha-numeric message board is positioned in front of the bus and provides the operator with instructions for executing various braking maneuvers. The rolling resistance of the dynamometer is pre-programmed to simulate the weight and rolling inertia of the bus itself.

The large wall-mounted display, shown in the right photo of Figure 48, was provided with analog dials to indicate: left and right brake forces; percent brake force differences; digital displays of brake system control air pressure; axle weight; and overall deceleration rates.

Figure 48. PBBT and Operators Display

5.1.4.1 Installation

The offboard PBBT system was installed at the Four-Mile Run maintenance facility. The offboard system monitored the rolling resistance and service brake force for the test fleet and the control fleet.

5.2 CONTROL VEHICLES

To facilitate the evaluation of the BPMSs, data related to brake condition, maintenance and cost was also monitored for a group of buses that did not utilize any type of brake performance monitoring system (i.e., standard buses). These buses were the same make and model as the test buses and included bus numbers: 2513–2524. The buses were operated out of the Four Mile Run facility, and used in a similar service environment as the test fleet.

5.3 TEST RESULTS

This section of the report presents the results of an evaluation of the brake performance monitoring systems based on analyses of data and information collected throughout the field test.

The analysis of the data and information collected focused on assessing:

- Reliability, durability, and maintainability of the systems.
- Whether BPMSs can be used by fleet and maintenance mangers to improve the efficiency of brake system maintenance by reducing the need for visual inspections.

Data collected for the test vehicles included:

- Weekly visual inspections of brake systems (brake chambers; drums, linings, etc).
- Maintenance records for the brake system as well as the BPMSs.
- Weekly visual inspections of the brake monitoring systems, including recording the status of the display units (presence of warnings, alarms, etc.).
- Periodic downloads of the brake monitoring system’s fault code logs.

The visual inspections were completed over a 14-month period, from September 2006 to November 2007. During the first 2 months, the test vehicles and their newly installed equipment were validated and confirmed to be working properly. Full data collection began in November 2006. Visual inspections were performed approximately once a week by a study team engineer and included brake assemblies, pad wear, brake stroke, and system status. Information was recorded on brake data forms as shown in Appendix A.

Each bus was inspected approximately 50 times throughout the course of the test, resulting in a total of 590 bus inspections and 2,360 separate wheel-end inspections (see Table 15). In addition, electronic reports listing all recorded fault codes were downloaded from the systems’ ECUs approximately once per month, depending on the system.

Table 15. Total Bus and Wheel-End Visual Inspections by System

System	Bus Inspections	Wheel-End Inspections
eStroke	190	760
Brake Insight	199	796
StrainSert	201	804
Total	**590**	**2,360**

The 24 buses were also tested on the PBBT approximately once per month to record the "actual" performance of the braking system, for a total of approximately 200 PBBT records.

5.3.1 Overall Braking System Performance and Reliability

A total of 124 brake maintenance records were generated and identified during the test period. These maintenance records included scheduled maintenance actions—specifically brake overhauls; and, unscheduled maintenance actions which included brake fault, brake overhaul, dragging brake, hardware failure, over-stroke, pulling brakes, sensor fault, and slack adjuster.

Table 16. Summary of Brake Maintenance Records on Test and Control Fleets

Brake Maintenance Issue	Test Vehicle Maintenance Records	Control Vehicles Maintenance Records	Total Maintenance Records
Brake Fault	10	6	16
Brake Overhaul	8	11	19
Dragging Brake	8	11	19
Hardware Failure	15	6	21
Overstroke	9	8	17
Pulling Brakes	6	2	8
Sensor Fault	9	4	13
Slack Adjuster	10	1	11
Total	**75**	**49**	**124**

The eight maintenance record categories in the table above were pre-defined by WMATA's maintenance management system (MAXIMO). Most category titles such as "brake overhaul", "dragging brakes", and "overstroke" define a specific abnormality or maintenance activity. In contrast, the "Brake Fault" category is a generic label for a variety of miscellaneous brake related maintenance actions. Many maintenance records labeled as a "Brake Fault" included descriptions such as brake noise, hot brakes, brake lock-up, and brake chamber leak. The maintenance records labeled as "Sensor Fault" were all associated with the eStroke system's wheel-end sensors (eStroke was factory installed on both the test and control buses). The most common cause for the sensor faults was a damaged wire harness near the MGM brake chamber that impaired communications between the eStroke sensor and ECU. During the test period, other than eStroke sensor faults, the BPMS only caused a single failure, which was due to a cable failure.

The brakes on the Orion VII buses were found to be quite reliable. Throughout the course of the test, the maintenance records did not highlight any significant brake failures. As shown in Table 16, the number of maintenance records on the 24 test and control buses were rather evenly distributed across the eight maintenance record categories (No one type of abnormality occurred with significantly greater frequency than the other seven types). In addition, the Orion VII buses' original equipment manufacturer-installed brake linings accumulated roughly 2.5 times the average mileage of the aftermarket brake linings used by WMATA on the general fleet. The first brake overhauls for the test and control buses were conducted after the buses had accumulated, on average, 62,000 miles. In comparison, WMATA's general bus fleet, equipped with aftermarket brake linings, required a brake overhaul after approximately 25,000 miles.

The durability of the factory brakes were so good that there were five buses that did not require a brake overhaul at all during the field test—and this group accumulated an average of 75,929 miles by the end of the test, (see Table 17)

Table 17. Brake System Overhauls: Test versus Control Fleets

Test Fleet Bus #	Test Fleet # of Brake Overhauls	Test Fleet Total Test Mileage	Test Fleet Mileage at Overhaul	Control Fleet Bus #	Control Fleet # of Brake Overhauls	Control Fleet Total Test Mileage	Control Fleet Mileage at Overhaul
2501	0	70,396	N/A	**2513**	1	84,263	58,146
2502	0	77,102	N/A	**2514**	0	80,616	N/A
2503	1	56,901	56,901	**2515**	1	84,042	60,327
2504	0	69,269	N/A	**2516**	1	84,691	68,874
2505	1	71,912	55,864	**2517**	1	65,290	63,070
2506	0	82,263	N/A	**2518**	1	76,400	65,607
2507	1	79,521	65,607	**2519**	1	76,936	75,112
2508	1	78,859	67,192	**2520**	1	77,898	64,773
2509	1	76,320	63,238	**2521**	1	72,524	61,259
2510	1	71,584	67,110	**2522**	1	71,748	69,359
2511	1	77,173	57,849	**2523**	1	74,021	59,247
2512	1	56,300	47,119	**2524**	1	73,489	65,160

The weekly visual inspections of the BPMSs identified a total of 69 brake "anomalies" as defined by the presence of a visual alert or fault signal at the display unit (see Table 18). Brake anomalies occurred in only 11.7 percent of the total weekly visual inspections.

Of the 69 "unsafe" brake conditions reported by the BPMSs, 50 were confirmed to be actual brake system faults (see Table 19). The remaining 19 brake faults were identified as false positives. A brake fault was categorized as a false positive when the reported unsafe brake conditions could not be visually validated through an inspection of the brake assemblies. The false positives accounted for 27.5 percent of the total brake inspections.

