Tire Pressure Monitoring and Maintenance Systems Performance Report

Task Order 8 of the
Commercial Vehicle Safety Technology Diagnostics
and Performance Enhancement Program

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

January 2007

Foreword

This project is one of several performed under the provisions of Section 5117 of the Transportation Equity Act of the 21st Century (TEA-21). The primary objective of this project was to explore the performance of commercial vehicle tire pressure monitoring and maintenance systems. The work performed under the project included:

- Conducting a market study to identify and select commercially available tire pressure monitoring and maintenance systems for testing.
- Developing a test matrix and test procedures to profile the performance and operation of the selected systems.
- Installing selected systems on representative tractor-trailer and motorcoach test vehicles, along with a robust instrumentation system for collecting and recording test data.
- Performing testing on a high-speed test track.
- Analyzing test data.
- Presenting research findings at a public forum.
- Developing a report detailing the results of the data analysis, observations, and conclusions (this document).

The study focused on commercially available tire pressure monitoring and maintenance systems. This information should prove useful to motor carriers in evaluating the capabilities and limitations of these systems. The findings should also be helpful to the systems' manufacturers and suppliers. This is the final report of the study performed under Task Order 8 of a multi-task research contract and does not supersede an earlier report on the subject.

Notice

Technical Report Documentation Page

1. Report No. FMCSA-PSV-07-001	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Tire Pressure Monitoring and Maintenance Systems Performance Report	5. Report Date January 2007 6. Performing Organization Code
7. Author(s) Stephen Brady, Brian Nicosia, Robert Kreeb (Booz Allen Hamilton), Peggy Fisher Fleet Tire Consulting	8. Performing Organization Report No.
9. Performing Organization Name and Address Booz Allen Hamilton Inc., McLean, VA Fleet Tire Consulting, Rochester Hills, MI	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-99-C-00025, Task Order 8
12. Sponsoring Agency Name and Address Federal Motor Carrier Safety Administration (FMCSA) Office of Bus and Truck Standards and Operations (MC-PSV) 400 7th Street, SW Washington, DC 20590-0001	13. Type of Report and Period Covered Final Project Report 14. Sponsoring Agency Code FMCSA

15. Supplementary Notes
Contracting Officer’s Technical Representative: Deborah M. Freund

16. Abstract
The overall objective of this research is to document the performance and operational characteristics of leading-edge technological approaches for monitoring and maintaining commercial vehicle tire pressures. Previous work sponsored by the Federal Motor Carrier Safety Administration (FMCSA) has documented the effects of improper tire inflation on both safety and direct operating costs. Improper tire inflation leads to accelerated tire wear (which subsequently leads to compromised braking, poor handling, and reduced stability), increased fuel consumption, increased propensity for catastrophic tire failures (blowouts), increased dangerous roadside debris, and increased road calls to repair deflated tires. In addition, FMCSA’s research has shown that despite these well-understood consequences, many fleets do not practice or enforce adequate tire maintenance practices—mostly because checking and maintaining proper inflation is a time-consuming, inconvenient chore. As a result, fleet operators are often unaware of tire pressure issues with their vehicles.

Tire pressure monitoring and inflation systems provide a means for greatly simplifying the task of checking and maintaining tire pressure. However, there is significant product diversity in the marketplace in terms of tire inflation and monitoring system design and technological approach. Further, the performance, accuracy, and overall adequacy of these systems has not been well documented in a controlled and systematic fashion.

This study focuses on testing and documenting the overall performance of a representative sample of commercial tire inflation and monitoring products. The study presents a technical examination of the accuracy, responsiveness, resolution, and reliability of the various tire pressure inflation and monitoring systems. This knowledge should prove useful to fleet operators in evaluating the capabilities and limitations of alternative approaches to tire pressure monitoring and maintenance, and may be helpful in determining specifications for future truck purchases. The information should also be useful to tire pressure maintenance and monitoring system suppliers and commercial vehicle manufacturers that are developing new tire pressure monitoring systems. To this extent, the objectives for the study include providing fundamental research results to industry stakeholders concerning various means of monitoring tire pressure.

17. Key Word Central Inflation Systems, Dual Tire Equalizers, Tire Pressure Monitoring Systems	18. Distribution Statement No restrictions

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 132	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

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

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

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ABSTRACT

The overall objective of this research is to document the performance and operational characteristics of leading-edge technological approaches for monitoring and maintaining commercial vehicle tire pressures. Previous work sponsored by the Federal Motor Carrier Safety Administration (FMCSA) has documented the effects of improper tire inflation on both safety and direct operating costs. Improper tire inflation leads to accelerated tire wear (which subsequently leads to compromised braking, poor handling, and reduced stability), increased fuel consumption, increased propensity for catastrophic tire failures (blowouts), increased dangerous roadside debris, and increased road calls to repair deflated tires. In addition, FMCSA's research has shown that despite these well-understood consequences, many fleets do not practice or enforce adequate tire maintenance practices—mostly because checking and maintaining proper inflation is a time-consuming, inconvenient chore. As a result, fleet operators are often unaware of tire pressure issues with their vehicles.

Tire pressure monitoring and inflation systems provide a means for greatly simplifying the task of checking and maintaining tire pressure. However, there is significant product diversity in the marketplace in terms of tire inflation and monitoring system design and technological approach. Further, the performance, accuracy, and overall adequacy of these systems have not been well documented in a controlled and systematic fashion.

This study focuses on testing and documenting the overall performance of a representative sample of commercial tire inflation and monitoring products. The study presents a technical examination of the accuracy, responsiveness, resolution, and reliability of the various tire pressure inflation and monitoring systems. This knowledge should prove useful to fleet operators in evaluating the capabilities and limitations of alternative approaches to tire pressure monitoring and maintenance, and may be helpful in determining specifications for future truck purchases. The information should also be useful to tire pressure maintenance and monitoring system suppliers and commercial vehicle manufacturers that are developing new tire pressure monitoring systems. To this extent, this study's objectives include providing fundamental research results to industry stakeholders concerning various means of monitoring tire pressure.

EXECUTIVE SUMMARY

Project Funding

Under Section 5117 of the Transportation Equity Act for the 21st Century of 1998 (TEA-21), Congress required the U.S. Department of Transportation (USDOT) to "conduct research on the deployment of a system of advanced sensors and signal processors in trucks and tractor trailers to determine axle and wheel alignment, monitor collision alarm, check tire pressure and tire balance conditions, measure and detect load distribution in the vehicle, and adjust automatic braking systems." The research program responding to this directive is called the Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program (CV Sensor Study Program).

This study was completed as a task under the CV Sensor Study Program.

Background and Rationale

Early research work sponsored by the Federal Motor Carrier Safety Administration (FMCSA) indicates that a significant portion of fleet operators do not regularly perform tire pressure maintenance to the standards recommended by tire manufacturers.[1] For example, FMCSA research has shown that:

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

Commercial vehicle tire inflation and condition directly link to stopping distance and handling, and thus overall safety. Properly maintained and performing tires aid drivers in preventing and mitigating crash situations. Properly inflated tires could help prevent or mitigate crashes even when the tires are not the initial cause of the crash. Eliminating or mitigating key mechanical

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[1] Federal Motor Carrier Safety Administration, *Commercial Vehicle Tire Condition Sensors*, United States Department of Transportation, Washington, DC, 2003.

problems, including tire issues, would likely yield a significant reduction in the number and severity of injuries sustained in commercial vehicle-related crashes.

To address these issues, numerous types of tire pressure monitoring and inflation systems have emerged in the marketplace over the last decade. However, the market penetration of tire pressure maintenance equipment has remained comparatively low. Tire pressure monitoring and inflation systems provide a means for simplifying the task of checking and maintaining tire pressure. However, there is significant product diversity in the marketplace in terms of tire inflation and monitoring system design and technological approach. Further, the performance, accuracy, and overall adequacy of these systems have not been well documented in a controlled and systematic fashion.

Study Objective

The overall objective of this research study is to document the performance, accuracy, and operational characteristics of leading-edge technological approaches to commercial vehicle tire pressure monitoring and maintenance systems (TPMS). The study focuses on the ability of the various sensors to present accurate tire pressure readings, to detect slow and rapid changes in tire pressure, and to maintain tire pressure under adverse conditions including partial failure of the device. The study examines the following TPMS technology categories:

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

Equipping a commercial motor vehicle (CMV) with sensors and transmitters to accurately and reliably measure the pressure in each tire could offer the following benefits:

- Warn the driver and/or maintenance personnel if tire pressure drops to an unsafe level—and help with diagnosis of the problem
- Provide information to enforcement personnel for use during roadside inspections
- Reduce tire wear and increase service life
- Alert the driver to a catastrophic failure of a tire, as sometimes there is little feedback to the driver by noise or vibration during operation (e.g., a trailer tire failure)

Systems that automatically (or continuously) maintain tire inflation pressure might offer even more benefits such as increased fuel economy—provided they had a high level of reliability, were easy to maintain, and were considered "affordable."

Overview of Project Approach

The study team installed a variety of tire pressure monitoring and automatic inflation systems (collectively described as tire pressure management systems, or TPMS) on a conventional tractor-trailer combination vehicle and on a motorcoach. The team tested both vehicles under controlled conditions on a test track at the Transportation Research Center (TRC) in Columbus, OH. This approach facilitated objective, accurate comparisons of the systems, and eliminated problems associated with the repeatability of the test procedures when comparing different systems.

In addition, the team contacted and interviewed numerous industry stakeholders during the study. These stakeholders included suppliers of the various technologies examined, who assisted the team in compiling information about the various TPMS technologies and their market penetration. The team used this information in recommending the systems for assessment. The stakeholders also assisted in developing the test program and the test procedures. The companies and individuals contacted provided information that was compiled in this report.

Summary of Results

The following are key observations and results from the testing of the sensor technologies.

Dual Tire Equalizers

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

The team installed dual tire equalizers from two different manufacturers on the tractor-trailer test platform. The following are some key observations and conclusions related to dual tire equalizers:

- Dual tire equalizers are effective in balancing the pressures between the two tires. The equalization technologies function as designed under both static and dynamic conditions.
- Both systems prevented the total loss of pressure in one or both tires in every failure mode implemented.
- The two equalization systems were effective in isolating an intact tire from the adjacent tire with an artificially induced major air loss.
- A disablement test, where a hose was cut to simulate damage from road debris, produces a total loss of air from one tire in a dual installation, while the other tire was protected by a check valve.
- Both equalizer systems included a visual indicator that can provide a gross indication of tire pressure. They provide an indication that the tire pressure is or is not within its target range. However, if the pressure falls below this range, they only show a “low” pressure condition and do not indicate the extent of under-inflation.

