U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

DOT HS 811 314 **June 2010**

Tire Pressure Monitoring System Tests for Medium and Heavy Trucks and Buses

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 811 314		

4. Title and Subtitle
Tire Pressure Monitoring System Tests for Medium and Heavy Trucks and Buses

5. Report Date
June 2010

6. Performing Organization Code
NHTSA/NVS-312

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8. Performing Organization Report No.

9. Performing Organization Name and Address
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Vehicle Research and Test Center
P.O. Box B37
East Liberty, OH 43319-0337

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
1200 New Jersey Avenue, SE
Washington, D.C. 20590

13. Type of Report and Period Covered
Feb 2008 – Feb 2009

14. Sponsoring Agency Code
NHTSA/NVS-312

15. Abstract

Tire Pressure Monitoring Systems (TPMS) are an aid to maintaining proper inflation pressure. TPMS for heavy vehicles, when compared to systems developed for vehicles with a Gross Vehicle Weight Ratings (GVWR) less than 10,000 pounds, must monitor tires that operate at significantly higher pressures and also monitor more tires. This report examines the development of a procedure that can be used to check the operation of TPMS on vehicles with GVWRs greater than 10,000 pounds, up to 80,000 pounds.

This study examined the operation of five aftermarket TPMS on two different heavy vehicles. The installation and operation of each system are described. It was conducted in two parts. It first examined the application of temperature compensation to low pressure detection test levels after initializing the TPMS with a “hot” calibration procedure. Then it compared data using uncompensated test pressure following a “cool” calibration procedure.

The data results have shown that 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 recommended Cold Inflation Pressures (CIP). By using a “cool” calibration procedure to initialize the TPMS before performing a low pressure detection test, the tires remained relatively cool, and therefore did not thermally bias the basic low pressure detection capability of each system.

By adding tire temperature compensation to the TPMS, 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.

16. Key Words
TPMS, Tire Pressure Monitoring System, Low Pressure Warning, Heavy Truck, Power Unit

17. Distribution Statement
Document is available to the public from the National Technical Information Service at www.ntis.gov

18. Security Classif. (of this report)	19. Security Classif. (of this page)	20. No. of Pages	21. Price
Unclassified	Unclassified	106	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures					Approximate Conversions to English Measures				
Symbol	When You Know	Multiply by	To Find	Symbol	Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4	millimeters	mm	mm	millimeters	0.04	inches	in
in	inches	2.54	centimeters	cm	cm	centimeters	0.39	inches	in
ft	feet	30.48	centimeters	cm	cm	centimeters	3.3	feet	ft
mi	miles	1.61	kilometers	km	km	kilometers	0.62	miles	mi
		AREA					AREA		
in^2	square inches	6.45	square centimeters	cm^2	cm^2	square centimeters	0.16	square inches	in^2
ft^2	square feet	0.09	square meters	m^2	m^2	square meters	10.76	square feet	ft^2
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)					MASS (weight)		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.45	kilograms	kg	kg	kilograms	2.2	pounds	lb
		PRESSURE					PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar	bar	bar	14.5	pounds per $inch^2$	psi
psi	pounds per $inch^2$	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY					VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h	km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION					ACCELERATION		
ft/s2	feet per $second^2$	0.3	meters per second2	m/s^2	m/s^2	meters per second2	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Fahrenheit) - 32 C	Celsius	°C	°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

NOTICE REGARDING COMPLIANCE WITH AMERICANS WITH DISABILITIES ACT SECTION 508

For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided in the text for graphical images contained in this report to satisfy Section 508 of the Americans with Disabilities Act (ADA).

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EXECUTIVE SUMMARY

The inflation pressure of a tire determines the load-carrying capacity of that tire. Properly inflated tires provide safe load-carrying capacity, proper vehicle handling and braking, and better fuel economy. Tire pressure monitoring systems (TPMS) are an aid to maintaining proper inflation pressure. TPMS for heavy vehicles, when compared to systems developed for vehicles with a Gross Vehicle Weight Rating (GVWR) less than 10,000 pounds, must monitor tires that operate at significantly higher pressures and also monitor more tires. As such, NHTSA conducted this preliminary test program to explore a series of test protocols that could be used to evaluate the efficacy of heavy truck TPMS. This report examines the development of a procedure that can be used to check the operation of TPMS on vehicles with GVWRs greater than 10,000 pounds, up to 80,000 pounds, and on vehicles with dual tires on each end of at least one axle with GVWRs of 10,000 pounds, or less.

Following the introduction, the report describes the five aftermarket TPMS tested. The test vehicles and the instrumentation are then described. The remainder of the report deals with test procedures and results.

This study was conducted in two parts. It first examined the application of temperature compensation to low-pressure detection test levels after initializing the TPMS with a "hot" calibration cycle. Then it compared data using uncompensated test pressure following a "cool" calibration initialization.

Following initialization, the test procedure was the same, regardless of initialization procedure. After initialization, a tire was deflated 3 psi below the low-pressure setpoint of each TPMS. A period of 15 minutes was allowed for the TPMS to signal low tire pressure. Once the signal was made, the unit was deactivated for 5 minutes and switched on to see if the low-pressure state was still indicated by the TPMS. The tires were then allowed to cool and re-inflated to recommended cold inflation pressure (CIP). The system was again checked to make sure that any low-pressure alarms remained cleared. These steps were repeated for three additional tires. A simultaneous multiple tire deflation and low pressure detection sequence was then performed followed by a failed system test.

The test results showed that type or brand of vehicle did not alter the behavior of the individual TPMS. The results for a given TPMS on a 10-tire single-unit 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. By using a "cool" calibration procedure to initialize the TPMS before performing a low pressure detection test, the tires remained relatively cool, and therefore did not thermally bias the basic low pressure detection capability of each system. Each system was able to recognize multiple tires with low pressure (10 to 20 percent below Cold Inflation Pressure). Not all the systems recognized when a system malfunction occurred, such as a failed pressure sensor or a disconnected antenna.

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, 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.

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 and may not be capable of installing these systems onto in-service vehicles successfully without aid from the system manufacturer. If TPMS is widely adopted in heavy vehicle applications, NHTSA anticipates that further product development / training will be required to overcome the complexities and challenges of installing certain TPMS systems across a range of vehicle configurations.

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.

Some of the tested TPMS provided system malfunction warnings on the display screens. These warnings appear beneficial in tracking symptoms of faulty sensors, missing or damaged receiving antennas, and related component malfunctions.

1.0. INTRODUCTION

The inflation pressure of a tire determines the load-carrying capacity of that tire. Properly inflated tires provide safe load-carrying capacity and proper vehicle handling and braking. Underinflated tires lead to poor fuel economy and can lead to tire failure. Tire pressure monitoring systems (TPMS) are an aid to maintaining proper inflation pressure. TPMS for heavy vehicles, when compared to systems developed for vehicles with a Gross Vehicle Weight Rating less than 10,000 pounds, must monitor tires that operate at significantly higher pressures and also monitor more tires. As such, NHTSA conducted this preliminary test program to explore a series of test protocols that could be used to evaluate the efficacy of heavy truck TPMS.

2.0. TPMS TYPES AND SYSTEMS TESTED

There are three types of tire pressure measurement and/or control systems that are currently available for use on heavy vehicles over 10,000 pounds GVWR. Each is described below, in order of increasing functionality and control.

Tire Pressure Monitoring System – senses tire pressures and alerts driver if pressures are outside of safety setpoints or pressure leakage rates. The "Monitor" systems may either 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).

Tire Pressure Maintenance System – adds automatic tire inflation capability, without driver intervention. Some of these "Maintenance" systems do NOT measure the actual tire pressure in individual tires, but provide only a central pressure monitor, which regulates the pressure in a series of tires that are attached to this control unit. For example, one maintenance controller may maintain the pressure in eight tires of a tandem-drive-axle Class 8 truck with only one centrally located pressure sensor. In this type of system, individual tires would have check valves installed on them so pressure could be increased only, not reduced.

Tire Pressure Management System – allows the driver to raise and lower tire pressures on demand (e.g., logging trucks that go on and off-road). Similar to some maintenance systems, many pressure "Management" systems do NOT use pressure sensors in individual tires, but depend upon a single pressure sensor or monitor to control a group of tires.

2.1. Five Types of Direct Pressure Reading Tire Pressure Monitoring Systems

Using ABS wheel speed sensing is not believed to be 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 together on one wheel, thus causing the rotational speeds for both tires to be the same. Therefore, individual tire pressures should be measured directly, to provide the operator with accurate information, enabling him or her to respond effectively to ensure that each tire is inflated 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), in-line (outside of tire), and end-of-valve stem mount (outside of tire).

2.2. Systems Tested

This program tested two rim-mount systems, two in-line systems, and one end-of-valve-stem unit. The two rim-mount 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, while 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, but Tire-SafeGuard did not provide a compensation chart or display acknowledgement of active compensation.

The following example shows the advantage of a system which provides temperature compensation. Suppose a truck tire has a recommended cold inflation pressure (CIP) of 130 psi. Also, suppose this tire is underinflated with a pressure of 117 psi at ambient temperature (65°F), and the truck is then driven for 30 miles on a hot day. The tires will quickly heat to 125°F. The hot tire pressure is now 132 psi. A temperature-compensated TPMS will alert the driver that the tire pressure is low. For a tire inflated to 132 psi at 125°F, this TPMS warns the driver that the tire is 13 psi lower than the prescribed 130-psi CIP. When the tire cools back to the reference temperature of 65°F, the pressure will decrease to 117 psi. A non-temperature-compensated TPMS cannot measure the temperature in the tire and will not activate the low-pressure warning while the tire is hot.

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 (Integrated Vehicle Tire Monitoring), 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 overpressure. 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. The following Tables 2.1 and 2.2 list additional specifications for the five heavy truck TPMS tested under this program.

Table 2.1 compares the basic functions and features of the five TPMS. Major categories are divided by function group: Sensor/Transmitter, Receiver/Gateway, and Driver display. Sensor details include airflow design, internal or external mounting, transmitting antenna, external visibility, and battery life. Receiver details include temperature compensation, receiving antennas, receiver mounting, and number of system low-pressure setpoints. The driver display section lists mounting location, user programming options, and specifications on setpoints.

Table 2.1. System Features

	System				
Features	A	B	C	D	E
Manufacturer	SmartWave Dana	Tire-SafeGuard HCI Corp	Tire-SafeGuard HCI Corp	WABCO-IVTM Michelin	PressurePro Advantage
Sensor Model	S14486	TPM-W206	TPM-P310B1	IVTM	CU41807684
Mounted Position	rim	rim	valve stem	wheel lug bolts	valve stem cap
Inside Tire	Y	Y	N	N	N
Transmitting Antenna	integral	attached	integral	integral	integral
Tire Temperature	Y	Y	Y	N	N
Sensor Visible	N	N	Y	Y	Y
Removal Necessary to Fill Tire	N	N	N	N	Y
Number of Receiving Antennas	1	3	1	1	1
Temperature Compensation	Y	N	N	N	N
Number of Low Pressure Setpoints	2	1	1	2	2
Setpoint 1 Factory Setting	CIP -10%	CIP -12%	CIP -12%	CIP -20%	CIP -12.5%
Setpoint 2 Factory Setting	CIP -20%	n/a	n/a	CIP -35%	CIP -25%
Number of High Pressure Setpoints	1	1	1	1	1
Integral Receiver Display	N	N	N	N	Y
Slow Leak Identification	N	Y	Y	Y	N
Programmable Setpoints	Y	Y	Y	N	N
Specific Pressure vs. Percentage	%	P	P	%	%

Table 2.2 compares the additional setpoints for each tested TPMS, whose functions include slow leak detection, and both upper temperature and upper pressure limits. Not all of these additional functions were provided by each TPMS and are listed as “function not available.”

Table 2.2. System Setpoint – Slow Leak and Upper Limits

System	Slow Leak		Setpoints	
TPMS	Rate (psi/min)	Status	Over Pressure (psi)	Over Temperature (°F)
SmartWave Dana S14486 A	function not available	function not available	CIP +10%	195°F
Tire-SafeGuard HCI Corp TPM-W210 B	used -1; rate -3 psi or more within 2 to 10 minutes	detect slow leak in <3 minutes	used 143 max; orig default was 130	used 194°F; range was 176°F to 230°F
Tire-SafeGuard HCI Corp TPM-P310B1 C	used -1; rate -3 psi or more within 2 to 10 minutes	detect slow leak in <3 minutes	used 143 max; orig default was 130	used 194°F; range was 176°F to 230°F
WABCO-Michelin IVTM D	used -1; rate not specified	detect slow leak in <3 minutes	max not specified	function not available
PressurePro Advantage CU41807684 E	function not available	function not available	used default CIP +24%; ranges = off or +10% to +45%	function not available

2.2.1. SmartWave System

Following are a series of copies of photographs showing SmartWave system components and mounting locations.

The SmartWave rim-mount installation kit included ten sensing transmitters, receiving antenna and mount, a receiver (Wireless Gateway), a driver's display, ten rim-mounting bands, and several interface cables to connect the receiving end components together (Figure 2.1). This system supports a maximum of ten sensors.

Figure 2.1. Components Kit for SmartWave 10-Tire System

Figure 2.2 shows the correct orientation of the sensor to the valve stem. This is the manufacturer's recommended installation procedure to indicate the approximate location of the sensor so that proper care is used when installing or removing tires from rims. The mounting position of the SmartWave Receiver/Gateway is shown in Figure 2.3 as viewed from the front of the vehicle.

Figure 2.2. SmartWave Sensor Mounted on Lowest Section of Rim with Steel Band

Figure 2.3. SmartWave Receiver/Gateway Mounted on Transmission Lower Crossmember

2.2.2. Tire-SafeGuard (Rim-Mount) System

The following copies of photographs show the mounting of the Tire-Safeguard sensors and an overview of the component installation kit. The Tire-SafeGuard sensing transmitters included a high-gain flexible monopole antenna attached to one end of the transmitter housing (Figure 2.4.). The antenna needed to be handled carefully so it wouldn't get damaged when installing the tire onto the rim (Figure 2.5). The manufacturer's installation procedure was for the sensor to be mounted at a position 180 degrees opposite of the valve stem (Figure 2.6).

Figure 2.4. Rim-Mounted Tire-SafeGuard Sensor with High-Gain Antenna
Note-Tire is Pushed Back and Must Clear Antenna When Tire is Moved to Final Position

Figure 2.5. Rim-Mount Tire-SafeGuard with Antenna Pushed Inside Tire
Just Before Seating Bead and Inflating Tire

Figure 2.6. Tire Being Removed from Rim-Mount Tire-SafeGuard

Service personnel need to be made aware of the significance of knowing which "rim mount" TPMS sensors are installed in a tire so as to be careful in removing the tires from the rims. The SmartWave installation guide specifies mounting the sensor on the opposite side of the rim (180 degrees away) to that of the Tire-SafeGuard installation guide. By not knowing which sensor installation procedure was followed, the tire may inadvertently be pushed off center in a direction that may shear off the sensor band grips, thus destroying the sensor.

The Tire-SafeGuard rim-mount installation kit included ten sensing transmitters, three remote receiving antennas, a receiver, a driver's display, ten rim-mounting bands, and several interface cables to connect the receiving end components together (Figure 2.7). This system supports a maximum of ten sensors.

Figure 2.7. Components Kit for Tire-SafeGuard 10-Tire Rim-Mount TPMS

2.2.3. Tire-SafeGuard (Flow-Through) System

The Tire-SafeGuard "flow-through" TPMS installation kit was considerably less complicated than the previous two rim-mount TPMS systems. The kit included ten external valve-stem-mount sensing transmitters with auxiliary inflation ports, a single remote antenna for mounting in proximity of the rear wheels, a small receiver, a driver display, a cigarette-lighter power plug, and cabling for the receiving end components (Figure 2.8). 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 report.) This system supports a maximum of ten sensors.

Figure 2.8. Components Kit for Tire-SafeGuard Flow-Through 10-Tire System

2.2.4. WABCO/Michelin IVTM (Flow-Through) System

The IVTM "flow-through" TPMS installation kit included ten external wheel lug mounted sensing transmitters with flexible rubber hoses for connection to the valve stems, driver display, Electronic Control Unit (ECU), and wiring harness. An ECU mounting bracket and weight counterbalances for the steer axle wheels were also provided. This system can support a maximum of sixteen sensors per ECU.

Following are a set of copies of photographs showing the IVTM field installation kit (Figure 2.9), driver display (Figure 2.10), and the sensing transmitter and wheel-lug mounting plate (Figure 2.11).

Figure 2.9. Components Kit for IVTM Flow-Through 10-Tire System

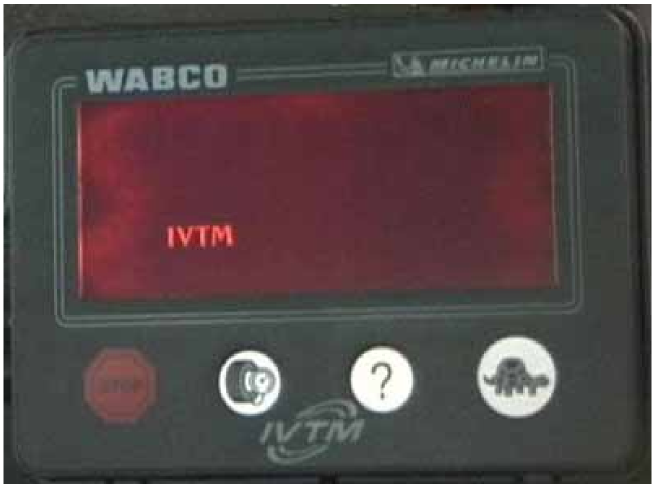

Figure 2.10. IVTM Driver Display

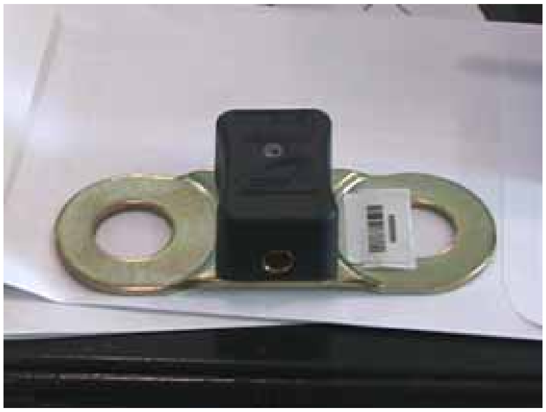

Figure 2.11. IVTM Wheel Lug Plate with Mounted Transmitter
Port at Front Connects Air Line to Valve Stem

2.2.5. PressurePro (Valve Stem Mount) System

The fifth TPMS system tested, PressurePro, contained a very small set of components and was easy to install. The single receiving antenna was mounted on the top of the driver display (Figure 2.12) so the only cable installation was for power to the TPMS.

Figure 2.12. PressurePro Driver Display Mounted in the Truck

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 proper tightness was applied to the sensor (Figure 2.13). The clearance around the sensor was less of a concern for installation on steel wheels with larger hand-holes in the rim (Figure 2.14).

Figure 2.13. PressurePro Transmitter on Valve Stem in Aluminum Steer Wheel of the Tractor with Small Hand Holes

Figure 2.14. Side View of Two PressurePro Sensors Mounted on Dual Steel Wheels Sensors Were Installed With the Wheels Already Mounted on the Hubs

Figure 2.15 shows the installation kit for the PressurePro TPMS. The packet contained ten sensors, a driver display, monopole antenna, and power cable. This system supports a maximum of thirty-four sensors.

Figure 2.15. Components Kit for PressurePro Valve-Stem Mount 10-Tire System

2.3. Startup and Warning Screens

Each manufacturer uses unique startup and programming sequences for their TPMS units. Similarly, the warning levels and screen icons are all different.

2.3.1. SmartWave System

SmartWave provides a round driver display with a red plasma display, an amber (yellow) warning lamp, and two programming buttons. VRTC connected an external buzzer to the provided annunciator output wire. The round driver display and the annunciator (buzzer) were mounted on a sheet metal bracket fabricated for these tests. Also a red LED was located on this bracket between the display and the buzzer. These components can be seen in Figure 2.16.

Figure 2.16. SmartWave Display

2.3.1.1. Startup

At power-up the display screen, warning lamp, and buzzer come on for approximately three seconds (Figure 2.17). Then the logo screen appears for about two seconds (Figure 2.18). The initialization progress is displayed for ten to fifteen seconds. This screen is followed by the "TPMS Ready" and the full tire icon (Figure 2.19).

Figure 2.17. Power-Up Lamp Check

Figure 2.18. Logo Screen

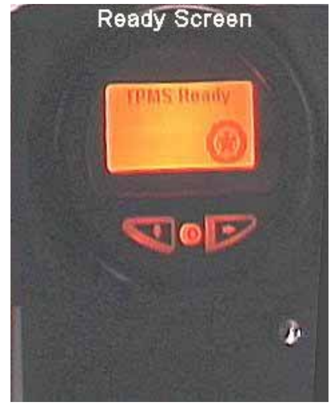

Figure 2.19. Ready Screen

2.3.1.2. Pressure Deviation Alert

The warning lamp flashes at a rate of about three times a second. The audible alarm (buzzer) is on for two seconds. On the display, the axle and wheel position are indicated graphically as is the pressure deviation icon; a triangle enclosing an exclamation point (Figure 2.20).

