TESTING OF HEAVY TRUCK TIRE PRESSURE MONITORING SYSTEMS (TPMS) IN ORDER TO DEFINE AN ACCEPTANCE TEST PROCEDURE

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ABSTRACT

Several manufacturers produce tire pressure monitoring systems for heavy trucks which are designed to detect low tire pressure and alert the driver. This paper reports on a series of test procedures conducted on these aftermarket TPMS to determine the suitability of these tests for use in developing performance requirements.

Five TPMS were installed one at a time on two heavy trucks. The minimum activation pressure of the TPMS was determined. After driving for a period of up to fifteen minutes, the vehicle was stopped and air was released from one tire to bring its inflation pressure to a point below the minimum activation pressure for the system. The vehicle was driven and the time needed for the system to detect the loss of pressure and alert the driver was recorded. Multiple tire deflations and failure modes were also tested.

Data were obtained from independent onboard instrumentation that measured tire pressure, vehicle speed and distance, and ambient temperature. A video of the TPMS driver display was recorded. Other properties were also evaluated, including temperature compensation accuracy of system pressure measurement and failure modes. The study's results are limited to the five systems tested. Although these systems were chosen to be representative of TPMS on the market, this was not an exhaustive study of all such systems.

INTRODUCTION

In 2000, Congress enacted the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) Act, amending Title 49, United States Code, to require reports concerning defects in motor vehicles and tires, and other mandates to improve vehicle safety. Section 13 of this Public Law 106-414 requires that tire pressure warning systems be installed in new motor vehicles to indicate when a tire is significantly underinflated. Following a one-year research project [1], NHTSA established Federal Motor Vehicle Safety Standard (FMVSS) No. 138, *Tire Pressure Monitoring Systems (TPMS)* [2], which mandated TPMS for vehicles of no more than 10,000 pounds in Gross Vehicle Weight Rating (GVWR). However, this rule did not cover heavy vehicles over 10,000 pounds GVWR. In 2006, the Federal Motor Carrier Safety Administration performed a test-track evaluation of a number of commercially available tire inflation and pressure monitoring systems [3]. This study reported the advantages and disadvantages of the tested systems.

This heavy truck test program addresses TPMS requirements for these heavy vehicles and it explores a series of test protocols which could be applied for verifying basic heavy truck TPMS performance capability.

DEFINITION OF TPMS

A Tire Pressure Monitoring System senses tire pressures and alerts the driver if pressures are outside of safety set points or pressure leakage rates. The "Monitor" systems read the actual pressure in each tire (direct TPMS) or estimate the relative pressure in a group of tires comparing the rotational speed of the tires using the antilock brake system (ABS) wheel speed sensors (indirect TPMS).

Five Types of Direct Pressure Reading TPMS

Using ABS wheel speed sensing is not a practical approach to determining if one tire in a pair of "duals" is low in tire pressure because both tires are mounted to the same hub. Although each tire has an individual rim, the rims are coupled such that the wheel speed for both tires is the same. Therefore, tire pressures must be measured directly to assure the

operator receives accurate information that will enable him to respond and ensure that each tire is provided with sufficient pressure to safely meet the expected load requirement placed upon the tire, as well as to ensure that the tire operates within its limits of pressure design criteria.

There are five types of tire pressure monitoring systems that are capable of directly reading the pressure of the air contained in individual tires of a heavy vehicle. The types are: rim mount (inside tire envelope), tire patch (mounted to tire inside tire envelope), interior valve stem (inside tire envelope), flow-through (outside of tire) and end-of-valve stem mount (outside of tire).

Systems Tested

This program tested two rim-mount systems, two flow-through systems, and one end-of-valve-stem unit. The two rim-mounted systems, the Dana/ SmarTire Smart-Wave S14486 and the HCI Corp Tire-SafeGuard TPM-W210, used internally mounted sensors (on bands around the rim) and included both pressure and temperature measurement of the air contained within the tire envelope. The SmartWave system applied the measured temperatures for "live" pressure compensation, whereas the Tire-SafeGuard system measured the temperatures for driver benefit to determine if a wheel was running hot and as a baseline for referencing cold inflation temperatures.

The sensors of the other three TPMS were mounted outside of the tire envelope, attached to the valve stem. The HCI Corp Tire-SafeGuard TPM-P310B1 provided tire temperature measurement that was acquired indirectly through the sensors mounted at the outboard end of the valve stems. Both it, and the WABCO/Michelin IVTM, provided auxiliary Schrader valves so the tires could be inflated without removing the sensors. The other TPMS system – Advantage Pressure-Pro CU41807684 - covered the end of the valve stem. The Pressure-Pro sensors needed to be removed from the valve stems in order to inflate the tires.

Characteristically, some TPMS have multiple pressure warnings, such as low tire pressure, extremely low pressure (or flat tire), and over-pressure. Some of the externally mounted TPMS have only one setpoint or pressure value for low tire pressure, but do provide for indication of a slow leak.

TEST VEHICLES AND TIRES

Two 10-tire, Class 8 vehicles were selected for demonstration of the TPMS acceptance procedure - a Volvo three-axle tractor and a Peterbilt three-axle straight truck.

The Volvo tractor was a 1991 Model No. WIA64T sleeper-cab tractor with a 189-inch wheelbase. The GVWR was 50,000 lb and the Gross Axle Weight Ratings (GAWR's) were 12,000 lb (steer axle) and 19,000 lb (each drive axle).

The vehicle tire placard specified 275/80R24.5 tires at 100 psi, with a load rating of G, for all tire positions and the tires used for this program matched the placard specifications for tire size. The steer tires were Michelin Pilot XZA-1 Plus rated for 6,175 lb (max "single") at 110 psi (DOT M591-BYUX-0508 and M591-BYUX-4207) and the drive tires were Michelin Pilot XDA-2 rated for 5,675 lb (max "dual") at 110 psi (DOT M591-CM9X-4307 and M591-CM9X-4407). For safety considerations, the Volvo steer tires were tested at 105 psi. The Volvo drive tires were tested at 100 psi as recommended on the vehicle tire placard.