- While the indicators provide a good visual indication of tire pressure, they can be difficult to read as they are mounted on the wheel and can become obscured by dirt.

Tire Pressure Monitoring Systems

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

The study team tested five different tire pressure monitoring systems for this project. These included one tire-mounted, two valve-stem-mounted, and two wheel-mounted tire pressure monitoring systems. The following are some key observations and conclusions on the TPMS technology.

General TPMS Observations

- In general, each valve-, wheel-, or tire-mounted system tested exhibited base-level functionality as specified by the manufacturer of the individual systems.
- The tire pressure monitoring systems tested were generally accurate to within 2 to 3 psi from the values measured by the calibrated test instrumentation pressure measurement transducers.
- Low-pressure warning thresholds are "factory set" on some systems, but user-configurable on others. For those systems with factory settings, different warning levels ranging from 12 to 25 percent below target pressure were observed. All systems tested were generally within a 2- to 3-psi range of the expected warning threshold (whether set at the factory or by the user).
- Many of the TPMS tested used RF communications to transmit data between the sensors and the display unit or ECU. The relatively long length of typical CMVs means that additional on-board antennas are required for some of the systems to receive the sensor signals from trailer or tag axle tires. Disconnected or damaged antennas can lead to signal loss from the sensors.

Valve-Stem-Mounted TPMS Observations

- Typically, valve-stem-mounted tire pressure monitoring systems do not compensate for increases in tire pressure as a result of increased tire temperature from high-speed driving. However, one valve-stem-mounted system tested in this study did include temperature compensation.
- One of the systems tested initiated a warning when the pressure fell below a preset value (~20 percent below target); however, the warning remained active until the tire was inflated to a higher value (~15 percent below target). This pressure band between the alarm pressure and alarm deactivation pressure prevents intermittent warnings to the driver.

- Valve-stem-mounted systems are susceptible to loss because they have to be removed during wheel mounting and dismounting for vehicle maintenance and inspection. Their relative ease of removal could also make them susceptible to theft.

Wheel-Mounted TPMS Observations

- The study team's understanding from a review of product literature was that wheel-mounted technology included temperature compensation, and typically provided the best performance in correcting for tire temperature. However, during the high-speed testing, both wheel-mounted systems tested had their active warnings disabled when the pressure increased in the tire as a result of increased tire temperature. This occurred intermittently between the various test runs on different axles, although the test data suggests that the systems were able to compensate for large increases in tire temperature (greater than 20 degrees F) a majority of the time, but smaller increases with corresponding pressure increases were not compensated for. This could result in increasing tire temperatures preventing a low-pressure warning.
- The team discovered during the TPMS installations that the wheel-mounted technologies may be vulnerable to damage during tire mounting/demounting.

Tire-Mounted TPMS Observations

- The tire-mounted technology tested included temperature compensation, which, when read by the handheld reader, displayed both the temperature-corrected pressure and the uncorrected pressure at ambient tire temperature.
- The tire-mounted technology tested required the use of handheld or gate reader devices to inspect tires (no in-cab display was provided with the systems). However, the system was unique among those tested in that it included an Internet-based tire maintenance and tracking database application hosted by the system manufacturer.
- For the tire-mounted units, the gate reader clearances were very tight and required very slow vehicle speeds, less than 5 mph.

Central Inflation Systems

Constant central tire inflation systems (CIS) use the air from the vehicle's air compressor that is stored in the air brake reservoirs (tanks) to maintain tire pressure at a desired level. The CIS are plumbed to the vehicle's secondary reservoir that supplies air to the front brakes. The CIS do not take air from the primary reservoir that supplies air for the rear brakes, which are responsible for the majority of the braking power of the CMV. These systems are either plumbed through the axle, or externally through the use of a rotary union at the wheel hub. They automatically sense the tire pressures and inflate the tires when air is lost. The benefits of these systems are the elimination of manual tire pressure checks and the ability to continue operating the vehicle with minor air leaks in the tires.

CIS are available for all types of CMVs. In this test, one system was tested on the motorcoach and one was tested on the trailer of a tractor-trailer. The following are key observations and conclusions regarding CIS.

Central Inflation System Observations

- The tested CIS generally perform as designed and specified by the manufacturer. The systems performed well in both static and dynamic conditions.
- In the testing involving leak rates, the motorcoach CIS was able to keep up with leak rates up to 5 to 8 psi/min. Ultimately, this system's performance was limited by the vehicle's air compressor duty cycle and the compressed air supply and storage system design.
- The CIS tested on the trailer could maintain adequate tire pressure with slow leakage rates (less than 1.0 psi/min), but would not maintain adequate tire pressure for higher leakage rates. This system appeared to be limited by its rate of air flow to the tires more than by a limitation of the on-board compressor and air system.
- During testing with heavy braking and simultaneous tire leaks, the vehicles' primary and secondary air reservoir pressures remained above the level required for safe brake operation. The compressor had no difficulty recharging the reservoirs without having to run continuously.
- Both CIS tested protected the intact tires from deflating when a catastrophic air leak was simulated in one of the other tires in the system. In this regard, the systems functioned in a manner similar to the dual tire equalizers isolation circuits.

Summary of General System Performance and Test Observations

Observations and conclusions about brake system performance and testing are as follows:

- Vehicle air systems are not optimized to support a CIS with very high leakage rates; therefore, the functionality of the CIS is often limited by the vehicle's air system. Additionally, there may be some long-term impact to the CMV's air system when subjected to a high leakage rate from the secondary reservoir, which the CIS utilizes for its supply air. These leak rates would cause an increase in the duty cycle of the compressor, and would increase maintenance requirements and decrease compressor service life.
- Installation time for systems vary. In general, valve-stem-mounted TPMS and dual tire equalizers were less time consuming to install (generally, several hours), followed by wheel-mounted TPMS, tire-mounted TPMS, and CIS that require up to a full day for installation.
- Temperature compensation in TPMS requires further refinement. During high-speed driving, the warning indicators actuated intermittently on some systems as tire temperatures increased. The effect of increased temperature deactivating low-pressure alarms could prevent the system from alerting a driver to a low-pressure condition.

Recommended Future Research

This project has provided comprehensive baseline assessments of a variety of state-of-the-practice tire pressure monitoring and inflation systems. These assessments were performed under controlled test track conditions. Between test sequences, the study team checked and recalibrated the various sensors and systems as needed. In the "real world" of CMV operations, inspection and maintenance are generally performed at much longer intervals—for CMVs operating in interstate commerce, the mandatory periodic inspection interval is 12 months. Furthermore, the useful operating life of a heavy-duty truck or motorcoach can be 10 to 12 years or longer, and the operating environment is much more severe than on the test track. Therefore, there is a need to subject tire pressure monitoring and maintenance sensors and systems to the rigors of operation that a CMV would experience during the course of revenue service.

FMCSA-sponsored field operational tests (FOT) involving the use of a transit bus fleet and a commercial trucking fleet are currently underway. This study should provide useful information on longer-term utility, reliability, and maintainability.

CHAPTER 1. INTRODUCTION

This chapter provides information on the following:

- Background on the Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program (CV Sensor Study Program)
- Background and rationale for this research project
- Current state of tire pressure technology development
- Research objectives
- Overview of process approach

1.1 Background on the CV Sensor Study Program

The purpose of the CV Sensor Study Program is to "define performance requirements, assess benefits, and accelerate deployment of driver and vehicle assistance products and systems and, in particular, advanced sensor and signal processors in trucks and tractor trailers with an emphasis in on-board diagnostic and improved safety-related products."

The program involved soliciting input from key industry stakeholders (fleet operators, manufacturers, and suppliers) on potential research initiatives that complement (rather than duplicate) efforts by private industry. Objectives of the research include evaluating the probable impact of selected vehicle technologies on improving overall trucking safety, and assessing their cost savings potential and/or operational benefits—thus helping to create market demand and encourage commercialization.

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

- An extensive literature search of relevant technical journals and databases
- Individual interviews and discussions with representatives from truck and trailer manufacturers, fleet operators, owner operators, and industry suppliers, as well as staff at the National Highway Traffic Safety Administration (NHTSA), FMCSA, and Federal Highway Administration (FHWA) who are involved in commercial vehicle safety research
- A meeting of key industry stakeholders to review candidate research areas and make suggestions regarding future work under the CV Sensor Study Program

As a result of this background research and interviews, the team identified the following candidate research areas:

- Brakes and related controls
- Tire inflation and condition monitoring systems
- Truck and tractor alignment ("dynamic alignment")
- Testing and analysis of high-speed data bus networks (J1939)
- Cost, benefits, and implementation issues
- "Active suspensions" and other systems related to event data recorder suspension

- Advanced vehicle diagnostic and prognostic tools
- Issues related to implementation of "Smart Copilot" on-board systems

This list was meant to be a "work in process" and to direct research. Project team members continue to monitor and assess new technologies that could improve vehicle safety, and to engage industry in discussions regarding the appropriateness of specific research projects.

The focus of this research effort is on the tire inflation and condition monitoring systems research area.

1.2 Background and Rationale for This Research Effort

TPMS technologies show significant promise for improving safety and reducing costs in the commercial vehicle industry. Improving tire pressure management directly relates to improved vehicle stability, reduced tire wear and damage, better braking, improved fuel efficiency, and fewer roadside breakdowns—thus enhanced safety. Overall, improving tire pressure maintenance and general tire management can impact carrier productivity.

FMCSA, in a prior task under the CV Sensor Study Program contract, completed a comprehensive survey of the tire pressure maintenance practices by fleets and owner operators. This prior study included a market assessment of TPMS available at the time and developed high-level cost-benefit analyses of TPMS based on preliminary estimates of the systems' effectiveness for improving the tire maintenance practice of various type of fleets. This previous research work indicates that a significant portion of motor carriers and other commercial vehicle fleet operators do not regularly perform tire pressure maintenance to the standards recommended by tire manufacturers. Improper inflation increases total tire-related costs by an estimated $600 to $800 annually per tractor-trailer combination. [2] At the time the study was completed, diesel fuel cost approximately $1.50 per gallon.

Many of the TPMS on the market today average between $1,000 to $1,500 per tractor-trailer. The conservative assumptions made in the 2003 study estimated a payback period for many fleets is likely less than 2 years—and almost certainly less than 3 years for most fleets. Despite this analysis, the market penetration rate of tire pressure maintenance equipment has remained comparatively low in the intervening period—fewer than 3 percent of for-hire fleets use tire pressure monitoring technology in regular operations. While the negative consequences of poor tire maintenance appear to be generally understood, there has been a lack of objective, accurate, independently conducted real-world test data concerning the effectiveness of current and emerging technologies focused on improving and simplifying tire pressure maintenance.