Table 18. Brake System Anomalies Identified by BPMSs During Visual Inspections

System	Yes	No	Total Entries
eStroke	2	188	190
Brake Insight	48	151	199
StrainSert	19	182	201
Total	**69**	**521**	**590**

Table 19. False Positive Brake Faults by System

System	Total Reports	Valid Reports	False Positive Reports
eStroke	2	2	0
Brake Insight	48	40	8
StrainSert	19	8	11
Total	**69**	**50**	**19**

The following sections are an analysis of the findings for each BPMS:

5.3.2 MGM eStroke System Analysis

The eStroke system has two methods of reporting brake system fault messages. The first method is through the use of the visual display on-board the vehicle. The second method was through the wireless transmittal of eStroke alerts (fault code logs) to a server residing at the maintenance garage, (this was accomplished by utilizing the vehicle's AVM system). A review of information collected by these two methods is reviewed in the following sections.

5.3.2.1 System Display Warnings

Shortly after the first of WMATA's Orion VII buses entered into service, the eStroke system generated numerous alerts for a dragging brake condition on each of the buses in service. WMATA technicians inspected the brake assemblies on several buses and verified the dragging brake warnings reported by eStroke. The WMATA maintenance staff determined that the buses were delivered from the manufacturer with an alignment problem between the brake chamber pushrod and the slack adjuster. The manufacturer had selected a camshaft retention method that allowed the removal of the automatic brake adjuster without removal of the wheel-end. The retention method necessitated use of a shorter S-cam shaft, which was not delivered with the brake assemblies. As a result, the pushrod and slack adjuster were misaligned, slowing the pushrod's travel and causing a dragging brake. An interim fix corrected the pushrod alignment by installing hardened spacers. The permanent retrofit replaced the original camshaft with a shorter version. The misaligned brakes could have gone undetected for months if eStroke had not alerted maintenance of the defect, proving the effectiveness of the system to the maintenance staff.

During the course of the field test, 190 visual inspections were completed on the eStroke test buses (bus numbers 2501 to 2504). The eStroke display alerted the inspector to brake system issues during two of the inspections—one a sensor fault and the other a dragging brake condition. The sensor fault was identified on the left rear brake assembly of bus number 2502 during an inspection in June, 2007. A physical inspection of the equipment revealed that the cable connecting the sensor to the system was disconnected (and therefore the eStroke correctly identified the issue). During the previous week, a maintenance record had been generated because of a cracked sensor at the same location that was replaced (the cracked sensor was most likely caused by the previously described slack adjuster alignment issue). It is assumed that the cable was not properly attached after the sensor was replaced.

5.3.2.2 eStroke System Brake Status Reports

As noted, the eStroke fault code logs (stored on the system's ECU) are wirelessly transmitted from the vehicle to server at the bus garage. The server generates automatic system reports and distributes them to WMATA daily via email. Fault code reports were tracked for test-group bus numbers 2501, 2502, 2503, and 2504. WMATA packaged the daily reports together and emailed them to the study team once per week.

A review of the weekly fault code logs identified a need to add a logic filter to eStroke's reporting method. The system reports a fault code for any and all "abnormalities", as well as a "cleared message" code when the fault is cleared as defined by the SAE 1708 protocol. During the course of the test, the eStroke system generated 4,230 messages. Many of the messages were related to overstroke conditions caused by the axle design, dragging brakes and cracked sensors associated with the early brake system misalignment issues. Compounding the problems with the brake system itself, was an overly sensitive dragging brakes threshold setting within MGM's eStroke software. WMATA stated that within 2 months of putting the eStroke-equipped buses into service, it recognized the need to establish a filtering method for fault codes in order to differentiate between "real" brake problems requiring maintenance attention—versus fault codes associated with lesser (or temporary) problems such as hot brakes, or the inherent sensitivity of the Orion bus brake system to dragging brakes (i.e. the alignment issue). Hence, WMATA monitored the daily eStroke reports to determine the number of messages that had to be generated before an "actionable" failure could be identified. In the end, WMATA only inspected buses that generated more than 30 alerts in a single day. Ideally, the brake system on the bus would have been be reconfigured to create a shorter brake stroke. Reducing the normal operating baseline stroke travel from 2.5 inches to 2.25 inches would significantly reduce the number of overstroke conditions detected by the eStroke system. In the current configuration, the pushrod stroke is within the acceptable FMVSS stroke range when the brakes are cold. However, when the current brake configuration becomes hot, the pushrod stroke can exceed 2.5 inches which is then logged as an overstroke condition. Such design changes however would not only require extensive modifications to the brake system but also changes to the orientation of the axle, changes Orion was unwilling to perform.

Similarly, the study team also developed a filtering method that could be applied to the weekly fault code reports to better identify those instances in which a real brake system failure likely existed. This was accomplished by comparing the eStroke fault code messages to actual brake maintenance actions performed. As shown in Table 20, the 4,230 alerts generated during the field test could only be correlated to 24 actual maintenance records where brake repairs were performed, (resulting in a reliability factor of less than 1 percent). To achieve a reliability factor higher than 90 percent, the eStroke system had to generate at least 60 fault codes in one week at a single wheel location. By flagging these instances, a reliability factor of 92 percent was achieved, with 12 eStroke alerts and 11 corresponding brake system maintenance records. A review of maintenance records showed that system "alerts" (as defined by 60 or more fault codes in one week) generally corresponded to maintenance actions such as: dragging brakes; brake overhauls; broken eStroke hardware; and overstroke conditions.

Table 20. eStroke System Report Filtering

Filter (Alerts Per Week)	Total Alerts	Number of Related Maintenance Actions	Reliability (%)
No filter	4,230	24	0.5
Greater than 20	39	15	38
Greater than 30	27	13	48
Greater than 40	16	12	75
Greater than 50	13	11	85
Greater than 60	12	11	92

The remaining alerts from the weekly eStroke system report were identified as false-positive reports. Some of these alerts were the result of a software problem which was identified during the preliminary testing phase. Specifically, in December 2006 the eStroke monitoring system detected intermittent dragging brake conditions but the brakes were inspected and found to be operating properly. The cause of the false (or improper) dragging brake condition alert was identified as a signal lag between the time the sensor signal was generated and the time the eStroke ECU received the signal. The signals were originally sent via the vehicles' network to the ECU through a J1708/J1587 connection. The lag time between signal generation and signal processing at the ECU was significant enough to generate inaccurate brake condition readings. The system was upgraded to accept and process signals directly from the signal source. As a result, the number of false alarms declined.

Other alerts identified in Table 20 were likely minor faults generated as a result of a momentary communication loss; or because of high (but within performance limits) brake temperatures. Although WMATA (and the study team) have generated tailored filters to eliminate an excessive number of false-positive alerts, the weekly fault code report does not provide a definitive evaluation of the condition of the brake assembly. However, the weekly fault code reports do provide sufficient information such that maintenance staff can interpret the data and decide whether to pull the bus from service and complete a more thorough inspection.