The Peterbilt truck was a 2004 Model No. 357 day cab straight truck with 273-inch wheelbase. The GVWR was 62,000 lb and the GAWR's were 18,000 lb (steer axle) and 22,000 lb (each drive axle).

The steer tires used were Bridgestone 315/80R22.5, M843 V-Steel Mix, Low Pro, M&S, load range L, rated for 9,090 lb (max) at 130 psi (DOT 2C4D-5BF-3007). They were tested at a cold inflation pressure (CIP) of 130 psi.

The drive tires were Firestone 11R-22.5 – 14PR, FD663 Radial, load range G, rated for 5,840 lb (max) at 105 psi (DOT 4D3T-3E3-0708). For the Peterbilt truck TPMS tests, the drive tires were inflated to the maximum specified on the tire sidewall, 105 psi. Therefore, all tires on the Peterbilt were inflated to their maximum tire pressures as labeled on the sidewalls.

INSTRUMENTATION

The setup of the TPMS components, including initialization of the Central Processing Unit (CPU), programming of the tire pressure warning setpoints, as well as documentation of significant events during testing, were vital to the mission of this project. All of these activities were established and recorded using a digital Computerized Data Acquisition System (CDAS), a thermal probe, and a video camera.

Data Channels

A ruggedized benchtop-PC computer collected 16 channels of data during the TPMS testing. Parameters measured included: 10 individual tire pressures, vehicle speed and distance, 3 types of event indications, and ambient temperature.

Tire Pressures

Individual tire pressures were transferred to the cab using a network of rotary unions, valves, tee couplings, hoses, and transducers. To allow for wheel rotation, rotary unions were installed in the air lines at each wheel to couple the pressures in the tire envelopes directly to the in-cab data acquisition system. The drive wheels used two port unions so pressures from both inner and outer tires of each dual set were monitored live. Air line tee couplings were added at each valve stem to allow for simultaneous connection to both TPMS and data collection system. Standard ¼-inch SAE J844 truck air line tubing connected the rotary unions to a manifold system mounted in the truck cab.

The manifold system consisted of 10 pressure-control ball valves and pressure transducers. The pressure transducers were configured for a range of 0 to 200 psi with accuracies of 0.5 percent of full scale. The tire pressure controllers allowed for remote inflation or venting of one or more tires simultaneously, zeroing of transducers, and logging of real-time tire pressures.

Vehicle Speed and Distance

Vehicle speed was measured using an ADAT DRS-6 Radar Speed Sensor by B&S Multidata. This dual antenna microwave device provided high accuracy logging of vehicle velocity over the dry surfaces driven without contact with the roadway surface. The digital output was then directly fed into a Labeco Model No. 625 Performance Monitor to log accumulated distance traveled.

Event Channels

Three event channels were configured on the CDAS data collection system to interface events real-time into the data set. A driver event button was installed so the observer riding in the truck during the track tests could signal the data set that an observation was made (this freed the driver to actually concentrate on driving). Driver events were logged when significant events occurred about the test track, such as when the vehicle reached the target speeds (i.e. “now at 60 mph”), when the vehicle stopped for intersections, or at the end of the driving segment of the test. If the observer heard a TPMS buzzer, the driver event button was also actuated.

Temperatures

Live tire temperature measurements were not logged for this project; however, constant vigilance was maintained for any indication of tire heating. Before and after each track run, individual tire temperatures were measured using a Fluke k-type thermal probe. The probe was inserted deep into the tread of each tire, maintained until the readings stabilized, and then the tire temperature measurements were recorded.

The CDAS maintained a real-time log of the variations measured in the ambient temperature experienced while the tire pressures were being adjusted in the preparation bay, and while the truck was being driven on the test track.

Video Log

A mini-DVD tape camera, zoomed in to view the TPMS displays and a portion of the CDAS monitor, was used to log all in-cab TPMS activity. The camera logged changes applied to pressures in test tires, TPMS events and display warnings, audible buzzer sounds, and verbal commentary from both the driver and the observer.

TEST PROCEDURES

Direct pressure reading TPMS do not rely upon ABS wheel speed sensing to indicate low tire pressures. Actual driving with the systems installed did not appear to modify any calibration parameters used by the TPMS tested. However, a calibration run was made before any low-pressure detection tests were begun to allow time for all sensors to begin active transmission of measured pressure values.

Once the calibration runs were completed, a series of tests were performed that evaluated the sensing capabilities of the various TPMS on individual tires with reduced tire pressures. After detecting the low tire pressure, the ignition switch power to the TPMS was cycled to assess the short-term memory retention of the alarm condition. After cooling the tires, the test tire was re-inflated to CIP and the re-inflation identification response of the TPMS was noted.

Preparation to Test TPMS Performance

To prepare to run the TPMS performance test program, the test vehicle was outfitted with new tires, plumbed with a tire pressure control system that regulated pressure in all tires, and instrumented with

individual tire pressure sensors and a central data acquisition system. A video camera was installed in the cab to log test events, along with both driver and observer commentary.

Once prepared, the truck was parked in a shaded area (such as the truck bay with the garage doors open) and the tires were inflated to the specified CIP. Then, the TPMS was turned on and observations made of the validity and completeness of the lamp check sequence. The TPMS was programmed to identify each tire pressure sensor (if needed) and actual TPMS pressure readings were collected. Tire temperature readings were made if the TPMS was so equipped, and a thermal probe was used to measure the external tire temperatures, between the ribs or lugs.

TPMS Calibration Test – Sensor Identification

The FMVSS No. 138, "Tire Pressure Monitoring Systems" [2] as written for light vehicle TPMS, specified that a calibration run should be provided before beginning any low-pressure detection tests. Following this lead, all heavy truck tests herein were given ample vehicle-in-motion time prior to actual low-pressure detection tests. The calibration test is part of the light vehicle test procedures, designed to allow the systems to make any necessary adjustments prior to the low tire detection test. The calibration procedure is intended primarily for indirect TPMS, but the procedure is recommended for the heavy vehicle TPMS test procedures so that the procedures are technology neutral.