Figure 2.20. Low-Pressure Warning

2.3.1.3. Critical Low-Pressure Alert

The warning lamp flashes at a rate of about three times a second. The audible alarm (buzzer) is on for two seconds. On the display, the axle and wheel position are indicated graphically as is the Second Alert Level icon; a tire cross section enclosing an exclamation point (Figure 2.21).

Figure 2.21. Critical Low-Pressure Warning

2.3.2. Tire-SafeGuard (Rim-Mount) System

The Tire-SafeGuard system provides a rectangular driver display with an LCD display and a red/green status lamp.

2.3.2.1. Startup

At power on, the green power light turns on and the tractor/truck icon with the wheel position indicators is displayed as shown in the left photo (Figure 2.22). The monitor display then cycles through each tire pressure and temperature. Then only the green status light remains lit in the normal mode as shown in the right photo (Figure 2.23). There is no audible alert sounded during startup unless there is a warning pending.

Figure 2.22. Display at Power-up

Figure 2.23. Display in "Run" Mode Immediately After Power-up Cycle

2.3.2.2. Low Tire Pressure Warning

The status light turns red and the audible alarm beeps 5 times about once a second. The position of the tire underinflated is highlighted on the tractor/truck wheel position icon. A low tire pressure icon is also displayed to the right of the tractor/truck icon on the monitor display (Figure 2.24). This icon is represented by an empty tire (hollow) shell as shown in the photo below. The tire temperature and tire pressure are also displayed. After the initial visual and audible alarm, the screen then cycles through the remaining tire pressures and temperatures.

Figure 2.24. Low-Pressure Detection in Right Front Steer Tire

2.3.2.3. Slow Air Leak Warning

The slow leak warning is indicated by a green status light, tire position indicator highlighted, and the slow air leak icon. The slow leak icon is represented by a graphic that shows the tire two-thirds full. This warning is shown in the photo below (Figure 2.25).

Figure 2.25. Slow Leak Warning for Left Front Steer Tire

2.3.3. Tire-SafeGuard (Flow-Through) System

The Tire-SafeGuard flow-through TPMS uses the same monitor as the Tire-SafeGuard rim-mounted system (2.3.2. Tire-SafeGuard (Rim-Mount) System). The display screens for setup and warnings are the same.

2.3.4. WABCO/Michelin IVTM (Flow-Through) System

The IVTM system provides a rectangular driver display, two warning lights, and two operator buttons.

2.3.4.1. Startup

At startup, the audible alarm beeps twice and all of the red icons light for a duration of about one second. The two warning symbols below the main display flash on for one second also (Figure 2.26). After initialization the normal mode displays only the IVTM icon as seen in the right photo (Figure 2.27).

Figure 2.26. Startup Lamp Check

Figure 2.27. Display in Ready Mode – for Normal Operation

2.3.4.2. Tire Pressure Display

From the normal mode, individual tire pressure readings can be read by pushing the button with the pressure gauge/tire graphic (bottom row, second icon from the left). Individual axles are highlighted one at a time. The following photo shows the steer axle with both the left and right tire pressures displayed. In the case of dual tires on a single wheel end, the outer tires are displayed first, and then the inner tires follow on the next screen, as the pressure/gauge icon is depressed to scroll through the pressures (Figure 2.28).

Figure 2.28. Steer Tire Pressures after "Hot" Calibration Test

2.3.4.3. First Setpoint Low-Pressure Alert

At the First Setpoint Low-Pressure Alert the tire position of the low pressure tire flashes once per second (Figure 2.29). The audible alert beeps twice at about the same rate. The yellow warning light with the turtle graphic lights and stays on (does not flash).

Figure 2.29. First Low-Pressure Warning in Right Front Steer Tire

2.3.4.4. Second Stage Low-Pressure Alert

The Second Stage Low-Pressure Alert is similar to the First Stage Alert, but the tire position indicator lamp flashes two times per second and the audible alert beeps twice per second (Figure 2.30). These two indicators activate in unison. The red warning light with the stop-sign graphic lights and stays on (does not flash).

Figure 2.30. Critical Low-Pressure Warning Indicates to Driver to Stop and Service Tire

2.3.4.5. Additional Information Screen

By pushing the button with the large question mark icon, detailed and additional information about an alert will be displayed. The photo below is an example of the information display for a low tire pressure alert. The tire pump signifies that a tire is underinflated and needs attention soon (Figure 2.31).

Figure 2.31. Information Screen Showing Tire Pump Signifying that a Tire Needs to be Re-Inflated

2.3.5. PressurePro (Valve Stem Mount) System

The PressurePro system provides a rectangular driver display using a truck figure, a green power indicator, red LEDs to mark tire positions, and an operator panel consisting of four buttons.

2.3.5.1. Startup

At power on, the green power light turns on and then flashes about every five seconds. The red tire position indicator LEDs for all programmed tires light for five seconds and then turn off. The LEDs remain off until prompted by the operator pressing a button, such as scrolling through the tire list to read tire pressures (Figure 2.32). The green power light continues to flash every five seconds in the normal mode (Figure 2.33). There is no audible-alert check during the startup lamp-check sequence.

Figure 2.32. Lamp Check at Power-On

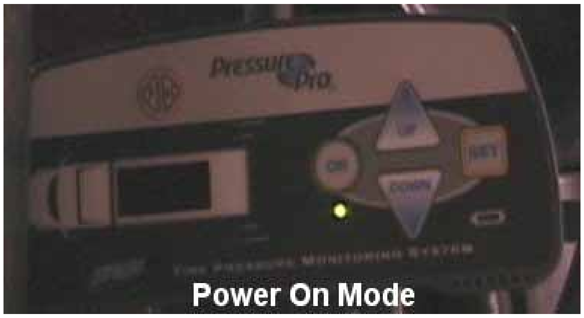

Figure 2.33. Display in Ready Mode

2.3.5.2. Tire Pressure Display

In the normal mode, individual tire pressure readings can be displayed by pushing either the up-arrow button or the down-arrow button. The up-arrow button scrolls through the tire positions clockwise and the down-arrow button scrolls through them counterclockwise. The tire position flashes about once per second while the pressure remains lit (Figure 2.34).

Figure 2.34. Current Pressure is 126 psi in Left Front Steer Tire

2.3.5.3. First Stage Low-Pressure Alert

At the First Stage Low-Pressure Alert the tire position indicator lamp and the pressure-display number flash once per second and the audible beeper sounds once per second. These three indicators alert in unison (Figure 2.35).

Figure 2.35. Inside Tire on Left Intermediate Axle Channel Is Warning of a First Stage Low-Pressure Detection

2.3.5.4. Second Stage Low-Pressure Alert

The Second Stage Low-Pressure Alert is similar to the First Stage Alert, but the tire position indicator lamp and the pressure display number flash two times per second and the audible beeper sounds two times per second. These three warning indicators activate in unison (Figure 2.36).

Figure 2.36. Left Front Steer Tire Channel
Is Warning of a Second Stage Low-Pressure Detection

Following are a set of photographs showing: the driver display in ready mode (Figure 2.37), showing a TPMS measured pressure of 126 psi in the right front tire (Figure 2.38), and showing all active sensors, but no pressure readings (Figure 2.39).

Figure 2.37. PressurePro Driver Display Showing "Ready Mode" on Screen;
Only the Green Light is Visible in This Mode When Not Hand Selecting Pressures

Figure 2.38. PressurePro Display Showing 126 psi Tire Pressure in Right Front Tire Instead of the Applied 130 psi CIP

Figure 2.39. PressurePro Display Showing All Active Sensors, But No Pressure Indications

3.0. TEST VEHICLES AND TIRES

Two 10-tire Class 8 vehicles were selected for demonstration of the TPMS systems - a Volvo three-axle tractor (Unit No. VR5) and a Peterbilt long three-axle straight truck (Unit No. VR8).

<u>Volvo Tractor</u> was a 1991 Model No. WIA64T sleeper-cab tractor with a 189-inch wheelbase (Figure 3.1). The GVWR was 50,000 lb and the Gross Axle Weight Ratings (GAWRs) were 12,000 lb (steer axle) and 19,000 lb (each drive axle).

Figure 3.1. Volvo Tractor

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 (DOT M591-BYUX) rated for 6,175 lb (max "single") at 110 psi and the drive tires were Michelin Pilot XDA-2 (DOT M591-CM9X) rated for 5,675 lb (max "dual") at 110 psi.

The Michelin Truck Tire Data Book – January 2008 (from their website), recommended that the steer tire cold inflation pressures be set to 105 psi (12,080-lb axle load), whereas Volvo only specified 100 psi for the 12,000-lb axle. According to the Michelin Data Book, 100 psi supports 11,670 lb which was only 95 percent of the load specified by Volvo. For safety considerations, the Volvo steer tires were tested at 105 psi.

The reverse situation was found for the drive tires. Michelin recommended 90 psi for the dual drive tires to haul 19,000 lb. (4,750 lb per tire). Here, Volvo recommended a higher pressure of 100 psi. According to the Michelin Data Book, 100 psi would support 21,240 lb (5,310 lb per tire), which is 12 percent higher than specified on the Volvo placard. Although 100 psi was below the Michelin maximum limit of 110 psi per dual drive tire, this pressure was 11 percent higher than the 90 psi specified by Michelin for the GAWR. The Volvo drive tires were tested at 100 psi as recommended on the vehicle tire placard. From this point forward, the Volvo tractor will be referred to as the "tractor."

<u>Peterbilt Truck</u> was a 2004 Model No. 357 day cab straight truck with a 273-inch wheelbase (Figure 3.2.). The GVWR was 62,000 lb and the GAWRs were 18,000 lb (steer axle) and 22,000 lb (each drive axle).

Figure 3.2. Peterbilt Straight Truck

The vehicle tire placard specified 18-22.5 steer tires (at 75 psi) with a load rating of H and 11-24.5 drive tires (at 90 psi) with a load rating of G. However, the steer tires used were Bridgestone 315/80R22.5, M843 V-Steel Mix, Low Pro, M&S load range L, (DOT 2C4D-5BF) rated for 9,090 lb (max) at 130 psi. The steer tires specified by the placard at 75 psi would have only supported a 12,000-lb axle, 67 percent of the 18,000 lb GAWR listed on the vehicle tire placard. The steer tires were tested at a cold inflation pressure of 130 psi, which is the minimum CIP recommended by the Firestone Tire book. Because this vehicle is shared among several testing programs, the steer tires were chosen to support the maximum loading condition for this truck. The inflation pressure for these tires provided a contrast with the lower pressure steer tires used on the Volvo.

The drive tires were Firestone 11R-22.5 – 14PR, FD663 Radial, load range G, (DOT 4D3T-3E3) rated for 5,840 lb (max) at 105 psi. Because the supplied tires were two inches smaller in diameter than specified on the tire placard, higher air pressures were required to support the 22,000-lb GAWR load. The tire placard specified 90 psi, which would have been appropriate for the 24.5-inch diameter tires, but a CIP of at least 100 psi would have been required to support the axle loads for the tires used. A pressure of 90 psi would have de-rated the axle load capacity to 20,820 lb, or 94.6 percent of GAWR. 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. From this point forward, the Peterbilt straight truck will be referred to as the "truck."

4.0. INSTRUMENTATION

The setup of the TPMS components including initialization of the Central Processing Unit (CPU) and 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 data acquisition system (CDAS), a thermal probe, and a video camera.

4.1. Data Channels

A ruggedized, bench-top-PC computer collected 16 channels of data during the TPMS testing. Parameters measured include: 10 individual tire pressures, vehicle speed and distance, three types of event indications, and ambient temperature. Appendix A provides a comprehensive table of CDAS data channel parameters and details of the correlating locations of the various TPMS tire pressure sensors.

4.1.1. 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 such that 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 a series of 10 individual sets of 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. Each tire pressure controller allowed for remote inflation or venting of one or more tires simultaneously, zeroing of transducers, and logging of real-time tire pressures. Pictures of the air pressure control system are presented in Appendix B.

4.1.2. Vehicle Speed and Distance

Vehicle speed was measured using an ADAT Model No. 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.

4.1.3. Event Channels

Three event channels were configured on the CDAS data collection system to record real-time events directly 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 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 observer activated the driver event button. On the SmartWave system, an output wire was available to add a buzzer. The buzzer signal was also directly fed into the CDAS as an independent event channel.

4.1.4. 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.

However, the CDAS did maintain 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.

4.2. 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. Appendix C presents pictures of the installation of the video camera and the other data acquisition system equipment.

5.0. TEST PROCEDURES

The direct TPMS currently used for virtually all heavy truck TPMS applications do not use the ABS wheel speed sensors or any other vehicle instrumentation to sense tire pressure; however, such systems may be developed in the future and a calibration run to familiarize the system with certain vehicle characteristics may be necessary. Also, new TPMS technology may be developed that will require driving the vehicle to activate the system. Therefore, the calibration run was included in the test procedures. Actual driving with the direct systems used in this project did not appear to modify any calibration parameters used by the TPMS; 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 examined the pressure sensing capabilities of the various TPMS on individual tires with reduced tire pressures. Vehicles with GVWRs of 10,000 lb or less are required by FMVSS No. 138 to indicate a low-pressure condition when 1 or more of the vehicle's tires, up to a total of 4 tires, is equal to or less than either the pressure 25 percent below the vehicle manufacturer's recommended CIP, or the minimum specified in the standard, whichever is higher. 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.

Initially, this test program sought to identify three independent test pressures that may bracket the alarm indications of the whole population of TPMS manufactured for heavy vehicles, but this approach was found to be cost inefficient and beyond the budget allotted. The program was redirected to concentrate on each system's ability to alarm at their individual low-pressure setpoints.

Table 5.1 compares vehicle setpoints and applied test pressures. All TPMS tested provided at least one low-pressure setpoint, where three systems each provided two low-pressure setpoints. The first system was tested at three different test pressures, but this only bracketed two actual low-pressure setpoints. The following four TPMS were tested either at one or two test pressures, which corresponded to their respective setpoints. The test pressures were 3 psi below the low-pressure setpoints.

Table 5.1. System Setpoints – Low Pressure Warning Limits (Not Temperature Compensated)

System	Applications		SP-1			SP-2			SP-2 Second Test Pressure		
TPMS	CIP	truck or tractor - axle	setpoint pressure or delta %	test pressure used (psi)	alarm	setpoint pressure or delta %	test pressure used (psi)	alarm	setpoint pressure or delta %	test pressure used (psi)	alarm
SmartWave Dana	130	truck - steer	-10%	114	low deviation	-20%	101	critical low pressure	-25%	94.5	extra test point
S14486	105	truck - drives	-10%	91.5	low deviation	-20%	81	critical low pressure	-25%	76	extra test point
A	105	tractor - steer	-10%	91.5	low deviation	-20%	81	critical low pressure	-25%	76	extra test point
	100	tractor - drives	-10%	87	low deviation	-20%	77	critical low pressure	-25%	72	extra test point
Tire-SafeGuard HCI Corp	130	truck - steer	114 psi (~ -12%)	111	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
TPM-W206	105	truck - drives	92 psi (~ -12%)	89	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
B	105	tractor - steer	92 psi (~ -12%)	89	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
	100	tractor - drives	88 psi (~ -12%)	85	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
Tire-SafeGuard HCI Corp	130	truck - steer	114 psi (~ -12%)	111	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
TPM-P310B1	105	truck - drives	92 psi (~ -12%)	89	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
C	105	tractor - steer	92 psi (~ -12%)	89	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
	100	tractor - drives	88 psi (~ -12%)	85	low pressure	n/a	n/a	n/a	n/a	n/a	n/a
WABCO-IVTM Michelin	130	truck - steer	-20%	101	low pressure	-35%	81.5	extremely low pressure	n/a	n/a	n/a
IVTM	105	truck - drives	-20%	81	low pressure	-35%	65	extremely low pressure	n/a	n/a	n/a
D	105	tractor - steer	-20%	81	low pressure	-35%	65	extremely low pressure	n/a	n/a	n/a
	100	tractor - drives	-20%	77	low pressure	-35%	62	extremely low pressure	n/a	n/a	n/a
PressurePro Advantage	130	truck - steer	-12.5%	111	first stage low pressure	-25%	94.5	second stage low pressure	n/a	n/a	n/a
CU41807684	105	truck - drives	-12.5%	89	first stage low pressure	-25%	76	second stage low pressure	n/a	n/a	n/a
E	105	tractor - steer	-12.5%	88	first stage low pressure	-25%	75	second stage low pressure	n/a	n/a	n/a
	100	tractor - drives	-12.5%	84	first stage low pressure	-25%	72	second stage low pressure	n/a	n/a	n/a

Once low-pressure limits were identified, additional features of the TPMS were assessed. These included slow-leak detection, overpressure limits, and failed systems identification strategies, which will be described in the following sections. Making an extensive analysis of over-temperature measurements was beyond the scope of this project.

5.1. Preparation to Test TPMS Performance

To prepare to run a TPMS performance test series, the test vehicle was first 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 at the "starting point," in a shaded area away from direct sunlight (such as in a truck bay with the garage doors open) and the tires were inflated to 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 collected. Tire *temperature* readings were made if the TPMS was so equipped, and a thermal probe was used to measure the external tire temperatures, near the center of the tire tread, between the ribs or lugs.

5.2. TPMS Calibration Test – Sensor Identification

The FMVSS No. 138, "Tire Pressure Monitoring Systems" as written for light vehicle TPMS, specified that a calibration run be provided before beginning any low pressure detection tests. This was to allow for the system to initialize sensors and to gather whatever vehicle information was needed by the system. Following this lead, all heavy truck tests herein were given ample vehicle-in-motion time prior to actual low pressure detection tests.

After initial installation and preparation, the TPMS was subjected to a system "calibration" test. With the pressures successfully set to CIP at ambient room temperature, the TPMS was powered up. Initial tire pressures and temperatures were logged with the CDAS data system and for the TPMS system. Several sensors did not immediately transmit pressure signals, thus necessitating the vehicle be driven to activate the sensing mechanism of the tire pressure transmitters. The truck was driven once around the 7.5-mile test track with constant running speeds near 60 mph and returned to the shaded starting point. The total tire rolling time ranged from 10 to 15 minutes round-trip. 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 a brief experiment using slower driving speeds for the calibration run, it was shown that more uniform pressures could be set for the follow-on low pressure detection tests if the tires were near ambient temperature, rather than drifting down from various elevated temperatures generated during the previous "hot" calibration series. In this "cool" calibration test, the tractor was driven for 8 to 10 minutes over a flat road. The vehicle speed was maintained as "slow," typically at not more than 25 mph for the 2-mile loop. The tire temperatures rose only 5 to 10 degrees above ambient and were fairly stable when the tire pressures were reduced for the follow-on 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. Because there was little heat added during these tests, the cooling period was reduced to one-half hour, further reducing the total test cycle period required for testing each tire.

5.3. TPMS Low Pressure Detection Test

The primary "Low Pressure Detection Test" sought to identify a tire pressure level where each TPMS would appropriately measure an unsafe condition in tire inflation pressure. After completing the preparatory calibration tests, a series of individual low tire pressure detection tests were run.

The pressure was reduced in one test tire (while the TPMS was turned off) to simulate that a leak had occurred when the driver was not driving the vehicle. After the pressure was adjusted, the TPMS was turned back on. If the display immediately activated an alarm corresponding to the test tire, 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 the 7.5-mile test track circuit (for a period of 10 to 15 minutes) on a low tire pressure detection run, where steady state speeds averaged 60 to 65 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 identify if a temporary lapse of power to the system (such as turning off the engine during a meal break or stop at the shipping office) would lose the warning of a TPMS alarm. 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. Next, the TPMS was turned off again, while the tires were allowed to cool.

The tires were helped to cool down using a large floor fan at each tire group location. Initially, two hours were allotted to cool the tires down to within 3 to 5°F of the current ambient temperature. While testing the fifth TPMS on the truck it was requested that the cooling time be reduced to 1 hour, then just 30 minutes. With this shortened cooling time, the tire temperatures were about midway between the initial hot readings and the room ambient temperature. One example that demonstrated this temperature phenomenon was the left front low pressure detection test using the PressurePro TPMS installed on the truck. The initial room ambient air temperature was 87°F and the initial left front tire temperature was 86°F. After the calibration test the room ambient temperature remained steady while the tire temperature rose to 113°F. After cooling for 30 minutes, the left front tire temperature had dropped to 95°F and the ambient has risen slightly to 87°F. The low pressure tire was re-inflated to the original pressure (at the 86°F temperature level) while still at 95°F. The TPMS was then turned on to read the new 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 circuit for a Reset Identification Test, in expectation that it would clear the warning.

This procedure was repeated for each of 4 individual tires on the test truck. An additional test was run using multiple tires with low inflation pressures simultaneously, to determine the order and extent of the warnings presented by the TPMS. For a complete procedure of this "hot" calibration and detection test, see Appendix D: Low Tire Pressure Detection Test Procedure (Recommendation No. 3).

For the tractor tests, the procedure was modified such that the tires were maintained at temperatures near to the initial ambient temperature, to minimize the effect of heating on the ability of the TPMS to detect a low tire pressure. This "cool" procedure characterized pressure detection capability without the interaction of tire heating. The details of the "cool" calibration and detection test procedure are listed in Appendix D: Low Tire Pressure Detection Test Procedure (Recommendation No. 1).

Additional variations of the calibration and detection tests were discussed, but testing was beyond the scope of this test program. One idea included calibrating the tires using the “cool” calibration procedure (to keep the tires relatively cool) and then run the “hot” low pressure detection test (to simulate detection during early morning driving). The procedure is detailed in Appendix D: Low Tire Pressure Detection Test Procedure (Recommendation No. 2).