5.3.2.3 Hardware Failures

During the first few months of field test, failures related to the eStroke wiring harness (that runs between the sensor units and the ECU) as well as the sensor units themselves, were identified as significant problems on the entire fleet of eStroke-equipped buses. (Note: all 24 buses that were the focus of this field test (12 in the "test" fleet and 12 in the "control" fleet) were equipped with the eStroke system since that system was ordered as standard equipment on all buses.)

Of the 124 brake system related maintenance records collected on the test and control fleet, 34 were generated as a result of a eStroke hardware malfunctions ("Hardware Failure" and "Sensor Fault" maintenance record categories, Table 16). These malfunctions (or failures) included chaffed wiring harnesses, pinched harnesses, cracked sensors, and loose sensors. Put another way, over the 12 month test period, every bus in the field test program experienced about 1.3 hardware failures on average, (34 hardware failures divided by 24 buses). Over time, the frequency of the failures decreased for a variety of reasons including:

- Replacement of the sensors and rerouting of the wire harnesses.
- Correction of the misaligned brake chambers installed by the vehicle manufacturer
- Engineering changes to MGM's sensor harnesses and wiring that include the addition of a protective loom around all cables with exposed single conductive wires.

5.3.2.4 Summary Observations (eStroke)

Overall, WMATA's confidence in the eStroke system, (developed through this field test program), led it to revise its brake maintenance intervals to eliminate a visual brake inspection during the "A" inspection, which occurs at the 3,000-mile interval. Instead, the technicians rely exclusively on the eStroke system log to identify any brake abnormalities. A thorough brake inspection is performed at the "B" inspection, which occurs at the 6,000-mile interval. At the B inspection, the technicians measure brake lining wear, measure brake stroke, verify slack adjuster operation, and perform other brake diagnostic procedures.

5.3.3 Brake Insight System Analysis

The weekly inspections of the Brake Insight-equipped buses included recording the presence of any alerts at the system display. The display, shown in Figure 49, consists of 14 lights. The system is operated by querying the status of each wheel-end. If a particular alarm was present at that location, a red indicator was illuminated, along with a separate indicator to identify the type of fault.

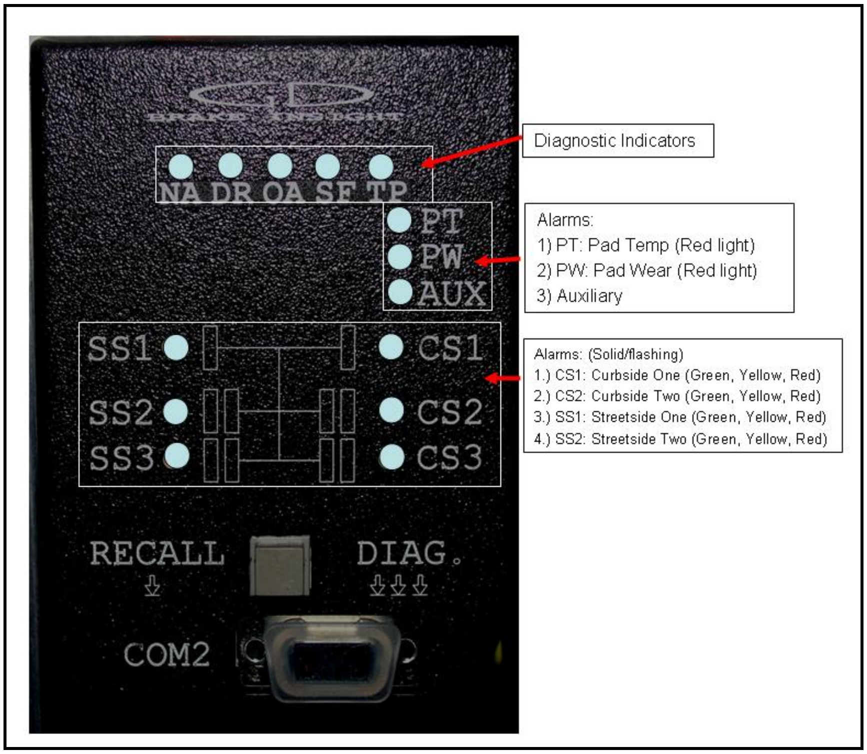


Figure 49. Brake Insight Display

During the field test, the Brake Insight system issued 48 alerts indicating dragging brakes, sensor faults, high temperature, worn shoe linings, and/or brake overstroke. Table 21 lists the total number of alerts by type.

Table 21. Brake Insight Visual Alerts

Bus #	Overstroke	Dragging Brake	High Temp	Sensor Fault	Lining Wear	Total
2505	1	1	7	4	0	14
2506	9	0	0	5	0	14
2507	5	3	2	3	0	13
2508	2	0	4	2	0	8
Total	**17**	**4**	**13**	**14**	**0**	**48**

5.3.3.1 Overstroke

The Brake Insight system recorded 17 overstroke alerts on the four test buses during the field test. This represents 35 percent of the total alarms. In 3 of the 17 cases, there is a corresponding service record in WMATA's maintenance database. Two of these records show that slack adjusters were serviced; the third record notes that the bus pulls to the left. For another nine of the overstroke alarms, the measured stroke was 2.5 inches, which is just at the adjustment limit for the rear brake assemblies. The alarms were cleared after the inspections. The cause of these alarms is assumed to be related to the original equipment manufacturer's brake design. During testing, the WMATA technicians noted that design of the brakes for the Orion VII buses provided little margin before an overstroke condition developed. As a result, the brakes were found to overstroke frequently during service as the brake drum heated and expanded. After the buses returned to the maintenance facility and the brakes cooled, the brake stroke was within the allowable stroke limits. Due to this heating and cooling effect, a large number of overstroke conditions reported by the Brake Insight system could not be validated during a visual inspection. (Note: this same phenomena occurred with the eStroke system).

The remaining five alarms could not be validated. A visual inspection found the brake stroke to be well within the adjustment limit. A review of the maintenance records showed that the WMATA technicians did not perform any brake adjustments or inspections on the identified buses. It is assumed these five alarms were simply false positives.

5.3.3.2 Dragging Brakes

The Brake Insight system detected four occurrences of dragging brakes representing 8 percent of the total alarms. All four alarms occurred within the first 2 months of the test program. The weekly inspections did not reveal any indication that the brakes were dragging. The dragging brake alerts were attributed to a software problem identified in January 2007. Brake Insight uses an algorithm to monitor and compare the current and previous positions of each stroke sensor. The software program's sampling rate monitored the stroke sensors at each brake chamber too frequently, causing the warning thresholds for a dragging brake condition to be too sensitive. Brake Insight installed a software upgrade to reduce the sampling rate of the stroke sensors on March 9, 2007. As a result, the detected number of dragging brakes was reduced to zero.