After initial installation and preparation, the TPMS was subjected to a system "calibration" test. With the pressures successfully set to CIP at ambient temperature, the TPMS was powered up. Initial tire pressure and temperature readings of both the CDAS and TPMS were recorded. If a sensor did not immediately transmit a pressure signal, its reading was taken after the vehicle was put into motion for the calibration procedure. The truck was driven once around a 7.5-mile test track with constant running speeds near 60 mph and returned to the starting point. The total tire rolling time ranged from 12 to 15 minutes. During this time, all sensors "woke up" and began actively transmitting pressure signals.

A variation of the calibration procedure was applied for the tractor (the second test vehicle). In this "cool" calibration test, the tractor was driven for 8 to 10 minutes over a flat road. The vehicle speed was limited to 25 mph for the 2-mile loop. The tire temperatures rose 5 to 10 degrees above ambient and were fairly stable at the time of the subsequent low-pressure detection tests. With tighter pressure ranges, the pressure detection tests frequently did not require driving the tractor to detect the set low tire pressure levels. As there was little heat added during these tests, the tire cooling period was reduced, thereby lowering the total test-cycle time required for testing each tire.

TPMS Low-Pressure Detection Test

The pressure was reduced in one test tire while the TPMS was turned off. After the pressure was adjusted, the TPMS was turned on. If the display immediately alarmed, the low-pressure detection test was considered successful and complete. If the display initialized, but did not identify the low-pressure tire, the truck was driven once around a 7.5-mile test track (for a period of 12 to 15 minutes) on a low tire pressure detection run, where steady state speeds reached or exceeded 60 mph for at least 5 minutes of the run. If the TPMS still did not identify the low tire pressure, the sensor channel for that tire was listed as "failed to detect" at that low-pressure setpoint. When the TPMS did display the low tire pressure alert, the time to alert was recorded.

After returning to the starting point, a five-minute memory check was performed to determine if a temporary lapse of power to the system (such as turning off the engine during a snack break or stop at the shipping office) would lose the low pressure warning display. The ignition power to the TPMS was turned off. After five minutes had elapsed, power was restored to the TPMS and the status of the alarms recorded. The TPMS was turned off again while the tires cooled.

The low-pressure tire was re-inflated to CIP and the TPMS was then turned on back to read the now-correct tire pressure levels. If the TPMS correctly identified the restored pressure, the Low Tire Pressure Detection Test was complete. However, if the TPMS failed to clear the previous low-pressure warning, the truck was again driven once around the 7.5-mile test track for a Reset Identification Test, in expectation that it would clear the warning.

This procedure was repeated for each of four individual tires. An additional test was run with simultaneous multiple low pressure tires to determine the order and extent of the warnings presented by the TPMS.

TPMS Malfunction Tests

This section of testing was unique, as each TPMS system contained different setup procedures, programming methods, and electronic components. One common feature for the systems tested was that none of the sensors had batteries that were user-replaceable. The transmitters could not be powered down to identify lack of communication. Therefore, each system was tested for absence of a transmitter by removing the tire and transmitter from the vehicle and physically moving them to a remote location over 100 feet from the receivers in the trucks. For the TPMS with remote antennas, the antennas were removed to simulate loss or damage to them as might occur while traveling on the highway.

SYSTEM TEST RESULTS FOR LOW PRESSURE DETECTION

Data were collected in multi-media style to ensure no details were missed. The highlights of the data collected for the various low-pressure setpoints are tabulated in separate tables by TPMS system, by vehicle, and then by setpoint pressure. Within each table, there is a comparison of the four individual tires tested at the same relative pressure setpoint (e.g., CIP - 10 percent), the test pressure actually applied, corresponding tire temperature at the time the pressure was reduced, the type of alarm expected to be displayed for the low-pressure level, a description of the alarm indication - when and where it occurred, and a description of the alarm indication moments after the tire was re-inflated to CIP.

System A – SmartWave – Rim Mount

The SmartWave system, tested first, was subjected to the prescribed tests at three different test pressure levels. Because it did provide two distinct low tire pressure identification setpoints, the first two test pressures were set to a allowance of 2 psi below the setpoints (which were factory set at -10 and -20 percent below CIP respectively) and the third test pressure at 2 psi below the CIP minus 25 percent level.

After reviewing the results of the first few tests run at pressures beyond the initial setpoint, it appeared that the test pressure allowance may have been set too tightly. A brief experiment was run using the truck to explore the possibility of increasing the allowance from 2 psi to 3 psi. This increase allowed for differences in the compensation scheme of the SmartWave system that tended to run 2 psi to 3 psi lower than data system reference pressures in random pressure comparisons. All TPMS tests performed after this initial truck/TPMS configuration applied the 3-psi allowance for all test pressures (3 psi below the TPMS setpoints).

The SmartWave system provided a tire pressure temperature-compensation chart with which to adjust tire pressures at elevated temperatures (beyond ambient) for an initial CIP referenced to 65°F. No other TPMS manufacturer's installation package included a temperature compensation chart.

Because the SmartWave was received with a temperature compensation chart, all target pressures were adjusted (for the Peterbilt truck only) to test pressures specified by the SmartWave compensation chart for the TPMS tire temperatures measured at the end of the calibration test. Therefore, the truck tire test pressures were adjusted to somewhat above the non-compensated target pressure levels used for the other TPMS. In contrast, the later tractor series tests of the SmartWave TPMS used non-temperature-compensated target pressures that were calculated using straight 90 percent and 80 percent of the actual CIP's before subtracting the 3 psi allowance allowance, which was the same approach used for the other TPMS installed on the tractor.

For the 10-percent "Low Deviation" tests on the truck tires, the SmartWave correctly identified the 10-percent low-pressure deviation level (Table 1) before completion of the 15-minute detection run, for 4 out of 4 cases. During one of the tests, the SmartWave identified the low-pressure deviation applied to the subject tire, soon after the TPMS was turned "on". During the other three tests, the SmartWave correctly identified the low-pressure deviation, but the alarm did not activate until the truck was already put into motion for the 15-minute detection run. The test pressures applied (as prescribed by the SmartWave temperature compensation chart) only ranged from 4.8 to 7.6 percent below the actual CIP pressures, as the elevated tire temperatures caused the pressures in the test tires to rise somewhat above CIP during the "hot calibration" test. As such, a pressure loss of 10 percent below the "hot" tire pressures was detected by the SmartWave TPMS. With temperature compensation, the SmartWave detected a pressure loss of 10 percent of the hot tire pressure reading, making it more sensitive to detecting pressure loss than TPMS without compensation.

