COMMERCIAL VEHICLE SAFETY TECHNOLOGIES: APPLICATIONS FOR TIRE PRESSURE MONITORING AND MANAGEMENT

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ABSTRACT

Tire deficiencies often cause commercial motor vehicles (CMVs) to be cited for regulatory violations and to be taken out-of-service during roadside inspections. As part of a major safety technology project to assess the state of the practice and potential contributions of advanced sensor systems, the Federal Motor Carrier Safety Administration (FMCSA) sponsored three studies between 2003 and 2008 on tire pressure management systems (TPMS). The first study focused on obtaining baseline information. Fleet records and limited field collections were used to develop a database of inflation readings for 35,000 CMV tires, providing the first large-scale source of information on CMV tire inflation in the United States. The second study assessed the performance of TPMS in a controlled test-track environment. Multiple systems were installed on a truck tractor, a trailer, and a motorcoach. These were run under nominal operating conditions and with tire and system faults deliberately introduced. Although all the systems functioned at the levels specified by their manufacturers, some had limited ability to compensate for changes in ambient temperature, to reset pressure "alert" thresholds, and to withstand repeated tire installation and removal cycles. The third study, performed in an operational setting in an urban transit fleet, assessed the performance and maintainability of tire pressure monitoring devices. Three types of TPMS were installed on 12 buses that accumulated more than 1.28 million km, in aggregate, during the 12-month test period. The results of this study pointed to sensor durability and data integration challenges that need to be overcome for these systems to be used successfully in a severe service environment. These studies provided new information directly comparing the performance of TPMS in controlled and operational settings. Results are limited to the particular systems and applications tested. Study data are available from the FMCSA.

INTRODUCTION

The load carrying capability of a tire is critically linked to the inflation pressure. Fleet operators will generally select a particular "target pressure" for their trucks based on the unique load, operating, and environmental conditions in which they operate. If not properly inflated, the useful tire life, as well as vehicle handling and safety, are compromised.

CMV tires lose air pressure for a variety of reasons. Air can escape between the bead and wheel, as well as through improperly tightened valves, torn rubber grommets, or valve cores that have been blocked open by dirt and ice. Additionally, air molecules are small enough to diffuse through rubber (albeit very slowly), and an air pressure drop of up to two psi per month is not uncommon. Most tire companies recommend that tire pressure be checked weekly, using properly calibrated tire gauges. However, tire pressure maintenance is labor and time intensive. It takes 20 to 30 minutes to check all the tires on an 18-wheeled tractor-trailer combination vehicle and to add air to 2or 3 tires that may be low. Due to this fact and the lack of time available, tires are often improperly inflated.

Improper tire inflation increases operating costs by reducing tire life and lowering fuel economy (an underinflated tire "flexes" and has higher rolling resistance). 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. Due to improper tire inflation, fuel economy decreases about 0.6 percent for typical truckload (TL) and less-than-truckload (LTL) operations. According to road-breakdown management service providers, weakened and worn tires due to improper tire inflation are estimated to be responsible for one road call per year per tractor-trailer combination vehicle.

Although most industry stakeholders intuitively recognize the importance of proper tire inflation maintenance and its impact on operating cost and safety, there was very little empirical data on CMV tire pressure maintenance practices. The extent of the under inflation problem had never been documented, and the costs of improper tire pressure maintenance had not been systematically analyzed. Although new tire pressure maintenance and management technologies have been introduced for the CMV market, such as automatic tire inflation systems and various types of tire monitoring systems, there was little information that fleet maintenance managers could use to determine whether those systems would provide a reasonable return on investment.

FIRST STUDY: TIRE PRESSURE SURVEY

The primary objectives of this project were to develop and document the impacts of tire inflation maintenance practices on CMV operating costs and safety and to provide a quantitative estimate of potential benefits of tire pressure monitoring sensors and automatic inflation systems. In order to address the dearth of comprehensive data on tire inflation practices, the study engaged in a cooperative effort with the Technology & Maintenance Council (TMC) of the American Trucking Associations to synthesize existing tire pressure survey data from a wide variety of truck and bus fleets and to collect new tire inflation field data for the owner-operator segment of the trucking industry. The study also gathered information from suppliers of tire pressure monitoring and automatic inflation systems and developed six hypothetical fleet operating scenarios to estimate potential costs and benefits from use of these systems.

Tire manufacturers perform fleet surveys for their CMV fleet customers to assist them with their tire maintenance programs and to determine the performance of their tires under various operating conditions. Experienced field service engineers use calibrated gauges to collect cold-inflation pressure data (the flexing of the sidewalls of tires in motion increases their temperature and leads to inaccurate air pressure readings). These fleet survey data provided the most accurate way to assess the relationship between a motor carrier fleet's target tire pressure and the actual cold inflation pressure of tires in service. The data are considered representative of motor carriers that participate in this type of maintenance program.

Conversely, no archival data from tire suppliers was available for tires on independent owner-operators' vehicles because owner-operators are generally responsible for their own operating costs. The only way to obtain cold tire pressure data was to collect it at locations in which owner-operator drivers would be stopped for at least 3 hours, in order for their tires to cool down to ambient temperature. Trucker appreciation events held the most promise for this data collection. TMC assisted in recruiting a group of senior field service engineers who collected owner-operators' tire pressure data at the Walcott (Iowa) Truckers Jamboree and the Reno Truckerfest, both held during the summer of 2001.