5.3.3.3 High Temperature

The Brake Insight system recorded 13 “high brake pad temperature” alarms, representing 27 percent of the alarms. A high brake pad temperature was detected when the system detected a pad temperature in excess of 685 degrees Fahrenheit, as set by the system vendor. The weekly inspections and maintenance records from the alarm period did not reveal any brake-related issues.

Two factors could have caused the high brake pad temperature alarms. First, all of the alarms occurred between May and August 2007. Because of the Washington, DC, summer climate, high brake pad temperatures caused by the stop-and-go operating service of a transit bus are not uncommon. The brake pad temperatures may have reached the 685 degrees threshold during normal operation without causing any abnormal (or unsafe) brake conditions. After the bus returned to the maintenance facility or reached the end of its route and remained idle for an extended period of time, the brake pad temperatures would have returned to normal. Second, the placement of the temperature sensor in the shoe lining may have induced false pad temperature alarms. In fact, 7 of the 13 brake pad temperature alarms occurred after a rear brake reline procedure which may have resulted in incorrectly installed temperature sensors; these 7 alarms also occurred in conjunction with a sensor fault. After the alarm was cleared and the sensor fault corrected, no further alarms were generated.

5.3.3.4 Sensor Fault

Fourteen wheel-end sensor faults occurred during the test program, representing 30 percent of the total alarms. The majority of the failures were identified as communication issues, but four alarms were traced to wiring issues. For example, on March 9, 2007, the display on bus number 2507 indicated a loss of communication between the S-Box (ECU) and the sensor at the right front wheel-end. An inspection of the hardware revealed a broken wire in the wire harness where the wheel-end cable was connected to the main trunk line leading to the S-Box. The wire harness was replaced, and the sensor fault alarm was extinguished. The cause of the broken wire was not identified. No actual sensor units were replaced or found to be faulty during the field test.

5.3.3.5 Lining Wear

As mentioned earlier, the Brake Insight system features a wear sensor imbedded in the shoe lining. As the lining wears out, the brake drum contacts and cuts the wire loop sensor, causing an open circuit and generating a lining wear alarm. No lining wear alarms were generated during the field test; however, on three different occasions, technicians recorded shoe lining thickness as having failed (minimum thickness requirement not met) the weekly inspections. All three failures resulted in the rear brakes being overhauled. Upon inspection, the lining wear sensors were installed deeper in the lining than the WMATA’s acceptable wear limit, resulting in the brake shoes being replaced before the sensor could be activated.

5.3.4 StrainSert System Analysis

The StrainSert system is designed to identify out-of-adjustment brakes, dragging brakes, oil soaked linings, and/or disconnected brakes. The weekly visual inspection of the StrainSert-equipped buses included identifying and logging the presence of any alerts or warnings at the system display. The display, shown in Figure 50 consists of two counters and a scrolling display.

The two counters identify the number of alerts and warnings generated at each wheel location. The scrolling display lists the potential brake problems at specific wheel locations. The StrainSert system categorizes brake problems as follows:

- **Warning.** The warning message is triggered if the difference in brake force between brakes on the same axle is greater than or equal to 30 percent. The occurrences are tracked per wheel location on the system display.
- **Alarm.** The alarm indicator is triggered if the system detects a difference greater than or equal to 40 percent in brake force between brakes on the same axle. (The out-of-service brake criteria used by the Commercial Vehicle Safety Alliance defines the alarm criteria). The system's algorithm is able to identify the specific wheel location that is likely to have a brake problem by comparing brake forces between axels (as well as between wheel-ends on the same axle), and determining which wheel-end (on each axle) deviates the most from the average of all wheel-ends. In Figure 50, the display shows that the system detected two instances of the brake force differential exceeding 40 percent between the left and right rear brake assemblies, with the brake problem likely in the left rear brake assembly.
- **Service Required.** The "service required" message indicates that a wheel-end has exceeded a pre-determined threshold limit for the number of alarms or warnings within a given timeframe. For the WMATA field test, a warning or alarm must have occurred 10 times at a single location during the same trip before the "service required" message appears on the display. The message indicates the wheel-end of the assembly requires immediate servicing.

Figure 50. StrainSert Display

The StrainSert-equipped buses generated 19 total alerts during the field test, indicating either a system warning, system alarm, or required brake service. Table 22 shows the alert distribution. The alerts were distributed among bus numbers 2509, 2510, and 2511. During the field test, StrainSert requested to use one of the installed systems in its labs to refine the software algorithms and thresholds. The system installed on bus number 2512 was removed and provided to StrainSert for lab testing. As a result, bus number 2512 did not record any failures.

Table 22. StrainSert Visual Warnings

Bus #	Warning	Alarm	Service Required	Total
2509	1	3	5	9
2510	1	1	2	4
2511	4	0	2	6
2512	0	0	0	0
Total	**6**	**4**	**9**	**19**

5.3.4.1 System Software

During the course of the test, StrainSert issued one software update and two threshold updates to improve the performance and accuracy of the system. The software update, issued December 13, 2006, upgraded the display unit software to provide wheel-end specific data. The original software tracked the alarms and warnings at the vehicle level but did not specifically identify the wheel-end that triggered the alert. The revised system software tracks the alarms and warnings for specific wheel-ends, incrementing the specific counter each time the ECU detects an alert.

As noted, the StrainSert system compares brake forces among wheel-ends and generates alerts if/when the differential readings exceed a pre-determined threshold. However, during early development, StrainSert found that comparing brake forces during light (or momentary) braking events can be problematic as the braking forces can vary significantly between wheel-ends even though the barking system is properly adjusted and in good working condition. The reason appears to be that no matter how perfectly balanced brake actuation systems are, contact between the brake pad and brake drum at each wheel end will inevitably occur at a different instant (in time) and with slightly different force. These difference are of no consequence as brake control pressure increases, but during mild or momentary braking, the brake forces at each wheel-end could be significantly different—if only for a moment, and until control pressure increases.

As a result, throughout the field test, StrainSert refined the “threshold braking force” value which determines the point at which the system begins comparing braking force between the left and right brake assemblies. When the StrainSert system was first installed, the system compared the braking force between the right and left brake assemblies if the braking force threshold at either wheel end exceeded 250 pounds in resultant force. During early testing, the StrainSert system produced an excessive number of alarms and warnings even though subsequent investigations confirmed the braking systems were functioning properly. During mild braking maneuvers the overall braking force at the wheel ends is correspondingly low—and the **absolute** differences in braking forces between wheel ends is relatively small. However, the **relative** (percentage) difference in brake forces at each wheel-end (on the same axle) can be significant—and this percentage difference is what was causing the excessive alerts on the StrainSert system.

To improve the accuracy of the StrainSert system, the brake force threshold was raised from 250 pounds to 2,500 pounds to ensure that the system only compared brake forces during a heavy application of the brakes. The threshold increase effectively reduced the number of false-positive alarms, and in fact the system did not report any unbalanced braking conditions between December 2006 and May 2007. StrainSert was concerned that the system was now too insensitive, and they reduced the brake force threshold to 1,800 pounds in June 2007. As a result, 19 system alerts were generated between June 2007 and the end of the field test.