In Table 1, a yellow highlighted Detection Status box indicates that the truck was actually driven to allow the TPMS to detect the low-pressure condition applied. Once the warning activated, the truck was

driven back to the shaded starting point (truck bay). Driving was discontinued to allow time for the low-pressure alarm to clear due to an increase in pressure caused by increasing tire temperature (thermal lag from the previous drive). A box in Table 1 that is not highlighted indicates that the TPMS properly identified the low-pressure deviation condition before the truck was driven; therefore, it was not driven for this step of the test procedure.

Table 1.
SmartWave (rim mount) low deviation setpoint = 10 percent below CIP - Truck

Tire	CIP (psi)	Test Pressure Used	Detection Status	Re-inflation Status After Cool Down
LF	130	123 psi. @95°F	alarm before driving	clear before driving
RF	130	123 psi. @95°F	alarm during driving	clear before driving @10.7min
LII	105	97 psi. @86°F	alarm at gate while driving	clear before driving
RRO	105	100 psi. @100°F	alarm backing out while driving	clear before driving

Tire positions: LF=left front, RF=right front, LII=left intermediate inner, RRO=right rear outer

For the second low-pressure setpoint on the truck installation of the SmartWave TPMS, the test tire pressures were reduced to 2 psi below the 20-percent-low level. The applied test pressures ranged between 14 and 19 percent below the actual CIP values (again as interpolated from the SmartWave tire pressure correction chart).

For this series, the level of alert appeared to be affected by the timing of setting the compensated test pressures. After the "hot calibration" tests, the tires began to cool quickly. The first tire temperature value read after the calibration test ended was used to determine the compensated test pressure for the following low tire pressure detection test. The test procedure guidelines followed allowed only 5 minutes to adjust the tire pressure for the low pressure detection test. The SmartWave alarm activated at the test pressure, but incorrectly displayed the low deviation alert instead of the critical low pressure alert. It was felt that the less severe warning activated because the test pressure applied was obtained using the temperature compensation chart, and was a value higher than would have been applied if a straight uncompensated test pressure were applied.

The SmartWave correctly identified the reset pressure immediately after the tires were re-inflated for 3 of 4 tests. For the fourth test, re-inflation identification "reset" automatically cleared the previous warning from the display screen as the truck was being backed from the building (Table 2). Therefore, the SmartWave did alert to the low-pressure conditions on each application, but it did not correctly indicate the severity level expected for the lower pressure tests using temperature compensation and allowing only a 2-psi allowance for the setpoint.

Table 2.
SmartWave (rim mount) critical low-pressure setpoint = 20 percent below CIP - Truck

Tire	CIP (psi)	Test Pressure Used	Alarm	Detection Status	Re-inflation Status After Cool Down
LF	130	108	Low Deviation, NOT Critical Low	alarm while driving T=7.8min Dist=0.6mi	clear before driving
RF	130	109.2	Low Deviation, NOT Critical Low	alarm while backing T=2.4 min Dist=16ft	clear while backing T=3.4min, Dist=132ft
LII	105	85.1	Critical Low Pressure	alarm while backing T=1.6min Dist=100ft	clear before driving
RRO	105	89.7	Low Deviation, NOT Critical Low	alarm before driving >1.9min	clear before driving
Multi	130 & 105	LF-95 RF-94 LII-75	Critical Low Pressure	alarm before driving	clear before driving

Note – 130 psi -25% = 97.5 psi; and 130 psi – 20% = 104 psi (the uncompensated setpoint)

An additional test was performed where three of the four test tires were simultaneously subjected to the same 20 percent pressure reduction. For detection of multiple low pressure tires, the SmartWave TPMS correctly identified a critical low tire pressure for each tire and alerted the driver before the vehicle needed to be driven on the detection run. Upon resetting the tire pressure to CIP, the TPMS display cleared all warnings without needing to drive again.

For the SmartWave TPMS, using temperature compensation to adjust tire pressure appears to be beneficial in determining early alerts of low tire pressure. Inflating a tire to CIP at 65°F provides sufficient load carrying capacity to meet tire design specifications. With compensation, a low tire pressure of 10 percent below expected pressure can be repeatedly detected, even at elevated tire temperatures.

To continue the original test procedure guidelines for the second vehicle (the tractor), the SmartWave pressure setpoints were re-programmed to the CIP requirements of the tractor tires. Because the "cool" calibration procedure was applied to all tractor tests, the measured tire temperatures were near ambient temperature when lowering the tire pressures down to the test pressures. The data presented in Table 3 reflect the procedural change to "testing without applying temperature compensation" to adjust the test pressures. All five TPMS systems tested on the tractor used the same "cool" calibration procedure

and no temperature compensation. For the SmartWave system, all test pressures were set to a fixed allowance of 3 psi below the 10-percent-low deviation setpoint without regard to measured tire temperature.

Table 3.
SmartWave (rim mount) low deviation setpoint = 10 percent below CIP - Tractor

Tire	CIP (psi)	Test Pressure Used (psi.)	Detection Status	Re-inflation Status After Cool Down
LF	105	92	alarm before driving	clear before driving
RF	105	92	alarm before driving	clear before driving
LII	100	87	alarm before driving	clear before driving
RRO	100	87	alarm before driving	clear before driving

For each tire position tested, the SmartWave detected the reduced tire pressure and activated a "low deviation" alert. After cooling the tires for one-half hour, the tires were re-inflated to uncompensated CIP. When the ignition power was restored to the TPMS, the previous warning flashed briefly on the display, then cleared without needing to drive the tractor on a re-inflation identification run.

Similar results were attained for the more severe Critical Low pressures summarized in Table 4. The test pressures 81 psi (steer) and 77 psi (drives) were set at 3 psi below fixed pressure decrements of 20 percent below CIP.