A total of 6,086 units (3,261 tractors, 1,300 trailers, and 1,525 motorcoaches) and 35,047 tires (18,039 on tractors, 7,501 on trailers, and 9,507 on motor coaches) were checked, and the pressures recorded. The survey data also noted the type of motor carrier operation (for-hire LTL, for-hire TL, private, and public and private motorcoach).

Tire pressure survey results

The results focused upon four important metrics:

- *Proportion of tires 20 percent or more underinflated.* In general, fleets accept small deviations from the targeted pressure. However, if a tire is 20 percent or more underinflated, it indicates the problem is more serious and is likely the result of inadequate maintenance or quality control procedures. The survey found approximately 7 percent of all tires underinflated by 20 psi or more.
- *Proportion of tires within 5 percent of the targeted pressure.* Higher percentages indicate a well-executed tire maintenance program. It is generally accepted by the trucking industry that a good fleet operator will have 70 percent or more of his or her tires within ±5 percent of the targeted pressure. The survey found only 44 percent of all tires sampled was within ±5 psi of their target pressure.
- *Proportion of tires 50 percent or more underinflated.* This degree of under inflation would indicate a major tire failure and would generally be considered a flat tire. The percentage of such tires within a fleet could be an indication of either a tire product or tire-mounting problem or a poor tire inflation maintenance program, as indicated above.
- *Proportion of tires 10 percent or more overinflated.* A high percentage of such tires might indicate that the fleet is systematically over inflating the tires to compensate for lack of a good quality control program. Since overinflated tires also have negative impacts on tread wear, this is not considered a viable strategy.

Other key observations indicated differences among fleet operational categories, as well as among fleet size. For-hire carriers (LTL, TL, and owner-operators) generally reflected better tire inflation maintenance practices than private carriers did. As a group, sampled for-hire carriers had 7 percent of all tractor tires underinflated by 20 psi or more. In contrast, the sampled private carriers had 13.2 percent of all tractor tires underinflated by 20 psi or more.

Fleets with 50 or fewer power units had 19.1 percent of their tires underinflated by 20 psi or more. In contrast, fleets with more than 3,000 power units had only 2.1 percent of their tires underinflated by 20 psi or more. Similarly, motorcoach fleets with fewer than 50 power units had 11.8 percent of their tires underinflated by 20 psi or more, while fleets with over 500 power units had only 2.1 percent of their tires underinflated by 20 psi or more.

Study sample data showed that transit bus operators had better tire pressure maintenance than chartered motorcoach operators did. Only 3.1 percent of transit bus tires were underinflated by 20 psi or more, while 9.4 percent of chartered motorcoach tires were underinflated by 20 psi or more. Additionally, 49.9 percent of transit bus tires were within ±5 psi of target, compared with only 34.2 percent of chartered motorcoach tires.

Tractors and trailers had a significant challenge with mismatched dual tires. Approximately 20 percent of all tractor dual tire assemblies had tires that differed in pressure by more than 5 psi. One out of four trailer dual assemblies (25 percent) had tires that differed in pressure by more than 5 psi.

SECOND STUDY: COMPARATIVE CONTROLLED TESTING OF TPMS

TPMS can offer safety and productivity benefits to CMV drivers and maintenance technicians. They can warn the driver and maintenance personnel if tire pressure drops to an unsafe level and can provide data to aid in problem diagnosis and resolution. They can alert the driver to a catastrophic tire failure (the loss of a trailer tire may not be noted through noise or vibration). Tires run at proper inflation pressures wear longer and have longer service lives. Systems that automatically maintain tire inflation pressure might offer additional benefits of increased fuel economy, provided they had a high level of reliability, were easy to maintain, and were considered affordable.

The overall objective of this second study was to document the performance, accuracy, and operational characteristics of several leading-edge technological approaches to commercial vehicle TPMS. The study focused on the ability of sensors to provide accurate tire pressure readings, detect both slow and rapid changes in tire pressure, and maintain tire pressure under adverse conditions, including partial failure of the device. The study examined three types of TPMS: dual tire equalizers to balance pressures between tires in a dual installation; tire pressure monitors; and tire pressure maintenance systems to maintain tire pressure at desired levels. The systems were installed on a conventional tractor-trailer combination vehicle and on a motorcoach. All testing was performed under controlled conditions on a high-speed test track at the Transportation Research Center in Columbus, Ohio.

The TPMS selected represented a sample of typical commercially available systems: two tire pressure-equalizing systems, five tire pressure-monitoring systems, and two central tire inflation systems. The systems and the vehicles on which they were installed are listed in Table 1.

Table 1.
TPMS Systems Used in Comparative Evaluation

Technology	Tractor	Trailer	Motor Coach	Recommended System for Testing
Dual Tire Equalizers				
Equalizing Systems #1	X	X		Cat's Eye (Link Manufacturing, Ltd.)
Equalizing Systems #2	X	X		Tire-Knight-S (V-Tech International, Inc.)
Tire Pressure Monitoring Systems				
Direct Monitoring System #1 (valve stem-mounted)	X	X		PressurePro (Advantage PressurePro, LLC)
Direct Monitoring System #2 (valve stem-mounted)			X	Integrated Vehicle Tire Pressure Monitoring (WABCO)
Direct Monitoring System #3 (wheel-mounted)	X	X		Tire-SafeGuard (HCI Corporation)
Direct Monitoring System #4 (wheel-mounted)			X	SmarTire (SmarTire Systems, Inc.)
Direct Monitoring System #5 (tire-mounted)	X	X		eTire (Michelin North America)
Tire Pressure Maintenance Systems				
Central Inflation System #1		X		PSI Tire Inflation System (Arvin Meritor)
Central Inflation System #2			X	Vigia (Gio-Set Corporation)