1.3 Current State of Tire Pressure Technology Development

Over the past decade, there has been significant investment by equipment suppliers serving the commercial vehicle market in tire pressure monitoring and inflation systems. New products have

[2] Federal Motor Carrier Safety Administration, *Commercial Vehicle Tire Condition Sensors*, Report # FMCSA-PSV-04-002, United States Department of Transportation, Washington, DC, 2003.

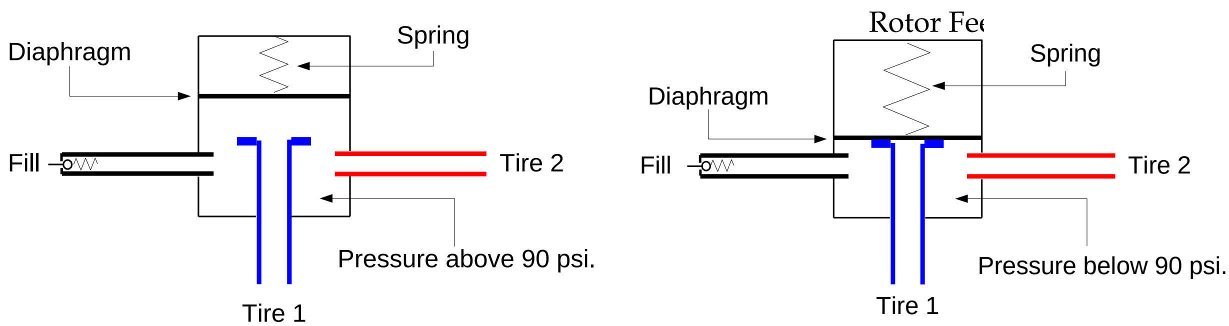
been introduced, other products have been refined, and (according to informal interviews with fleets) the development efforts of these companies have intensified. This section explores the current state of tire pressure monitoring and maintenance technology development.

1.3.1 Dual Tire Pressure Equalizers

Tire pressure equalizers are designed to balance the pressure between the two tires of a dual assembly. Equalizing the tire pressure reduces irregular tire wear and heat build up and decreases rolling resistance, which improves fuel economy. By reducing the number of tire airing points, they also reduce the time needed to check and maintain tire pressure. Most systems also include a visual indicator to provide a means for pressure monitoring.

Tire pressure equalizer systems balance pressure in dual tire configurations by allowing air to transfer between tires. Two hoses are plumbed to a check valve at one end and to the valve stems of each tire at the other. The check valve is mechanically bolted to the hub of the outer wheel. The valve opens to allow airflow between the tires, but closes and shuts the air off if there is an instantaneous air loss in either tire, which prevents both tires from going flat. In a slow leak situation, the valve isolates (i.e., closes) both tires after a pressure drop of approximately 10 psi. Exhibit 1.1 displays a simplified drawing of a dual tire equalizer with the equalizing valve in the open position and in the closed or isolating position. A spring and diaphragm assembly provides the equalizer's functionality. The pressure level that causes the valve to close to isolate the tires is set by the pressure required to push the diaphragm off the valve seat of one of the tire lines. In the example in Exhibit 1.1, the equalization pressure is 90 psi or greater.

Exhibit 1.1 – Dual Tire Equalizer Diagram



Because these devices have a central valve to serve both tires in the dual assembly, they eliminate the need to check and add air to each tire separately. These systems also provide a visual pressure indicator that is visible to a driver during a pre-trip inspection. They generally do not provide numerical inflation pressures, rather they provide different types of go/no-go gauges that can indicate whether the tires are under-inflated, over-inflated, or at the correct pressure. This display feature is the primary difference between these systems and tire pressure monitoring systems.

A problem with tire pressure equalizers, as reported by the informal interviews conducted with fleets as part of the 2003 study, is that the accuracy of the valves deteriorate as the internal diaphragms wear after a year or two. Hose breakage is also a relatively high maintenance item.

1.3.2 Tire Pressure Monitoring Systems

There are several types of tire pressure monitors. These systems can be categorized into the following types:

- Valve-stem-mounted tire pressure monitors
- Wheel-mounted tire pressure monitors
- Tire-mounted tire pressure monitors

These systems monitor tire pressure through a device that senses the pressure and forwards an RF signal to a display unit. Displays may be mounted inside the tractor cab, attached externally on the tractor or a handheld off-board reader can be used. Some of these systems also monitor temperature and convert the actual hot tire pressure to cold pressure so that meaningful data is related to the user (i.e., temperature compensation is included). Exhibit 1.2 shows a typical tractor trailer installation of a wheel-mounted tire pressure monitoring system.

Exhibit 1.2 – Example Wheel-Mounted Tire Pressure Monitoring System

1.3.3 Tire Pressure Maintenance Systems

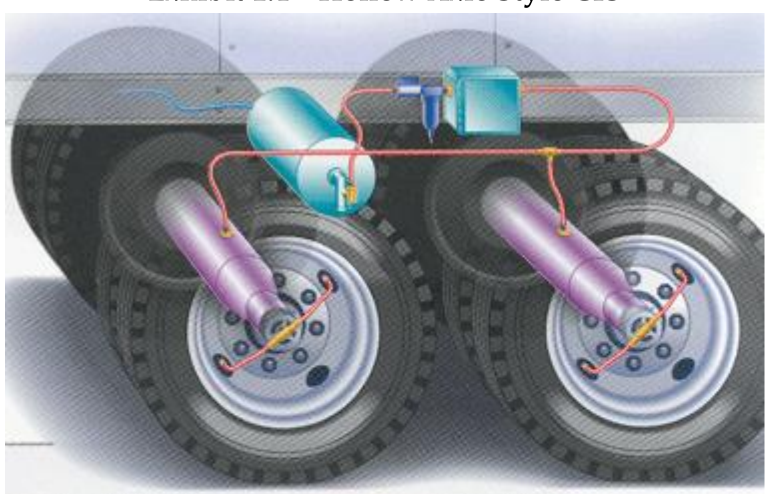
There are basically two types of tire inflation systems. The first type uses air from the vehicle's air system to inflate the tires. These systems are generally referred to as central tire inflation systems. The second type uses a pump that is separate from the vehicle's air system to generate air. These systems are referred to as continuous tire pressure pumps.

Central tire inflation systems use the air stored in the vehicle's air brake wet tanks to supply air to the tires. Manufacturers of such systems use one of two general approaches for filling the tires with air during dynamic conditions (while the tires are rotating). Both approaches rely on the use of a rotating slip ring/seal arrangement. The Gio-Set Vigia, shown in Exhibit 1.3, uses an air-filled rotary union mounted externally on the center of the wheel hub.

Exhibit 1.3 – Rotary Union Style CIS

An alternative approach, used by Arvin Meritor, uses the axle to deliver air to the wheel with the rotary union located in the hubcap at each wheel end, as shown in Exhibit 1.4.

Exhibit 1.4 – Hollow Axle Style CIS



Central tire inflations systems can supply air to the tires either on demand via a manual request by the driver, or automatically triggered through sensors that monitor tire pressure. Central tire inflation systems can be broken down into two types—constant and variable.

Constant central tire inflation systems maintain tire pressure at a single preset level. They eliminate the need to check tire pressure manually and allow a vehicle to remain in service despite small air leaks in one or more of its tires. Constant tire inflation systems require no involvement from the driver. They automatically sense the pressure in the tires and inflate as necessary when the tires lose air. A drawback to these systems is that the external hoses or air supply tubes can get damaged and render the systems ineffective, and may even allow tires to deflate suddenly. Also, the slip ring seal that allows air to enter the rotating hub through the axle can become worn over time. An additional drawback is that a slow leak, such as from a nail hole through the tread, could go undetected because the inflation system effectively “masks” the problem. Over time, the presence of the foreign object could lead to tread separation.

Variable central tire inflation systems are designed to raise or lower tire pressures during vehicle operation to compensate for varying load and road conditions, in addition to maintaining tire pressure. These systems allow interaction from the driver such as changing the tire pressure on demand. They are usually used for on-off road operations such as logging, construction, mining, gravel hauling, concrete, exploration, and military. The costs of these systems tend to be higher than for tire pressure maintenance systems.

1.3.4 Other Systems and Technologies

In response to the Firestone tire recall of 2000, new and innovative systems and technologies are being explored to address the problem of tire failures. Some of these technologies do not fit the general category of tire pressure monitors, but do address detection of tire failures. Appendix A provides a listing of several new TPMS and tire failure monitoring technologies.

1.4 Research Objectives

The primary objective of this research study was to document the performance and operational characteristics of leading-edge commercial vehicle TPMS.

This study focused on examining the ability of various TPMS to detect tire pressure, temperature (for the purpose of converting to cold pressure readings), and air leakage rates under a variety of test conditions and in a controlled test track environment. The study team examined inflation systems under dynamic conditions for their ability to maintain tire pressure under various simulated leak conditions, as well as performing selected failure mode tests of the systems. The study also included a limited review of driver acceptance issues associated with the various systems, and of reliability and maintenance issues. The purpose of the test was to assess the relative performance of different types of tire pressure monitoring and maintenance technologies, rather than to compare various manufacturers’ products.

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

The following sections describe the specific objectives and questions addressed by the study.

1.4.1 Dual Tire Pressure Equalizers

The dual tire pressure equalizer research objectives for the program were to:

- Validate that pressure is equalized between the two tires if pressure drops in one tire.
- Determine the time to equalize pressure under various test conditions.

- Validate that the "isolating" valve will engage to protect the other (non-leaking) tire if one tire experiences significant pressure loss. Also, measure the pressure threshold that the isolation valve engages.
- Determine what happens when one hose is not attached to a valve stem (simulating a cut hose).
- Determine whether both tires can be inflated through the central valve stem.
- Determine whether the indicator shows changes due to pressure loss (i.e., was there a visual indication?).
- Observe the effects of weather (ambient temperature) on performance.
- Determine whether the system works when the vehicle is parked as well as when it is in motion.