5.3.4.2 Brake Overhauls

During the field test, three brake overhauls were performed on the StrainSert-equipped buses. The StrainSert system gave advance notice of the need for one of the three brake overhauls. On September 30, 2007, the StrainSert system on bus # 2510 issued a “service required” warning on the right rear brake assembly. At the subsequent inspection, the rear brake linings were identified as worn, and the rear brake stroke was measured as 2.5 inches. The shoe lining was worn to the point that its performance was diminished, which reduced the force on the anchor pin at a set brake application pressure relative to the other three brake assemblies. Following the brake overhaul, the system issued no further alarms, the brake lining met the wear criteria, and the brake stroke was measured as 2.25 inches.

The remaining two brake overhauls occurred on bus numbers 2509 and 2511. On these two buses, the shoe linings were replaced prior to the point at which the brake would have degraded sufficiently to cause an alert.

5.3.4.3 Overstroke and Maintenance Actions

On two separate occasions the StrainSert system correctly identified overstroke conditions. In the first instance, bus number 2509 had three “service required” alerts at the left front brake assembly between September 29, 2007, and October 28, 2007. During the visual inspections, the brake stroke at the front left brake was measured as 2.0 inches, just at the adjustment limit for the front brake assemblies.

In the second instance, the StrainSert system issued an alert because of intermittent rear brake force differentials in excess of 30 percent for the left rear brake assembly of bus number 2510. The force recorded on the left rear brake was 30 percent higher than on the right rear brake. The alert coincided with a maintenance record reporting that a driver had experienced a brake shimmy while in service. A visual inspection measured the brake stroke as 2.5 inches, the maximum allowable stroke measurement. As a result, the left rear brake assembly was adjusted. After the corrective action was completed and the system was reset, the StrainSert system did not generate any further warnings.

5.3.4.4 StrainSert Hardware Failures

There was one equipment anomaly that occurred on the StrainSert-equipped buses during the field test. During a weekly inspection, the StrainSert system measured a large, constant force load of 21,000 lbs on one of the StrainSert anchor pins of bus number 2509. Because the bus was stationary, the StrainSert system should not have been recording a load force at any of the anchor pins. After troubleshooting the left front brake equipment and the anchor pin, the cable to the anchor pin was inspected and a gash was identified approximately 3 inches from the anchor pin connector (see Figure 51). The gash caused a short between the exposed metal shielding and the copper wiring. After installing a new cable, the force load on the left front anchor pin was measured at 0 pounds, as expected. No similar failures were identified on other vehicles during the course of the test.

Figure 51. StrainSert Anchor Pin Cable Failure

5.3.4.5 Unsubstantiated System Alerts

The StrainSert system generated eight false-positive alerts. Bus number 2511 generated five warnings at the right front brake assembly. The five alerts spanned nine visual inspections, between June 24, 2007, and August 19, 2007. In most cases, the brake overstroke was measured at or below 1.5 inches. No maintenance actions or visual brake inspections could provide a basis for the warning. A sixth warning was generated on bus number 2511 on November 4, 2007. A warning was generated at the left front brake assembly. Again, no failures were identified during the visual inspection, and no maintenance records were generated during this time. After the alarm was cleared, no further warnings were generated during the test.

The final two false-positive alerts were generated on bus number 2509 at the left front brake assembly. The alerts occurred during two consecutive visual inspections. Before the false alarms, a brake overstroke condition had been identified at the same location. A maintenance record was generated to adjust the brake stroke. It is assumed that the two false reports were a direct result of the system not being reset after the overstroke condition was corrected. If this assumption is correct, the StrainSert system only generated six false-positive alarms during the year-long field test.

5.3.5 PBBT System Analysis

The PBBT is a brake monitoring system installed at the WMATA maintenance garage that served as a reference check of actual braking performance (see Section 5.1.4 for additional information on the PBBT used for this field test). This system was used to document (or baseline) the performance of the vehicle’s braking system as needed throughout the field test. Along with providing a check of total vehicle brake performance, the PBBT also was used to monitor the force differential between the left and right brake assemblies, as well as the differences in total brake force between the front and rear wheels. The PBBT indicated a possible brake defect if it detected a difference between the braking force at the left and right wheel ends greater than 30 percent.

Originally, the test and control vehicles were to be tested once a month on the PBBT, and the results were to be compared to the findings of the onboard BPMSs. However, the test plan required modifications after it became apparent that PBBT system data could not be compared with the onboard BPMS data. The condition of the vehicle's braking system could well have been be in a different state of repair at the time of the PBBT test versus when various alerts were recorded by BPMSs. In other words, the temporal difference between data that was collected by the PBBT versus the BPMSs effectively clouded the analyses.

The PBBT performed 179 bus inspections during the field test. Table 23shows the distribution of the inspections by bus number for both the control and test fleets. Each inspection recorded the rolling resistance and service brake force for both the front and rear axles, providing 716 readings of brake force differential (between the left and right wheels on each axle).

Table 23. Total PBBT Inspections

Test Fleet Bus #	Test Fleet # of Inspections	Control Fleet Bus #	Control Fleet # of Inspections
2501	9	2513	7
2502	9	2514	8
2503	8	2515	6
2504	7	2516	6
2505	8	2517	6
2506	7	2518	7
2507	7	2519	6
2508	8	2520	8
2509	9	2521	6
2510	8	2522	8
2511	6	2523	8
2512	9	2524	8

Of the 716 brake force differential tests completed, 74 (10 percent) were identified with a brake force differential of greater than 30 percent, which is defined as a fault or failure. During the test period a mechanical failure of the PBBT was identified that had an effect on the test data. The data shown in Table 24 includes warnings generated as a result of PBBT hardware failure. Table 25 shows the revised data and identifies only those warnings that occurred when the test stand was operating properly (49 fault/failures, or 6.8 percent of total tests).

Table 24. PBBT Measured Warnings[**]

Test Fleet Bus #	Test Fleet # of Faults	Control Fleet Bus #	Control Fleet # of Faults
2501	6*	2513	2*
2502	1	2514	3*
2503	6*	2515	2
2504	3*	2516	0
2505	3	2517	2
2506	2	2518	1
2507	1	2519	4*
2508	4*	2520	5*
2509	3	2521	1
2510	6*	2522	6*
2511	2	2523	6*
2512	4	2524	1

An asterisk (*) identifies the warning totals affected by the hardware failure, deeming that data inaccurate.