Dual Tire Equalizers

Tire pressure equalizer systems balance dual tire pressures by providing a pathway for air to transfer between two tires in a dual installation, and they also provide an indication of tire pressure. A pressure-actuated valve connected by hoses to the valve stems of the tires maintains an open position to allow air to flow between the tires when the combined pressure of the two tires is above a preset level (typically 90 psi). The pressure actuated valve closes and isolates the tires during slow leaks or instantaneous air losses (after the combined pressure of the two tires drops approximately 10 psi) to prevent both tires from going flat. A central fill valve incorporated in these devices allows both tires in the assembly to be aired simultaneously. The use of equalizers should improve irregular tire wear (i.e., cupping) caused by pressure differentials between dual tires. Visual indicators are also incorporated in the equalizers to provide the operator with a quick indication of the tire pressure levels during the pre-trip inspection without requiring the operator to perform a manual tire pressure check.

Tire Pressure Monitoring Systems

Tire pressure monitoring systems consist of a valve stem, wheel- or tire-mounted sensor, antennae, receiver, and display unit. The battery-powered sensors mounted on each valve stem, wheel, or tire on the vehicle transmit a radio frequency (RF) signal, which includes the tire pressure data, to an antennae mounted on the vehicle. A receiver, with an integrated electronic control unit (ECU), processes the signal transmitted to the antennae and displays the tire pressure information on a driver's cab-mounted display. The system also includes audible alarms and visible warning lights.

The study team tested five different tire pressure monitoring systems for this project. These included one tire-mounted, two valve-stem-mounted, and two wheel-mounted tire pressure monitoring systems. Figure 1 and Figure 2 display the Tire-SafeGuard and WABCO IVTM TPMS hardware respectively.

Figure 1. Tire-SafeGuard Wheel-Mounted System.

Figure 2. WABCO IVTM Wheel-Mounted/Tire Valve-Stem-Connected.

Automatic Tire Inflation Systems

Automatic tire inflation systems (ATIS) for tires use the air from the vehicle's air compressor that is stored in the air brake reservoirs (tanks) to maintain tire pressure at a desired level. The ATIS are plumbed to the vehicle's secondary reservoir that supplies air to the front brakes. The ATIS do not take air from the primary reservoir that supplies air for the rear brakes (which are responsible for the majority of the braking power of the CMV). These systems are plumbed either through the axle or externally, using a rotary union at the wheel hub. They automatically sense the tire pressures and inflate the tires when air is lost. The benefits of these systems are the elimination of manual tire pressure checks and the ability to continue operating the vehicle with minor air leaks in the tires. ATIS are available for all types of CMVs. In this test, one system was tested on the motorcoach and one was tested on the trailer of a tractor-trailer. Figure 3 shows the detail of the PSI trailer-mounted ATIS, and Figure 4 shows the Vigia ATIS mounted on a motorcoach.

Figure 3. PSI Trailer-Mounted ATIS.

Figure 4. Vigia ATIS Mounted on a Motorcoach.

Test Vehicles and Data Acquisition System

The test vehicles were a 2001 Freightliner FLD tractor, coupled to a 2001 Utility Trailer Manufacturing Co. 2000S tandem axle flatbed semi-trailer, and a 2003 MCI motorcoach. To acquire highly accurate pressure and temperature measurements (i.e., to establish "ground truth" against which readings from the various test articles could be compared), laboratory grade sensors were installed at each test wheel position. This required removing the wheels, machining replacement wheels for mounting thermocouples and pressure taps, and routing wire bundles to the data acquisition system (DAS) mounted in the cab of the truck and motorcoach. Figure 5 shows the installation location of each of the instrumentation packages on the tractor-trailer and motorcoach.

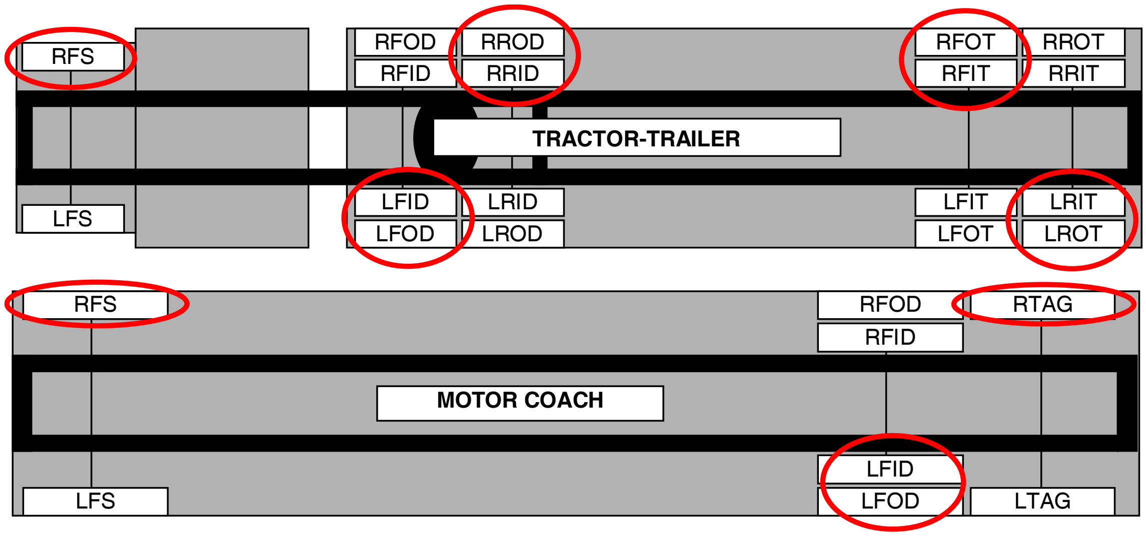

Figure 5. Tractor-Trailer and Motorcoach Instrumentation Package Location.