1.4.2 Tire Pressure Monitoring Systems

The tire pressure monitoring system research objectives for the program were to:

- Determine at what pressure change an alert is sent to the in-cab monitor.
- Determine the accuracy of the pressure monitor display (display readings versus actual readings), and the ability to display the correct wheel position and pressure on demand.
- Determine whether the signal from the trailer can consistently reach the tractor's display.
- Test the handheld reader for its accuracy and ability to read pressures. Determine the maximum distance between the handheld reader and the tire transmitter that allows data to be read.
- Determine what happens when the valve stem is bent or the sensor is otherwise damaged.
- Determine what happens if the sensor is removed or falls off the valve stem.
- Observe the effects of the environment, such as temperature and rain, on performance.
- Determine whether audio and visual display alerts are sufficient to notify drivers (e.g., loud enough, bright enough).
- Determine whether the system advises the driver of failed sensors, missing sensors, or sensors that are operating with depleted batteries.
- Determine whether the systems work when the vehicle is parked as well as when it is in motion.
- For systems using gate readers, test to determine the maximum speed the signals from all wheel positions can be accurately sensed by the gate reader. Test the percentage and consistency of the reads.
- Determine the system's response to the sensors separating from the valve, wheel, or tire.

1.4.3 Tire Pressure Maintenance Systems

The tire pressure maintenance system research objectives for the program were to:

- Determine at what pressure the indicator light on the trailer is illuminated to signal air delivery to trailer tires, and at what pressure the driver is alerted (via the in-cab display) if tractor tires are being filled.
- Determine the system's ability to correct low inflation conditions.
- Determine what happens when an air line is not connected to the valve stem (simulate cut hose).
- Determine whether pressure is equalized between both tires if pressure drops in one tire.
- Determine at what pressure the bypass valve closes to protect an intact tire if another tire suffers a rapid air loss.
- Determine whether the pressure in the brake system is maintained during a "catastrophic" air loss situation in a tire.
- Observe the effects of ambient air temperature on performance.
- Determine whether the system works when parked as well as when in motion.

1.5 Overview of Experimental Approach

The team installed the various tire pressure monitoring and inflation systems in a planned sequence on two types of commercial motor vehicles—first, on a conventional tractor-trailer, and then on a motorcoach—and tested them under controlled operating conditions on a test track. All work was conducted at the TRC in Columbus, OH. The study team considered installing all of the sensor systems on the vehicle at the same time, and then conducting each test (simulated leaks, failure modes, etc.) in sequence. Such an arrangement would have ensured that all of the TPMS were examined under identical conditions. However, such an arrangement was not feasible. For example, two RF systems cannot be operated side by side at the same time because of the possibility of interference between the two systems. Similarly, it is not possible to connect and test two equalizing systems on the same wheel end at the same time due to lack of space and the inability to determine which system was influencing the pressure in the tires. Fortunately, technicians and engineers at TRC have considerable experience with conducting tests under consistent and repeatable conditions and the test conditions for all "runs" in the test matrix were tightly controlled.

The team recorded data from the TPMS using an on-board, PC-based data-logging system capable of recording digital, analog, and discrete sensor outputs. (This system is described in more detail in Chapter 3.) The team then processed the data off-board using conventional database and engineering analysis software.

CHAPTER 2. DESCRIPTION OF TESTED SYSTEMS

The study team selected representative products from within the three categories of TPMS (tire equalization, tire pressure monitoring, and automatic inflation) for testing, as shown in Exhibit 2.1. Tested products included two dual tire equalizers, four tire pressure monitoring systems, and two tire pressure maintenance systems (central inflation systems only since hub-mounted tire pressure pumps are currently unavailable). The selected systems represented a reasonable cross-section of technological approaches to tire pressure monitoring and inflation. All systems tested are commercially available, and none were prototypes.

Exhibit 2.1 – Selected Systems for Testing

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

The following is a brief explanation for including each of these systems in the test plan:

- Cat's Eye (Link Manufacturing, Ltd.) is a dual-tire equalizer with a visual inflation condition reading at the wheel end.
- Tire-Knight-S (V-Tech International, Inc.) is a uniquely designed dual-tire equalizer system. The Tire-Knight-S has separate valves and chambers for inflating and checking each tire separately.
- PressurePro (Advantage PressurePro) is a representative valve-stem-mounted tire pressure monitor using an in-cab display.

- Integrated Vehicle Tire Pressure Monitoring, or IVTM, system (Meritor WABCO) is a valve-stem-mounted tire pressure monitor developed cooperatively between Michelin and Meritor WABCO for commercial vehicles.
- Tire-SafeGuard (HCI Corporation) is a representative wheel-mounted tire pressure monitor with in-cab display.
- SmarTire (SmarTire Systems, Inc.) produces a wheel-mounted tire pressure monitoring systems for light-duty vehicles. They have recently launched a similar system for commercial vehicles and are marketing it through original equipment manufacturers (OEMs).
- eTire (Michelin North America) is a passive tag, tire-mounted pressure monitoring system. Unlike the other monitoring systems, it does not have an in-cab display but uses a gate reader and/or handheld reader to read the tire pressures.
- PSI Tire Inflation System (Arvin Meritor) is a representative central tire inflation system for trailers.
- Vigia (Geo-Set Corporation) is new to the North American market but has been used for many years in Central and South America. The system is unique in that it can be installed on both non-drive and drive axles.

The project team recommended testing each of these systems on the proposed platforms in Exhibit 2.1, as they presented a good combination of representative systems and emerging technologies for the commercial vehicle industry. The following sections briefly describe each of the selected systems.

2.1 Dual Tire Equalizers

Link Manufacturing, Ltd. produces the ***Cat's Eye Tire Pressure Maintenance System***[3] shown in Exhibit 2.2. A solid yellow indication on the air valve indicates that the tire pressure is +/- 2 percent of the recommended inflation level. As the pressure drops, a vertical black line, the "Cat's Eye," appears in the center of the display. As pressure drops further, the line widens until an all-black display indicates that tire pressure is approximately 10 psi below the specified level. The display is factory set for a specific pressure and is non-adjustable. This system currently costs about $50 an axle end to the end-user with rubber hoses, and $60 an axle end with stainless steel hoses. The company has been marketing the Cat's Eye Tire Pressure Maintenance System since 1990, and estimates that it has sold 125,000 units to date. It now sells approximately 30,000 annually.

[3]Link Manufacturing, Ltd., 223 15th Street, N.E., Sioux Center, IA 51250-2120, (800) 222-6283, Pat Coghlan, National Sales Director, www.linkmfg.com.

Exhibit 2.2 – Link Cat's Eye TPMS Dual-Tire Equalizer

V-Tech International, Inc. produces the ***Tire-Knight-S*** for dual-truck tires.[4] It is similar to the Link system described above and to other equalizer systems, using a check valve assembly mounted on the wheel with hoses attached to the valve stems of both dual tires. Exhibit 2.3 displays the V-Tech Tire-Knight-S Equalizer system. However, in the Tire-Knight-S system, each tire is connected to its own chamber and has its own valve for individual inflating and pressure checking in the unit. A bypass connects and equalizes the pressure in both tires when a piston opens or closes the bypass. (The piston is the only moving part in the unit.) The piston opens the bypass if both tires have a pressure greater than 85 to 90 psi. The piston closes the bypass if one tire experiences a sudden and catastrophic air loss, if one hose is unhooked or cut, or if both tires have a pressure of less than 80 to 85 psi. The position of the piston can be checked at a glance. In the event of an air loss in one tire of a pair of duals, the system configured as tested would not indicate which is leaking. V-Tech stated it has sold about 100 to 200 units in the Wisconsin area, including some to a major truckload motor carrier headquartered in that state. The retail price per unit is $80, or $640 for 16 positions.

Exhibit 2.3 – V-Tech Tire-Knight-S Dual-Tire Equalizer

[4]V-Tech International, Inc., 227 Barbie Drive, West Bend, WI 53090, (262) 306-1708, Gottfried Hoffmann, President, www.vtechint.com

2.2 Tire Pressure Monitors

Advantage PressurePro LLC markets ***PressurePro*** (formerly known as Tire Mate).[5] The company began its entry into the tire pressure monitor market in 1992 with a device called Tire Mate, which fits over the valve stem like a valve cap and transmits an RF signal indicating the tire pressure.

The company's current product is called PressurePro. It is approximately 1 inch in diameter and ¾ inch in length, weighs 0.25 ounce, is completely sealed, and fits over the valve stem. Exhibit 2.4 displays the Advantage PressurePro TPMS valve-stem-mounted unit and display console. There is no RF "cross-talk" between systems on adjacent wheels as each sensor signal is uniquely identified by its own serial code. The sensors check tire pressure every 15 seconds. The PressurePro system can monitor 1 to 34 tires with pressure from 10 to 150 psi. The target pressure is set at the current tire pressure at the time of installation of the sensor on the valve stem.

The receiver/monitor is battery operated. The monitor is 6 inches wide x 3 inches tall and 0.5 inch thick, and weighs just under 8 ounces. When tire pressure drops below the low trigger pressure set by the user, the monitor triggers an alert that displays tire location, low pressure reading, and battery power in the sensor. An audio and visual alert comes on when a tire is 10 percent below target pressure, and a more aggressive alert identifies a tire that is 20 percent below. The driver can scroll through the display to check all tires on demand as well. The battery life in the valve-stem sensors is expected to be 5 years in automobiles, 3 to 3.5 years in RV applications, and 2 years on commercial trucks. The life of the battery is dependent upon mileage since the sensor is activated by tire rotation. The RF signals from the trailer tires are linked to the tractor receiver with a relay box that fits on the front of the trailer and sends an RF signal to the cab.

Alternatively, a handheld receiver called the PressurePro Wand can read sensors within one foot of the tire. A gate reader will be added to the product line as well. PressurePro is currently being field tested. The company has 600 units installed on a variety of commercial vehicles. The cost for an 18-wheel, tractor-trailer combination will be around $1,075 for the sensors and on-board receiver. Between 35,000 and 40,000 Tire Mate units have been sold, primarily to the RV industry and owner-operators. Advantage estimates that about 600 to 800 of the new PressurePro systems are operating on commercial vehicles at this time.

[5] Advantage Pressure Pro LLC, Inc., 205 Wall Street, Harrisonville, MO 64701, (800) 959-3505, Phil Zaroor, President, www.advantagepressurepro.com

Exhibit 2.4 – Advantage PressurePro TPMS

Meritor WABCO and **Michelin** developed the ***WABCO Integrated Vehicle Tire Pressure Monitoring (IVTM) System*** for commercial vehicles.[6] The IVTM system was launched in 2003; no unit sales numbers are available at this time. Each tire and wheel assembly is equipped with a wheel module that is attached to the outside of the wheel rim using two wheel bolts and nuts. It is connected to the tire valves using pneumatic hoses. Exhibit 2.5 displays the wheel-mounted module and dashboard display of the WABCO IVTM system. The system checks pressure constantly and transmits tire pressure via an RF signal every 15 minutes to the electronic control unit (ECU) if tire pressure remains in the target range, or every 30 seconds if a tire exhibits a loss of pressure variation. RF operating frequency is 433 MHz. Power is supplied from a built-in lithium battery with a 5-year service life.