Another variation included driving the truck continuously, until the tires were heat saturated like during continuous over-the-road operation (Appendix D, Recommendation No. 4). With a truck that was fully loaded to GVWR and being driven at 60 mph, the tires would heat up and the temperature would stabilize in two or more hours. While still driving the vehicle at the same speed, the pressure would be quickly lowered to the test pressure and then 15 minutes would be allowed for the TPMS to detect the low tire pressure. This test was not run as it was considered more time consuming and inherently more dangerous due to the speed and long period of driving without stopping. With the tires operating at elevated temperatures, a fixed loss of 10 or 15 psi would not be detected by the TPMS, unless it was applying some sort of temperature compensation.

Therefore, this test program sought to identify a TPMS performance test that was safe to run, could be conducted in a relatively short period of time, and would fairly offer a means of identifying if the TPMS would effectively detect a low tire pressure.

5.4. TPMS Slow Leak Detection Test

Once the low pressure detection tests were completed, a second feature of the TPMS was tested. Whereas not all TPMS units provided the slow leak detection function, those that did were tested at a moderate leak rate. The Tire-SafeGuard system specified a leakage rate range of 3 or more psi loss in 2 to 10 minutes. Therefore, a nominal air loss rate of 1 psi per minute was established as the test criterion.

To test, the tires were all inflated to CIP. A special needle valve was fitted to the exhaust port on the manifold to control the release of air for a given test tire. The video and data collection were begun, and then the tire pressure reduction was initiated. The pressure was vented for a period of three minutes, or until the TPMS identified the slow leak. If three minutes expired before the TPMS identified the slow leak, a note was entered into the log. Then the pressure was reduced further, at the same rate, until either the slow leak alarm sounded or a low-pressure warning occurred. If the pressure dropped to the point where the low-pressure alarm sounded, the tire sensing channel was listed as failed to detect a slow leak within three-minute time limit or just failed to detect slow leak.

For a complete description of this test procedure, see Appendix E – Slow Leak Detection Test Procedure.

5.5. TPMS Overpressure Detection Test

The overpressure test was not prescribed, but one system unexpectedly displayed an alarm. Upon inspection of the first system (SmartWave), the default CIP value was set at 100 psi. This was installed on a tire inflated to a CIP of 130 psi. Before the defaults were updated, the TPMS alarmed that it was reading an overpressure reading in that tire. The SmartWave system provided a pressure deviation alarm of +/- 10 percent and the alarm sounded as the pressure exceeded the upper bound of 110 psi. The CIP was then raised to the correct 130 psi for this tire, which raised the corresponding limit window to +/-13 psi, with an upper limit at 143 psi. After resetting the TPMS, the alarm for overpressure cleared.

A similar result occurred for the Tire-SafeGuard system, where the upper limit pressure level had a default setting of 130 psi. This was increased to 150 psi, but later found that the Tire-SafeGuard upper measuring limit was 143 psi.

The IVTM did not specify an upper-pressure limit; therefore, no maximum pressure tests were attempted.

The PressurePro literature indicated a default upper pressure limit setting of CIP +24 percent, but an overpressure application of 138 psi (to a 105-psi CIP tire) did not cause an overpressure alarm. It was not determined if the pressure was too low to alarm on overpressure or if that feature was not functioning correctly. When the PressurePro procedure to view the programmed overpressure setpoint was attempted, the PressurePro system dumped the setup configuration and no longer identified any of the tire sensors. The TPMS needed to be reprogrammed and each of the sensors to be sequentially reduced in pressure for over one minute each, in order to complete the reprogramming and reidentification of all 10 sensors.

5.6. TPMS Failed Systems (Malfunction) Tests

This section of testing was unique to each TPMS, as each TPMS contained different setup procedures, programming methods, and electronic components. One common feature for the systems tested was none of the sensors tested had user-replaceable batteries. The transmitters could not be powered down to show loss 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.

6.0. SYSTEM TEST RESULTS FOR LOW PRESSURE DETECTION

Data were collected by a computerized data acquisition system, recorded by a digital video cassette recorder, and observations were recorded in handwritten notes 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, by vehicle, and then by low-pressure setpoint. Within each table, there is a comparison of the following metrics:

- Tire position,
- CIP,
- Test pressures actually applied (for example (CIP - 10 percent) - 3 psi),
- Correlation of tire temperature at the time the pressure was reduced during the low pressure detection tests,
- Type of alarm expected to be displayed for the low pressure level,
- Description of the alarm indication - when and where it occurred, and
- Description of the alarm indication moments after the tire was re-inflated to CIP.

6.1. System A – SmartWave – Rim Mount

The SmartWave system was tested first. As the initial test protocol was somewhat experimental, two modifications were made during completion of the test matrix to clarify and streamline some of the procedures. This section will first look at the test pressure allowances which compared an initial 2 psi to a later 3 psi allowance below the low-pressure setpoints, followed by the overall low pressure detection setpoint data for the SmartWave TPMS (as installed on the test truck). Then, when the SmartWave was moved to the tractor, a second experiment was performed to identify the effect calibration temperature had on the sensitivity of setting the applied test pressures. After this test, only the “cool” calibration tests were run prior to performing the low pressure detection tests from the final SmartWave data set.

6.1.1. Test Pressure Allowance Below Setpoint Pressures

The SmartWave TPMS was installed on the straight truck with sensors installed in each tire assembly. It was subjected to the prescribed tests at three different test pressure levels. Because it did provide two distinct low tire pressure detection setpoints, the first two test pressures were set to an allowance of 2 psi below the setpoints (which were factory set at -10 and -20 percent respectively, below the recommended CIP) and the third test pressure at 2 psi below a pressure that corresponded to 25 percent below CIP.

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. When the 1-psi allowance of the CDAS pressure measurement system was added to the 1 to 2-psi difference between the SmartWave and the CDAS pressure readings, it appeared reasonable to increase the allowance from 2 psi to 3 psi, below the setpoint. This increase in allowance enabled more repeatable results as the emphasis was shifted from the accuracy of pressure readings to emphasis of low pressure detection. Appendix F lists the low pressure detection setpoints and their respective 2- or 3-psi allowance as applied to the test pressures. All TPMS low pressure detection tests performed (after this initial truck-TPMS configuration) applied the -3-psi allowance for all test pressures (i.e., test pressures used were 3 psi below the TPMS setpoints).

6.1.2. Low Pressure Detection Tests - Truck

The SmartWave system provided a tire pressure temperature-compensation chart with which to adjust tire pressures at elevated temperatures (above ambient) for an initial CIP referenced to 65°F. The copyrighted table was not included in this report, but an expanded linear interpolation of such is included for the truck tires in Appendix G, Table G., and for the lower tire pressures of the tractor in Appendix G, Table G.2. Each table includes columns of pressure reduction steps of 10, 20, and 25 percent (relative to the current pressure expected at the "hot" calibration tire temperature), along with low-side pressure allowances of -3 psi. The TPMS manufacturer's installation packages for the other systems tested during this research project did not include a temperature compensation chart.

As the SmartWave was received with a temperature compensation chart, all low pressure detection "target" pressures were adjusted (for the 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 uncompensated target pressure levels. In contrast, the later tractor series tests 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.

For the -10-percent "Low Deviation" pressure detection tests on the truck tires, the SmartWave correctly identified the -10-percent level (Table 6.1) before completion of the 15-minute detection run, for four out of four 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 preliminary "hot" calibration test. As such, a pressure loss of 10 percent below the "hot" tire pressures was detected by the SmartWave TPMS, showing a primary benefit for using temperature compensation while reading tire pressures. With temperature compensation, the SmartWave TPMS detected a pressure loss of 10 percent of the hot tire pressure reading, making it more sensitive to detecting pressure loss than systems without compensation and adjustment of low-pressure setpoints.

In Table 6.1 a yellow-highlighted Detection Status box indicates that the truck was actually driven to allow the TPMS to detect the low pressure condition. Once the warning activated, the truck was driven back to the shaded starting point. A box in Table 6.1 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 6.1. SmartWave (rim mount) Low Deviation Setpoint = 10 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
SmartWave Dana S14486 A	LF	130	6/17/2008	-10%	123 @95F	Low Deviation	alarm before driving	clear before driving
	RF	130	6/19/2008	-10%	123 @95F	Low Deviation	alarm during driving	clear before driving @10.7min
	LII	105	6/23/2008	-10%	97 @86F	Low Deviation	alarm at gate while driving	clear before driving
	RRO	105	6/24/2008	-10%	100 @100F	Low Deviation	alarm backing out while driving	clear before driving

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

For the second low-pressure setpoint of the SmartWave TPMS, while installed on the truck, the test tire pressures were reduced to 2 psi below the -20-percent of CIP 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 Table G.). The load capacity of the tires was greatly diminished for these low tire pressure settings. However, the test was continued, knowing that if the detection test needed to be run, only a limited distance would be driven with the tire in a reduced capacity state.

For three of the four individual tire tests at 20 percent below CIP, the SmartWave alarm activated at the test pressure, but incorrectly displayed only a "low deviation" alert, whereas a more severe "critical low pressure" alert was expected. Only one test saw the SmartWave warn correctly of the critical low tire pressure while using a pressure setpoint allowance of -2 psi. The typical elapsed time required for alarm activation ranged from 1 to 3 minutes after tire deflation, with three of the activations occurring while the truck was being driven on the detection run. The slowest response alarm sounded approximately 8 minutes after the TPMS was turned on. After reviewing the percentage of compensation, the three activations that indicated only a low-pressure alert were set to test pressures 14 to 17 percent below actual CIP. The fourth activation was set at 19 percent below the actual CIP and did display the correct low pressure severity, a "critical low pressure." The warning pressure level appeared to be set at a critical low pressure of 18 percent below the actual CIP for this test series.

For the CIP minus 20-percent test series, the level of alert appeared to be affected by the timing for setting the compensated test pressures. After the "hot" calibration tests, the tires began to cool quickly. Depending upon the rate at which the TPMS temperatures were updating, the tire temperature reading may have been either a stored reading or a fresh update. The first tire temperature value logged from the SmartWave display, after the calibration test ended, was used to determine the compensated test pressure for the following low tire pressure detection test. A reading of the tire temperature immediately after the "hot" calibration run may have led to the application of a higher compensation temperature than was warranted by the temperature of the contained air in the tire at the end of the 5-minute period allowed between the calibration run and the beginning of the detection test. Waiting for a new screen update would have extended the pressure adjustment window from 5 minutes to 10 or 15 minutes. The test procedure guidelines followed allowed for only 5 minutes for the measurements and test pressure adjustment. It was determined that an additional test would need to be run at a lower test pressure near 25 percent below CIP (detailed later in this section).

Upon re-inflating the truck tires, the SmartWave TPMS correctly sensed that the tires had been properly re-inflated before driving for 3 of the 4 tests for the CIP minus 20-percent tests. For the fourth test, the previous low deviation pressure warning from the display screen “cleared” as the truck was being backed from the truck bay (Table 6.2). Therefore, the SmartWave did alert to the low pressure conditions applied for each test, but it did not correctly indicate the severity level expected (in three cases, low pressure deviation was logged for the lower pressure tests using temperature compensation.

Table 6.2. SmartWave (rim mount) Critical Low Pressure Setpoint = 20 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
SmartWave Dana S14486 A	LF	130	6/19/2008	-20%	108	Low Deviation, NOT Critical Low	alarm while driving T=7.8min, Dist=0.6mi	clear before driving
	RF	130	6/23/2008	-20%	109.2	Low Deviation, NOT Critical Low	alarm backing out while driving T=2.4 min Dist=0.003mi	clear while backing out to drive T=3.4 min, Dist=0.025mi
	LII	105	6/24/2008	-20%	85.1	Critical Low Pressure	alarm backing out while driving T=1.6min Dist=0.019mi	clear before driving
	RRO	105	6/24/2008	-20%	89.7	Low Deviation, NOT Critical Low	alarm before driving >1.9min	clear before driving
	Multi	130/105	7/1/2008	-20%	LF-95, RF-94 LII-75	Critical Low Pressure	alarm before driving	clear before driving

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer
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 (“Multi” in Table 6.2). 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. It took longer to set three test tire pressures to the 20-percent-below-CIP inflation level (rather than just one tire as before). Therefore, the time required to adjust the pressure in all three tires may have allowed enough time delay (during the cool-down period after the “hot” calibration run) for the compensated pressures to better match the TPMS temperature readings and correctly sense the low pressure severity level of critical low pressure.

It was not determined from this test series if the lesser alarm response for a single low tire pressure was due to over-compensation for temperature rise, or if not enough allowance was given on measuring the setpoint pressure. Therefore, a third series was run at a lower test pressure, but still using the same -20 percent setpoint on the TPMS.

A third test pressure was set somewhat below the lower critical alert level (Table 6.3). That pressure level was expected to see the TPMS sending second level “Critical Low Pressure” alarms for all low tires. However, the test pressures were increased slightly above the -25 percent pressures by using the SmartWave temperature compensation chart (Table G.). The applied compensated test pressures ranged from 20 to 26 percent below CIP. The test with tire pressure at 20 percent below actual CIP displayed only a low tire pressure warning, but increased to a critical alert beyond 23 percent below actual CIP. The other three test tires displayed critical low-pressure warnings with compensated pressure of 21 to 26 percent below actual CIP.

Table 6.3. SmartWave (rim mount) Third Low Pressure Test – Pressure at CIP-25% - 3 psi - Truck

VR8 6x4 Straight Truck			Test Pressure 3 = -20% alarm setpoint, pressurized down to 3 psi below CIP - 25%					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
SmartWave Dana S14486 A	LF	130	6/26/2008	-25%	102	Critical Alert	alarm while driving, T=3.0min, Dist=0.026mi	clear while driving T=2.8 min, Dist=0.026mi
	RF	130	6/26/2008	-25%	104.2	Deviation Alert - not critical alert	alarm before driving, reduced pres to 99 psi to reach critical low alert	clear before driving T=2.4 min
	LII	105	6/30/2008	-25%	78	Critical Alert	alarm before driving	clear before driving T=3.0 min
	RRO	105	6/25/2008	-25%	83.3	Critical Alert	alarm while driving, T=4.0min, Dist=2.23mi	clear before driving T=3.5 min

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

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.

However, a question arises as to what load capacity would be available if using temperature compensation for low ambient temperature tire operation. Compensation may indicate that at 25°F, a standard tire pressure equivalent at 65°F would carry 100 percent of rated load, but the actual tire pressure would be reading only 91.5 percent (130-psi CIP would be reading only 119 psi). Therefore, should the vehicle be driven with the temperature compensated tire pressure, or should the tire be inflated to 130 psi while cool at 25°F?

Because this test series was mostly run during warm weather, the immediate concern was setting tire pressures while the ambient temperature was above 65°F. For the initial “truck tests” the CIP was set to the pressure specified on the tire compensation table (Table G.). Frequently, the inflation pressures were above the specified CIP’s which were referenced to 65°F only for the compensated pressure tests. As some of the second level tire pressure warnings did not clearly detect the severity of degree of deflation, alternative calibration tests were considered for the tractor tests. A small experiment was conducted to compare low tire pressure detection using slower calibration speeds and possibly not using tire temperature compensation for a basic pressure detection test.

6.1.3. Experiment to Optimize Calibration Test Procedure That Precedes Low Tire Pressure Detection Tests

During the truck tests, the "hot" calibration procedure appeared to be both quite time consuming and causing erroneous adjustment of the test pressure levels. In section 6.1.1, with hot tires (after running the "hot" calibration tests), the five-minute window allotted for taking TPMS temperature and pressure readings and then adjusting the test tire to the prescribed test pressure, was relatively abrupt. However short, the time window was still long enough to encounter varying amounts of temperature drift-back down towards ambient temperature. From day to day, as well as throughout a single day, the amount of drift varied due to the fluctuation in weather, sunlight, and track temperatures. Because the pressures were adjusted only after the calibration test, a procedure was sought to reduce the effect of heating induced by the high speed driving during the calibration test, to help mitigate the day-to-day test variations.

Using the tractor as the test vehicle, a brief experiment was performed to examine ways to reduce tire heating, yet still provide sufficient wheel rotation time (time when the wheels were rolling at highway speeds) to allow the TPMS to begin active sensor transmission. Three variants included: the original "hot" calibration procedure, a modified "cool" calibration test (both of which used temperature compensation), and a repeat of the "cool" calibration that was followed by low pressure tests using no temperature compensation when setting the test pressures.

For the first variant of the "calibration procedure" experiment, the original "hot" calibration was used from the previous *truck* tests. Calibration driving speeds reached 60 mph for at least 5 minutes during a 15-minute run. The second variant administered a "cool" calibration run, where driving speeds were maintained at or below 25 mph and the distance was reduced from 8.5 miles to 2 miles. The shorter driving cycle also reduced the circuit time from 15 minutes down to 8 to 10 minutes. The combined lower speed and shorter driving distance provided sufficient time for all sensors to "wake up" and actively transmit tire pressures to the SmartWave display unit, all while producing considerably less heat in the tires. For the subsequent low pressure detection tests, test pressures were set using the temperature compensation table. The third variant test procedure repeated the "cool" calibration cycle, but the subsequent low pressure detection test pressures were set using face value, no temperature compensation was applied. In all three cases, the cooling time after the low pressure detection test was limited to just one-half hour before re-inflating the test tire to CIP (Appendix H lists the details of the experiment).

The primary goal of this experiment was to identify if the basic tire pressure sensitivity of an installed TPMS could accurately be determined without the influence of tire heating. In the experiment, it was found that the "hot" calibration procedure being used added considerable heat to the tires. Immediately after calibration, when the vehicle was stopped to make the adjustment to test pressure, the tires began to cool quickly. The test tire temperature was read immediately from the TPMS display and applied to the temperature compensation lookup table. By the time the tire pressure was finally adjusted down to the prescribed test pressure, the tire temperature had dropped considerably. With the lower tire temperature, the baseline pressure would have also decreased, indicating that the tire test pressure would need to be lowered more to maintain the expected pressure decrease applied. But the test program only allowed for a single pressure adjustment that corresponded to the initial tire temperature reading.

In the original truck TPMS tests, it appeared that a 2-psi change was not enough air reduction from the test tire to produce an effective test of the low-pressure-detection function when only a minimal pressure reduction was applied to the tire using temperature compensation and with rapidly cooling tires. In this experiment, using the tractor as the test vehicle, the severity of level of the low-pressure alarm did not repeat those indications from the truck tests, but other temperature parallels were presented. For a given CIP, the temperature compensated test pressure applied for a low pressure detection test following a “hot” calibration procedure was 4 psi higher than for an uncompensated test pressure which followed a “cool” calibration. When comparing compensated to uncompensated test pressures (following “cool” calibration tests), the compensated pressures were slightly higher than the uncompensated test pressures, but only by 1 percent. Therefore, TPMS with compensation would produce test results similar to TPMS without temperature compensation only when following a “cool” calibration” test. The primary concern with uncompensated systems is that they need to see much greater pressure losses (than compensated systems) in tires operating at temperatures that are elevated above ambient, before they activate a low-pressure alarm.

Hence, the remaining tractor TPMS tests used the “cool” calibration procedure. By reducing the speed and distance traveled during the preliminary calibration test, the tire temperatures only increased a few degrees, thus still allowing sufficient time for all sensors to begin transmitting pressure data, but not to raise the tire temperatures to a point where they would be drifting upon later pressure adjustment down to the detection test pressures. The shorter calibration run time reduced the total test time and also allowed for a shorter cooling time after the low pressure detection had occurred. The total cooling time was reduced from 2 hours down to 30 minutes per tire pressure sensor tested as the resulting temperatures were only 5° to 10°F above ambient, which also improved the overall efficiency of the low pressure detection test procedure.

Further discussion of the Calibration Test development and data tables may be found in Appendix I - Comparison of Hot versus Cool Calibration Driving Times, Steady-State Speeds, and Distances Traveled.

6.1.4. Low Pressure Detection Tests - Tractor

To maintain continuation of the original test procedural guidelines for the second vehicle (the tractor), the SmartWave pressure setpoints were reprogrammed to the CIP requirements of the tractor tires. As the "cool" calibration procedure was applied to all remaining 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 6.4 reflect the procedural change such that no temperature compensation was to be used to adjust the applied test pressures; therefore, all five TPMS systems tested on the tractor used the same "cool" calibration procedure and no temperature compensation. All test pressures were set to a fixed allowance of 3 psi below the -10-percent of CIP low deviation setpoint without regard to measured tire temperature.

Table 6.4. SmartWave (rim mount) Low Deviation Setpoint = 10 Percent below CIP - Tractor

VR5 6x4 Tractor			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
SmartWave Dana S14486 A	LF	105	10/7/2008	-10%	92	Low Deviation	alarm before driving	clear before driving
	RF	105	10/8/2008	-10%	92	Low Deviation	alarm before driving	clear before driving
	LII	100	10/8/2008	-10%	87	Low Deviation	alarm before driving	clear before driving
	RRO	100	10/9/2008	-10%	87	Low Deviation	alarm before driving	clear before driving
	Multi	105/100	10/9/2008	-10%	92 & 87	Low Deviation	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. The TPMS was able to determine that the pressure was restored to CIP without the vehicle being driven. Similar results were produced for critical low-pressure alarms using lower setpoint pressures which were set at 20 percent below CIP (Table 6.5).