Table 4.
SmartWave (rim mount) critical low-pressure setpoint = 20 percent below CIP - Tractor

Tire	CIP (psi)	Test Pressure Used (psi.)	Detection Status	Re-inflation Status After Cool Down
LF	105	81	alarm before driving	clear before driving
RF	105	81	alarm before driving	clear before driving
LII	100	77	alarm before driving	clear before driving
RRO	100	77	alarm before driving	clear before driving
Multi	105 & 100	81 & 77	alarm before driving	clear before driving

*1: TPMS alarmed for RIO non-test tire that went out of normal operating pressure range.

Following are two pictures which show the installation of the sensor on a rim without the tire (Figure 1) and the array of antennas, sensors, display, rim bands, and hardware associated with the SmartWave TPMS (Figure 2).

Figure 1. SmartWave sensor mounted on the tractor steer axle rim.

Figure 2. SmartWave components kit.

System B – Tire-SafeGuard – Rim Mount

The Tire-SafeGuard "rim mount" was tested second. Its sensors mounted with bands onto the rims, similar to those of the SmartWave system. The primary difference between the SmartWave and the Tire-SafeGuard was that the Tire-SafeGuard only had one low-pressure setpoint for each axle group of tires. The setpoints needed to be programmed as actual declared pressures, rather than deviation percentages of an initial pressure. The pressures added to the program corresponded to the nearest whole unit psi resulting from an assumed low-pressure indication (similar to some other TPMS units tested) of CIP minus 12 percent. Actual test pressures applied were presented as 3 psi below the low-pressure setpoints. Upon operation, a low-pressure alert was expected to activate for each tire that was set to run low on inflation pressure. Figure 3 shows the three receiving antennas, ten sensor transmitters, and the steel mounting bands.

Figure 3. Tire-SafeGuard (rim mount) components kit.

Care was taken when installing the tire onto the rim to ensure no damage was incurred by the sensor transmitter antennas. Figure 4 shows the tight clearance encountered when lifting the tire over the sensor to seat the tire on the bead.

Figure 4. Tire-SafeGuard sensor and rim-mounting band – showing antenna.

For the straight truck tests, the steer tire low-pressure warning setpoints were set to 114 psi, which was approximately 12 percent below the 130 psi CIP. The setpoints for the drive tires were set to 92 psi, or approximately 12 percent below the drive tire CIP of 105 psi. The test pressures applied were 3 psi below the setpoints at 111 psi (steers) and 89 psi (drives). The "hot calibration" procedure was used for all tests on the straight truck. For all four individual tire tests, the Tire-SafeGuard rim mount TPMS displayed the correct low pressure alert. Three of the four tests responded quickly, before moving the vehicle. The fourth unit alarmed while the truck was being driven to the test track on the detection run. After cooling the tires, all four sensors showed the appropriate response to re-inflating the tires by displaying a "ready" display after cycling through system power-on and a quick check of sensors. After lamp check, the display would briefly show the previous low tire warning, and then abruptly clear and reset to ready mode (Table 5).

Table 5.
Tire-SafeGuard (rim mount) low-pressure setpoint = ~ 12 percent below CIP – Truck

Tire	CIP (psi)	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	130	114 psi (~ -12%)	111	alarm before driving	clear before driving
RF	130	114 psi (~ -12%)	111	alarm before driving	clear before driving
LII	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
RRO	105	92 psi (~ -12%)	89	Alarm at gate while driving	clear before driving
Multi	130 & 105	114 & 92 psi (~ -12%)	111 & 89	alarm before driving	clear before driving

A simultaneous multi-tire low-pressure detection test followed (last row in Table 5), to identify more than one tire in a low-pressure condition. The results duplicated the single tire tests in that the Tire-SafeGuard alerted to all four tires being low in pressure (and without driving the detection run). After re-inflating the four tires, the display promptly cleared the faults and displayed a ready screen.

When the Tire-SafeGuard "rim mount" TPMS was transferred to the tractor, the setpoints were adjusted to meet the new CIP requirements. The steer tire low-pressure warning setpoints were set to 92 psi, which was approximately 12 percent below the 105 psi CIP. The setpoints for the drive tires were set to 88 psi, or 12 percent below the drive tire CIP of 100 psi. The applied test pressures were 89 and 85 psi, respectively. The "cool calibration" procedure was used for all tests on the tractor (Table 6).

Table 6.
Tire-SafeGuard (rim mount) low-pressure setpoint = ~ 12 percent below CIP - Tractor

Tire	CIP (psi)	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
RF	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
LII	100	88 psi (~ -12%)	85	alarm before driving	clear before driving
RRO	100	88 psi (~ -12%)	85	alarm before driving	clear before driving
Multi	105 & 100	92 & 88 psi (~ -12%)	89 & 85 psi	alarm before driving	clear before driving

Note: only one setpoint pressure was tested for this unit as it only had one level to test.

For this configuration, in all four tests using single tires with low pressure, the Tire-SafeGuard "rim

mount" TPMS rapidly responded with a low-pressure warning before the truck was driven for the detection run. The same response resulted from the four-tire multiple-low-tire pressure test, as well. As in the truck tests, the system again reset appropriately after re-inflating the multiple deflated test tires to CIP.

System C – Tire-SafeGuard – Flow Through

An additional Tire-SafeGuard TPMS was tested, except, instead of mounting the sensors on the rims, the sensors were mounted on the valve stems externally, in a flow-through mode. It had a driver display and operating functions similar to the previous Tire-SafeGuard unit. One drawback to the flow-through sensors was the fact that the temperature measurements provided by the TPMS were measured in the valve stems, outside of the captive air inside of the tire envelope (Figure 5). The flow-through sensors traded ease of installation and maintenance for temperature precision. This flow-through system only required the use of one receiving antenna. Figure 6 shows the receiving antenna, 10 small valve-stem mounted flow-through sensors, and small driver display.

Figure 5. Tire-Safeguard (flow-through) sensor with test hose attached for remote inflation.

Figure 6. Tire-Safeguard (flow-through) components kit.