The IVTM ECU is mounted on the vehicle chassis attached equidistant between the front/rear axles and contains a built-in antenna to receive the pressure data from all tires. According to the manufacturer, this location eliminates the need for additional antennas in the wheel modules themselves. Trailers are equipped with their own ECU/transmitter, which sends the tire inflation pressure RF signals to the ECU on the tractor.

The dashboard-mounted display warns the driver optically and acoustically when the inflation pressure of a tire on the tractor or trailer has decreased to a critical value. A yellow lamp indicates a slow rate of pressure loss or slight decrease in pressure; a red lamp indicates extremely low pressure. The position of any instrumented tire can be selected and its inflation pressure can be queried at the push of a button. If all tires are within an appropriate inflation pressure range, the display is blank.

[6] WABCO GmbH, Vehicle Control Systems, Am Lindener Hafen 21, D-30453, Hanover, Postfach 91 21 62, Germany, 49-511-922-2144, www.ivtm.com.

Exhibit 2.5 – WABCO Integrated Vehicle Tire Pressure Monitoring TPMS

HCI Corporation manufactures the ***Tire-SafeGuard*** tire pressure monitoring system.[7] This system alerts drivers of low-pressure situations by providing the location, temperature, and pressure readings via a display unit and an audible signal. The system has been on the market since 1991, and there are approximately 20,000 units in operation. Exhibit 2.6 displays the wheel-mounted sensor and driver's display of the Tire-SafeGuard TPMS. It monitors tire pressure continuously with detection of abnormal tire pressure even while the vehicle is parked. The Tire-SafeGuard product for commercial vehicles (TPM-S206) uses a sensor mounted on the wheel rim inside the tire. The low-pressure and temperature warning is user adjustable and has a range of 18 to 130 psi. The sensor transmitter automatically switches on when the vehicle is moving faster than 15 mph and reports pressure readings to the receiver using an RF signal. Pressure measurement accuracy is said to be +/- 1 psi. The sensor module has an operating temperature range of -40 to 250 degrees and a battery life of over 5 years. The receiver for the display can be plugged into a 12 VDC auxiliary power outlet or can be directly hardwired to the main power source. It is 3 ½ x 1 $^{1}/_{8}$ x $^{5}/_{8}$ inches in size and weighs 1.5 ounces. The cost to equip a tractor (10 positions) is $650 or $1,245 for a tractor-trailer (18 positions).

Exhibit 2.6 – HCI Tire-SafeGuard TPMS

[7] HCI Corporation, 11245 E. 183rd Street, Cerritos, CA 90703, (562) 926-7123 x 212, Tim Glassford, Sales Manager, www.tiresafeguard.com.

SmarTire Systems, Inc. [8] SmarTire's system in the marketplace at the time of this study uses RF transmission of data to monitor the air pressure and temperature in tires. A small sensor is strapped on each wheel and collects temperature and pressure data every 7 seconds. This data is transmitted via radio frequency to a receiver display located inside the vehicle that indicates individual tire pressure and temperature. Exhibit 2.7 displays the display and wheel-mounted sensor of the SmarTire system. The transmitted tire data is captured by the receiver mounted in the cab, which in turn sends the information to the display unit. The display unit allows the driver to toggle through each wheel position and to select the type of information being displayed—tire pressure, temperature, or pressure deviation. The display incorporates a bright red LED light, which is activated whenever a tire pressure irregularity is detected or when the temperature of a tire goes above a preset level. SmarTire currently sells tire-monitoring products for the RV vehicle market and for the CMV market and has had systems available on the market since 1985 (no unit sales numbers are available). These products monitor pressures up to 188 psi and accommodate up to 20 wheel positions. The cost for a motorcoach installation is $1,074 (8 positions).

Exhibit 2.7 – SmarTire TPMS

Michelin North America introduced its **eTire** system for medium-duty trucks in October 2002. [9] The eTire system uses Michelin's battery-less InTire Sensors that the manufacturer states can be applied to any commercial truck tire using sidewall-mounted "SensorDocks," which are molded rubber pieces that chemically cure to the inside of the sidewalls, similar to tire sidewall repair units. The sensor unit slips over a knob on the rubber dock and locks into place. Once installed, the sensors are designed to last throughout the entire life of the tire carcass, including retread processes. The sensor is also designed to be removable and reused on a different truck tire equipped with a new SensorDock. The sensors measure temperature and pressure on demand and communicate this information along with wheel position, and a programmable identification number for its respective tire, to drive-by and handheld readers that power the sensors. Other sensors located on the tractor and trailer provide vehicle identification information at the same time. The sensors include an RF transmitter, pressure and temperature sensors, and an antenna, which are encased in impact- and heat-resistant plastic. The unit measures 4 x 1.5 inches and

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[8] SmarTire Systems, Inc., Suite 150 – 13151 Vanier Place, Richmond, BC, Canada V6V 2J1, (604) 276-9884 x 308, John Bolegoh, Product Manager, *www.smartire.com*.
[9] Michelin North America Inc., PO Box 19011, Greenville, SC 29602, (864) 458-5476, Randy Clark, Vice President of Marketing, Truck Tire Unit, *www.michelintruck.com*.

weighs less than an ounce. Exhibit 2.8 displays the Michelin eTire TPMS system components including the sensor, handheld reader, and gate reader installation.

Unlike the other systems, e-Tire does not use an in-cab display. Instead, readings are taken when the vehicle passes a gate reader or by using a handheld reader. The vehicle must travel about 5 mph or less for the gate reader to receive the information from all the tire sensors. The sensors include a temperature compensation function. The information gathered for each fleet is reported via the Internet to a Michelin file server. The fleet accesses Michelin's BIBTRACK web site that tracks tires and provides recommended actions to be taken on tires identified that require pressure adjustment. Fleets can get up-to-date information on their tires, track tire costs, and monitor inventories around the clock by going on-line. No data is stored on the sensors themselves. The InTire Sensors do not have 360-degree read capability so the handheld reader must be positioned over the sensor to read it. Michelin places an eTire label on the outside of the tire that visually locates the sensor. Each sensor unit costs about $30, but actual fleet cost will vary based on fleet size. Handheld readers are approximately $6,000, and gate readers are approximately $10,000 to $12,000. No unit sales numbers are available.

Exhibit 2.8 – Michelin eTire TPMS

2.3 Automatic Inflation Systems

Arvin Meritor distributes **Pressure System International's (PSI's)** ***Tire Inflation System***.[10] This system currently addresses only trailer tires but the company stated that it was working on developing a system for tractors during the time the tests were conducted. Since 1994, 500,000 units have been sold, with the manufacturer reporting an average of 30,000 to 40,000 in annual

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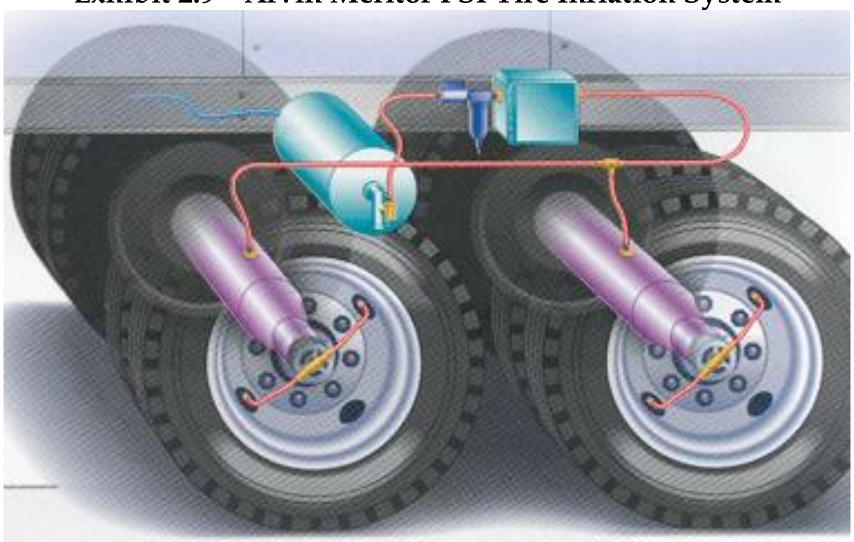
[10] Arvin Meritor Commercial Vehicle Systems, Meritor Heavy Vehicle Systems, LLC, 2135 West Maple Road, Troy, MI 48084, (800) 435-5560, *www.arvinmeritor.com*. Pressure Systems International, 3023 Interstate Drive, San Antonio, TX 78219, (210) 222-1926, Frank Sonzala, Executive Vice President.

sales. The Tire Inflation System uses compressed air from the trailer to inflate any tire that falls below pre-defined specifications. Air from the existing trailer supply tank for the air brakes is routed to a control box and then into each axle (see Exhibit 2.9). The hollow trailer axles carry the air through a rotary union assembly at the spindle end, which then distributes the air to each tire as needed. Tire pressure is constantly monitored. When a tire experiences a leak, an indicator light mounted on the trailer in a position visible by the driver's mirror comes on to signal air delivery and that tires are being inflated. A one-way check valve located in the hose connected to the valve stem protects each tire against air pressure loss. If a tire is punctured during operation and loses air pressure, the check valve prevents loss of pressure in the other tires. A pressure protection valve located between the shut-off valve and the reservoir allows air to flow to the tire inflation system only when the brakes have sufficient pressure to operate correctly. The estimated cost for this system is approximately $350 to $400.

Exhibit 2.9 – Arvin Meritor PSI Tire Inflation System



Gio-Set Corporation produces the ***Vigia Automatic Tire Pressure System*** for tractor-trailer combinations and RVs.[11] This system continuously reports and automatically regulates tire pressure. When the pressure falls 2 to 3 psi in one or more tires, the Vigia system reports the existence and location of the problem to the driver via an in-cab display. At the same time, the inflation process starts to correct the pressure loss. In case of a tire blowout, the equipment automatically shuts down to protect the operation of the other air-powered components on the vehicle such as the brakes, clutch, suspension, etc. Air pressure is supplied from the secondary air reservoir. A dedicated air filter absorbs the impurities in the air from the secondary reservoir. Once the air is filtered, it reaches the control panel and from there is redistributed to the tires (see Exhibit 2.10). A small control panel in the truck cab controls all the functions in the system. The lights indicate the normal function of the equipment, the loss of pressure in tires, the air circuit where the loss is taking place, and the low air pressure of the compressor. A separate control panel is placed on the front corner of the trailer so that the driver can readily see it. This system

[11] Gio-Set Corporation, 37 Landing, Laguna Niguel, CA 92677, (949) 412-9393, Ruben Giosa, Distributor. *www.gio-set.com.*

costs $2,300 to $3,200 depending on the axle setup for a tractor and trailer combination. The Vigia system was first marketed in 1975 in South America, and 250,000 units have been sold in 15 countries.