Table 25. Revised PBBT Measured Warnings

Test Fleet Bus #	Test Fleet # of Faults	Control Fleet Bus #	Control Fleet # of Faults
2501	4	2513	1
2502	1	2514	2
2503	4	2515	2
2504	2	2516	0
2505	3	2517	2
2506	2	2518	1
2507	1	2519	2
2508	1	2520	2
2509	2	2521	1
2510	3	2522	4
2511	2	2523	4
2512	2	2524	1

5.3.5.1 PBBT Hardware Failure

During the inspections in October 2007, a hardware failure was identified on the PBBT. The left roller assembly was exhibiting a rolling resistance that was two times the rolling resistance of the right roller assembly. During testing of bus number 2510, the PBBT's left roller assembly locked up prematurely, almost immediately upon brake application. The incident repeated itself while testing two additional buses. An inspection of the equipment revealed no visual problems with

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[**] As explained in the "PBBT Hardware Failure" section, the data in Table 24 was found to be inaccurate because the PBBT test stand failed. Table 25 excludes the readings taken during the PBBT failure.

the left roller assembly, motor, or chain. The manufacturer was contacted, and a date was scheduled to troubleshoot and repair the PBBT.

On December 12, 2007, the manufacturer determined that the weld securing the roller to the roller bearing on the PBBT's left roller assembly was broken, as indicated by the arrow in the left side of Figure 52. As a result, the disc that had been secured within the roller became exposed. When functioning properly, the disc is secured within the roller, as shown in the right side of Figure 52. It is responsible for holding the roller in position, centered between the PBBT frame, and turning the roller during a test. With the failed weld, the roller assembly was not centered within the frame and had actually shifted far enough to the left to contact the PBBT frame. By contacting the PBBT frame, the rolling resistance for the left roller assembly had increased significantly, as compared to the right roller assembly. The manufacturer stated that the weld failure in this location was a known design flaw that it had identified and resolved on the new PBBT assemblies. A new roller was installed on December 19, 2007. After the new roller was installed, the PBBT operated properly.

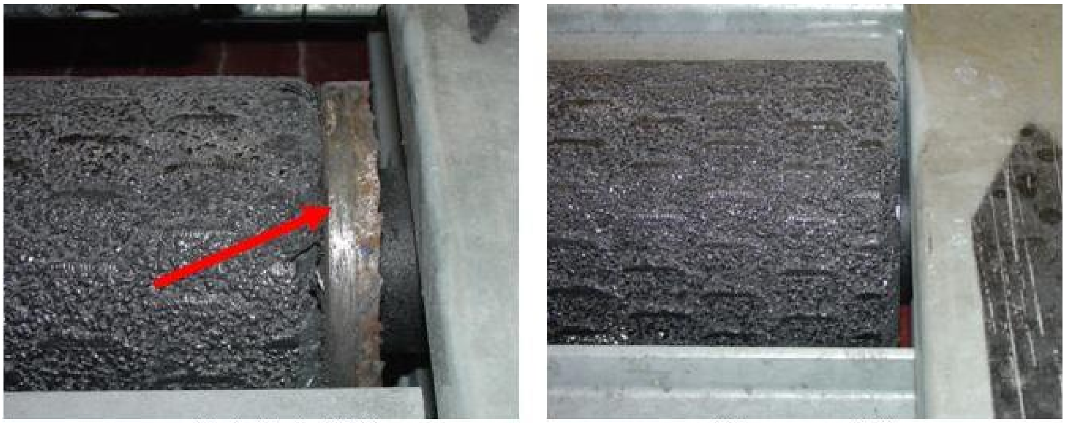
a) Failed Roller Weld b) Functioning Roller

Figure 52. Failed Weld at Left Roller Assembly

After the questionable brake performance measurement data (i.e. data taken while the PBBT was not functioning properly) were removed from the overall data set, the remaining data revealed that two of the test buses experienced the highest incidence of brake force differential. On December 19, 2006, the rear axle of bus number 2502 had a rolling resistance differential of 51 percent and a service brake force differential of 4 percent. Neither the brake performance monitoring system (eStroke) nor the maintenance records logged a system fault during this time. On June 21, 2007, the rear axle of bus number 2503 had a rolling resistance differential of 51 percent and a service brake force differential of 7 percent. Again, neither the on-vehicle braking system (eStroke) nor the maintenance records logged a system fault during this time. The cause of the failures could not be identified.

5.3.6 Brake Technician Interviews

The interview process with brake technicians was an open discussion about the fleet study, brake maintenance practices, and the BPMSs. The responses related to the individual BPMSs are presented below.

5.3.6.1 eStroke

Of the three BPMSs tested in the fleet study, the participants were most familiar with the eStroke brake monitoring system. The entire fleet of 40-foot transit buses operating out of the Four-Mile Run maintenance facility is equipped with the factory-installed eStroke system.

The eStroke system experienced few failures during the field test. The most common failure was the result of a short circuit in the wire harness at the wheel-end, resulting in a complete replacement of the wiring harness. The stroke-sensing hardware mounted inside the brake chamber experienced minimal failures. The reliability of this hardware was attributed to the equipment's protection from the environment.

The eStroke system successfully detected the two most common brake problems—dragging brakes and slack brakes (overstroke). Initially, the buses were delivered from the manufacturer with the brakes shimmed incorrectly, resulting in a dragging brake condition. As discussed earlier, the eStroke system detected the dragging brake condition, alerted the maintenance staff of the problem, and ultimately increased brake life. Also, the early detection of slack brakes identifies an improperly functioning slack adjuster and reduces driver complaints concerning hot brakes.

WMATA's confidence in the eStroke system resulted in the elimination of the measurement of the pushrod stroke during the "A" preventative maintenance inspection (every 3,000 miles). Originally, the brakes were inspected on each bus during the A inspection and the B inspection (at 6,000 miles). The eStroke system is now used to monitor the brake system prior to the more complete B inspection. During the B inspection, the brake system is inspected thoroughly, including brake stroke travel. The B inspection has also been updated to inspect the eStroke cabling for any defects and to verify proper functioning of the eStroke sensors.

5.3.6.2 Brake Insight

Unlike the eStroke system, which integrates sensor apparatus within the brake chamber, the Brake Insight equipment is mounted outside the brake chamber. Technician raised concerns about the vulnerability of the externally mounted system hardware to damage from road debris.

The use of lining wear sensors was deemed ineffective by the technicians. As noted earlier, the wear sensors never flagged a brake lining for replacement because the sensor was placed too deep in the brake shoe. Also, current maintenance procedures require the inspection of brake assemblies every 6,000 miles, which results in brake shoe replacement before the wear sensor flags the need for replacement.

The ability to measure brake temperature through the use of a thermocouple was identified as beneficial. The thermocouples helped determine whether the brake had properly burnished after a brake overhaul. Also, it was suggested by the technicians that the thermocouples could possibly reduce the number of driver complaints caused by "hot brakes."

5.3.6.3 StrainSert

The StrainSert system was cited by the technicians as an effective tool for detecting brake problems. Unlike stroke-sensing brake monitoring systems, StrainSert can detect brake performance changes caused by oil-soaked brake linings, which warn of a leaking wheel seal.