The installed sensors appeared compact and unobtrusive to would-be vandals. These flow-through sensors attached directly to the valve stem, thereby eliminating the need for any external connecting hoses for a standard installation. It is not known if the added mass may lead to valve stem leakage or fatigue. (Durability issues are outside the scope of this paper.)

In operation, the "flow-through" Tire-SafeGuard system provided only a single setpoint for determining low tire pressures. Again, the setpoints needed to be programmed as pressure levels, not percentages of CIP, so the pressure levels from TPMS unit B Tire-SafeGuard "rim mount" were also applied for TPMS unit C – the Tire-SafeGuard "flow-through" system.

For the truck tests, the "hot calibration" test procedure was followed. Under subsequent low pressure detection tests, the Tire-Safeguard flow-through system correctly identified all four individual low tire pressure readings using a test pressure of 3 psi below the setpoints (which were set at approximately 12 percent below CIP). The TPMS display responded quickly with a low pressure warning, eliminating the need to run a detection test on the test track.

After cooling and re-inflating the tires, the Tire-SafeGuard quickly reset and cleared the faults, thereby returning to a quiescent ready mode (Table 7). A simultaneous low tire pressure test was not performed for the truck installation, but was conducted later for the tractor installation.

Table 7.
Tire-SafeGuard (flow-through) low-pressure setpoint = ~ 12 percent below CIP - Truck

Tire	CIP (psi)	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	130	114 psi (~ -12%)	111	alarm before driving	clear before driving
RF	130	114 psi (~ -12%)	111	alarm before driving	clear before driving
LII	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
RRO	105	92 psi (~ -12%)	89	alarm before driving	clear before driving

For the tractor tests using the Tire-SafeGuard "flow-through" sensor system, results obtained were similar to those measured in the truck tests. The display alarmed before the detection run was begun; therefore the tractor was not driven for this test sequence. After cooling and re-inflating the test tires, the TPMS reset correctly, shortly after repowering the display.

A multi-tire low-pressure test was performed (Table 8) on the tractor installation, following a "cool calibration" preparatory test. The TPMS detected all four low tire pressure readings in rapid succession and did not require the tractor to be driven on a detection run. After cooling and re-inflating the tires, the display showed that the TPMS successfully reset to the ready mode.

Table 8.
Tire-SafeGuard (flow-through) low-pressure setpoint = ~ 12 percent below CIP – Tractor

Tire	CIP (psi)	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
RF	105	92 psi (~ -12%)	89	alarm before driving	clear before driving
LII	100	88 psi (~ -12%)	85	alarm before driving	clear before driving
RRO	100	88 psi (~ -12%)	85	alarm before driving	clear before driving
Multi	105 & 100	92 & 88 psi (~ -12%)	89 & 85 psi	alarm before driving	clear before driving

Therefore, the Tire-SafeGuard "flow-through" TPMS correctly measures and responds to test pressures of 3 psi below low-pressure setpoints without temperature compensation. The drawback is that if the tires get hot after the initial tire inflation to CIP at ambient temperature, a 105 psi CIP tire that is heated to running temperature may see an increase of 5 to 10 psi (or more) to over 115 psi. At these temperatures, the tire would have to experience a pressure loss of 23 psi before this system would activate a low tire pressure alarm (below 92 psi). The pressure may drop down to the low 80's in psi when returned to the original ambient temperature, where the load capacity would be greatly diminished.

System D - WABCO/Michelin IVTM – Flow Through

The fourth TPMS tested was manufactured by WABCO and distributed by Michelin. The IVTM provided a valve stem mounted "flow-through" tee coupling to accommodate simultaneous tire pressure measurement and tire re-inflation through an auxiliary supply port. A short length of flexible hose coupled the tee to the IVTM sensing transmitter. The sensor was mounted on a steel plate that attached to two of the wheel lug bolts after the hub-piloted wheels were installed onto the hub. Normal torque was applied to tighten the wheel lug nuts. If two sensors were used to measure a set of dual wheels (on a drive axle), they were placed opposite one another. When only one tire pressure sensor was used (on a steer axle), a counterbalance weight provided by WABCO was installed on the wheel opposite of the sensor (Figure 7). The long-term effects of the mounts on lug nut tightness were not studied.

Figure 7. IVTM mounted on right steer tire with plumbing for data system.

This was the most complex of the externally mounted TPMS as the sensors were mounted on wheel-lug plates and included valve stem extension hoses with tee-fittings (Figure 8).

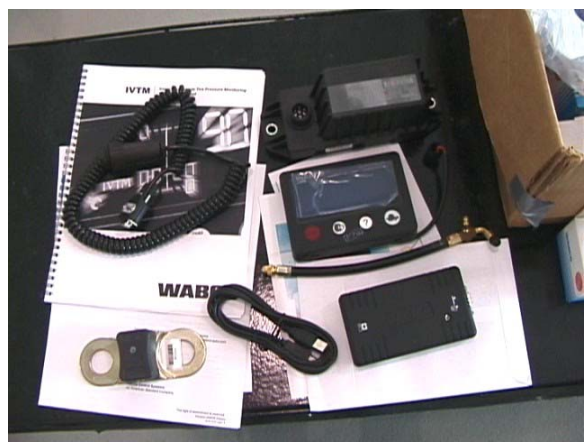

Figure 8. IVTM components kit.

No low-pressure setpoint values were listed in any of the numerous brochures and manuals supplied with the IVTM. Hence, a slow leak-down test was performed to derive empirically the two low-pressure setpoints of the IVTM. A low-pressure setpoint was found to be 20 percent below the CIP and the second setpoint at 35 percent below CIP.

The truck was tested first and used the "hot calibration" procedure prior to the low tire pressure detection tests. For the first setpoint, all four individual tire tests produced timely first level alarms using a test pressure of 3 psi below the CIP minus 20 percent level. Therefore, no low-pressure detection test track driving tests were needed at this pressure

level. After cooling the tires and then re-inflating with air to CIP, the IVTM delayed in clearing the low-pressure alert until nearly the end of the reset identification run, (5.8 miles into the 8.3-mile test track course and after 11.2 minutes) (Table 9). For the other three single tire tests, the IVTM produced a first level alert and cleared promptly after re-inflating, without necessitating any driving on the track, beyond the initial calibration runs.