Exhibit 2.10 – Gio-Set Vigia Automatic Tire Pressure System

CHAPTER 3. TEST HARDWARE AND SETUP

All TPMS were installed on the test vehicles per manufacturers' recommendations and instructions. The test vehicles were also equipped with a data acquisition system and other instrumentation such as fifth-wheel sensors, thermocouples, and pressure transducers. After installation, all systems were calibrated according to the manufacturers' instructions. This chapter provides specifics on the test platform and instrumentation used to acquire, store, and analyze data for the study. TRC completed all test activities related to vehicle setup, instrumentation installation, and data acquisition setup and programming.

3.1 Test Platforms

The test vehicles were a 2001 Freightliner FLD tractor, shown in Exhibit 3.1, coupled to a 2001 Utility Trailer Manufacturing Co. 2000S tandem axle flatbed semi-trailer and a 2003 MCI motorcoach, shown in Exhibit 3.3. The flatbed trailer design provided easy loading and unloading with a forklift. Concrete blocks (4,300 pounds each) were chained to the deck of the semi-trailer to achieve an 80,000-pound maximum gross combination weight rating (GCWR). Exhibit 3.2 provides detailed specifications on the tractor and trailer. Exhibit 3.4 provides detailed specifications on the motorcoach.

Exhibit 3.1 – Tractor/Trailer Test Platform

Exhibit 3.2 – Tractor/Trailer Specification

TRACTOR		TRAILER	
Tractor Make	Freightliner FLD	Trailer Make	Utility 2000S
Model Year	2001	Model Year	2001
Transmission	Meritor 10-speed Manual	Suspension	Spring
Front Suspension	Spring	Length (feet)	48
Rear Suspension	Spring	Wheelbase (inches)	477
GVWR (pounds)	80,000		

TEST TIRES			
	Steer	**Intermediate /Rear Drive**	**Trailer**
Manufacturer	Bridgestone	Bridgestone	Bridgestone
Make/Type	R250	M726	R195
Size	295/75R22.5	295/75R22.5	295/75R22.5
Pressure (psi)	100	100	100

WEIGHT DISTRIBUTION				
	Steer Axle	**Drive Tandem**	**Trailer Axles**	**Total**
GAWR/GCWR	12,500	38,000	40,000	80,000
Loaded w/Trailer	11,950	33,640	34,030	79,620
Empty w/Trailer	11,410	13,280	8,920	33,610
Bobtail	11,210	8,350	N/A	19,560

Exhibit 3.3 – Motorcoach Test Platform

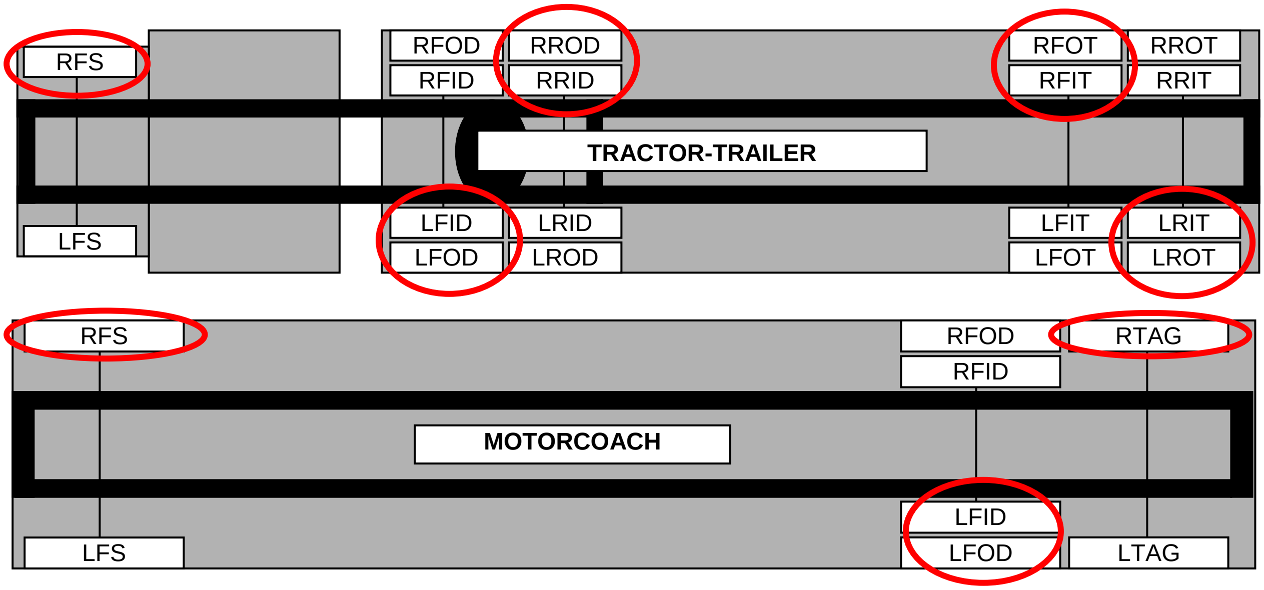
Exhibit 3.4 – Motorcoach Specification

MOTORCOACH				
Coach Make/Model	MCI/102EL3 E-Coach			
Model Year	2001			
Transmission	Alison 5-speed Automatic			
Front Suspension	Air			
Rear Suspension	Air			
GVWR (pounds)	50,000			
TEST TIRES				
	Steer	**Drive**	**Tag**	
Manufacturer	Bridgestone	Bridgestone	Bridgestone	
Make/Type	R296	R296	R296	
Size	315/80R22.5	315/80R22.5	315/80R22.5	
Pressure (psi)	110	110	105	
WEIGHT DISTRIBUTION				
	Steer Axle	**Drive**	**Tag Axles**	**Total**
GAWR/GVWR	15,900	19,240	14,520	49,660

3.2 Test Instrumentation Installation

To acquire highly accurate pressure and temperature measurements (i.e., to establish "ground truth" against which readings from the various test article could be compared), laboratory grade sensors were installed at each test wheel position. This required removing the wheels, machining replacement wheels for mounting thermocouples and pressure taps, and routing wire bundles to the data acquisition system (DAS) mounted in the cab of the truck and motorcoach. Exhibit 3.5 shows a diagram of a tractor-trailer and motorcoach and illustrates the installation location of each of the instrumentation packages.

Exhibit 3.5 – Instrumentation Locations



Reference	Location	Reference	Location
LFS	Left front steer	LFOT	Left front outer trailer
RFS	Right front steer	LFIT	Left front inner trailer
LFOD	Left front outer drive	RFIT	Right front inner trailer
LFID	Left front inner drive	RFOT	Right front outer trailer
RFID	Right front inner drive	LROT	Left rear outer trailer
RFOD	Right front outer drive	LRIT	Left rear inner trailer
LROD	Left rear outer drive	RRIT	Right rear inner trailer
LRID	Left rear inner drive	RROT	Right rear outer trailer
RRID	Right rear inner drive	RTAG	Right tag axle
RROD	Right rear outer drive	LTAG	Left tag axle

Test equipment consisted of:

- Internal tire temperature thermocouples (9, analog)
- Tire pressure transducers (2, analog)
- Custom dual-flow combination rotary union and slip ring assemblies (5)
- Custom pressure control manifold (1)
- Primary and secondary brake reservoir and treadle valve pressure transducer (3, analog)
- Digital marker switch (for indicating when a warning was observed) (1, analog)
- Non-contact fifth wheel (1, digital)
- DAS (1)

The following sections briefly describe this equipment.

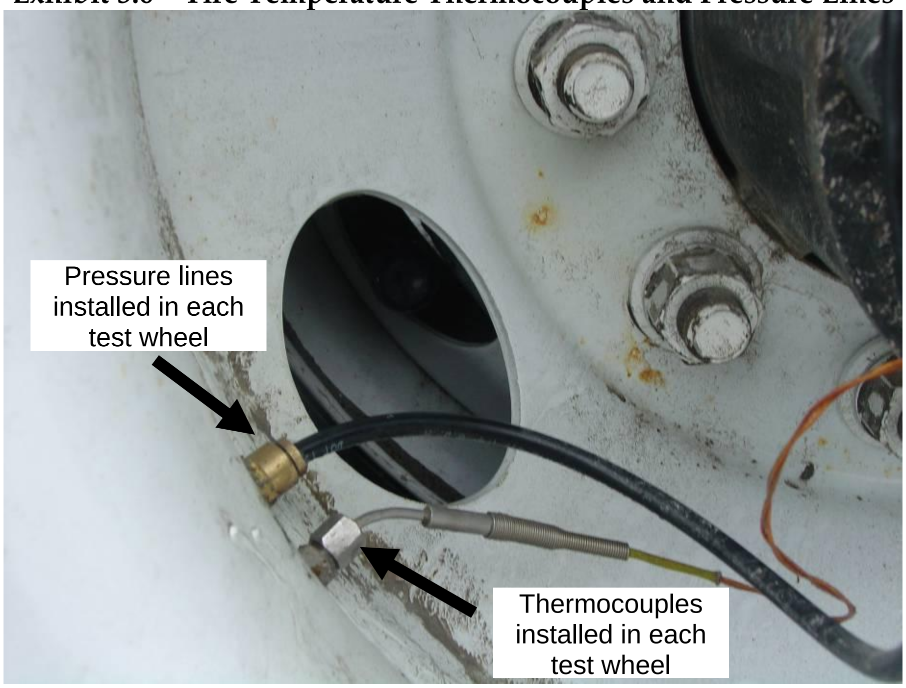
3.2.1 Thermocouples

Type J thermocouples, with a range of -200 to 320 degrees Fahrenheit, were installed in each of the test wheels (9 wheels for the tractor-trailer and 4 wheels for the motorcoach) as shown in

Exhibit 3.6. The thermocouples were used to assist in evaluating the systems, particularly understanding the effects of increased tire pressure as a result of heating due to sustained high-speed driving. Additionally, the thermocouples provided a temperature reference to evaluate the performance of the systems under both normal and high-temperature conditions and to provide insight to the conditions in the tires during testing.

This approach involved attaching the slip ring/rotary union assembly to the center of each instrumented wheel. A thermocouple was attached to the slip ring and fed into the wheel using a threaded connection separate from the normal valve stem. The voltage levels from the slip rings were fed into the data acquisition system.