Table 6.5. SmartWave (rim mount) Critical Low Pressure Setpoint = 20 Percent below CIP - Tractor

VR5 6x4 Tractor			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
SmartWave Dana S14486 A	LF	105	10/7/2008	-20%	81	Critical Low Pressure	alarm before driving 16 sec. after restart	clear before driving
	RF	105	10/8/2008	-20%	81	Critical Low Pressure	alarm before driving 16 sec. after restart	clear before driving
	LII	100	10/8/2008	-20%	77	Critical Low Pressure	alarm before driving 16 sec. after restart	clear before driving
	RRO	100	10/9/2008	-20%	77	Critical Low Pressure	alarm before driving 16 sec. after restart	clear before driving
	Multi	105/100	10/9/2008	-20%	81 & 77	Critical Low Pressure	alarm before driving	clear before driving

6.2. System B – Tire-SafeGuard – Rim Mount

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

6.2.1. Low Pressure Detection Tests - Truck

For the 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 (steer) and 89 psi (drives). The "hot" calibration procedure was used for all preliminary pressure tests on the 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 4 sensors showed the appropriate response to re-inflating the tires to proper CIP - 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 6.6).

Table 6.6. Tire-SafeGuard (rim mount) Low Pressure Setpoint = ~ 12 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
Tire-SafeGuard HCI Corp TPM-W210 B	LF	130	7/8/2008	114 psi (~ -12%)	111	Low Pressure	alarm before driving	clear before driving
	RF	130	7/8/2008	114 psi (~ -12%)	111	Low Pressure	alarm before driving	clear before driving
	LII	105	7/9/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	RRO	105	7/9/2008	92 psi (~ -12%)	89	Low Pressure	alarm at gate while driving	clear before driving
	Multi	130 & 105	7/16/2008	114 & 92 psi	111 & 89 psi	Low Pressure	alarm before driving	clear before driving

A simultaneous multi-tire low pressure detection test followed (Table 6.6), 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.

6.2.2. Low Pressure Detection Tests - Tractor

After the Tire-SafeGuard "rim mount" TPMS was installed on 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 pressure calibration tests on the tractor (Table 6.7).

Table 6.7. Tire-SafeGuard (rim mount) Low Pressure Setpoint = ~ 12 Percent below CIP - Tractor

VR5 6x4 Tractor			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
Tire-SafeGuard HCI Corp TPM-W210 B	LF	105	10/16/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	RF	105	10/16/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	LII	100	10/16/2008	88 psi (~ -12%)	85	Low Pressure	alarm before driving	clear before driving
	RRO	100	10/17/2008	88 psi (~ -12%)	85	Low Pressure	alarm before driving	clear before driving
	Multi	105/100	10/20/2008	92 & 88 psi	89 & 85 psi	Low Pressure	alarm before driving	clear before driving

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

By using the "cool" calibration procedure for the tractor, the low pressure levels were easy to set for the detection test, as the tires were only a few degrees above ambient temperature and were not changing very rapidly. For this configuration, in all four tests using single tires with low pressures, 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 all of the tires to the CIP.

6.3. System C – Tire-SafeGuard – Flow Through

An additional Tire-SafeGuard TPMS was tested, only the sensors for that unit were mounted on the valve stems externally, in an in-line flow-through mode. It had a driver display and operating functions similar to the previous Tire-SafeGuard unit. However, the system provided easier installation of the sensing transmitters by placing them on the valve stems after the tires were installed on the truck. The previous rim-mount sensors had to be installed by removing the tires from the truck and breaking down the tires. One drawback to the flow-through sensors was the temperature measurements provided by the TPMS were measured in the valve stems, outside of the captive air inside of the tire envelope. The flow-through sensors traded ease of installation and maintenance for less temperature precision and increased exposure to vandalism.

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.

6.3.1. Low Pressure Detection Tests - Truck

For the truck tests, the "hot" calibration test procedure was followed. Under subsequent 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 in warning of the low pressure conditions, eliminating the need to run a detection test on the test track circuit.

After cooling and re-inflating the tires, the Tire-SafeGuard quickly reset and cleared the faults, thereby returning to a quiescent ready mode (Table 6.8). A simultaneous low tire pressure test was not performed for the truck installation, but was performed later for the tractor installation.

Table 6.8. Tire-SafeGuard (Flow Through) Low Pressure Setpoint = ~ 12 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
Tire-SafeGuard HCI Corp TPM-P310B1 C	LF	130	7/24/2008	114 psi (~ -12%)	111	Low Pressure	alarm before driving	clear before driving
	RF	130	7/24/2008	114 psi (~ -12%)	111	Low Pressure	alarm before driving	clear before driving
	LII	105	7/24/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	RRO	105	7/28/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving

6.3.2. Low Pressure Detection Tests - Tractor

For the tractor tests using the Tire-SafeGuard “flow-through” sensor system, results obtained were similar to that measured in the truck tests. The low pressure warning signal was displayed before the low pressure detection run was begun; therefore, the tractor was not driven for this test sequence. After cooling and re-inflating the test tires to the CIP, the TPMS reset correctly, shortly after repowering the display (Table 6.9).

Table 6.9. Tire-SafeGuard (Flow Through) Low Pressure Setpoint = ~ 12 Percent below CIP – Tractor

VR5 6x4 Tractor			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
Tire-SafeGuard HCI Corp TPM-P310B1 C	LF	105	10/23/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	RF	105	10/27/2008	92 psi (~ -12%)	89	Low Pressure	alarm before driving	clear before driving
	LII	100	10/27/2008	88 psi (~ -12%)	85	Low Pressure	alarm before driving	clear before driving
	RRO	100	10/27/2008	88 psi (~ -12%)	85	Low Pressure	alarm before driving	clear before driving
	Multi	105/100	10/27/2008	92 & 88 psi	89 & 85 psi	Low Pressure	alarm before driving	clear before driving

As a research item, the Tire-Safeguard "flow-though" TPMS was subjected to one additional low tire pressure test while still configured on the truck. Although this TPMS only had one setpoint, an extreme reduction in pressure was applied once to identify system response at that level. Using the original nominal setpoint of ~12 percent below CIP, the pressure in the right rear outer (RRO) tire position was drastically reduced to 75 psi, which was 3 psi below a reduction of 25 percent from the CIP of 105 psi. At 75 psi, the TPMS display quickly signaled a low pressure condition when turned on (and without needing to drive the detection course). Upon re-inflating the cooled tire, the display reset and cleared to the ready screen.

Therefore, the Tire-SafeGuard "flow-through" TPMS correctly measured and responded to test pressures of 3 psi below low-pressure setpoints that were fixed at distinct pressure levels (in psi) below CIP and without using temperature compensation. The drawback was if the tires got hot after the initial tire inflation to CIP at ambient temperature, a 105-psi CIP tire that was heated to road operation temperature might see an increase of 5 to 10 psi (or more) to a pressure level over 115 psi, and actually need to lose more than 23 psi before this system would activate a low tire pressure alarm (below 92 psi). Without re-inflating the tire as it cooled, the pressure might have dropped down to the low 80's psi when returned to the original ambient temperature, with load capacity greatly diminished.

6.4. 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 adjustment 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. (It is not known what the long-term detrimental effects of these plates will have on the wheel nuts and studs.) If two sensors were used to measure a set of dual wheels (on a drive axle), they were placed opposite one another. If only one tire pressure was measured, a counterbalance weight (provided by WABCO) was installed opposite of the sensor on the wheel.

This system provided a proprietary USB-type interface module to adapt the ECU to a standard computer for programming the sensor identification numbers into the TPMS. The software would not function on a new PC running Microsoft Vista or an older PC running Windows 98 operating systems. The intermediate-vintage bench-top computer (controlling the in-vehicle data collection system – CDAS) was configured with Windows 2000. This operating system was found to be compatible with the IVTM software that was provided with the TPMS hardware package. Once running, the program prompted the user to program the CIP pressures for each axle set of tires.

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 empirically discover the two low-pressure setpoints of the IVTM. The first low-pressure setpoint was found to be 20 percent below the CIP and the second setpoint was preprogrammed at 35 percent below CIP.

6.4.1. Low Pressure Detection Tests - Truck

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 - 20 percent level. Therefore, no low pressure detection test track driving runs were needed at this pressure level, for this system. After cooling the tires and then re-inflating to CIP, the IVTM delayed in clearing the low-pressure alert for one tire until nearly the end of the reset identification run, which was at 5.8 miles into the 8.3-mile test track course and after 11.2 minutes elapsed since the TPMS was turned on (Table 6.10). For the other three single tire tests, the IVTM produced a first level alert and cleared promptly after re-inflation, without necessitating any driving.

Table 6.10. IVTM (Flow Through) Low Pressure Setpoint 1 = 20 Percent below CIP – Truck

VR8 6x4 Straight Truck			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
WABCO / Michelin IVTM G8960 D	LF	130	8/20/2008	-20%	101	SP-1	alarm before driving	clear during driving T=11.2 min Dist=5.8 mi
	RF	130	8/21/2008	-20%	101	SP-1	alarm before driving	clear before driving
	LII	105	8/21/2008	-20%	81	SP-1	alarm before driving	clear before driving
	RRO	105	8/25/2008	-20%	81	SP-1	alarm before driving	clear before driving
	Multi	103/105	8/28/2008	-20%	both	SP-1	alarm before driving	clear before driving

For the multiple-alert, 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 VRTC 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.

6.4.2. Low Pressure Detection Tests - Tractor

The CIP values were reprogrammed for the tractor tests to match the lower tire pressure requirements. The tractor was only driven on the "cool" calibration circuit before beginning low tire pressure tests. Again, the IVTM displayed appropriate low-pressure warnings for the -20 percent pressure level, and reset upon restoring the tires to CIP pressures (Table 6.11).

Table 6.11. IVTM (Flow Through) Low Pressure Setpoint 1 = 20 Percent below CIP – Tractor

VR5 6x4 Tractor			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
WABCO / Michelin IVTM G8960 D	LF	105	10/29/2008	-20%	81	SP-1	alarm before driving	clear before driving
	RF	105	10/29/2008	-20%	81	SP-1	alarm before driving	clear before driving
	LII	100	10/30/2008	-20%	77	SP-1	alarm before driving	clear before driving
	RRO	100	10/30/2008	-20%	77	SP-1	alarm before driving	clear before driving
	Multi	105/100	11/3/2008	-20%	81/77	SP-1	alarm before driving	clear before driving

To test the Low Pressure Setpoint No. 2 (called the serious defect level), the individual tire test pressures were decreased to 3 psi below the respective levels of 35 percent below the CIP. These extremely low pressure levels presented a potential safety problem for driving the detection run on the 7.5-mile test track, as the loading limits dropped to 69 percent of GAWR on the steer axle tires and 76 percent of GAWR on the drive axle tires. However, the second level alarm, serious defect, sounded shortly after the TPMS was energized and driving for this level of detection tests was not required. Upon re-inflating the individual tires, the second level low-pressure warnings promptly cleared and the system reset (Table 6.12).

Table 6.12. IVTM (Flow Through) Low Pressure Setpoint 2 = 35 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
WABCO / Michelin IVTM G8960 D	LF	130	8/28/2008	-35%	81.5	SP-2 Serious Defect	alarm before driving	clear before driving
	RF	130	8/26/2008	-35%	81.5	SP-2 Serious Defect	alarm before driving	clear before driving
	LII	105	8/26/2008	-35%	65	SP-2 Serious Defect	alarm before driving	clear before driving
	RRO	105	8/26/2008	-35%	65	SP-2 Serious Defect	alarm before driving	clear before driving
	Multi	130/105	9/02/2008	-35%	81.5/65	SP-2 Serious Defect	alarm before driving	clear before driving

The serious defect test was repeated with extremely reduced pressure applied simultaneously in four tires. After the calibration run, the IVTM was switched "off" and the pressure reduced in the four tires that were previously tested individually. Upon turning on the ignition power to the IVTM, the second level alarm sounded for all four tires. The IVTM was turned back off and the tires were allowed to cool. After re-inflating the tires, the TPMS was turned on and it showed that the warnings had all cleared. No driving on the track was required after the initial calibration run.

The final series of tractor tests at the same serious defect pressure level replicated the base results found during the truck tests (Table 6.13). The IVTM correctly identified the critically low tire pressures and affirmatively reset after tire re-inflation.

Table 6.13. IVTM (Flow Through) Low Pressure Setpoint 2 = 35 Percent below CIP - Tractor

VR5 6x4 Tractor			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Test Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
WABCO / Michelin IVTM G8960 D	LF	105	10/30/2008	-35%	65	SP-2 Serious Defect	alarm before driving	clear before driving
	RF	105	10/30/2008	-35%	65	SP-2 Serious Defect	alarm before driving	clear before driving
	LII	100	10/30/2008	-35%	62	SP-2 Serious Defect	alarm before driving	clear before driving
	RRO	100	10/30/2008	-35%	62	SP-2 Serious Defect	alarm before driving	clear before driving
	Multi	105/100	11/3/2008	-35%	65/62	SP-2 Serious Defect	alarm before driving	clear before driving

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

The PressurePro TPMS came pre-configured with two low pressure level setpoints, with the "first stage low pressure" set at 12.5 percent below CIP and the "second stage low pressure" or critical low pressure set at 25 percent below CIP. To set CIP, the tires were properly inflated to CIP (using the CDAS data system in place of a hand gauge). 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 warning setpoints (CIP - 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 sense 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 6.14 and Table 6.15).

Table 6.14. PressurePro (Valve-Stem Cap) First Low Pressure = 12.5 Percent below CIP – Truck

VR8 6x4 Straight Truck			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
PressurePro Advantage CU41807684 E	LF	130	9/03/2008	-12.5%	111	First Stage Low Pressure	alarm before driving	clear before driving
	RF	130	9/04/2008	-12.5%	111	First Stage Low Pressure	alarm before driving	clear before driving
	LII	105	9/04/2008	-12.5%	89	First Stage Low Pressure	alarm before driving	clear before driving
	RRO	105	9/8/2008	-12.5%	89	First Stage Low Pressure	alarm before driving	clear before driving
	Multi	130/105	9/9/2008	-12.5%	111/89	First Stage Low Pressure	alarm before driving	clear before driving

Table 6.15. PressurePro (Valve-Stem Cap) First Low Pressure = 12.5 Percent below CIP – Tractor

VR5 6x4 Tractor			Setpoint 1					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	Detection Status	Refill Status After Cooldown
PressurePro Advantage CU41807684 E	LF	105	11/5/2008	-12.5%	88	First Stage Low Pressure	alarm before driving	clear before driving
	RF	105	11/5/2008	-12.5%	88	First Stage Low Pressure	alarm before driving	clear before driving
	LII	100	11/5/2008	-12.5%	84	First Stage Low Pressure	alarm before driving	clear before driving
	RRO	100	11/6/2008	-12.5%	84	First Stage Low Pressure	alarm before driving	clear before driving
	Multi	105/100	11/6/2008	-12.5%	88/84	First Stage Low Pressure	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 LEDs showing exact mounting location of the four underinflated tires. After re-inflating the tires, the PressurePro again cleared its display and returned to the ready mode.

The PressurePro was tested at a critical low tire pressure level for both the truck and the tractor. Test pressures were set to 94.5 psi (steers) and 76 psi (drives) on the truck, and for the tractor, to 75 and 72 psi, respectively. For both vehicles configured with the PressurePro TPMS, the second stage low tire pressure alarm activated promptly after restarting the TPMS (by energizing the lead to the ignition switch power). The alarm activated before the vehicle was driven on a detection run; therefore, the vehicles were not driven for this sequence of the test series. After the tires cooled and were re-inflated, the TPMS reset and cleared the previous second stage low-pressure warnings, and returned to the ready condition (Table 6.16 and Table 6.17).

Table 6.16. PressurePro (Valve-Stem Cap) Second Low Pressure = 25 Percent below CIP - Truck

VR8 6x4 Straight Truck			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
PressurePro Advantage CU41807684 E	LF	130	9/8/2008	-25.0%	94.5	Second Stage Low Pressure	alarm before driving	clear before driving
	RF	130	9/8/2008	-25.0%	94.5	Second Stage Low Pressure	alarm before driving	clear before driving
	LII	105	9/9/2008	-25.0%	76	Second Stage Low Pressure	alarm before driving	clear before driving
	RRO	105	9/9/2008	-25.0%	76	Second Stage Low Pressure	alarm before driving	clear before driving

Table 6.17. PressurePro (Valve-Stem Cap) Second Low Pressure = 25 Percent below CIP – Tractor

VR5 6x4 Tractor			Setpoint 2					
TPMS	Tire Position	CIP	Test Date	Setpoint Pressure or Delta %	Test Pressure Used (psi)	Alarm	DetectionStatus	Refill Status After Cooldown
PressurePro Advantage CU41807684 E	LF	105	11/6/2008	-25.0%	75	Second Stage Low Pressure	alarm before driving	clear before driving
	RF	105	11/6/2008	-25.0%	75	Second Stage Low Pressure	alarm before driving	clear before driving
	LII	100	11/6/2008	-25.0%	72	Second Stage Low Pressure	alarm before driving	clear before driving
	RRO	100	11/6/2008	-25.0%	72	Second Stage Low Pressure	alarm before driving	clear before driving
	Multi	105/100	11/12/2008	-25.0%	75/72	Second Stage Low Pressure	alarm before driving	clear before driving

Although the multiple tire response was not repeated for the second setpoint level on the truck, it was performed for the tractor. The same successful result was achieved as in the first level low-pressure tests (four LEDs indicating the critically low pressure tires), with the only difference being the indication of the advanced severity level in low pressure.

6.6. Low Pressure Detection Synopsis

After reviewing the data for TPMS low-pressure detection, four potential procedures evolved for evaluating the performance of these systems. The procedures vary in: length of time to perform;

level of complexity of test; parameters of vehicle speed and distance traveled during calibrations and detections; and sensitivity to elevated temperatures.

The primary differences in the procedures relate to tire heating. Shorter calibration or detection test periods allow sufficient time for the TPMS to respond to low tire pressures, but without the complication of elevating tire temperatures above ambient – these are referred to as "cool" calibrations or "cool" detections. A "cool" calibration followed by a cool detection test will test the basic low pressure detection capability of a TPMS, but it will not indicate if there is a variation in low-pressure detection due to tire heating (column 2 in Table 6.18). Tests should be limited to driving rather slowly (e.g. up to 25 mph) over a relatively short route (of approximately 2 miles). The low-pressure detection should occur within 10 minutes of reducing the tire pressure to the test pressure.

Table 6.18. Comparison of Four Approaches to Low Pressure Detection Tests

Test Conditions	Cool Calibration And Cool Detection	Cool Calibration And Hot Detection	Hot Calibration And Hot Detection	Continuous Run Hot Calibration and Detection
Calibration Test				
Time (minutes)	8-10	8-10	10-15	>120
Speed (mph)	<25	<25	60-65 *	60-65 *
Distance (miles)	2	2	8-10	Not Specified
Detection Test				
Time (minutes)	8-10	10-15	10-15	10-15
Speed (mph)	<25	60-65 *	60-65 *	60-65 *
Distance (miles)	2	8-10	8-10	8-10
Maximum Time to Low-Pressure Detection				
Time (minutes)	10	15	15	15
"Memory of Warning" Test				
Time (minutes)	5	5	5	5
Tire Cooling Time (Back To Initial CIP Temperature)				
Time (minutes)	30	30-120	30-120	30-120
Reset Identification Test				
Time (minutes)	8-10	8-10	10-15	>120
Speed (mph)	<25	<25	60-65 *	60-65 *
Distance (miles)	2	2	8-10	Not Specified

* or at the maximum speed allowed by the tire specifications

In a second scenario, to allow tire heating to occur during detection, the maximum time to detection would be increased to 15 minutes. This would increase the distance the vehicle would be driven to 8 or 10 miles, while maintaining regular highway speeds (averaging 60 to 65 mph, or at the maximum allowed by the tire specifications) for at least 5 minutes (column 3 in Table 6.18).

If the TPMS is equipped with temperature compensation, a better third scenario would be to pre-heat the tires somewhat (during the calibration test), before beginning the low pressure detection test (column 4 in Table 6.18). Here, the calibration and detection tests would both be run for 8 or

10 miles each, at similar speeds of 60-65 mph (as in the previous scenario). Again, a time limit of 15 minutes would be allowed for the TPMS to detect a low tire pressure condition. The difference here would be that with temperature compensation, the test pressure would be determined by measuring the tire temperature with the TPMS and applying a test pressure that corresponds to a temperature compensation chart, table, or formula, supplied by either the vehicle or TPMS original equipment manufacturer (OEM). With temperature compensation, the deviation between current expected pressure (as adjusted by the temperature compensation system) and low pressure is identified as a fixed pressure decrement or fixed percent of pressure loss, where a non-temperature-compensated TPMS will not respond to the temperature increase, and may likely experience a greater total pressure loss before detection.

For an all-out heat run (the fourth scenario described in column 5 of Table 6.18), the tires would need to be heated to the temperature level experienced during actual "Continuous Run" on-the-road operation. The vehicle would require being loaded to GVWR and driven at 60 to 65 mph (or at the maximum speed permitted by the tire design) for at least 2 hours, to fully saturate the tires at a constant temperature. Without stopping the vehicle, pressure and temperature measurements would be made so the test pressure could be set, again using a value obtained from the tire pressure compensation chart. The tire pressure would then be adjusted while still driving. Within 15 minutes of adjusting the tire pressure down to the test pressure, the TPMS would be required to detect the low pressure, and then the vehicle returned to the starting point to end the detection test.