Table 9.
IVTM (flow-through) low-pressure setpoint 1 = 20 percent below CIP – Truck

Tire	CIP (psi)	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	130	101	alarm before driving	clear during driving 11.2 min, 5.8 mi
RF	130	101	alarm before driving	clear before driving
LII	105	81	alarm before driving	clear before driving
RRO	105	81	alarm before driving	clear before driving
Multi	130 & 105	both	alarm before driving	clear before driving

For the multiple-alert test (last row in Table 9), simultaneous-low-tire-pressure test, the same 4 tires were deflated to the previous individual test pressures (3 psi below CIP-20%). The driver display was inadvertently left turned on during the release of air from the tires. Because the "vents" dumped air from the selected tires very rapidly, the IVTM display alerted to critical low pressures every time the vents discharged air. With the test apparatus close coupled in a tee formation at the wheel, the TPMS read the sudden decrease in pressure from the venting lines, thereby indicating critical alerts. Each time the release of air was stopped for more than a few seconds, the critical alert for that channel cleared. The TPMS was turned off at approximately 2.5 minutes into the adjustment period, with the 4 pressures still being vented down to the setpoints. After the test pressures were established in the 4 tires, the IVTM was turned back on. The IVTM quickly displayed 4 first level low-pressure alerts (portrayed by a "turtle" icon). Having passed the multiple-low-tire pressure detection test, the tires were re-inflated. The system cleared the faults after repowering the display.

The CIP values were reprogrammed for the tractor tests to match the lower tire pressure requirements. The tractor was driven on the "cool calibration" circuit before beginning low tire pressure tests. Again, the IVTM displayed appropriate low-pressure warnings for the 20 percent low pressure level, and reset upon restoring the tires to CIP pressures (Table 10).

Table 10.
IVTM (flow-through) low-pressure setpoint 1 = 20 percent below CIP – Tractor

Tire	CIP (psi)	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	105	81	alarm before driving	clear before driving
RF	105	81	alarm before driving	clear before driving
LII	100	77	alarm before driving	clear before driving
RRO	100	77	alarm before driving	clear before driving
Multi	105 & 100	81 & 77	alarm before driving	clear before driving

System E - Pressure-Pro – Valve-Stem-End Mount

The fifth TPMS system tested was from PressurePro. That system contained the least number of components and was the simplest to install. The single receiving antenna was mounted directly to the top of the driver display; therefore, the only cable to install was for system power.

The sensors were installed by removing the valve stem caps and replacing them with the sensors. However, there was some concern raised when installing the sensors on aluminum rims with small hand-holes. The sensor nearly filled the opening in the rim, thus making it challenging for the installer to ensure that proper tightness was applied to the sensor. The clearance around the sensor was less of a concern for installation on steel wheels with larger hand-holes in the rim (Figure 9).

Figure 9. Two adjacent PressurePro sensors in initial setup for dual tractor tires.

After consulting the manufacturer, the outer wheel was rotated 180 degrees to balance out the weight of the two sensors.

Figure 10 shows the installation kit for the PressurePro TPMS. The packet contained ten sensors, a driver display, and a power cable.

Figure 10. Components kit for PressurePro valve-stem-mounted 10-tire system.

The PressurePro TPMS came configured with two low pressure level setpoints. The "first stage low pressure" setpoint was 12.5 percent below CIP. The "second stage low pressure" or critical low-pressure setpoint was fixed at 25 percent below CIP. To initialize the system, the tires were properly inflated to CIP. Next, the sensors were installed one at a time in the PressurePro wheel sequence, while confirming both position and pressure on the driver display. No actual setpoint pressure values were programmed into the TPMS. The Pressure Pro used the initial pressure readings as the CIP reference for each wheel. Caution was exercised to ensure that the correct CIP pressure was contained in the tire when initializing the sensors. When lowering the air pressures for the respective low-pressure detection tests, the test pressures were set 3 psi below the setpoints for each pressure warning level and for each vehicle.

For the first level low-pressure warnings setpoints (CIP minus 12.5%), the truck test pressures were set to 111 psi (steers) and 89 psi (drives). For the tractor, the test pressures were 88 and 84 psi, respectively. The results from the individual wheel low-pressure tests showed that the PressurePro correctly read and displayed pressures for the two distinct setpoint levels for each vehicle, and quickly warned of the low tire pressures. Upon re-inflating the tires and turning on the TPMS power, the display indicated that the warnings of low tire pressure had appropriately cleared (Table 11 and Table 12).

Table 11.
PressurePro (valve-stem cap) first stage low-pressure = 12.5 percent below CIP – Truck

Tire	CIP (psi)	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	130	111	alarm before driving	clear before driving
RF	130	111	alarm before driving	clear before driving
LII	105	89	alarm before driving	clear before driving
RRO	105	89	alarm before driving	clear before driving
Multi	130 & 105	111 & 89	alarm before driving	clear before driving

Table 12.
PressurePro (valve-stem cap) first stage low-pressure = 12.5 percent below CIP – Tractor

Tire	CIP (psi)	Test Pressure Used (psi)	Detection Status	Re-inflation Status After Cool Down
LF	105	88	alarm before driving	clear before driving
RF	105	88	alarm before driving	clear before driving
LII	100	84	alarm before driving	clear before driving
RRO	100	84	alarm before driving	clear before driving
Multi	105 & 100	88 & 84	All alarmed before driving (in a span of 111 sec.)	clear before driving

Additionally for each vehicle, four tire sensors were tested simultaneously for low tire pressure warning. The display responded with a composite array of red LED's showing the exact mounting locations of the four underinflated tires. After re-inflating the tires, the PressurePro again cleared its display and returned to the ready mode.

MALFUNCTION TESTS

The following procedure was used to test each system for a simulated failed sensor and for a disconnected antenna.

All tires were inflated to the proper CIP. The tire pressures were logged from both the TPMS and the data acquisition system. The right front tire was the target in this test (except for the Flow-Through Tire-SafeGuard System which used the left intermediate axle inner tire). The target tire was removed and rolled out of the area about 100 ft from the truck. The TPMS was then monitored to see if it detected the removed sensor, and if so, the time required for detection. The tire was then replaced to see if the system cleared the display of the failed system (malfunction) signals.