Exhibit 3.6 – Tire Temperature Thermocouples and Pressure Lines



3.2.2 Tire Pressure Transducers

To perform the analysis, it was necessary to continuously monitor internal tire pressure in tires under test using a reference transducer at a data rate of 10 Hz. Pressure transducers, displayed in Exhibit 3.7, were connected to a tee in the pressure line in the control manifold. The pressure transducers were a 2-wire transmitter with a 0 to 200 psi range and a 0.5-percent accuracy rating.

Exhibit 3.7 – Pressure Transducer

3.2.3 Custom Dual-Flow Rotary Union and Slip Ring Assemblies

During the development of the test matrix and test procedures, it became apparent that an instrumentation package was needed to allow test engineers to monitor and adjust tire pressure within the tire and wheel assemblies while the vehicle was in motion (i.e., to simulate a puncture). The team considered using wireless RF-type pressure monitoring systems, but did not due to concerns of possible interference with the RF-based TPMS technologies to be tested. A system of direct pressure measurement was therefore required.

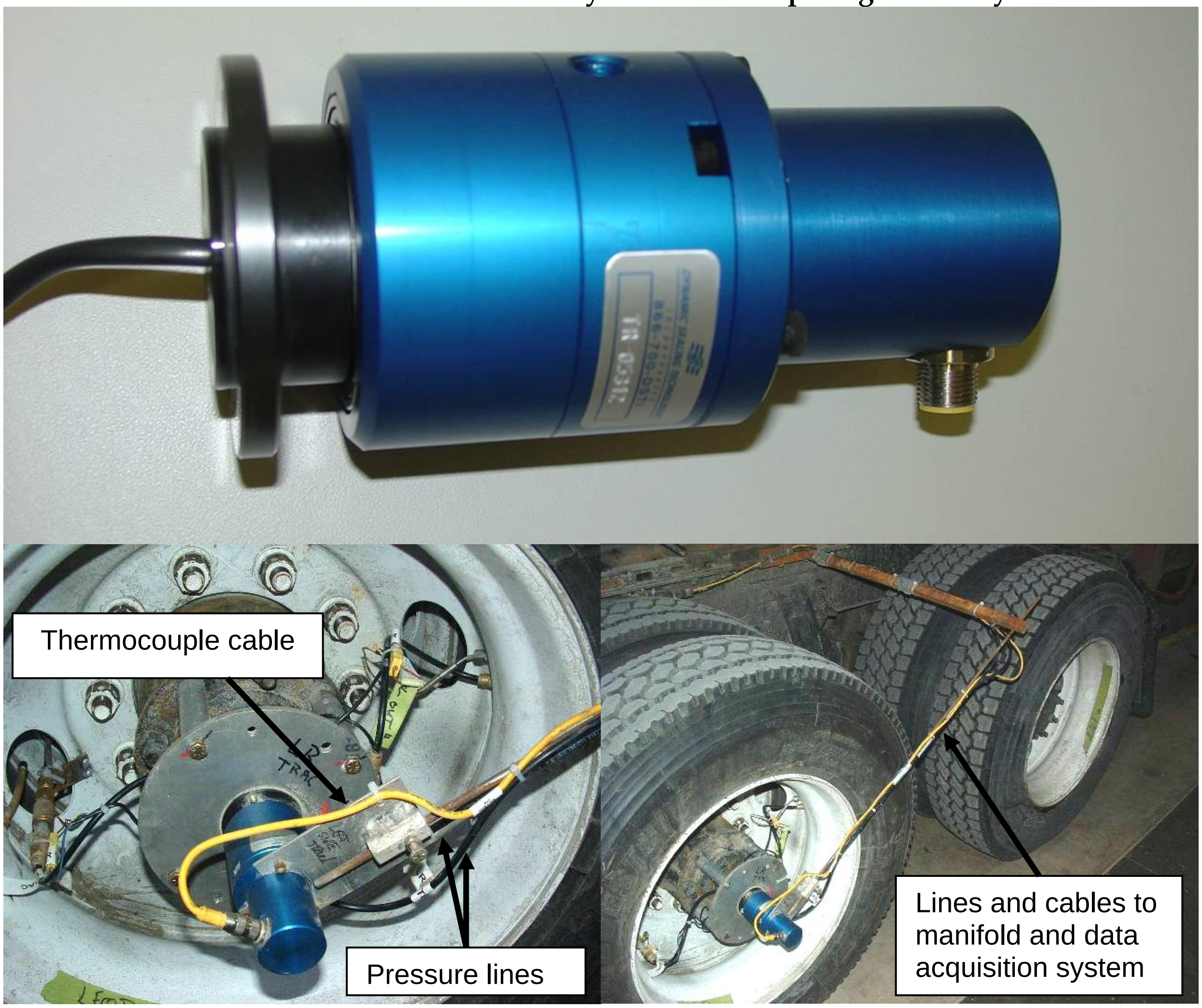
For dual wheel assemblies, it was also necessary that the technicians be able to monitor temperature and pressure and adjust the pressure in both wheels simultaneously. This functionally required a sophisticated custom-designed slip ring assembly capable of passing air and data signals from the rotating wheels to the non-rotating tractor-trailer frame and up to the cab. The thermocouple data was read directly by the DAS while the pressure lines were plumbed into a manifold to allow the selection of the tire(s) to be monitored by the pressure transducers. The use of the same lines to both monitor and adjust the tire pressures required the test engineer to periodically close the exhaust valves when making adjustments to tire pressures to check the pressure of the tire being adjusted. This process, while somewhat inconvenient, minimized the number of pressure lines on the vehicle.

The test team identified a manufacturer capable of supplying five of these slip ring assemblies in a rugged package designed for the vehicle environment, Dynamic Sealing Technologies Incorporated.[12]

[12] Dynamic Sealing Technologies Incorporated, 13941 Lincoln Street NE, Minneapolis, MN 55304, (763) 786-3758, www.dynamicsealing.com.

Exhibit 3.8 shows some photographs of the dual-flow rotary union and slip ring assembly.

Exhibit 3.8 – Dual-Flow Rotary Union and Slip Ring Assembly

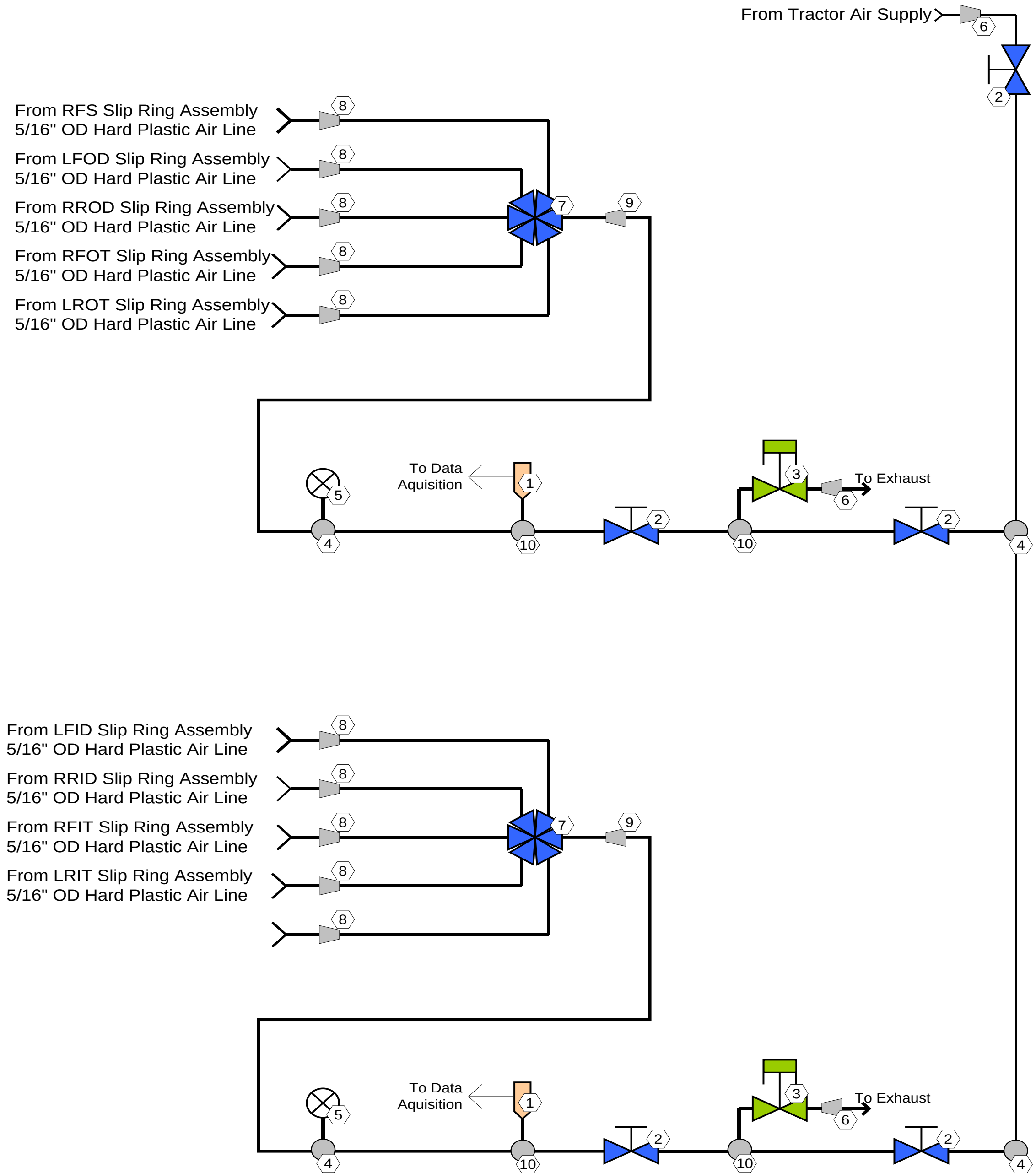


3.2.4 Custom Pressure Control Manifold

The use of the slip ring assemblies required the design and assembly of a cab-mounted pressure control manifold. The control manifold provided the test engineer with the ability to regulate tire pressure by removing and adding air within the tire and wheel assembly while the vehicle is in motion. The control board also included the pressure transducers.

Exhibit 3.9 shows a schematic of the custom pressure control manifold, while Exhibit 3.10 shows a photograph of the assembled manifold.