Additional test equipment consisted of: internal tire temperature thermocouples (nine, analog); tire pressure transducers (two, analog); custom-fabricated dual-flow combination rotary union and slip ring assemblies (five); a custom-fabricated pressure control manifold; primary and secondary brake reservoir and treadle valve pressure transducer (three, analog); a digital marker switch for the test driver's use to indicate when a warning was observed; and a digital non-contact fifth wheel. Figure 6 displays the details of the wheel end rotary union instrumentation package.

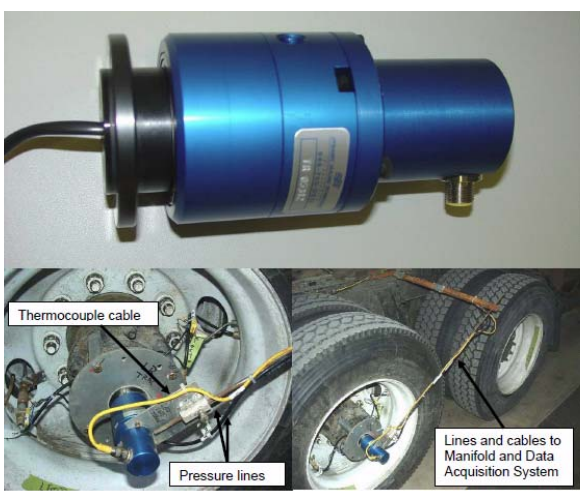

Figure 6. Rotary Union and Wheel Installation Detail.

The failure modes test required that the air brake systems be monitored to determine whether the central tire inflation systems degraded the vehicle's potential braking ability. Therefore, it was necessary to monitor the air brake system pressure at three points: primary air reservoir, secondary air reservoir, and application pressure. Three pressure transducers, similar to those used for tire pressure monitoring, were spliced in a T into the brake lines at a T serving the primary air reservoir, the secondary air reservoir, and the application pressure gauge line upstream of the gauge.

The DAS was manufactured by Link Engineering Company, Detroit, Michigan. A PC-based laptop computer operated the system, stored data as it was acquired, and performed real-time analyses. The system software supported a variety of interface options, ranging from direct user interaction with the system during measurement to completely autonomous operation based on various pre-programmed trigger events that caused the system to begin data collection. The system was also capable of issuing prompts to a test driver or an instrumentation technician. The Link DAS system received information from 16 individual channels at a frequency of 10 Hz. The average TPMS test lasted about 10 to 30 minutes and generated approximately 5,000 to 10,000 data points. In total, the testing program generated approximately 450 Mb of data.

The test engineer was responsible for manually recording the test identification number and other information, including environmental conditions and tire(s) under test; as well as any specific warnings or indications by the TPMS. This was necessary because TPMS were self-contained and were not connected directly to the Link DAS, as they did not have signal outputs that could be tapped for direct recording.

Test Program

The test program included seven tests:

- *Functionality Test (Static and Dynamic)*. This was an overview or shakedown test series, performed to characterize the operational, maintenance, and installation processes for each system.
- *Threshold Warning Level Test*. This test determined the thresholds at which low tire pressure warnings were given. In the case of the ATIS, the test determined the leak rate (psi/min) at which the inflation system could no longer keep pace and a low tire-pressure warning was given.
- *Loaded Test at High Speed*. This test examined the effects of tire heating, due to sustained high-speed driving, on the warning indicator/light of the systems.
- *Failure Modes Test*. This test had two components. For central tire inflation systems, this test determined whether a large or catastrophic air leak depleted the air supply for the pneumatic brakes or forced the system to run continuously, without giving the driver a warning that a tire had lost air. For systems where tires were interconnected (dual-tire equalizing and ATIS technologies), the purpose was to ensure that loss of inflation pressure in a single tire did not affect the interconnected tires.
- *Disablement Test*. This test determined the system's ability to provide a warning or advisory when it was disabled, either by an intentional act or because of a failure of a system or component.
- *Operator Interface Evaluation*. This test was a qualitative evaluation of the effectiveness of the driver interface.
- *Gate Reader Evaluation*. This test evaluated the performance and reliability of the drive-thru gate readers, used with tire-mounted monitoring systems. The objective was to determine the speed and consistency of the gate readers in capturing pressures of all 18 tires on the tractor-trailer.

Results of Comparative Tests

In general, all of the tested valve-, wheel-, or tire-mounted systems exhibited base-level functionality as specified by the manufacturer of the individual systems. The tire pressure values were generally accurate to within two to three psi of the values measured by calibrated pressure transducers.

Low-pressure warning thresholds were factory set on some systems but user-configurable on others. For those systems with factory settings, different warning levels, ranging from 12 to 25 percent below target pressure, were observed. All tested systems were generally within a 2- to 3-psi range of the expected warning threshold.

Many of the tested TPMS used RF communications to transmit data between the sensors and the display unit or ECU. The relatively long length of typical CMVs meant that additional on-board antennae were required for some of the systems to receive the sensor signals from trailer or tag axle tires. Disconnected or damaged antennae could lead to signal loss from the sensors.