7.0. TEST RESULTS FOR SLOW LEAK DETECTION

The Slow Leak Detection Test was done on 3 of the 5 TPMS systems. Both test vehicles (6x4 Straight Truck and 6x4 Tractor) were each tested with the IVTM (flow through), Tire-SafeGuard (rim mount), and the Tire-SafeGuard (flow through) systems. The SmartWave (rim mount) and the PressurePro (valve-stem cap) systems did not have the slow leak function available. A special needle valve was fitted to the exhaust port on the manifold to control the release of air for a given test tire. This was a static test employing a nominal air loss rate of 1 psi per minute as the established test criteria. For a complete description of this test procedure, see Appendix E – Slow Leak Detection Test Procedure.

The pressure loss rate established for this test series was obtained from the Tire-SafeGuard performance specification that indicated a slow air leak should be detected for a loss of 3 psi or more in a period of 2 to 10 minutes. VRTC chose a target pressure loss rate from the middle of this range. The resulting expectation included detection within three minutes of the beginning of pressure loss which was changing at a nominal rate of 1 psi per minute.

7.1. Tire-SafeGuard (rim mount) Slow Leak Detection Test – Truck

The left front (LF) tire sensed a slow leak within three minutes. The remaining three test tires alerted to the slow leak warning, but in more than three minutes. In the multiple-tire test, none of the four test tires alerted to the slow leak warning, but sensed low tire pressures instead (Table 7.1).

Table 7.1. Tire-SafeGuard (Rim Mount) - Truck

TPMS	Tire Position	Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
Tire-SafeGuard HCI Corp TPM-W210 B	LF	7/14/2008	0.51	Yes	Met criteria	clear before driving
	RF	7/14/2008	0.58	No	Slow Leak @ 125 psi, 12.6 min	clear before driving
	LII	7/14/2008	1.35	No	Slow Leak @ 96.9 psi, 5.9 min	clear before driving
	RRO	7/14/2008	1.17	No	Slow Leak @ 100 psi, 4.7 min	clear before driving
	Multi	7/16/2008	7 to 12	No	All alerted of the more severe low tire warning	clear before driving

7.2. Tire-SafeGuard (Rim Mount) Slow Leak Detection Test – Tractor

All of the four test tires had slow leak warnings in more than three minutes. In the multiple tire tests three of four tires alerted to slow leaks, but in more than three minutes elapsed time. The RRO only warned to a low tire pressure alarm (Table 7.2).

Table 7.2. Tire-SafeGuard (Rim Mount) - Tractor

TPMS	Tire Position	Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
Tire-SafeGuard HCI Corp TPM-W210 B	LF	10/22/2008	1.00	No	Slow Leak @ 97 psi, 9.5 min	clear before driving
	RF	10/22/2008	0.93	No	Slow Leak @ 102 psi, 5.5 min	clear before driving
	LII	10/22/2008	0.85	No	Slow Leak @ 97 psi, 7 min	clear before driving
	RRO	10/22/2008	0.88	No	Low tire pressure @ 96 psi, 6.5 min	clear before driving
	Multi	10/22/2008		No	3 of 4 tires warned of slow leak but in more than 3 min	3 tires cleared within 90 sec of re-inflation start. RF-took almost 15 min.

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

7.3. Tire-SafeGuard (Flow Through) Slow Leak Detection Test – Truck

Although the pressure loss rate was somewhat higher than 1 psi per minute, 3 of the 4 single test tires gave the slow leak warning in less than the 3 minutes allowed. The LII test tire took more than 3 minutes to warn, and then it was of low tire pressure. The multiple-tire test was not done for this system on the truck (Table 7.3).

Table 7.3. Tire-SafeGuard (Flow Through) - Truck

TPMS	Tire Position	Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
Tire-SafeGuard HCI Corp TPM-P310B1 C	LF	7/23/2008	1.81	Yes	Met criteria	clear before driving
	RF	7/23/2008	1.71	Yes	Met criteria	clear before driving
	LII	7/23/2008	1.53	No	Low tire pressure @ 89 psi, 6 min	clear before driving
	RRO	7/23/2008	1.50	Yes	Met criteria	clear before driving

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

7.4. Tire-SafeGuard (Flow Through) Slow Leak Detection Test – Tractor

All of the four test tires gave the slow leak warning, but in more than three minutes. In the multiple tire test, three of four test tires alerted the slow leak alarm, but after three minutes elapsed time. The LF tire warned of a low tire pressure, not of a slow leak (Table 7.4). It appears that a reasonable suggestion for a slow leak detection system would be to set an alarm within ten minutes after the leak begins.

Table 7.4. Tire-SafeGuard (Flow Through) - Tractor

TPMS	Tire Position	Test Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
Tire-SafeGuard HCI Corp TPM-P310B1 C	LF	10/24/2008	0.94	No	Slow Leak @ 102 psi, 4.5 min	clear before driving
	RF	10/27/2008	0.94	No	Slow Leak @ 101 psi, 5.5 min	clear before driving
	LII	10/28/2008	0.81	No	Slow Leak @ 98 psi, 5.5 min	clear before driving
	RRO	10/28/2008	0.88	No	Slow Leak @ 97 psi, 5 min	clear before driving
	Multi	10/28/2008	RF - 0.78 LII - 0.7 LF - 0.8 RRO - 0.58	No	RF slow leak at 7.5 min LII slow leak at 9 min LF low tire at 9.5 min RRO slow leak at 17.5 min	clear before driving

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

7.5. IVTM (Flow Through) Slow Leak Detection Test – Truck

A leak rate specification was not available for the IVTM; therefore the VRTC loss rate was again used for the slow leak detection tests. None of the four test tire sensors warned of a slow leak. All warned of low tire pressure, but each took longer than 24 minutes to alert. The multiple-tire test was not done for this system on the straight truck (Table 7.5).

Table 7.5. IVTM (Flow Through) – Truck

TPMS	Tire Position	Test Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
WABCO / Michelin IVTM G8960 D	LF	8/28/08	1.01	No	Low Pressure @ 105 psi @ 28 minutes	cleared at TPMS start-up
	RF	8/26/08	1.15	No	Low Pressure @ 101 psi @ 27 minutes	cleared at re-inflation start
	LII	8/26/08	1.37	No	Low Pressure @ 83 psi @ 28 minutes	cleared after re-inflation
	RRO	8/26/08	0.87	No	Low Pressure @ 84 psi @ 27 minutes	cleared after re-inflation start

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

7.6. IVTM (Flow Through) Slow Leak Detection Test – Tractor

None of the 4 individual-tire tests warned of a slow leak. Instead, all warned of Low tire pressures and each took longer than 20 minutes to alert. In the multiple-tire test, none of the 4 test tires alerted the slow leak alarm. All had warnings of low tire pressure. The time to alert ranged from 15 to 37 minutes of total air pressure release time (Table 7.6). The IVTM also exceeded the 10 minute maximum slow leak detection time specified by the Tire-SafeGuard TPMS. A slow leak was not detected by the IVTM when applied to either test vehicle.

Table 7.6. IVTM (Flow Through) – Tractor

TPMS	Tire Position	Test Date	Rate (psi/min)	Detect slow leak in <3 minutes	Status	Re-inflation Status
WABCO / Michelin IVTM G8960 D	LF	10/31/2008	0.73	No	Low Pressure @ 28.9 minutes	clear before driving
	RF	10/31/2008	0.8	No	Low Pressure @ 28 minutes	clear before driving
	LII	11/3/2008	1	No	Low Pressure @ 21minutes	clear before driving
	RRO	11/4/2008	0.84	No	Low Pressure @ 29minutes	clear before driving (20 sec after refill start)
	Multi	11/4/2008	LF - 0.6 RF - 1.2 LII - 0.66 RRO - 1.4	No	Low Tire Press. @ LF-30min.,RF-16min. LII-37min.,RRO-15min.	clear before driving (within 30 sec after refill start)

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RRO = Right Rear Outer

8.0. MALFUNCTION TESTS

Tests were performed on each system to observe how they responded to various malfunctions. To simulate a sensor failure, one wheel was removed and placed beyond the radio transmission range of the sensor. To simulate an antenna failure, an antenna was removed from the system receiver. The results of these tests are presented in the succeeding sections.

8.1. Malfunction Test Procedure

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 feet from the truck. The TPMS was then monitored to see if it detected the removed sensor, and if so, the time required for detection. If the system did not detect a malfunction, then the pressure in the removed tire was reduced to see if the system was monitoring the tire. For some systems, it may be necessary to separate the tire from the vehicle by more than 100 feet. The tire was then replaced to see if the system cleared the display of the failed system (malfunction) signals. The vehicle did not move during this test.

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. If the system did not detect a malfunction, then the pressure in the removed tire was reduced to see if the system was monitoring the tire. The antenna was then reconnected to see if the system would clear the fault warning from the display.

The results for the sensor and antenna malfunction tests are presented in Table 8.1. Malfunction Test Results.

Table 8.1. Malfunction Test Results

		Sensor Test Results							Antenna Test Results						
Vehicle	TPMS	Identified Malfunction	Not Affected By Malfunction	Did Not Recognize Malfunction	Time To Malfunction Warning	Type Of Malfunction Warning	Other Warning(s)	Note	Identified Malfunction	Not Affected By Malfunction	Did Not Recognize Malfunction	Time To Malfunction Warning	Type Of Malfunction Warning	Other Warning(s)	Note
6x4 Straight Truck	SmartWave Dana S14486 8 A	X			39 min	SENSOR FAULT	None	TPMS warned of a SENSOR FAULT after reducing tire pressure by 36 psi.	X			33 min	SENSOR FAULT	None	None
	Tire-SafeGuard HCI Corp TPM-W210 8 B			X		No warning	Low tire pressure	Did not give a warning while tire was off truck, but did warn of low tire pressure 12 min. 53 sec. after pressure had been dropped and the tire was back on the truck.		X		No warning	N/A	Low tire pressure	Warned of a low tire pressure in the RF 1 min. 10 sec. after air was released, even though the antenna was still disconnected.
	Tire-SafeGuard HCI Corp TPM-P310B1 8 C		X		No warning	No warning	Low tire pressure	Low tire pressure warning alerted while reducing air pressure when RF tire was 100+ ft away.			X	No warning	N/A	Low tire pressure	Air was released from the LII tire. The TPMS warned of the low air pressure in tire LII, but not until 4 min. after the antenna was reconnected.
	WABCO/ Michelin IVTM G8960 8 D	X			30 min	“~~IVTM~~” (system fault)	Low tire pressure	Low tire pressure warning alerted immediately when air plumbing unhooked for tire removal; also low tire pressure warning alerted 30 ft. from truck when rolling tire back to truck.	N/A	N/A	N/A	N/A	N/A	N/A	None
	PressurePro Advantage CU41807684 8 E				5 min	No warning	00’	TPMS second stage warning given when the sensor was removed from the tire while 120 ft. away from the truck.	N/A	N/A	N/A	N/A	N/A	N/A	None
6x4 Tractor	SmartWave Dana S14486 5 A	X			35 min	SENSOR FAULT	None	None	X			32 min	SENSOR FAULT	none	None
	Tire-SafeGuard HCI Corp TPM-W210 5 B			X	No warning	No warning	Low tire pressure	Low pressure warning for RF tire alerted after air pressure was lowered, but not until tire was placed back on the tractor.		X		N/A	No warning	Low tire pressure	Warned of a low tire pressure in the RRO after air was released, even though the antenna was still disconnected.
	Tire-SafeGuard HCI Corp TPM-P310B1 5 C			X		No warning	Low tire pressure	Air was released 94 min. after the start of the test. However, the low pressure warning for the RF tire did not alert until the tire was being rolled back to the tractor (to within 60 ft.).			X	N/A	No warning	Low tire pressure	Warned of a low tire pressure in the RRO after air was released, but not until 90 sec. after the antenna was reconnected.
	WABCO/ Michelin IVTM G8960 5 D	X			60 min	“~~IVTM~~” (system fault)	Low tire pressure	The “~~IVTM~~” system fault alerted 19 min. after lowering the tire pressure to the setpoint 1 level. A “low pressure” warning was given as the tire was being rolled back to the tractor.							Test not done.
	PressurePro Advantage CU41807684 5 E	X			25.5 min	“---“ (3 dashes)	None	(3 dashes) indicates a lost sensor or power interruption.		X		N/A	N/A	Low tire pressure	Warned of a low tire pressure in the LF 10 sec. after air was released, even though the antenna was still disconnected.

9.0. OBSERVATIONS AND PROBLEMS ENCOUNTERED

Although all the TPMS tested measured tire pressures directly, each had unique attributes that raised questions concerning sensors, monitor displays and system functions.

9.1. Sensors

Numerous problems were encountered with identifying and installing the TPMS sensors.

9.1.1. Installation

One problem arose between two of the low tire pressure tests, in which one of the jumper hoses between the valve stem and the sensor was rotated (1/4 turn at the sensor end) and the hose uncoupled from the sensor, while still under pressure. The force from the escaping air sliced one of the two o-rings on the hose fitting. To avoid creating a potential leak hazard, the o-ring needed replacement; therefore, the system was depressurized (just at that wheel), the rubber o-ring replaced, and then the system was reassembled for the next pressure test. A caution is recommended to users, removing this air coupling under pressure may result in hazardous expulsion of flying debris (o-ring pieces) and that the Schrader valve end should be decoupled prior to disengaging the sensor end of the jumper hose.

Some sensors were installed by removing the valve stem caps and replacing them with the sensors. When installing the sensors on aluminum rims with small hand holes, there was concern that the limited clearance would hinder the installer from applying proper tightening torque to the sensor. The sensor nearly filled the opening in the aluminum rim. This was less of a concern for installation on steel wheels with larger hand holes in the rim.

Sensors with a jam-nut type locking security device were found to have trouble fitting over some of the existing valve stems. The diameter of the unthreaded section of the valve stem varied by type and by brand. In some cases this diameter was too large to allow the security locking device to slide on for installation.

One of the TPMS sensors researched, but not tested, required custom made valve stems to match the type and composition of the wheel rim. This was an internal valve stem mounted sensor that bolted through the valve stem opening in place of the standard valve stem.

9.1.2. Identification of the Type and Position of Internal Sensors

Service personnel need to be trained to identify which “rim mount” TPMS sensors are installed in a tire such that proper care will be given in removing the tires from the rims. The SmartWave installation guide specifies mounting the sensor on the opposite side of the rim (180 degrees away) from that of the position specified by the Tire-SafeGuard installation guide. By not knowing which sensor installation procedure was followed, the tire may inadvertently be pushed off center in a direction that may shear off the sensor band grips, thus destroying the sensor.

Most sensors require specific tire numbering patterns, but these patterns vary by TPMS manufacturer (Figure A.2. Differences in Tire Location Identification among TPMS Suppliers in the Appendix), not by vehicle manufacturer. This may be confusing for tire maintenance shops which move tires around on the trucks during tire change outs or rotations. Both TPMS installers and the tire maintenance crews would greatly benefit by standardization of the tire numbering sequence.

Some sensors did not have permanent identification tags that indicated channel codes or serial numbers required to program the displays to monitor the respective channels.

9.1.3. Sensor Performance

At TPMS startup, some sensor response times to begin operation varied within the test vehicle tire set. This delayed logging the pressure measurements prior to the test runs. It may not be possible to use TPMS readings to re-inflate low tires discovered during pre-trip inspection walk-around as it may be necessary to move the truck (physically spin the tires) to get the sensors to transmit.

Differences between sensor temperature readings and the probe temperature readings ranged from typically 1 or 2 degrees to as much as 9°F.

9.1.4. Durability

One durability issue raised was steel band breakage on sensors installed internally on the rim. This stressed the need for special, extra care in tightening the worm gear screw to the proper torque and trimming the band to proper length. The worm gear mechanism on bands included with one of the TPMS had a feature that allowed the band to slide through the screw housing before final tightening of the band. This helped to save time installing sensors.

One of the valve stem mounted sensors developed a leak on the periphery of the sensor body. This leak was not coming from the mounting threads or seal, but from the midsection of the sensor housing as denoted by the arrow in Figure 9.1.

Figure 9.1. Sensor Body Leak

Possible problems with the use of valve stem mounted or lug mounted sensors may include fatigue and vibration causing air pressure leaks. Because of the configuration and added weight of the hardware and plumbing to connect to the data acquisition system these issues were not tested at this time.

9.2. Monitor Function

It was found that some TPMS display screens may wash out in bright sunlight and become difficult to read. However, this was not a problem in more subdued lighting.

9.3. Overall Program Function (Performance)

Residual heat from the Calibration Test may raise the tire internal air temperature slightly, which in turn may increase the tire pressure. Without temperature compensation an apparent valid low-pressure warning may clear and then reoccur upon cooling.

One TPMS failed to alarm during an over-pressure application. It was not determined if the pressure was too low to alarm on over-pressure or if that feature was not functioning correctly. When the procedure to view the programmed over-pressure setpoint was attempted, the system dumped the setup configuration and no longer identified any of the tire sensors.

A few TPMS require special programming tools or a PC to assign sensors to respective wheel locations. The tools range in price from several hundred to several thousand dollars.

It was found that when using a PC or laptop computer to program a TPMS, there could be operating system, monitor screen resolution, and USB connection driver compatibility issues.

10.0. SUMMARY AND CONCLUSIONS

The data results have shown that 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 CIPs.

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. By using a “cool” calibration procedure to initialize the TPMS before performing a low pressure detection test, the tires remained relatively cool, and therefore did not thermally bias the basic low pressure detection capability of each system.

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 (such as in SmartWave TPMS) 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, whereas the systems without temperature compensation allowed much larger pressure drops before activating their alarms.

Identification of sensor temperature sensitivity needs to be isolated from raw pressure detection as identified by the low pressure detection test procedures used in this report. A second test may need to be run using either fixed pressures and the tires run through a heating and cooling cycle, or the tires may 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 declare a low tire pressure alert. This second “hot” driving test would be required to identify the TPMS capability to detect tire pressure loss while the vehicle was being driven. As long as the vehicle is parked (or has been stopped for a considerable period of time) a non-temperature-compensated TPMS will provide sufficient low-pressure detection; however, once the vehicle resumes over-the-road operation, applying temperature compensation will be required for the most effective method of detecting low tire pressure.

In order to better match TPMS performance to tire safety needs, additional tire tests may need to be performed to characterize the mortality conditions of tires when subjected to full load conditions while underinflated. The key to heavy truck TPMS response needs to be coordinated with tire failure time such that low tire pressure can be effectively identified and corrected before the tire is damaged or destroyed.

The capability to detect a slow leak is beneficial for in-use vehicles, but would provide little benefit to parked vehicles as variation in tire pressures, due to daily temperature fluctuations, may likely exceed the magnitude of any extremely slow leak. However, a slow leak detector would be of benefit to in-use vehicles that develop a leak (e.g., at a moderate rate of 1 psi per 3 minutes) so the driver could be alerted to a deteriorating condition before the tire becomes critically low or goes flat. It appears that a reasonable slow leak detection system might set an alarm within ten minutes after the leak begins, which is faster than the cooling rate of the tire when the vehicle is parked, yet at less air volume lost than during a full low-pressure detection.

Most systems tested provided an indication of which tire sensor was detecting the low tire pressure. Although this feature may not be necessary for heavy trucks, it does provide an on-the-spot identification of the low-pressure tire's location and it could eliminate the need for the driver to stop and go around the truck looking for an unspecified tire that is low on inflation pressure.

A few of the TPMS tested provided over-temperature or overpressure features. These functions provide information that is beyond the basic low pressure detection capability, but might be beneficial especially to heavy-hauler and oversize-load operations. These optional features were not tested in this program.

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 and may not be capable of installing these systems onto in-service vehicles successfully without aid from the system manufacturer. Therefore, it is anticipated that vehicle manufacturers and TPMS suppliers would work together to develop efficient systems if TPMS would become common 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 failed system recognition.

Some of the tested TPMS provided system malfunction warnings on the display screens. These warnings are beneficial in tracking symptoms of faulty sensors, missing or damaged receiving antennas, and related component malfunctions.

11.0. REFERENCES

TPMS Related References

[1] Grygier, P., Garrott, W.R., Mazzae, E.N., MacIsaac, Jr., J.D., Hoover, R.L., Elsasser, D., and Ranney, T.A. 2001. *An Evaluation of Existing Tire Pressure Monitoring Systems,* U.S. Dept. of Transportation, DOT HS 809 297.

[2] FMVSS No. 138. 2006. U.S. Dept. of Transportation, National Highway Traffic Safety Administration, FMVSS No. 138, Tire Pressure Monitoring Systems, 49 CFR, Ch. V.

[3] Brady, S., Nicosia, B., Kreeb, R., and Fisher, P. 2007. *Tire Pressure Monitoring and Maintenance Systems Performance Report*, U.S. Dept. of Transportation, FMCSA-PSV-07-001.

Other TPMS Reports

Daniel, S. 2005. *Status of TPMS Rulemaking,* SAE Government/Industry Meeting - May 10, 2005

Grygier, Paul and Samuel Daniel, Jr., National Highway Traffic Safety Administration and Richard Hoover and Timothy Van Buskirk, Transportation Research Center Inc., June 2009, *Testing Of Heavy Truck Tire Pressure Monitoring Systems (TPMS) In Order To Define An Acceptance Procedure*, 21st International Technical Conference on the Enhanced Safety of Vehicles, Paper No. 09-0551.