Another malfunction test was performed by disconnecting the antenna. The antenna cable was disconnected and the time logged. The TPMS was then monitored to see if it warned of a fault. The antenna was then reconnected to see if the system

would clear the fault warning from the display. The results for both tests are presented in Table 13.

Table 13.
Results of malfunction testing

System	Sensor Test		Antenna Test	
	Result	Time to Warning	Result	Time to Warning
SmartWave	Passed	36 min	Passed	33 min
Tire SafeGuard (rim mount)	Failed	N/A	Failed	N/A
Tire-SafeGuard (valve-stem mount)	Failed	N/A	Failed	N/A
Wabco IVTM	Passed	30 sec	N/A	N/A
PressurePro	Passed	5 min	N/A	N/A

SUMMARY AND CONCLUSIONS

The data results have shown that the type or brand of vehicle did not alter the individual TPMS results. The results for a given TPMS on a 10-tire truck were repeated when later installed on a 10-tire tractor, without observing any vehicle influence on the test results even though the vehicles were equipped with different tires, rims, and the TPMS were adjusted to different CIP's.

Each of the five TPMS tested during this research project was successful at identifying at least one preset level of low tire pressure, signaling low tire pressure to a driver display, and clearing the low-pressure warning from the display after the tire was re-inflated. Some problems were encountered during installation of the systems onto the test vehicles and there were also some problems with the setup and operation of the systems. The problems were overcome by the engineers and technicians assigned to this research project; however, a commercial carrier may not have similar resources available and may not be able to successfully add these systems to in-service vehicles without aid from the system manufacturer. However, it is anticipated that vehicle manufacturers and TPMS suppliers would work together to develop efficient systems if TPMS is mandated for heavy vehicles.

A major factor in considering TPMS for heavy vehicles is an assessment of the durability of the available systems. There have been several studies of the accuracy of available systems with regard to pressure sensing, but there has been little published information to date on the durability and long term operating costs of heavy vehicle TPMS. The Federal Motor Carrier Safety Administration has initiated a field operation study of heavy vehicle TPMS that is designed to provide durability, as well as cost/benefit data, for several of the systems that were tested by this research project for pressure sensing accuracy and for malfunction recognition.

With and without temperature compensation, tire test pressures set to 3 psi below TPMS "factory" setpoints were satisfactorily detected by each TPMS tested. By adding tire temperature compensation (SmartWave only) the variation between a "hot" over-the-road tire pressure reading and low-pressure alerts for both 10 and 20 percent pressure losses was maintained at tire temperatures elevated to nearly 30° F above initial CIP temperatures. It maintained a fixed ratio of pressure drop from current temperature operating pressures to activate the low-pressure alarm, where the systems without temperature compensation allowed much larger pressure drops before activating their alarms. These large pressure drops could result in significant load reduction capability of the tires; and the tires should be re-inflated as soon as possible after the warnings are received. A disadvantage of temperature-compensation is adverse driver reaction when driving through extreme temperature fluctuations (e.g., mountains and valleys). More research will be required to answer the human factor questions of this technology.

As seen in the malfunction tests performed on these systems, several systems did not recognize or acknowledge through the display that communication had been lost with one of the pressure sensors. In order to maintain the safety benefits of the TPMS, it is important that the system inform the driver when it is not operating normally.

Identification of sensor temperature sensitivity needs to be isolated from raw pressure detection as identified by the low-pressure detection test procedure in this paper. A second test would need to be conducted using either fixed pressures and the tires run through a heating and cooling cycle, or the tires would need to be heated fully to on-the-road operating temperatures and a nominal slow leak rate of 1 psi per minute be established through a test pressure controller (as was used for this test program) while driving to detect the level where the TPMS would detect and alert low tire pressure.

Test Procedure Summary

The following section provides the procedural steps for testing a TPMS as described earlier in the paper, but without commentary.

Inflate all tires to Cold Inflation Pressure (CIP). Take readings by measuring individual tire pressures and temperatures with both TPMS and data collection system, and measure all tire external temperatures

with a noninvasive probe. Log all measurements that are not collected electronically.

Drive for 8 to 10 minutes over a flat road (calibration). Limit the vehicle's maximum speed to 25 mph for a 2-mile loop. Within 5 minutes of completing calibration, read TPMS pressures and temperatures, deactivate TPMS, and deflate test tire to 3 psi below the setpoint (which is set at 10 to 15 percent below the CIP). Immediately reactivate the TPMS, take pressure and temperature readings, observe TPMS display for warnings, and then run a Detection Test (same course as in the calibration) The test is complete when the TPMS signals a low-tire-pressure detection or 15 minutes have elapsed since activating the TPMS. Cool tires and re-inflate to CIP. Go to the next test.

When the TPMS detects the low tire pressure within the 15-minute period, return to the starting point. Take readings. Deactivate the TPMS and wait for 5 minutes (this is a TPMS memory check). After 5 minutes have expired, reactivate the TPMS and confirm that the same warning returns to the TPMS Display. If the same warning does not re-display, the TPMS has failed to remember the fault after a power-down cycle (an engine shutdown).

Deactivate the TPMS and allow the tires to cool to ambient temperature from 30 minutes up to 2 hours. With the TPMS deactivated, re-inflate the tires to CIP. Activate the TPMS, take readings, observe TPMS display for warnings. If no warnings are indicated by TPMS display, the test is complete. Proceed to the next test.

When warnings are present, either activate the TPMS reset function (if available) or run Reset Identification Test (same course as the calibration). If the TPMS fails to clear any unwarranted warnings, then the system has failed to identify a properly re-inflated tire.

Repeat the above steps for each test tire and for each pressure setpoint. Once the Detection tests have been completed, conduct a failed system or system malfunction test by disconnecting the power source to any TPMS component, by disconnecting any electrical connection between TPMS components, by removing a wheel and locating it outside of radio range, or by installing a tire or wheel on the vehicle that is incompatible with the system being tested.

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