The dual tire equalizer systems functioned as designed under both static and dynamic conditions, and they were found to be effective in balancing the pressures between the two connected tires. Figure 7 and Figure 8 show the equalization system balancing tire pressures under static and dynamic conditions respectively. The two systems tested prevented a total loss of pressure in one or both tires in every failure mode implemented, effectively isolating an intact tire from the adjacent tire with an artificially induced major air loss. Similarly, in a disablement test where a hose was cut to simulate damage from road debris, one tire of a dual installation sustained a total loss of air while the other tire was protected by a check valve. Figure 9 and Figure 10 demonstrate the effectiveness of the equalizer in isolating a slow and fast leaking tire from an intact tire.

Both tested equalizer systems included a visual indicator that provided a gross indication of whether tire pressure was within its target range. However, if the pressure fell below this range, they only showed a "low" pressure condition and did not indicate the extent of underinflation. Finally, although the indicators provided a good visual indication of tire pressure, they could be difficult to read as they were mounted on the wheel and could become obscured by dirt.

Despite their relative ease of installation, valve-stem-mounted TPMS had several limitations. When tire temperatures increased during high-speed driving, not all of these systems compensated for the related

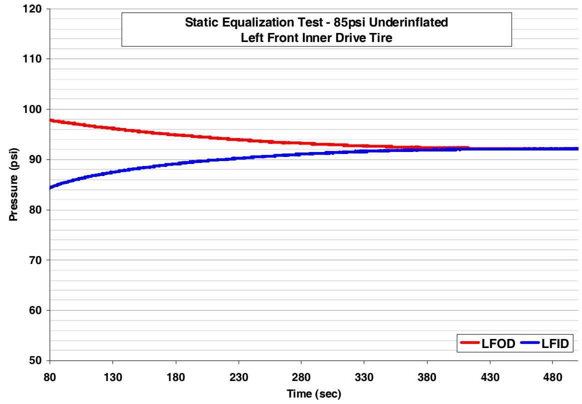

Figure 7. Static Equalization Test.

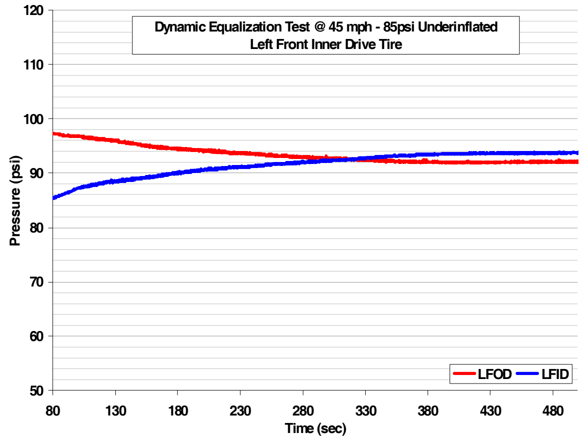

Figure 8. Dynamic Equalization Test.

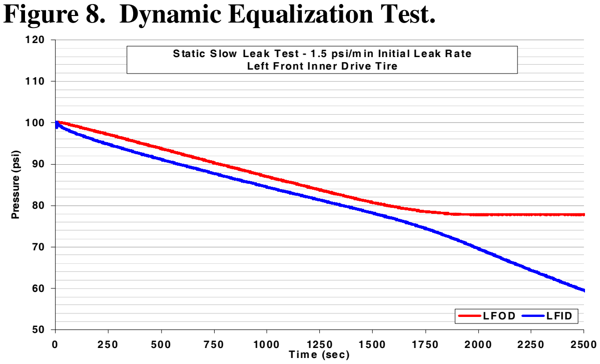

Figure 9. Equalizer Static Slow Leak Test.

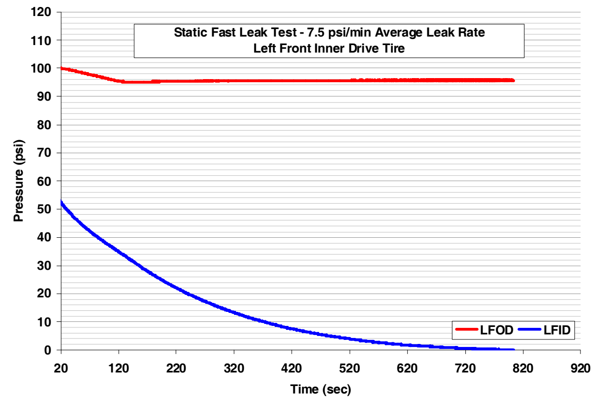

Figure 10. Equalizer Static Fast Leak Test.

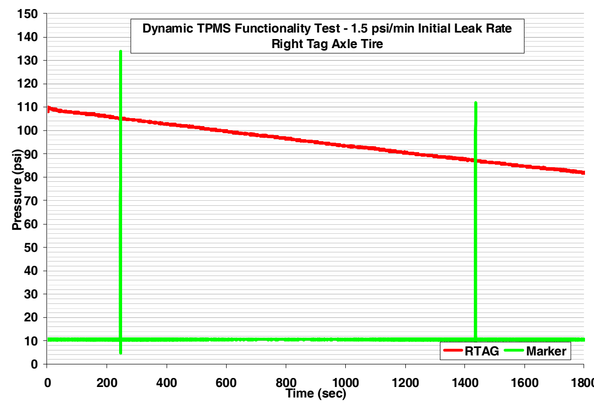

Figure 11. Initial Low Pressure Alarm and Second Critical Pressure Alarm Points.