12.0. APPENDICES

12.1. Appendix A: Data Channels

Table A.1. VRTC's CDAS Computer Data Channel List

Data Channel Configuration						
	SampleRate:		25	Hz		
	Pretrig:		5	sec		
	Posttrig:		3600	= 1 hour		
Chan	Description	Mnem	Units	Slope	Offset	FSO
0	Vehicle Speed	SPVHAA	mph	12.344	0	123
1	Distance	DSSTAA	miles	0.326307	0	3.2468
2	Driver Event	VTDEAA	volts	1	0	10
3	Buzzer	VTTRAA	volts	1	0	10
4	TPMS Lamp	VTTRBL	volts	1	0	10
5	Ambient Temperature	TMAMAA	deg_F	140	32	1400
6	Press LF Steer	PRT1A1	psi	20.1	0	200
7	Press RF Steer	PRT1A2	psi	20.1	0	200
8	Press LII Drive	PRT1A3	psi	20.1	0	200
9	Press RII Drive	PRT1A4	psi	20.1	0	200
10	Press LRI Drive	PRT1A5	psi	20.1	0	200
11	Press RRI Drive	PRT1A6	psi	20.1	0	200
12	Press LIO Drive	PRT2A3	psi	20.1	0	200
13	Press RIO Drive	PRT2A4	psi	20.1	0	200
14	Press LRO Drive	PRT2A5	psi	20.1	0	200
15	Press RRO Drive	PRT2A6	psi	20.1	0	200

LF = Left Front, RF = Right Front, LII = Left Intermediate Inner, RII = Right Intermediate Inner,
LRI = Left Rear Inner, RRI = Right Rear Inner, LIO = Left Intermediate Outer,
RIO = Right Intermediate Outer, LRO = Left Rear Outer, RRO = Right Rear Outer

For nearly 30 years, VRTC has indexed wheel locations in a simple order for standard brake testing. Typically, the left side wheels are assigned odd numbers and the right side wheels, even numbers. The driver's steer axle wheel is number 1, as this is the first tire the driver sees, and numbering follows in normal American writing progression, thereby increasing from left to right, and from front to rear, on the truck. Because multiple tires were attached to the normally singular wheel assignments, an additional overlay "tire location" pattern was added. Thus, the following 3-character numbering sequence was applied for TPMS test tire allocations. The first character identified the orientation of the tire on the axle. A number "1" indicated an inward facing (concave inward) rim, such as for a steer tire or inner tire of a set of duals (on the drive axle). A "2" identified the outer tire of the dual drive tires. The second character represented the vehicle number (using alphabetical characters) starting from the first unit of a long combination vehicle. For this test program, TPMS sensors were only installed on single unit vehicles; therefore, both test vehicles were labeled "A," as one was a single unit truck (VR8) and the other was a tractor (VR5). The last character identified the wheel position (1 to 6) starting from the left-front. For example, "2A6" indicated the outer tire of a lead unit (truck or tractor) at the right-rear drive position (tire number 6).

When tire pressure lines were connected from each individual tire to the pressure transducers on the data system, a 3-character prefix was added to each data channel. "PR" indicated a pressure transducer. The third character "T" declared that it was attached to a tire position. Therefore, a CDAS data acquisition system channel representation of the previous example was programmed as "PRT2A6," or pressure transducer for an outer tire on the right-rear drive wheel of a lead vehicle. Figure A.1 displays the wheel layout of the two, 10-tire trucks, and overlays the assigned CDAS tire data channel names.

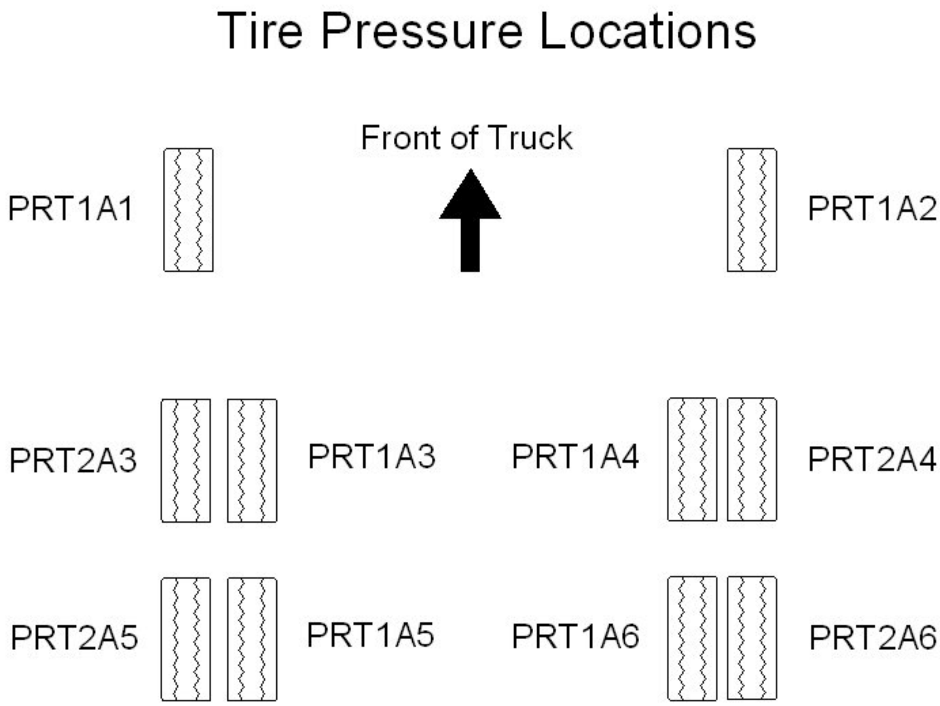

Figure A.1. CDAS Computer Orientation for Tire Pressure Control System

Once the CDAS data system was configured using the VRTC Heavy Truck standard character strings, the TPMS sensors were installed onto the wheels of the truck. However, the numbering order prescribed by each TPMS manufacturer differed from the VRTC array (Figure A.2). Each time a different TPMS was installed, a meticulous overlay was produced to ensure direct correlation between collected data and TPMS sensed data. Three of the four different brand systems began the numbering on wheel number 1, where the fourth was the reverse.

The SmartWave used a counter-clockwise U-orientation, as though walking around the truck, starting from wheel number 1 (left steer). Upon arriving at the next wheel group, the inner tire was the lower numbered tire of the pair.

The Tire-SafeGuard systems (each using similar installation patterns) applied a U-pattern, but reversed the direction by going clockwise, beginning from the right front wheel. Upon reaching each wheel group in the sequence, the rightmost tire was labeled with the lower number. Therefore, on the right side of the truck, the outer drive tires were numbered lower than the inner tires; but the trend reversed on the left side of the truck, where now the inner tires were numbered lower than the outer tires. This was confusing for the installers, as they found it challenging to keep inner and outer numbers straight for opposite sides of the truck.

WABCO used a pattern of increasing numbers progressing left-to-right, from the front to the rear. The IVTM display showed two tires at a time. For dual-tire axle sets, the pairings were outer tires on an axle, then the inner tires on that same axle.

For the PressurePro installation, the driver's steer tire was first, followed by a clockwise progression around the front of the truck. At each wheel group, the inner tire was always numbered lower than the outer tire of the dual set.

Both installers and the tire maintenance crews could greatly benefit by standardization of the tire numbering sequence. With the disarray in the current numbering schemes, much time may be wasted trying to keep the sensors assigned to specific tire locations during tire rotations or replacement. Some sensors do not have permanent ID tags that indicate channel codes or serial numbers required to program the displays to read the respective channels.

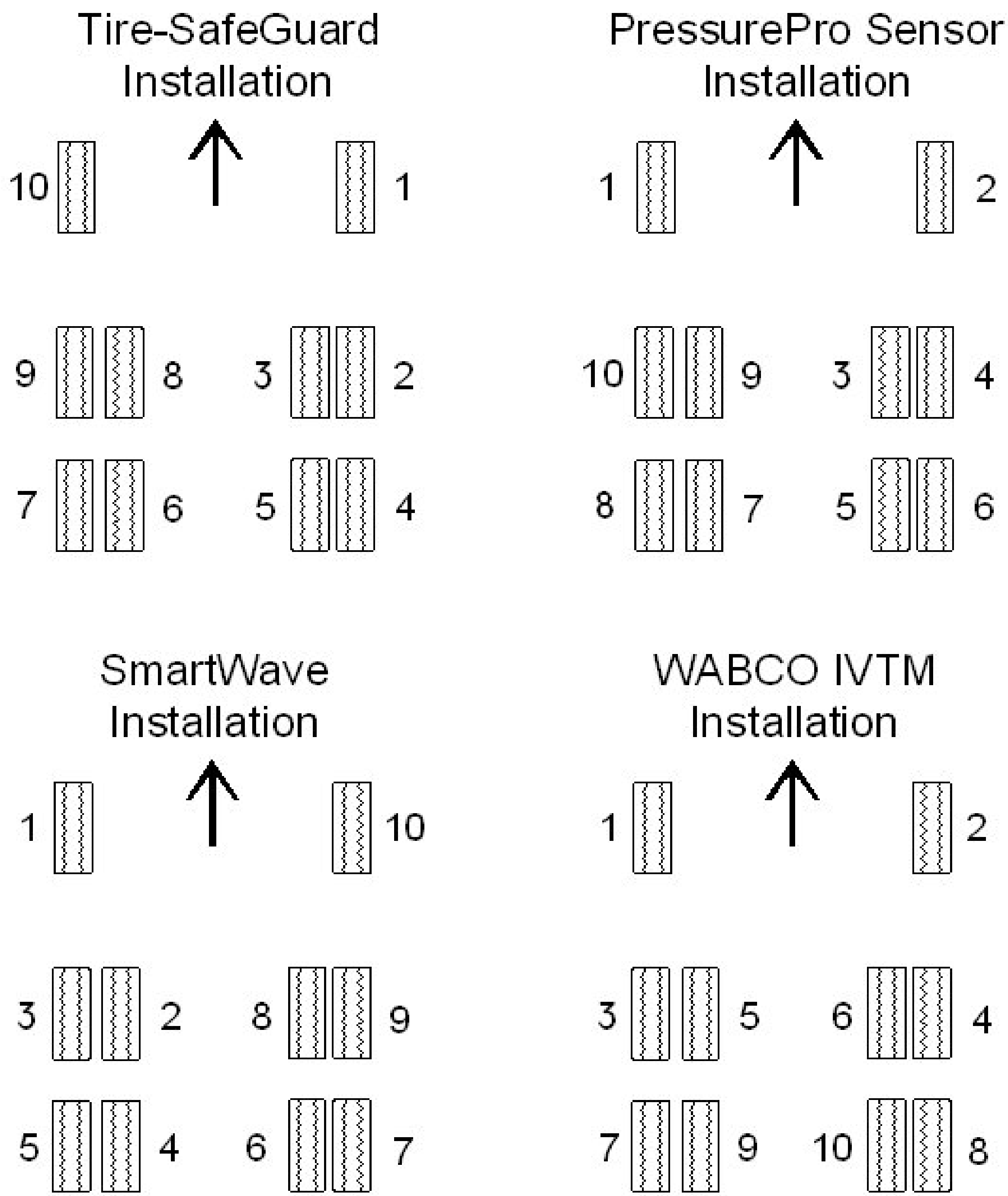

Figure A.2. Differences in Tire Location Identification among TPMS Suppliers

12.2 Appendix B: Pictures of Pressure Control System

A pressure control system was adapted from the valve network used previously for light vehicle TPMS tests. The supply manifold was converted from operation on stored-air tanks to direct connection to the truck air brake supply lines. A check valve was installed in the connecting air line so the air in the tires would not return to the air brake system. The manifold was increased from 4 to 10 control circuits so every tire on the truck could be re-inflated from the manifold. Each control circuit included a 200-psi pressure transducer, a zeroing valve for daily offset adjustment, a pressure calibration port, and a port to connect an air line to the assigned tire. Four control circuits also included additional "vent" ports, which were used to reduce tire pressure for the specified TPMS tests.

Figure B.1. Pressure Transducers and Signal Conditioners

Figure B.2. Air Lines and Rotary Unions on Right Side Drive Tires of the Truck

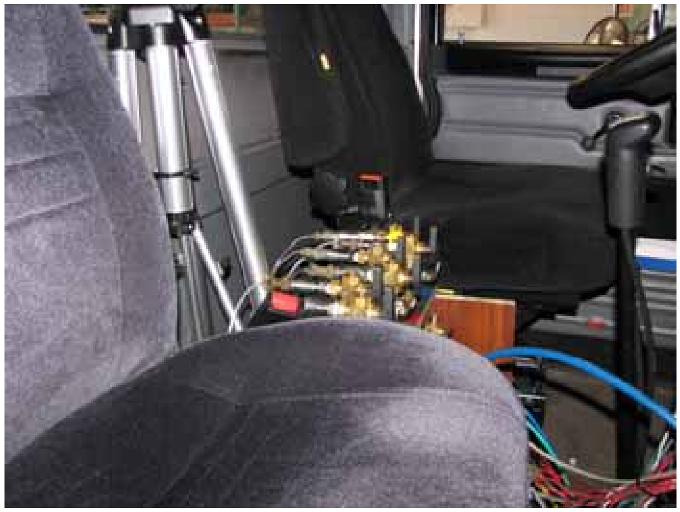

Figure B.3. Observer's View of Tire Pressure Control Manifold

Figure B.4. Pressure Control Manifold Showing All Ten Ports

Figure B.5. Close-up View of Pressure Control Manifold

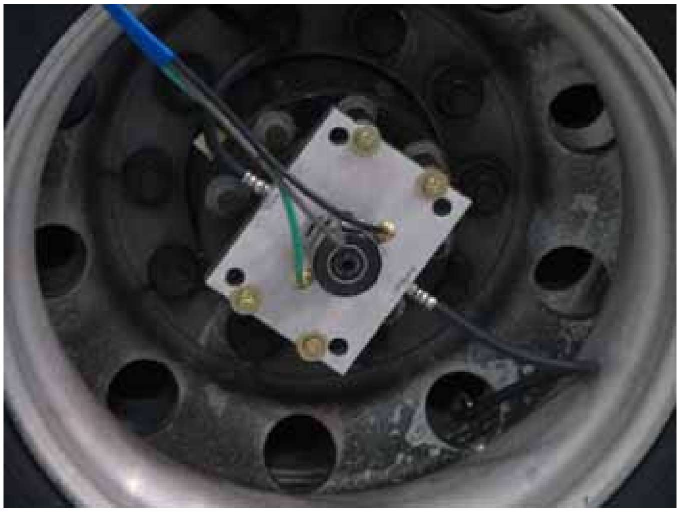

Figure B.6. Two Port Rotary Union on Drive Wheel

12.3 Appendix C: Pictures of Video and Data Acquisition System

Figure C.1. Video Camera Mounted Between Driver and Observer For Logging All Test Activities

Figure C.2. SmartWave Display (Lower-Right) Along with CDAS Screen and Speed and Distance Measuring Equipment

Figure C.3. Right-Seat Observer's View of Instrumentation Displays

Figure C.4. Data Acquisition Computer Mounted Beneath the Observer's Seat

Figure C.5. Noncontact Radar Speed Sensor Mounted Beneath the Aluminum Fuel Tank

12.4 Appendix D: Low Tire Pressure Detection Test Procedure

The following procedures are proposed for heavy truck TPMS applications. The light vehicle TPMS regulation, *FMVSS No. 138, Tire Pressure Monitoring Systems*, was used as a starting point for most of the procedures examined for heavy truck TPMS. The same sensor technology that is used in light vehicle systems is also used by the heavy vehicle systems. The heavy vehicle TPMS procedure is applicable to single-unit motorized vehicles, with a GVWR greater than 10,000 lb (such as trucks, truck tractors, buses, and motor coaches). This procedure would also apply to vehicles with more than four tires and a GVWR of less than 10,000 lb.

12.4.1. Performance Capabilities

The pressure at which the TPMS signals the driver when one or more tires are at a pressure below the threshold for safe operation is one of the most important properties of a TPMS. In the case of the light vehicle standard, the regulation requires that the driver be warned when 1 or more of the vehicle's tires, up to a total of 4 tires, is equal to or less than either the pressure 25 percent below the vehicle manufacturer's recommended CIP, or the minimum specified in the standard, whichever is higher. The "25 percent below" value was chosen based on tire testing at low pressures indicating that P-metric and LT tires could be safely operated for an acceptable time period at this inflation level. However, for heavy truck TPMS, a low pressure warning level of 10 to 15 percent below the vehicle manufacturer's CIP is currently suggested. Heavy vehicles are designed such that there is not as much margin of load capacity between a tire's maximum load/pressure and the actual operating load/pressure. Based on the gross axle weight ratings (GAWR) of the heavy vehicles and the recommended CIP of the tires, we believe that heavy vehicle tires cannot operate safely at pressures of more than 15 percent below the CIP for the wheel-end load. In addition, low tire pressure induces handling problems for heavy trucks.

The time limit at which the system must detect a low-pressure condition after the low-pressure threshold has been reached is another important performance parameter. FMVSS No. 138 requires that the light vehicle TPMS signal a low tire warning to the driver within 20 minutes after the low-pressure threshold has been reached. However, due to the much higher load concentrations found on heavy truck tires, a quicker detection time is likely imperative. We believe that at least 10 minutes may be appropriate for a TPMS to differentiate noise from a true low-pressure signal and respond with a low-pressure warning, but not more than 15 minutes. Most direct systems are capable of detecting low pressure within 5 minutes after the threshold had been reached, but more time may be required by indirect systems. It would be preferred that the test procedures show that the TPMS capabilities are timely (responsive), accurate, and technology neutral.

The light vehicle standard specifies the icons or telltales that are to be displayed within plain view of the driver and illuminated or flashed when tire pressure is below the warning value or the system is not operating normally. The same would appear reasonable for a heavy vehicle TPMS display such that drivers, inspectors, and maintenance personnel would be able to move from one vehicle to another without changes in the depictions of TPMS display messages.

12.4.2. Test Conditions

The following list includes basic test conditions that could be applied during the performance measurement of a heavy truck TPMS:

1. The ambient temperature during testing should be between 0°C (32°F) and 40°C (104°F);
2. The road surface is dry during testing;
3. The vehicle may be tested at any weight between its lightly loaded weight and GVWR; and
4. The vehicle is tested with the tires installed at the time of initial sale (or OEM equivalents).
5. The tires must be at ambient temperature.

12.4.2.1. Test Procedure Recommendation No. 1 – With Cool Calibration and Cool Tire Pressure Detection Sequence

1. With the vehicle in a dry, non-sunny area (the starting point), inflate all tires to Cold Inflation Pressure (CIP).
2. Turn "on" the TPMS and verify that "lamp check" confirms all display components and buzzer functions are working correctly.
3. Take readings by measuring individual tire pressures and temperatures with the TPMS, tire pressures with the data collection system, and all tire external temperatures with a noninvasive probe. Log by hand all measurements that are not collected electronically.
4. Cool Calibration test: Drive for 8 to 10 minutes over a flat road. Limit the vehicle's maximum speed to 25 mph for 2 miles or more, beginning and ending at the starting point (vehicle maneuvers may include driving, backing, turning, and stopping). This low temperature procedure prevents the tire temperatures from increasing much above the initial ambient temperature; therefore, test pressures may be accurately set for more consistent low pressure detection tests.
5. Within 5 minutes of completing calibration, read the displayed TPMS pressures and temperatures, record pressures with the data collection system, turn "off" TPMS, and deflate test tire to 3 psi below the low-pressure setpoint being tested. Immediately turn "on" TPMS, take readings (as in step No. 3), observe TPMS display for warnings, and then begin Low Pressure Detection Test (in step No. 6).
6. Cool Low Pressure Detection Test: If the TPMS activated a low-pressure warning in step No. 5, log the event and proceed to TPMS Memory Check in step No. 9. If the TPMS did not activate a low-pressure warning in step no. 5, drive the vehicle for a Low Pressure Detection test which includes: drive for 8 to 10 minutes over a flat road and limit the vehicle's maximum speed to 25 mph for 2 miles or more, beginning and ending at the starting point (vehicle maneuvers may include driving, backing, turning, and stopping). The detection step is satisfied when a prompt low-pressure warning is activated by the TPMS.
7. If the TPMS does not display a warning during detection-driving and within 10 minutes of turning on the TPMS (in step 5), the TPMS has failed to detect low pressure in this tire. Go to Tire Cooling in step No. 10.
8. If the TPMS does display a warning within 10 minutes of turning on the TPMS (in step 5), the TPMS has passed the low pressure detection test for this tire. Log the event and proceed to TPMS memory check in step No. 9.
9. TPMS Memory Check: Turn "off" TPMS and wait for 5 minutes. After 5 minutes have expired, turn "on" the TPMS and confirm that the same low-pressure warning returns to the

TPMS Display. If the same warning does not redisplay, the TPMS has failed to remember the fault after a simple power-down cycle (e.g., an engine shutdown).