Technicians noted that when performing brake overhauls, the brake anchor pins, springs, and brake shoes are discarded and replaced with new hardware. As a result, care is not taken in removing the old brake hardware. For example, an original anchor pin is often stuck in the pre-overhaul brake assembly. To free the anchor pin from the brake assembly, the technician can break the pin free by using a hammer. This overhaul procedure is not appropriate for StrainSert's instrumented anchor pins. Pounding a StrainSert's anchor pin to remove it from the assembly could damage the internal strain gauges. As a result, the damaged StrainSert anchor pins could negatively affect the system's ability to accurately detect brake problems.

The technicians also provided suggestions for future system improvements. One suggestion was to further develop the StrainSert software to communicate with an AVM.

5.4 OBSERVATIONS AND CONCLUSIONS

The team evaluated three different BPMSs during the year-long field test of 12 urban transit buses operated by WMATA. Two of the systems monitored brake performance by monitoring pushrod stroke, and the third system measured the strain exerted on the brake anchor pins. Below are the observations regarding the performance of the systems evaluated under this program.

Onboard BPMSs were found to favorably affect WMATA's inspection practices. WMATA inspects buses at 3,000- and 6,000-mile intervals. With more than 200 buses operating out of a maintenance facility, these inspections require a significant amount of time. For the A inspection (3,000 miles), WMATA has begun relying on the BPMS to assess the brakes. This is reducing inspection times and allowing more buses to be inspected in a given period.

The BPMSs were found to withstand the rigors of the urban transit operating environment. A single sensor failure occurred during the roughly 1 million miles traveled by the 12 test buses during the test program. The maintenance actions performed on the buses were limited to broken wires, loose connectors, and sensor adjustments.

In transit service, information from onboard monitoring systems must 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 a bus onboard monitoring system to a server housed at the maintenance garage. This data is offloaded each time the bus returns to the garage and emailed to maintenance supervisors. The eStroke systems evaluated under this program were integrated into this CAN network. The study team found that buses with eStroke alarms were inspected and problems corrected in a timely fashion (same day or next day), whereas 1 week or more could elapse before brake problems were addressed on buses with monitoring systems that only communicated via an in-vehicle display. Of note, transit managers limit the amount of prognostic maintenance data operators receive because of union work rules.

MGM's eStroke system aided in identifying a manufacturing issue with the alignment between the brake chamber and slack adjuster on the new Orion VII low-floor buses. The foundation brake manufacturer selected a camshaft retention method for the Orion VII buses that made it possible to remove the slack adjuster without removing the wheel-end. This retention method required a shorter S-cam shaft and a specific installation method. This caused an alignment issue that in-turn caused the rear brakes to drag, which the eStroke system identified. Inspections performed as a result of the eStroke alerts revealed the cause of the dragging brake to be this alignment issue. The vehicle and brake manufacturer corrected the issue under warranty.

Based on interviews, the prognostic alerts from the BPMSs provided technicians with useful information to quantify driver complaints and reduce complaint frequency. Complaints with brakes are time consuming to troubleshoot because they require an inspection performed on a lift. Technicians commented that BPMSs reduce the number of driver complaints and provide real-time information used to decide whether to hold the bus from service.

The BPMSs evaluated in this program did not indicate 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. None of the systems evaluated triggered an alarm before these rebuilds. Of note, the Brake Insight system featured a wire-loop lining wear sensor embedded in the shoe lining. Unfortunately, the sensor embedded in the lining was lower than the minimum thickness criteria used by WMATA to replace shoe linings.

Onboard BPMSs provide a new source of information for technicians to use to identify and address brake issues. As with any new data source, time is required to understand, interpret, and obtain confidence in the data generated by these monitoring systems. WMATA and the study team went through this process with the systems evaluated in this program. They worked with the system vendors to tailor algorithms to minimize false positives and improve system reliability. The algorithms were modified to function more effectively with a foundation brake setup that operated close to adjustment limits, and in an operating environment that cycled the brakes frequently causing hot brake conditions. Based on previous independent testing and participation in this program, WMATA has confidence in BPMSs and plans to equip all future buses with a BPMS system.

6. REFERENCES

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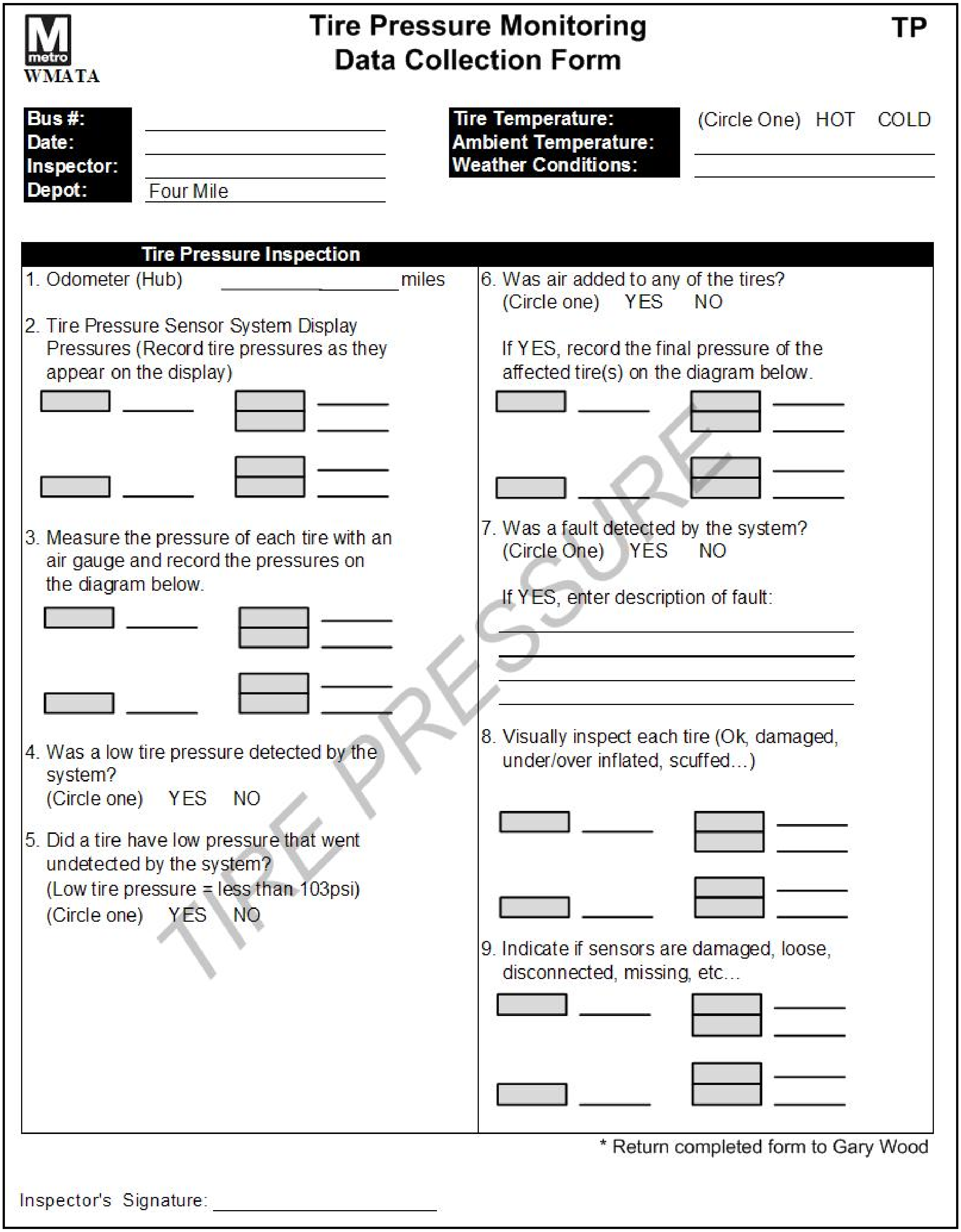
APPENDIX A—DATA COLLECTION FORMS