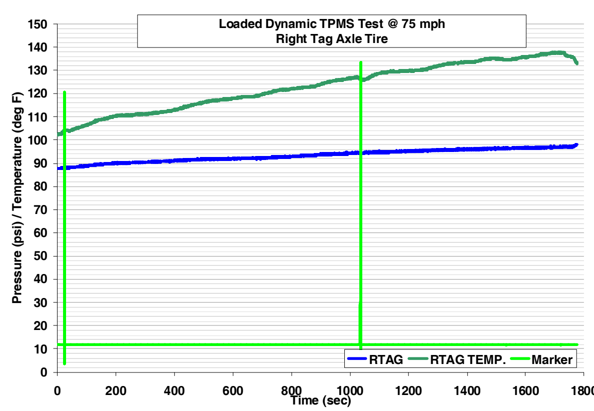

Figure 12. Initial Low Pressure Alarm and Point of Low Pressure Alarm Reset.

increases in tire pressure. One of the two tested systems in this study provided temperature compensation. One of the tested systems initiated a warning when the pressure fell below a preset value (~20 percent below target). Figure 11 shows the two alarm points on a wheel-mounted TPMS as the pressure in the tire bleeds down. However, the warning remained active until the tire was inflated to a higher value (~15 percent below target). This pressure band between the alarm pressure and alarm deactivation pressure prevented intermittent warnings to the driver. Lastly, valve-stem-mounted systems were susceptible to loss because they had to be removed during wheel mounting and dismounting for vehicle maintenance and inspection. Their relative ease of removal could also make them susceptible to theft.

With respect to wheel-mounted TPMS, product literature asserted that wheel-mounted technology included temperature compensation and typically provided the best performance in correcting for tire temperature. However, during the high-speed test sequences, both evaluated wheel-mounted systems had their active warnings disabled when tire pressure increased because of increased tire temperature. This occurred intermittently in various test runs and on different axles. Figure 12 shows the point where a low pressure alarm was cancelled due to increasing tire temperature causing a corresponding increase in tire pressure. However, the test data suggested that the systems were generally able to compensate for large increases in tire temperature (greater than 20 degrees Fahrenheit), but were less able to compensate when the temperature increases were lower. Increasing tire temperatures could prevent a low-pressure warning from being generated. In addition, the team found that the wheel-mounted technologies could be vulnerable to damage during tire mounting and dismounting.

The evaluated tire-mounted TPMS included temperature compensation. A handheld reader displayed both the temperature-corrected pressure and the uncorrected pressure at ambient tire temperature. This system was the only one that required the use of a handheld or gate reader to inspect tires. No in-cab display was available. Figure 13 shows the hand reader in the charger and download docking station.

The gate reader clearances were very tight and required very slow vehicle speeds, less than five mph. However, this particular system was unique among those tested in that it was linked to an Internet-based tire maintenance and tracking database application hosted by the system manufacturer. Figure 14 and Figure 15 show the eTire tag and installation tools respectively.

Figure 13. eTire Handheld Reader.

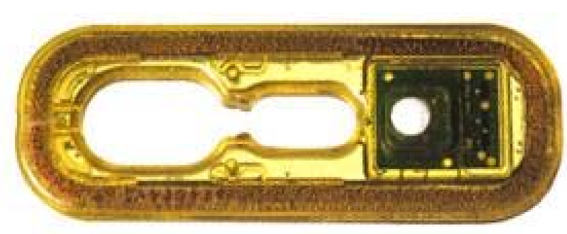

Figure 14. eTire Tire Tag.

Figure 15. eTire Mounting Patch and Installation Tools.

In general, the ATIS performed as designed and specified by the manufacturers and performed well in both static and dynamic conditions. Figure 16 displays the rate of inflation of the trailer-mounted ATIS from various initial inflation pressures. In the leak rate tests, the motorcoach ATIS was able to keep up with leak rates up to 5 to 8 psi/min. Ultimately, this system's performance was limited by the vehicle's air compressor duty cycle and the compressed air supply and storage system design. The ATIS tested on the trailer could maintain adequate tire pressure with slow leakage rates (less than 1.0 psi/min) but did not maintain adequate tire pressure for higher leakage rates. This system appeared to be limited by its rate of airflow to the tires more than by a limitation of the onboard compressor and air system. Figure 17 shows the ability of the trailer-mounted ATIS to maintain pressure at various leakage rates.

During testing with heavy braking and simultaneous tire leaks, the vehicles' primary and secondary air reservoir pressures remained above the level required for safe brake operation. The compressor had no difficulty recharging the reservoirs without having to run continuously. Figure 18 shows the trailer-mounted ATIS maintaining pressure in the primary and secondary reservoirs during brake snub maneuvers with a leaking tire. Both tested ATIS protected the intact tires from deflating when a catastrophic air leak was simulated in one of the other tires in the system. In this regard, the systems functioned in a manner similar to the dual tire equalizers isolation circuits. Figure 19 shows the motorcoach-mounted ATIS maintaining pressure in a tire with a significant leak while operating at highway speeds.

Vehicle air systems are not optimized to support an ATIS with very high leakage rates; therefore, the functionality of the ATIS was often limited by the vehicle's air system. Additionally, there may be some long-term impact to the CMV's air system when subjected to a high leakage rate from the secondary reservoir, which the ATIS utilizes for its supply air. These leak rates would cause an increase in the duty cycle of the compressor and would increase maintenance requirements and decrease compressor service life.