10. Tire Cooling: Turn "off" TPMS. When the current test tire probe temperature is not more than 10°F above ambient temperature, cool the tire for 30 minutes. When the test tire probe temperature is more than 10°F above ambient temperature, cool the test tire from 30 minutes to 2 hours (use cooling fans as needed).
11. When the test tire probe temperature has returned to within 3°F of ambient temperature, with the TPMS still turned "off," re-inflate test tire to CIP.
12. Turn "on" TPMS, take readings, observe TPMS display for warnings.
13. If no warnings are indicated by TPMS display, the test is complete. Proceed to the next test.
14. When low-pressure warnings are still present, either activate TPMS reset function (if available) or run Reset Identification Test (a repeat of the Cool Calibration test in step No. 4). If TPMS fails to clear any unwarranted warnings, then the system has failed to identify a properly re-inflated tire.
15. Repeat steps 1 through 14 for each test tire and for each pressure setpoint.
16. Once low pressure detection tests have been completed, conduct TPMS failed systems tests as detailed in vehicle manufacturer's operating manual.

12.4.2.2. Alternate Test Procedure Recommendation No. 2 – With Cool Calibration and Hot Tire Pressure Detection Sequence

1. With the vehicle in a dry, non-sunny area (the starting point), inflate all tires to Cold Inflation Pressure (CIP).
2. Turn "on" the TPMS and verify that "lamp check" confirms all display components and buzzer functions are working correctly.
3. Take readings by measuring individual tire pressures and temperatures with TPMS, tire pressures with data collection system, and all tire external temperatures with a noninvasive probe. Log by hand all measurements that are not collected electronically.
4. Cool Calibration test: Drive for 8 to 10 minutes over a flat road. Limit the vehicle's maximum speed to 25 mph for 2 miles or more, beginning and ending at the starting point (vehicle maneuvers may include driving, backing, turning, and stopping). This low temperature procedure prevents the tire temperatures from increasing much above the initial ambient temperature; therefore, test pressures may be accurately set for more consistent low pressure detection tests.
5. Within 5 minutes of completing calibration, read the displayed TPMS pressures and temperatures, record pressures with the data collection system, turn "off" TPMS, and deflate test tire to 3 psi below the low-pressure setpoint being tested. Immediately turn "on" TPMS, take readings (as in step No. 3), observe TPMS display for warnings, and then begin Low Pressure Detection Test (in step No. 6).
6. Hot Low Pressure Detection Test: If the TPMS activated a low-pressure warning in step No. 5, log the event and proceed to TPMS Memory Check in step No. 9. If the TPMS did not activate a low-pressure warning in step No. 5, drive the vehicle for a Low Pressure Detection test which includes: drive the vehicle for 10 to 15 minutes over a flat road for a distance between 8 and 10 miles, reach and maintain a vehicle speed from 60 to 65 mph (or maximum design speed of tires if below 60 mph) for at least 5 minutes during the test, and begin and end at the starting point (vehicle maneuvers may include driving, backing, turning, and

stopping). The detection step is satisfied when a prompt low-pressure warning is activated by the TPMS.

7. If the TPMS does not display a warning during detection-driving and within 15 minutes of turning on the TPMS (in step 5), the TPMS has failed to detect low pressure in this tire. Go to Tire Cooling in step No. 10.
8. If the TPMS does display a warning within 15 minutes of last turning on the TPMS (in step 5), the TPMS has passed the low pressure detection test for this tire. Log the event and proceed to TPMS memory check in step No. 9.
9. TPMS Memory Check: Turn "off" TPMS and wait for 5 minutes. After 5 minutes have expired, turn "on" the TPMS and confirm that the same low-pressure warning returns to the TPMS Display. If the same warning does not re-display, the TPMS has failed to remember the fault after a simple power-down cycle (e.g., an engine shutdown).
10. Tire Cooling: Turn "off" TPMS. When the current test tire probe temperature is not more than 10°F above ambient temperature, cool the tire for 30 minutes. When the test tire probe temperature is more than 10°F above ambient temperature, cool the test tire from 30 minutes to 2 hours (use cooling fans as needed).
11. When the test tire probe temperature has returned to within 3°F of ambient temperature, with the TPMS still turned "off," re-inflate to CIP.
12. Turn "on" TPMS, take readings, observe TPMS display for warnings.
13. If no warnings are indicated by TPMS display, the test is complete. Proceed to the next test.
14. When low-pressure warnings are still present, either activate TPMS reset function (if available) or run Reset Identification Test (a repeat of the Cool Calibration test in step No. 4). If TPMS fails to clear any unwarranted warnings, then the system has failed to identify a properly re-inflated tire.
15. Repeat steps 1 through 14 for each test tire and for each pressure setpoint.
16. Once low pressure detection tests have been completed, conduct TPMS failed systems tests as detailed in vehicle manufacturer's operating manual.

12.4.2.3. Alternate Test Procedure Recommendation No. 3 – With Hot Calibration and Hot Tire Pressure Detection Sequence

1. With the vehicle in a dry, non-sunny area (the starting point), inflate all tires to Cold Inflation Pressure (CIP).
2. Turn "on" the TPMS and verify that "lamp check" confirms all display components and buzzer functions are working correctly.
3. Take readings by measuring individual tire pressures and temperatures with TPMS, tire pressures with data collection system, and all tire external temperatures with a noninvasive probe. Log by hand all measurements that are not collected electronically.
4. Hot Calibration test: Drive the vehicle for 10 to 15 minutes over a flat road for a distance between 8 and 10 miles. Reach and maintain a vehicle speed from 60 to 65 mph (or maximum design speed of tires if below 60 mph) for at least 5 minutes during the test. Begin and end at the starting point (vehicle maneuvers may include driving, backing, turning, and stopping). This procedure will result in tires that are heated above the ambient temperature in most cases.
5. Within 5 minutes of completing calibration, read the displayed TPMS pressures and temperatures, record pressures with the data collection system, turn "off" TPMS, and deflate test tire to 3 psi below the low-pressure setpoint being tested. For temperature compensated

systems, the test pressures may be adjusted from baseline pressure setpoint levels using a temperature compensation chart, table, or formula, supplied by either the vehicle or TPMS original equipment manufacturer (OEM). For the current test tire, the TPMS temperature measurement shall be the input parameter used to correlate the modified setpoint pressure to which the TPMS will activate a low-pressure warning. For non-temperature-compensated TPMS, the setpoint will be either a fixed 10 or 15 percent below original CIP or an equivalent pressure deflation below CIP. Once the test pressure is adjusted, immediately turn "on" the TPMS, take readings (as in step No. 3), observe TPMS display for warnings, and then begin Low Pressure Detection Test (in step No. 6).

6. Hot Low Pressure Detection Test: If the TPMS activated a low-pressure warning in step No. 5, log the event and proceed to TPMS Memory Check in step No. 9. If the TPMS did not activate a low-pressure warning in step no. 5, drive the vehicle for 10 to 15 minutes using the driving sequence in step No. 4. The detection step is satisfied when a prompt low-pressure warning is activated by the TPMS.
7. If the TPMS does not display a warning during detection-driving and within 15 minutes of last turning on the TPMS (in step 5), the TPMS has failed to detect low pressure in this tire. Go to Tire Cooling in step No. 10.
8. If the TPMS does display a warning within 15 minutes of last turning on the TPMS (in step 5), the TPMS has passed the low pressure detection test for this tire. Log the event and proceed to TPMS memory check in step No. 9.
9. TPMS Memory Check: Turn "off" TPMS and wait for 5 minutes. After 5 minutes have expired, turn "on" the TPMS and confirm that the same low-pressure warning returns to the TPMS Display. If the same warning does not re-display, the TPMS has failed to remember the fault after a simple power-down cycle (e.g., an engine shutdown).
10. Tire Cooling: Turn "off" TPMS. When the current test tire probe temperature is not more than 10°F above ambient temperature, cool the tire for 30 minutes. When the test tire probe temperature is more than 10°F above ambient temperature, cool the test tire from 30 minutes to 2 hours (use cooling fans as needed).
11. When the test tire probe temperature has returned to within 3°F of ambient temperature, with the TPMS still turned "off," re-inflate to CIP.
12. Turn "on" TPMS, take readings, observe TPMS display for warnings.
13. If no warnings are indicated by TPMS display, the test is complete. Proceed to the next test.
14. When low-pressure warnings are still present, either activate TPMS reset function (if available) or run Reset Identification Test (a repeat of the Hot Calibration test in step No. 4). If TPMS fails to clear any unwarranted warnings, then the system has failed to identify a properly re-inflated tire.
15. Repeat steps 1 through 14 for each test tire and for each pressure setpoint.
16. Once low pressure detection tests have been completed, conduct TPMS failed systems tests as detailed in vehicle manufacturer's operating manual.

12.4.2.4. Alternate Test Procedure Recommendation No. 4 – Continuous Driving Hot Calibration and Tire Pressure Detection Sequence

1. With the vehicle in a dry, non-sunny area (the starting point), inflate all tires to Cold Inflation Pressure (CIP).
2. Turn "on" the TPMS and verify that "lamp check" confirms all display components and buzzer functions are working correctly.

3. Take readings by measuring individual tire pressures and temperatures with TPMS, tire pressures with data collection system, and all tire external temperatures with a noninvasive probe. Log by hand all measurements that are not collected electronically.
4. Hot Calibration test: With the vehicle loaded to GVWR, drive the vehicle over a flat road. Reach and maintain a constant vehicle speed from 60 to 65 mph (or maximum design speed of tires if below 60 mph) for at least 2 hours. This procedure will result in tires that are heated to a typical over-the-road operating temperature in most cases.
5. Hot Low Pressure Detection test: While still driving at the end of the two hour Calibration driving period, take TPMS and data collection system readings (as in step No. 3), then adjust the pressure in the test tire to a test pressure of 3 psi below the low-pressure setpoint. For temperature compensated systems, the test pressures may be adjusted from baseline pressure setpoint levels using a temperature compensation chart, table, or formula, supplied by either the vehicle or TPMS original equipment manufacturer (OEM). The current TPMS test tire temperature measurement shall be the input parameter used to "look up" the modified setpoint pressure to which the TPMS will activate a low-pressure warning. For non-temperature-compensated TPMS, the setpoint will be either a fixed 10 or 15 percent below original CIP or an equivalent pressure deflation below CIP. Continue driving the vehicle (at the same speed as in step No. 4) for up to 10 to 15 minutes. The detection step is satisfied when a prompt low-pressure warning is activated by the TPMS. When the low-pressure warning activates, log the event and proceed to TPMS Memory Check in step No. 7.
6. If the TPMS does not display a warning during driving and within 15 minutes of completing the pressure reduction to the test pressure level (in step 5), the TPMS has failed to detect low pressure in this tire. Go to Tire Cooling in step No. 8.
7. TPMS Memory Check: Turn "off" TPMS and wait for 5 minutes. After 5 minutes have expired, turn "on" the TPMS and confirm that the same low-pressure warning returns to the TPMS Display. If the same warning does not re-display, the TPMS has failed to remember the fault after a simple power-down cycle (e.g., an engine shutdown).
8. Tire Cooling: Turn "off" TPMS. When the current test tire probe temperature is not more than 10°F above ambient temperature, cool the tire for 30 minutes. When the test tire probe temperature is more than 10°F above ambient temperature, cool the test tire from 30 minutes to 2 hours (use cooling fans as needed).
9. When the test tire probe temperature has returned to within 3°F of ambient temperature, with the TPMS still turned "off," re-inflate to CIP.
10. Turn "on" TPMS, take readings, observe TPMS display for warnings.
11. If no warnings are indicated by TPMS display, the test is complete. Proceed to the next test.
12. When low-pressure warnings are still present, either activate TPMS reset function (if available) or run Reset Identification Test (a repeat of the Hot Calibration test in step No. 4). If TPMS fails to clear any unwarranted warnings, then the system has failed to identify a properly re-inflated tire.
13. Repeat steps 1 through 12 for each test tire and for each pressure setpoint.
14. Once low pressure detection tests have been completed, conduct TPMS failed systems tests as detailed in vehicle manufacturer's operating manual.

12.5. Appendix E – Slow Leak Detection Test Procedure

This section details the procedure used for observing tire slow leak detection. It does not suggest options that may influence future testing methods. The procedure was:

1. Inflate all tires to CIP at room temperature.
2. Initiate recording of data with the data collection system. Record the ambient temperature and all tire pressures with the data collection system.
3. With Omega Meter and K-type temperature probe – measure ambient and all tire tread temperatures (near the core of the center tread blocks) – log on data sheet.
4. Turn on video tape recorder – Field of View (FOV) centered on TPMS display, driver event LED indicator, and lower right portion of the data collection system display to show data collection system file number, clock time, and data file time remaining.
5. Turn on power to TPMS unit and log buzzer and display lamp activity startup sequence and completion.
    a. If TPMS system is not active, press reset button to activate.
    b. If this does NOT cause TPMS display to activate, drive vehicle for up to 15 minutes at continuous speeds up to 60 mph.
    c. If the system fails to activate, troubleshoot the cause for failure to activate.
    d. If TPMS activation is not possible – note that the system has failed and then end the test.
6. Log initial TPMS measurements (if system is active) for each monitored tire.
7. Press driver event switch, then immediately begin to decrease the air pressure in the "selected test tire." The flow rate should provide a decrease in tire pressure of 1 psi per minute. Do not vent air for more than 3 minutes.
    a. If the TPMS does identify a "slow leak" before the 3 minutes have expired, immediately close the air release valve. Log the data collection system and TPMS measurements for the selected test tire, and note that this tire pressure sensor successfully passed the requirement to detect a "slow leak," and then go to "re-inflate the tire."
    b. If the 3-minute leak down period expires before a "slow leak" warning activates, close the air release valve. Log the data collection system and TPMS measurements for the selected test tire, and note that this tire pressure sensor failed to identify a "slow leak" within the 3-minute requirement. Then, reopen the air release valve and continue to deflate the tire at 1 psi per minute until either a "slow leak" warning activates or a "low tire pressure" warning activates. Do not reduce the pressure of the selected test tire below an ultimate lower pressure level equal to 3 psi below the preset lower tire pressure warning level. Close the air release valve if any warnings activate.
        i. If the TPMS fails to activate either of these two prescribed warnings before reaching the ultimate lower pressure level, close the air release valve – note that the system failed to sense a "slow leak" and failed to sense "low tire pressure" on this tire pressure sensor. Log the data collection system and TPMS measurements, and then go to "re-inflate the tire."
        ii. If the TPMS did NOT identify the "slow leak" condition in the selected test tire, but did identify a low tire pressure level before reaching the ultimate

lower pressure level, close the air release valve – note that the system failed to sense a “slow leak,” but did sense “low tire pressure” on this tire pressure sensor. Log the data collection system and TPMS measurements, and then go to “re-inflate the tire.”

iii. If the TPMS correctly identifies the “slow leak” condition, but not until after the 3-minute leak down period has expired, close the air release valve – note that the system succeeded in sensing a “slow leak,” but required longer than 3 minutes to activate a “slow leak” warning at the pressure leak rate of 1 psi per minute. Log the data collection system and TPMS measurements, and then go to “re-inflate the tire.”

8. “Re-inflate the tire” to the original CIP. Note if any TPMS warnings remain active after the tire has been re-inflated. Log the data collection system and TPMS measurements.
   a. If any TPMS warnings are still active, log the time required between the beginning of tire re-inflate and the moment of TPMS warning cancellation. Log the data collection system and TPMS measurements. End the test.
   b. If no TPMS warnings are still active, note when all TPMS warnings cleared. Log the data collection system and TPMS measurements. End the test.

12.6. Appendix F – Test Pressure allowance Summary on Truck with SmartWave TPMS

Table F.1. Test Pressure Allowance Summary –Truck with SmartWave TPMS

Peterbilt 8A										
	LF		RF		LII		RRO		Multiple	
Date	setpoint	allowance	setpoint	allowance	setpoint	allowance	setpoint	allowance	setpoint	allowance
6/17/2008	-10%	-2 psi								
6/19/2008	-20%	-2 psi	-10%	-2 psi						
6/23/2008			-20%	-2 psi	-10%	-2 psi				
6/24/2008							-10%	-2 psi		
6/24/2008					-20%	-3 psi	-20%	-3 psi		
6/25/2008							-25%	-2 psi		
6/26/2008	-25%	-2 psi	-25%	-2 psi						
6/30/2008					-25%	-3 psi				
7/2/2008			-20 & -25%	-3 psi						
Peterbilt 8B										
7/8/2008	-12%	-3 psi	-12%	-3 psi						
7/9/2008					-12%	-3 psi				
7/10/2008							-12%	-3 psi		
7/16/2008									-12%	-3 psi

Notes:
1. All tests through 6/23/08 used -2 psi allowance adjustment.
2. Tests 6/24/08-6/26/08 experimentally compared allowances of -2 or -3psi.
3. All following tests (beginning Monday 6/30/08) used only -3 psi allowance adjustment.
4. This allowance adjustment only affects data for the first truck (Pete) using the SmartWave TPMS.

12.7. Appendix G – Expanded Temperature Compensation Charts

Table G.1. SmartWave Temperature Compensation Chart for Truck Tests

SmarTire Temperature Compensation Chart

Pete VR8		Steer Tires							Drive Tires						
°F		for 130 psi							for 105 psi						
		pressure	-10%	-10% -3psi	-20%	-20% -3psi	-25%	-25% -3psi	pressure	-10%	-10% -3psi	-20%	-20% -3psi	-25%	-25% -3psi
61	-0.04	129	116	113	103	100	97	94	104	94	91	83	80	78	75
63	-0.02	129	116	113	104	101	97	94	105	94	91	84	81	78	75
65	0.00	130	117	114	104	101	98	95	105	95	92	84	81	79	76
67	0.02	131	118	115	104	101	98	95	105	95	92	84	81	79	76
69	0.04	131	118	115	105	102	98	95	106	95	92	85	82	79	76
71	0.06	132	119	116	105	102	99	96	106	96	93	85	82	80	77
73	0.08	132	119	116	106	103	99	96	107	96	93	85	82	80	77
75	0.10	133	120	117	106	103	100	97	107	97	94	86	83	80	77
77	0.12	133	120	117	107	104	100	97	108	97	94	86	83	81	78
79	0.14	134	121	118	107	104	100	97	108	97	94	87	84	81	78
81	0.16	134	121	118	108	105	101	98	109	98	95	87	84	82	79
83	0.18	135	122	119	108	105	101	98	109	98	95	87	84	82	79
85	0.20	136	122	119	108	105	102	99	110	99	96	88	85	82	79
87	0.22	136	123	120	109	106	102	99	110	99	96	88	85	83	80
89	0.24	137	123	120	109	106	103	100	111	99	96	88	85	83	80
91	0.26	137	124	121	110	107	103	100	111	100	97	89	86	83	80
93	0.28	138	124	121	110	107	103	100	111	100	97	89	86	84	81
95	0.30	138	125	122	111	108	104	101	112	101	98	90	87	84	81
97	0.32	139	125	122	111	108	104	101	112	101	98	90	87	84	81
99	0.34	140	126	123	112	109	105	102	113	102	99	90	87	85	82
101	0.36	140	126	123	112	109	105	102	113	102	99	91	88	85	82
103	0.38	141	127	124	113	110	105	102	114	102	99	91	88	85	82
105	0.40	141	127	124	113	110	106	103	114	103	100	91	88	86	83
107	0.42	142	128	125	113	110	106	103	115	103	100	92	89	86	83
109	0.44	142	128	125	114	111	107	104	115	104	101	92	89	86	83
111	0.46	143	129	126	114	111	107	104	116	104	101	92	89	87	84
113	0.48	143	129	126	115	112	108	105	116	104	101	93	90	87	84
115	0.50	144	130	127	115	112	108	105	117	105	102	93	90	87	84
117	0.52	145	130	127	116	113	108	105	117	105	102	94	91	88	85
119	0.54	145	131	128	116	113	109	106	117	106	103	94	91	88	85
121	0.56	146	131	128	117	114	109	106	118	106	103	94	91	88	85
123	0.58	146	132	129	117	114	110	107	118	107	104	95	92	89	86
125	0.60	147	132	129	117	114	110	107	119	107	104	95	92	89	86
127	0.62	147	133	130	118	115	111	108	119	107	104	95	92	89	86
129	0.64	148	133	130	118	115	111	108	120	108	105	96	93	90	87
131	0.66	148	134	131	119	116	111	108	120	108	105	96	93	90	87
133	0.68	149	134	131	119	116	112	109	121	109	106	97	94	90	87
135	0.70	150	135	132	120	117	112	109	121	109	106	97	94	91	88
137	0.72	150	135	132	120	117	113	110	122	109	106	97	94	91	88
139	0.74	151	136	133	121	118	113	110	122	110	107	98	95	92	89
141	0.76	151	136	133	121	118	113	110	122	110	107	98	95	92	89
143	0.78	152	137	134	121	118	114	111	123	111	108	98	95	92	89
145	0.80	152	137	134	122	119	114	111	123	111	108	99	96	93	90
147	0.82	153	138	135	122	119	115	112	124	111	108	99	96	93	90
149	0.84	154	138	135	123	120	115	112	124	112	109	99	96	93	90
151	0.86	154	139	136	123	120	116	113	125	112	109	100	97	94	91
153	0.88	155	139	136	124	121	116	113	125	113	110	100	97	94	91
155	0.90	155	140	137	124	121	116	113	126	113	110	101	98	94	91
157	0.92	156	140	137	125	122	117	114	126	114	111	101	98	95	92
159	0.94	156	141	138	125	122	117	114	127	114	111	101	98	95	92
161	0.96	157	141	138	126	123	118	115	127	114	111	102	99	95	92
163	0.98	157	142	139	126	123	118	115	128	115	112	102	99	96	93
165	1.00	158	142	139	126	123	119	116	128	115	112	102	99	96	93

'Note: yellow bar is baseline pressures at SmarTire Standard Temperature of 65° F.