WMATA

Tire Pressure Monitoring Data Collection Form

TP

Bus #: ____________________

Date: ____________________

Inspector: ____________________

Depot: Four Mile

Tire Temperature: (Circle One) HOT COLD

Ambient Temperature: ____________________

Weather Conditions: ____________________

Tire Pressure Inspection

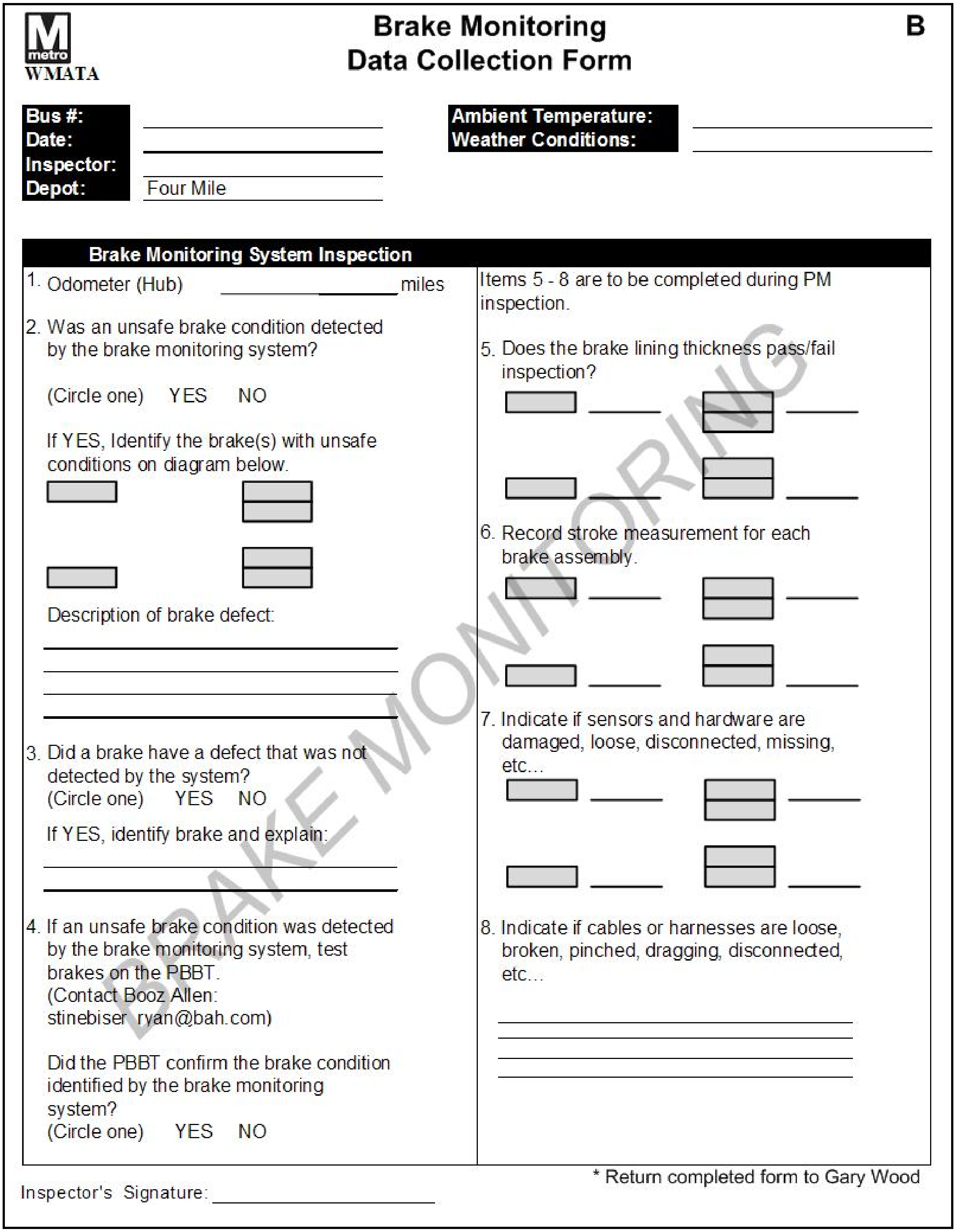
1. Odometer (Hub) ____________ miles
2. Tire Pressure Sensor System Display Pressures (Record tire pressures as they appear on the display)
3. Measure the pressure of each tire with an air gauge and record the pressures on the diagram below.
4. Was a low tire pressure detected by the system?
   (Circle one) YES NO
5. Did a tire have low pressure that went undetected by the system?
   (Low tire pressure = less than 103psi)
   (Circle one) YES NO
6. Was air added to any of the tires?
   (Circle one) YES NO

   If YES, record the final pressure of the affected tire(s) on the diagram below.
7. Was a fault detected by the system?
   (Circle One) YES NO

   If YES, enter description of fault:
8. Visually inspect each tire (Ok, damaged, under/over inflated, scuffed…)
9. Indicate if sensors are damaged, loose, disconnected, missing, etc…

* Return completed form to Gary Wood

Inspector's Signature: ____________________



WMATA

Brake Monitoring
Data Collection Form

B

Bus #:	
Date:	
Inspector:	
Depot:	Four Mile

Ambient Temperature:	
Weather Conditions:	

Brake Monitoring System Inspection

1. Odometer (Hub) ______________ miles

2. Was an unsafe brake condition detected by the brake monitoring system?

(Circle one) YES NO

If YES, Identify the brake(s) with unsafe conditions on diagram below.

Description of brake defect:

3. Did a brake have a defect that was not detected by the system?
(Circle one) YES NO

If YES, identify brake and explain:

4. If an unsafe brake condition was detected by the brake monitoring system, test brakes on the PBBT.
(Contact Booz Allen:
stinebiser ryan@bah.com)

Did the PBBT confirm the brake condition identified by the brake monitoring system?
(Circle one) YES NO

Items 5 - 8 are to be completed during PM inspection.

5. Does the brake lining thickness pass/fail inspection?

6. Record stroke measurement for each brake assembly.

7. Indicate if sensors and hardware are damaged, loose, disconnected, missing, etc...

8. Indicate if cables or harnesses are loose, broken, pinched, dragging, disconnected, etc...

Inspector's Signature: ____________________

* Return completed form to Gary Wood