Installation time for systems varied. In general, valve-stem-mounted TPMS and dual tire equalizers were less time consuming to install (generally, several hours), followed by wheel-mounted TPMS, tire-mounted TPMS, and ATIS that required up to a full day for installation.

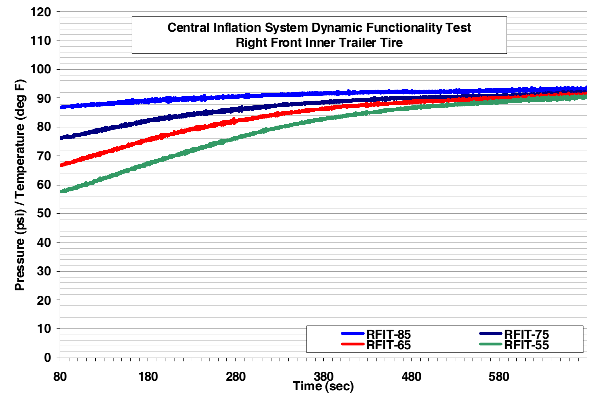

Figure 16. Trailer-mounted ATIS Static Inflation From Various Initial Pressures.

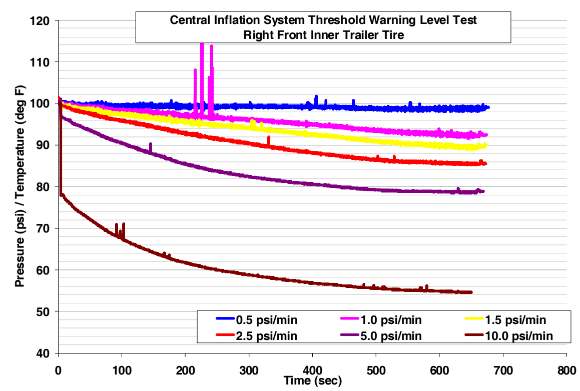

Figure 17. Trailer-Mounted ATIS With Various Leak Rates.

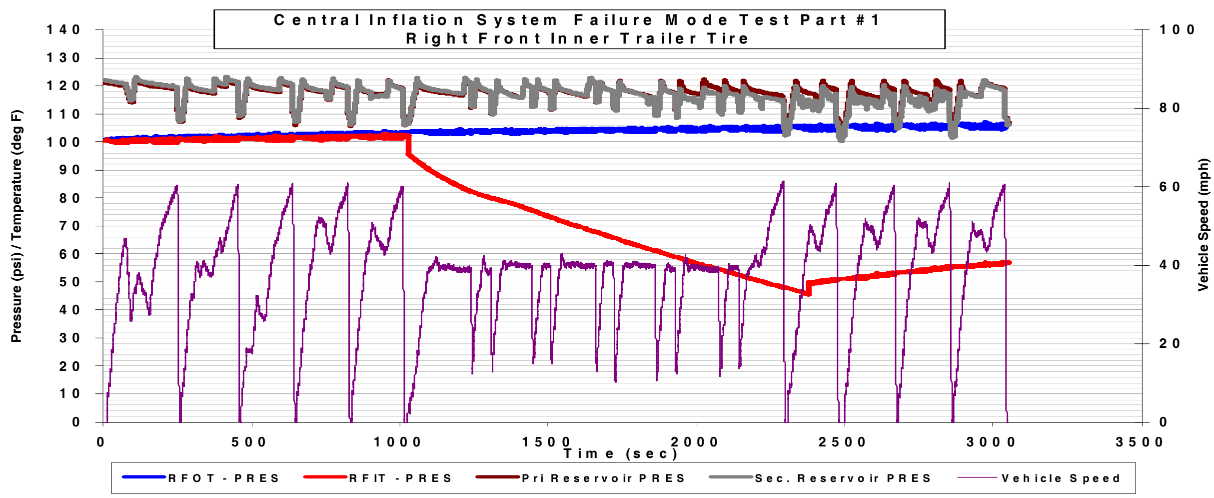

Figure 18. Trailer-Mounted ATIS Brake Snubs With Tire Leak.

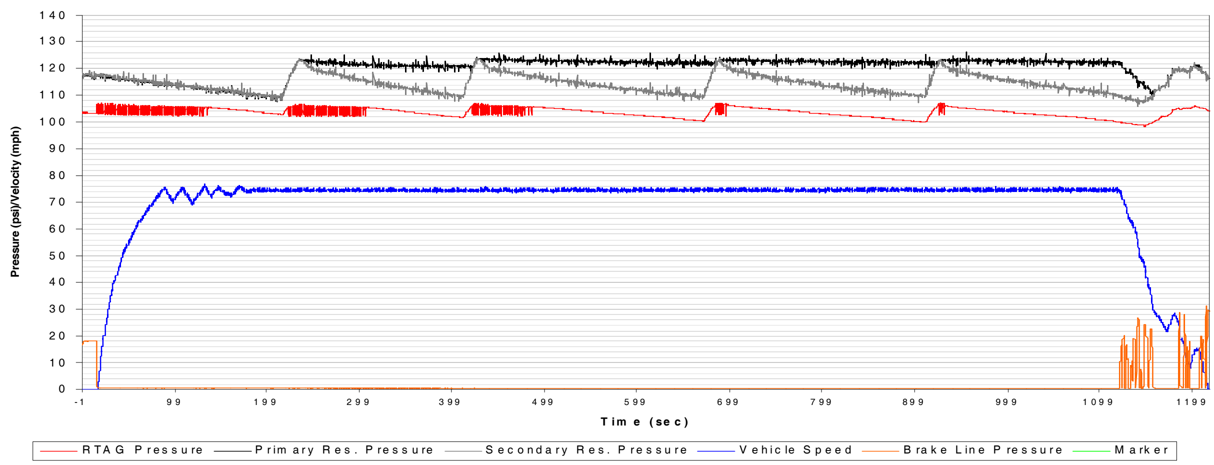

Figure 19. Motorcoach-Mounted ATIS Tire Leak at Highway Speed.