Table G.2. SmartWave Temperature Compensation Chart for Tractor Tests

SmarTire Temperature Compensation Chart

Volvo VR5		Steer Tires							Drive Tires						
°F		for 105 psi							for 100 psi						
		pressure	-10%	-10% -3psi	-20%	-20% -3psi	-25%	-25% -3psi	pressure	-10%	-10% -3psi	-20%	-20% -3psi	-25%	-25% -3psi
61	-0.04	104	94	91	83	80	78	75	99	89	86	79	76	74	71
63	-0.02	105	94	91	84	81	78	75	100	90	87	80	77	75	72
65	0.00	105	95	92	84	81	79	76	100	90	87	80	77	75	72
67	0.02	105	95	92	84	81	79	76	100	90	87	80	77	75	72
69	0.04	106	95	92	85	82	79	76	101	91	88	81	78	76	73
71	0.06	106	96	93	85	82	80	77	101	91	88	81	78	76	73
73	0.08	107	96	93	85	82	80	77	102	92	89	81	78	76	73
75	0.10	107	97	94	86	83	80	77	102	92	89	82	79	77	74
77	0.12	108	97	94	86	83	81	78	103	92	89	82	79	77	74
79	0.14	108	97	94	87	84	81	78	103	93	90	82	79	77	74
81	0.16	109	98	95	87	84	82	79	104	93	90	83	80	78	75
83	0.18	109	98	95	87	84	82	79	104	94	91	83	80	78	75
85	0.20	110	99	96	88	85	82	79	104	94	91	84	81	78	75
87	0.22	110	99	96	88	85	83	80	105	94	91	84	81	79	76
89	0.24	111	99	96	88	85	83	80	105	95	92	84	81	79	76
91	0.26	111	100	97	89	86	83	80	106	95	92	85	82	79	76
93	0.28	111	100	97	89	86	84	81	106	96	93	85	82	80	77
95	0.30	112	101	98	90	87	84	81	107	96	93	85	82	80	77
97	0.32	112	101	98	90	87	84	81	107	96	93	86	83	80	77
99	0.34	113	102	99	90	87	85	82	107	97	94	86	83	81	78
101	0.36	113	102	99	91	88	85	82	108	97	94	86	83	81	78
103	0.38	114	102	99	91	88	85	82	108	98	95	87	84	81	78
105	0.40	114	103	100	91	88	86	83	109	98	95	87	84	82	79
107	0.42	115	103	100	92	89	86	83	109	98	95	87	84	82	79
109	0.44	115	104	101	92	89	86	83	110	99	96	88	85	82	79
111	0.46	116	104	101	92	89	87	84	110	99	96	88	85	83	80
113	0.48	116	104	101	93	90	87	84	111	100	97	88	85	83	80
115	0.50	117	105	102	93	90	87	84	111	100	97	89	86	83	80
117	0.52	117	105	102	94	91	88	85	111	100	97	89	86	84	81
119	0.54	117	106	103	94	91	88	85	112	101	98	90	87	84	81
121	0.56	118	106	103	94	91	88	85	112	101	98	90	87	84	81
123	0.58	118	107	104	95	92	89	86	113	101	98	90	87	85	82
125	0.60	119	107	104	95	92	89	86	113	102	99	91	88	85	82
127	0.62	119	107	104	95	92	89	86	114	102	99	91	88	85	82
129	0.64	120	108	105	96	93	90	87	114	103	100	91	88	86	83
131	0.66	120	108	105	96	93	90	87	115	103	100	92	89	86	83
133	0.68	121	109	106	97	94	90	87	115	103	100	92	89	86	83
135	0.70	121	109	106	97	94	91	88	115	104	101	92	89	87	84
137	0.72	122	109	106	97	94	91	88	116	104	101	93	90	87	84
139	0.74	122	110	107	98	95	92	89	116	105	102	93	90	87	84
141	0.76	122	110	107	98	95	92	89	117	105	102	93	90	88	85
143	0.78	123	111	108	98	95	92	89	117	105	102	94	91	88	85
145	0.80	123	111	108	99	96	93	90	118	106	103	94	91	88	85
147	0.82	124	111	108	99	96	93	90	118	106	103	94	91	89	86
149	0.84	124	112	109	99	96	93	90	118	107	104	95	92	89	86
151	0.86	125	112	109	100	97	94	91	119	107	104	95	92	89	86
153	0.88	125	113	110	100	97	94	91	119	107	104	95	92	90	87
155	0.90	126	113	110	101	98	94	91	120	108	105	96	93	90	87
157	0.92	126	114	111	101	98	95	92	120	108	105	96	93	90	87
159	0.94	127	114	111	101	98	95	92	121	109	106	97	94	91	88
161	0.96	127	114	111	102	99	95	92	121	109	106	97	94	91	88
163	0.98	128	115	112	102	99	96	93	122	109	106	97	94	91	88
165	1.00	128	115	112	102	99	96	93	122	110	107	98	95	92	89

'Note: yellow bar is baseline pressures at SmarTire Standard Temperature of 65° F.

12.8. Appendix H – Temperature Sensitivity Test Using SmartWave TPMS With and Without Temperature Compensation – Tractor Tests Only

After moving the SmartWave system to the tractor, a procedure to set more stable test pressures was sought. Therefore, this experiment did not seek to identify the temperature sensitivity of the TPMS sensors while in a fully configured system, as only the SmartWave system used temperature compensation (and the other four TPMS did not). Rather, it sought to streamline the low tire pressure detection test procedure without the compounding issue of temperature sensitivity. Identification of sensor temperature sensitivity needs to be isolated from pressure sensing capability by this low pressure detection test procedure. A second test may need to be run using either fixed pressures and the tires subjected to a heating and cooling cycle, or the tires may 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 the vehicle to detect the level where the TPMS would signal a low tire pressure alert.

A brief study was performed to attempt to determine the low pressure detection sensitivity of a TPMS to variations in calibration procedure and temperature-compensation application. The tests were performed on the SmartWave TPMS when it was installed on the tractor. The data compared were obtained from the left front (LF) tire sensor during actual performance tests (Table H.1).

Three calibration/temperature-compensation combinations were applied for each of the two low pressure detection setpoints. In configuration No. 1 (Config-1), high temperature tests were used for both the calibrations and for the low pressure detection tests, along with a temperature-compensated test pressure. In the second configuration (Config-2), a “cool” calibration was followed by a hot tire low pressure detection test and the test pressures were set using temperature compensation (however, the TPMS activated the low-pressure alarm within seconds of completion of power-on lamp check; therefore, the tractor was not driven during the detection tests). For the third configuration (Config-3) parameters duplicated those in Config-2 with the exception that no temperature compensation was used for the test pressures applied).

A baseline comparison of the initial measurements showed that the probe ambient temperatures ranged 1 to 4°F below the data collection system ambient temperatures, the probe tire temperatures ranged 2 below to 4°F above the probe ambient temperatures, the TPMS tire temperatures ranged 0 to 8°F above the probe tire temperatures (all within the 10°F accuracy of the measuring devices), and the TPMS tire pressures were within +/- 1-percent of the reference data collection system tire pressures.

After the calibration tests, the tire temperatures were typically higher than the initial ambient temperatures. The tire probe temperatures averaged 85°F for the hot calibrations (Config-1), and 68 and 76°F for the two “cool” calibration tests (Configs-1 and 2). The average TPMS tire temperature change from ambient was 17°F for the “hot” calibration and 3°F for the “cool” calibration.

Table H.1. Low Pressure Detection Sensitivity to Varied Calibration Run Time and Speed

	TPMS - Calibration and Temperature Compensation Applications	**Original** Test Procedure- Hot Calibration Run **With** Temperature Compensated Pressure	Test Procedure Modification 1- Cool Calibration Run **With** Temperature Compensated Pressure	Test Procedure Modification 1- Cool Calibration Run **Without** Temperature Compensated Pressure	**Original** Test Procedure Hot Calibration Run **With** Temperature Compensated Pressure	Test Procedure Modification 1- Cool Calibration Run **With** Temperature Compensated Pressure	Test Procedure Modification 1- Cool Calibration Run **Without** Temperature Compensated Pressure
		Setpoint 1			Setpoint 2		
	Tire Position	LF	LF	LF	LF	LF	LF
	CIP	105	105	105	105	105	105
Initial	CDAS Ambient Temperature (°F)	69	70	71	73	69	73
	Probe Ambient Temperature (°F)	68	67	68	69	65	71
	TPMS Tire Temperature (°F)	69	73	71	80	68	77
	Probe Tire Temperature (°F)	69	67	69	73	64	69
	TPMS Tire Pressure (psi)	105	105	106	106	105	105
	CDAS Tire Pressure (psi)	106	105	106	107	105	105
After Cal. Run - Before Adjustment	CDAS Ambient Temperature (°F)	69	61	70	72	61	73
	Probe Ambient Temperature (°F)	65	66	69	69	67	71
	TPMS Tire Temperature (°F)	86	71	73	91	71	77
	Probe Tire Temperature (°F)	83	67	75	87	69	77
	TPMS Tire Pressure (psi)	111	105	107	110	106	106
	CDAS Tire Pressure (psi)	112	105	107	112	106	107
	Setpoint Pressure (psi) or Delta (%)	-10%	-10%	-10%	-20%	-20%	-20%
	Target 'Test Pressure (psi)	96	93	92	85	82	81
	CDAS Applied Pressure (psi)	96	93	92	85	82	81
	TPMS Corresponding Pressure (psi)	95	92	90	84	82	81

Table H.1. - Continued

	TPMS - Calibration and Temperature Compensation Applications	**Original** Test Procedure-Hot Calibration Run **with** temperature compensated Pressure	Test Procedure Modification 1-Cool Calibration Run **with** temperature compensated Pressure	Test Procedure Modification 1-Cool Calibration Run **without** temperature compensated Pressure	**Original** Test Procedure Hot Calibration Run **with** temperature compensated Pressure	Test Procedure Modification 1-Cool Calibration Run **with** temperature compensated Pressure	Test Procedure Modification 1-Cool Calibration Run **without** temperature compensated Pressure
		Setpoint 1			Setpoint 2		
	Tire Position	LF	LF	LF	LF	LF	LF
Alarm-Warning Status	Alarm	Low Deviation	Low Deviation	Low Deviation	Critical Low Pressure	Critical Low Pressure	Critical Low Pressure
	Detection Status	alarm before driving	alarm before driving	alarm before driving	alarm before driving	alarm before driving	alarm before driving
	ET from end of TPMS Lamp Check to alarm	2 sec.	2 sec.	2 sec.	3 sec.	2 sec.	2 sec.
Before Re-inflation	CDAS Ambient Temperature (°F) Before Re-inflation	72	67	73	73	69	75
	Probe Ambient Temperature (°F) Before Re-inflation	70	66	71	71	67	73
	Probe Tire Temperature (°F) Before Re-inflation	75	67	72	73	69	73
	CDAS Tire Pressure (psi) Before Re-inflation	92	93	92	83	82	81
After Re-inflation	CDAS Ambient Temperature (°F) After Re-inflation	72	68	73	72	70	75
	Probe Ambient Temperature (°F) After Re-inflation	70	63	71	71	68	73
	TPMS Tire Temperature (°F)	80	69	77	84	73	80
	Probe Tire Temperature (°F)	75	65	75	73	68	73
	TPMS Pressure (psi) After Re-inflation	106	104	104	105	105	108
	CDAS Pressure (psi) After Re-inflation	106	105	106	106	104	108
	Cleared Alarm After Cool Down and Before Driving	YES	YES	YES	YES	YES	YES

12.9. Appendix I - Comparison of Hot versus Cool Calibration Driving Times, Steady-State Speeds, and Distances Traveled

The drive time, nominal steady-state speed, and the road course driven for the TPMS Calibration Tests (run prior to the detection tests) are summarized in Tables I.1 through I.3. Data for each TPMS system A through E was analyzed for the four tires tested individually, which included the left front (LF), right front (RF), left intermediate inner (LII), and the right rear outer (RRO) tire locations. The results were categorized into tan cells of the tables. Some of the tests were repeated due to a discontinuity in data collection files or unexpected time delays encountered during the performance of the test. The gray "not tested" cells indicate where repeat tests were not run.

The left half of each table contains the total time driven (in minutes) for each calibration run, with the average for each system given in the blue cell (a row average). The right half of each table lists the nominal steady speed in miles per hour for each calibration run. The average time for each system is shown in the blue cells. The top half of each table lists values for the straight truck which used the longer, faster "hot" calibration runs. The bottom half of each table lists the values for the tractor which utilized the slow speed shorter calibration runs. Table I.1 refers to Setpoint No. 1 test pressures for both vehicles. Table I.2 refers to the Setpoint No. 2 test pressure data, again for both vehicles. The abbreviated Table I.3 lists the drive times and speeds for a third test pressure, but repeated the same Setpoint No. 2 TPMS setting, and was limited to performance testing only on the truck. The last column in each sub-table shows the course where the calibration was run.

Overall the average speeds were about 63 mph for the truck and 26 mph for the tractor. Driving time averages were 12 minutes for the truck and about 8 minutes for the tractor.

Table I.1. Test Pressure 1 at Setpoint 1

Calibration Test - Drive Time (min.) - Setpoint 1 - Test Pressure 1- Truck

VR8 Straight Truck	LF (min.)	LF Retest (min.)	RF (min.)	LII (min.)	RRO (min.)	RRO Repeat (min.)	Multi (min.)	System Average Cal.-drive Time (min.)	Calibration Loop Where?
SmartWave Dana S14486 [A]	11.53	not tested	12.80	10.87	11.15	not tested	not tested	11.59	HSTT
Tire-SafeGuard HCI Corp TPM-W210 [B]	11.67	not tested	10.60	10.82	11.48	12.23	11.00	11.30	HSTT
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	11.63	not tested	13.25	11.72	11.45	not tested	not tested	12.01	HSTT
WABCO/Michelin IVTM G8960 [D]	11.18	not tested	11.92	11.28	11.05	not tested	12.47	11.58	HSTT
PressurePro Advantage CU41807684 [E]	11.83	not tested	11.68	12.55	11.50	not tested	10.98	11.71	HSTT
							Truck Average	11.61	

Calibration Test - Nominal Steady Speed (mph) - Setpoint 1- Test Pressure 1- Truck

VR8 Straight Truck	LF (mph.)	LF Retest (mph.)	RF (mph.)	LII (mph.)	RRO (mph.)	RRO Repeat (mph.)	Multi (mph.)	System Average (mph.)	Calibration Loop
SmartWave Dana S14486 [A]	64	not tested	62	62	61	not tested	not tested	62	HSTT
Tire-SafeGuard HCI Corp TPM-W210 [B]	63	not tested	62	63	62	63	62	63	HSTT
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	63	not tested	62	62	62	not tested	not tested	62	HSTT
WABCO/Michelin IVTM G8960 [D]	64	not tested	63	63	63	not tested	60	63	HSTT
PressurePro Advantage CU41807684 [E]	63	not tested	63	62	64	not tested	63	63	HSTT
							Truck Average	63	

Calibration Test - Drive Time (min.) - Setpoint 1 - Test Pressure 1- Tractor

VR5 6 x 4 Tractor	LF (min.)	LF Retest (min.)	RF (min.)	LII (min.)	RRO (min.)	RRO Repeat (min.)	Multi (min.)	System Average Cal.-drive Time (min.)	Calibration Loop Where?
SmartWave Dana S14486 [A]	7.15	not tested	8.93	8.57	7.38	not tested	6.98	7.80	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-W210 [B]	7.88	not tested	7.55	7.30	7.55	not tested	6.97	7.45	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	7.45	not tested	6.93	6.88	14.67	not tested	7.12	8.61	Short 2 mile course
WABCO/Michelin IVTM G8960 [D]	7.05	not tested	10.25	7.97	9.10	not tested	6.85	8.24	Short 2 mile course
PressurePro Advantage CU41807684 [E]	7.10	not tested	7.23	7.00	6.67	not tested	6.78	6.96	Short 2 mile course
							Tractor Average	7.81	

Calibration Test - Nominal Steady Speed (mph) - Setpoint 1- Test Pressure 1- Tractor

VR8 Straight Truck	LF (mph.)	LF Retest (mph.)	RF (mph.)	LII (mph.)	RRO (mph.)	RRO Repeat (mph.)	Multi (mph.)	System Average (mph.)	Calibration Loop
SmartWave Dana S14486 [A]	27	not tested	19	24	27	not tested	27	25	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-W210 [B]	24	not tested	26	24	25	not tested	26	25	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	26	not tested	26	27	26	not tested	27	26	Short 2 mile course
WABCO/Michelin IVTM G8960 [D]	27	not tested	27	26	27	not tested	26	27	Short 2 mile course
PressurePro Advantage CU41807684 [E]	26	not tested	27	26	27	not tested	27	27	Short 2 mile course
							Tractor Average	26	

Table I.2. Test Pressure 2 at Setpoint 2

Calibration Test - Drive Time (min.) - Setpoint 2 - Test Pressure 2- Truck

VR8 Straight Truck	LF (min.)	LF Retest (min.)	RF (min.)	LII (min.)	RRO (min.)	RRO Repeat (min.)	Multi (min.)	System Average Cal.-drive Time (min.)	Calibration Loop Where?
SmartWave Dana S14486 [A]	10.80	not tested	12.83	10.98	10.53	not tested	11.97	11.42	HSTT
Tire-SafeGuard HCI Corp TPM-W210 [B]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	not tested	not tested	not tested	not tested	11.42	not tested	not tested	11.42	HSTT
WABCO/Michelin IVTM G8960 [D]	13.02	14.63	11.15	11.47	11.27	not tested	11.93	12.24	HSTT
PressurePro Advantage CU41807684 [E]	11.68	not tested	12.37	11.90	11.18	not tested	not tested	11.78	HSTT
							Truck Average	11.82	

Calibration Test - Nominal Steady Speed (mph) - Setpoint 2- Test Pressure 2- Truck

VR8 Straight Truck	LF (mph.)	LF Retest (mph.)	RF (mph.)	LII (mph.)	RRO (mph.)	RRO Repeat (mph.)	Multi (mph.)	System Average (mph.)	Calibration Loop
SmartWave Dana S14486 [A]	64	not tested	62	62	62	not tested	63	63	HSTT
Tire-SafeGuard HCI Corp TPM-W210 [B]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	not tested	not tested	not tested	not tested	62	not tested	not tested	62	HSTT
WABCO/Michelin IVTM G8960 [D]	63	60	63	63	63	not tested	63	63	HSTT
PressurePro Advantage CU41807684 [E]	63	not tested	64	64	63	not tested	not tested	64	HSTT
							Truck Average	63	

Calibration Test - Drive Time (min.) - Setpoint 2 - Test Pressure 2- Tractor

VR5 6 x 4 Tractor	LF (min.)	LF Retest (min.)	RF (min.)	LII (min.)	RRO (min.)	RRO Repeat (min.)	Multi (min.)	System Average Cal.-drive Time (min.)	Calibration Loop Where?
SmartWave Dana S14486 [A]	7.03	not tested	8.20	7.73	7.58	not tested	7.7	7.65	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-W210 [B]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
WABCO/Michelin IVTM G8960 [D]	7.13	not tested	6.97	7.17	6.85	not tested	6.85	6.99	Short 2 mile course
PressurePro Advantage CU41807684 [E]	6.85	not tested	6.63	6.70	6.33	not tested	6.87	6.68	Short 2 mile course
							Tractor Average	7.11	

Calibration Test - Nominal Steady Speed (mph) - Setpoint 2- Test Pressure 2- Tractor

VR8 Straight Truck	LF (mph.)	LF Retest (mph.)	RF (mph.)	LII (mph.)	RRO (mph.)	RRO Repeat (mph.)	Multi (mph.)	System Average (mph.)	Calibration Loop
SmartWave Dana S14486 [A]	27	not tested	22	27	26	not tested	28	26	Short 2 mile course
Tire-SafeGuard HCI Corp TPM-W210 [B]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
Tire-SafeGuard HCI Corp TPM-P310B1 [C]	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested	not tested
WABCO/Michelin IVTM G8960 [D]	27	not tested	26	26	27	not tested	26	26	Short 2 mile course
PressurePro Advantage CU41807684 [E]	26	not tested	27	26	26	not tested	27	26	Short 2 mile course
							Tractor Average	26	

Table I.3. Test Pressure 3 at Setpoint 2

Calibration Test - Drive Time (min.) - Setpoint 2 - Test Pressure 3- Truck

VR8 Straight Truck	LF (min.)	LF Retest (min.)	RF (min.)	LII (min.)	RRO (min.)	RRO Repeat (min.)	Multi (min.)	System Average Cal.-drive Time (min.)	Calibration Loop Where?
SmartWave Dana S14486 [A]	10.80	not tested	12.83	10.98	10.53	not tested	not tested	11.29	HSTT
							Truck Average	11.29	

Calibration Test - Nominal Steady Speed (mph) - Setpoint 2- Test Pressure 3- Truck

VR8 Straight Truck	LF (mph.)	LF Retest (mph.)	RF (mph.)	LII (mph.)	RRO (mph.)	RRO Repeat (mph.)	Multi (mph.)	System Average (mph.)	Calibration Loop
SmartWave Dana S14486 [A]	62	not tested	61	62	62	not tested	not tested	62	HSTT
							Truck Average	62	

DOT HS 811 314
June 2010

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