THIRD STUDY: TPMS MINI-FIELD OPERATIONAL TEST

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

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

The test fleet consisted of 12 Orion VII series, 2005 model year, urban transit buses. The buses were a "low floor" design, 40 feet long and 102 inches wide, and operated on compressed natural gas. Each bus's gross vehicle weight rating was 42,540 pounds. The passenger capacity was 41 seated and 36 standing passengers for a total of 77 passengers. The curb weight of the buses was 30,990 pounds.

The study team evaluated three TPMS (as well as three brake performance monitoring systems, as discussed in the companion paper) on 12 heavy-duty urban transit buses in revenue service for a period of 1 year. A control fleet of 12 identical buses was operated in a similar manner and used for comparison. A maintenance garage located in Arlington, Virginia was selected as the test site, based on the availability of buses of a consistent age and operating environment and because of the experience and low turnover of the maintenance staff. With the assistance of WMATA and TPMS system vendors, the study team retrofitted the candidate systems on the buses at the garage. The buses operated in an area covering approximately 300 square-miles south and west of Washington, D.C. The majority of miles were accumulated in an urban environment with minimal high-speed highway travel. The buses averaged 16 miles per hour in revenue service and were driven an average of 129 miles per day.

Over the course of the 12-month 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. WMATA staff recorded all maintenance and fueling activities and entered the data into a maintenance management database. This information was made available to the study team for evaluation. At the conclusion of the test, maintenance staff were interviewed about their experience operating and maintaining the systems. Other than the standard data-recording capabilities of the candidate systems, no additional (or special-purpose) data-logging devices were added to the vehicles. The system status displays were located out of the drivers' view per the request of WMATA fleet managers. The study team and WMATA technicians were responsible for monitoring the systems' display status. This was done to limit driver distraction, as well as to reduce the incidence of operators ceasing bus service because of information from the displays. Limiting vehicle-related information to the bus driver (system diagnostic information, dash-mounted warning lights, and fuel gauge readings) is common in the transit industry.

Three TPMS were installed in the test vehicles:

- *The WABCO Integrated Vehicle Tire Pressure Monitoring (IVTM) System* 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 are wirelessly transmitted to an ECU on-board the vehicle.
- *The HCI Tire-SafeGuard 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. Data are transmitted wirelessly, similar to the WABCO system.
- *The Michelin eTire System* for CMVs was introduced by Michelin North America in October 2002. The system includes an 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 can also be used with a handheld reader.

Results of Field Operational Test

To evaluate the performance (or accuracy) of the TPMS, manual tire pressure measurement readings were taken once a week on each bus and then compared with pressures as reported by the TPMS 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 TPMS systems themselves or, in a few instances, because of problems associated with manually checking the tires.

Key observations related to the on-board monitoring systems include the following:

- The TPMS provided accurate tire inflation pressure data when compared to measured (tire-gauged) values. System sensors were found to be consistent and reliable in 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, found in 17.6 percent of inspections, was "no reads," resulting from missing sensors and sensors in the wrong wheel location.
- Keeping track of the 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 sensor mounting locations were out of view of technicians and the lack of fleet-wide training on system awareness and operation accounted for lost or discarded sensors. 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 just 2 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 of this type from occurring. 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. 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 pressure: 115 psi). Tire life and fuel economy were also similar in both fleets. This was likely the case because the real time display of tire pressure readings was purposefully not made available to drivers but only to maintenance personnel and technicians. Therefore, drivers could 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 have been provided to drivers; and drivers would have had the opportunity to act on the information as needed (for example, if low pressure was detected, adding air to tires at the next convenient time) 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 need to be available to the driver in real time, as well as to maintenance staff.
- Technicians preferred the wheel-mounted tire pressure sensors for two reasons: (1) they were easier to install, and (2) 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.

CONCLUSIONS

Tire pressure maintenance has been a significant and persistent problem for operators of CMVs. After brakes, tires are the most expensive maintenance item for fleets and the most common vehicle-related defect cited in crash reports. Tire deficiencies are the second-ranked reason for CMVs to be cited for defects during roadside inspections. A collection of tire pressure readings from over 35,000 tires provided the first large-scale source of tire inflation readings in the United States. A series of controlled test-track assessments of nine TPMS, representing the three types in the commercial marketplace, provided a comprehensive comparison of the characteristics and operation of these systems and suggested opportunities for improving their usability and performance. A 12-month field operational test of three monitoring-type TPMS provided information on tire pressure status that was useful for improving maintenance practices and detecting low tire pressures to perform timely repairs. This information had a significant impact on inspection practices and enhanced the overall efficiency of operations at WMATA. While no firm procurement commitments were made, WMATA maintenance managers indicated that they would consider using one or more monitoring technologies on new vehicle procurements and the retrofit of existing buses. A study to test the TPMS technologies on commercial tractor-trailer fleets is currently underway.

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