Exhibit 3.9 – Pressure Control Manifold Schematic



Component	Description	Manufacturer	Part Number	Quantity
1	Pressure Transducer	STI	PTL1C200PSIGE3WOPONOM1VOKOSO	2
2	Shutoff Valve	Swagelok	B-43S4	6
3	Metering Valve	Swagelok	B-4L-MH	2
4	Tee	Swagelok	B-400-3	4
5	Pressure Gauge	REOTEMP	PT45P1A4P20	2
6	1/4" to 5/16" Fitting	Swagelok	B-500-6-4	3
7	Switching Valve	Swagelok	B-43Z6FS2	2
8	1/8" to 5/16" Fitting	Swagelok	B-500-6-2	9
9	1/8" to 1/4" Reducer	Swagelok	B-400-R-2	2
10	Female Tee Branch	Swagelok	B-400-3-4TTF	4

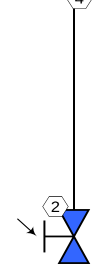
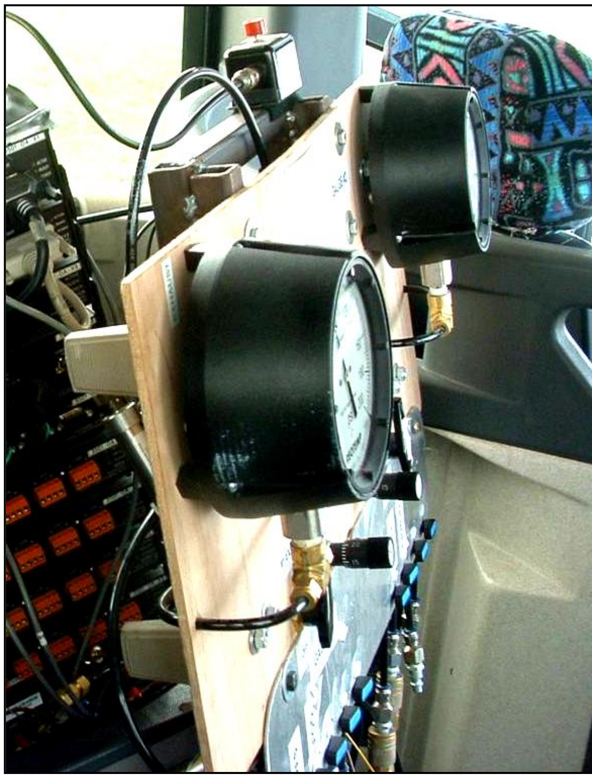


Exhibit 3.10 – Pressure Control Manifold and Metering Valve



3.2.5 Brake Reservoir and Treadle Valve Pressure Transducers

The failure modes test (Test #4) required that the air brake systems be monitored to determine whether the central tire inflation systems degraded the vehicle's potential braking ability (see Chapter 4 for test matrix description). It was necessary to monitor the air brake system pressure at three points—primary air reservoir, secondary air reservoir, and application pressure. Three pressure transducers similar to those used for tire pressure monitoring were spliced into the brake lines at a tee in the following locations:

- The primary air reservoir
- The secondary air reservoir
- The application pressure gauge line upstream of the gauge.

Output voltage levels from the transducers were then connected to the data acquisition system.

3.2.6 Digital Marker Switch

Many of the test procedures required recording when a warning indicator activates/illuminates. Since many of these products tested were a closed system design and could not be integrated with the DAS, a device was needed to allow the test engineer to electronically mark/tag the DAS data when a low-pressure warning was observed. This was accomplished by placing a simple switch at the control manifold that placed a voltage signal on a channel in the DAS when pressed. (See Exhibit 3.11 for a photo of a digital marker switch.)

Exhibit 3.11 – Digital Marker Switch Photo

3.2.7 Non-Contact Fifth Wheel

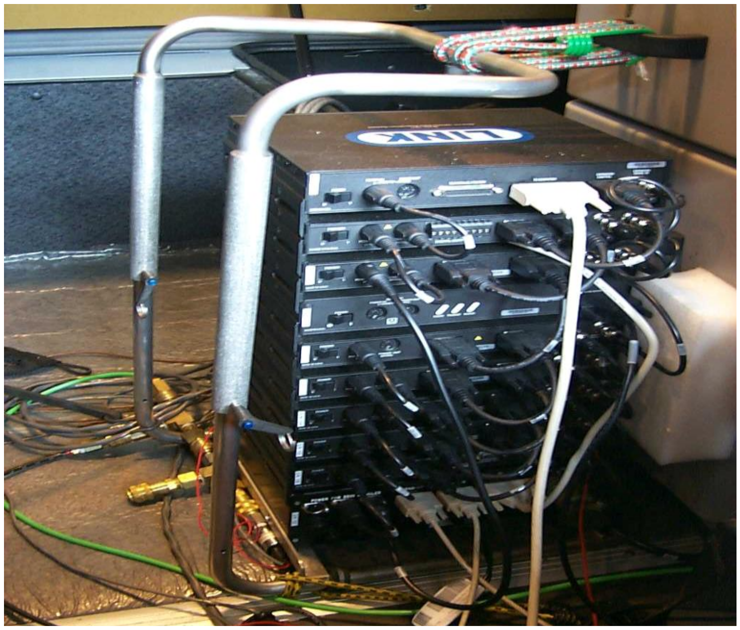
A non-contact (optical) fifth wheel was installed on the tractor and motorcoach to provide a reference vehicle speed. On both vehicles, the fifth wheel was hard-mounted to the driver side of the vehicle just aft of the driver's position.

3.2.8 DAS

The sensor data was electronically processed by a DAS manufactured by Link Engineering Company[13] of Detroit, MI, as shown in Exhibit 3.12. A PC-based laptop computer operates the system, stores data as it is acquired, and performs real-time analyses. The system software supports a variety of interface options ranging from direct user interaction with the system during measurement to completely autonomous operation based on various pre-programmed "trigger" events that cause the system to begin data collection. The system is also capable of issuing prompts to a test driver or an instrumentation technician.

[13] Not associated with Link Manufacturing, which produces the "Cat's Eye" equalizer tested in this study.

Exhibit 3.12 - Link DAS



The system is modular and, for this test program, was configured with eight multi-channel signal-processing modules. See Exhibit 3.13 for complete specifications.

Exhibit 3.13 - Links DAS Specification

Specification	
Model Number	2060
Noise, Vibration and Harshness Channels	5-32
Base Analog Channels	8
Maximum Additional Analog Channels	64
Maximum Samples per Second: General Analog High-Speed NVH (Noise/Vibration/Harshness)	 1,000 51,200
Temperature Channels	8-64
Thermocouple Type	J or K
Real-Time Data Display	Yes
Heads-up Driver Display	Yes
Review Data in Vehicle	Yes
Continuous Data Sampling	Yes
Real-Time Spectrum Analysis	25,000 Hz for 5 channels sampled simultaneously
Typical System Dimensions	11” wide x 8.5” deep x 5.5” high
Power Requirements – Volts	9 to 15
Power Requirements – Amps	4 Max.

The processing modules included three thermocouple modules, one pressure module, one force module, one frequency counter module, one network module, and the master module. The master module housed the power supply, computer, and heads-up display ports. A memory cache within the Link system stores one second of data before the beginning of the data logging event.

The Link 2060 DAS was set up to record the following information for each test:

- Test tire pressures (and associated dual tire pressure where applicable)
- Internal tire temperatures
- Primary and secondary brake reservoir pressures
- Treadle valve pressures
- Vehicle speed
- Warning indicator marker (manually triggered marker used to indicate in the data when a warning is displayed by the system).

In particular, 16 data channels were recorded, as shown in Exhibit 3.14.

Exhibit 3.14 – Sensor Channels

Channel #	Description	Units
1	Non Contact 5th Wheel Speed	mph
2	Pressure Transducer #1	psi
3	Pressure Transducer #2	psi
4	Primary Reservoir Pressure Transducer	psi
5	Secondary Reservoir Pressure Transducer	psi
6	Break Pedal Control Pressure Transducer	psi
7	Temperature Right Front Steer Tire	degrees F
8	Temperature Left Front Outer Drive Tire	degrees F
9	Temperature Left Front Inner Drive Tire	degrees F
10	Temperature Right Rear Inner Drive Tire	degrees F
11	Temperature Right Rear Outer Drive Tire	degrees F
12	Temperature Right Front Inner Trailer Tire	degrees F
13	Temperature Right Front Outer Trailer Tire	degrees F
14	Temperature Left Rear Outer Trailer Tire	degrees F
15	Temperature Left Rear Inner Trailer Tire	degrees F
16	Marker Switch	On/Off

CHAPTER 4. TEST PLAN

Each one of the TPMS was installed sequentially, first on the tractor-trailer and then on the motorcoach, and tested at loaded conditions based on a pre-defined test plan. As each test series was completed and the results analyzed, the test plan was modified by either eliminating certain planned test sequences that were not expected to generate new and useful data, or by adding tests to investigate specific issues or new areas of interest. This section of the report describes the:

- Specific TPMS testing regimens performed under this program (the test matrix)
- Processes used for collecting data

All track testing occurred at the TRC in East Liberty, OH, using TRC drivers.

4.1 Test Matrix

The test program consisted of the following seven specific tests, not all of which were performed on each system or technology:

- Test #1: Functionality Tests
- Test #2: Threshold Warning Test
- Test #3: Loaded Test at High Speed
- Test #4: Failure Mode Test
- Test #5: Disablement Test
- Test #6: Operation Interface Evaluation
- Test #7: Gate-Reader Evaluation

Exhibit 4.1 shows an overview of the test matrix that maps each of the systems tested to the specific tests above.

Exhibit 4.1 – Test Matrix

Technology	Tractor	Platform Trailer	Motor-coach	Test Number						
				1	2	3	4	5	6	7
Dual Tire Equalizers										
Link Manufacturing Cat's Eye	X	X		X	X	X	X	X	X	
V-Tech International Tire Knight-S	X	X		X	X	X	X	X	X	
Tire Pressure Monitoring Systems										
Advantage Pressure Pro (valve stem mounted)	X	X		X	X	X		X	X	
WABCO IVTM (valve stem mounted)			X	X	X	X		X	X	
HCI Tire SafeGuard (wheel mounted)	X	X		X	X	X		X	X	
SmarTire Systems4 (wheel mounted)			X	X	X	X		X	X	
Michelin eTire (tire mounted)	X	X			X	X		X		X
Central Inflation Systems										
Arvin Meritor PSI (trailer-only)		X		X	X		X	X	X	
Gio-Set Vigia			X	X	X	X	X	X	X	

4.1.1 Functionality Test (Static and Dynamic)

This is an overview or "shakedown" test phase that characterizes the operational, maintenance, and installation processes for each system.

The major objective of this test phase was to evaluate the overall ability of the various sensor technologies to detect tire pressure problems or otherwise perform as intended.

4.1.2 Threshold Warning Level Test

This test determines the thresholds at which low tire pressure warnings are given. In the case of the automatic inflation systems, the test determines the leak rate (psi/min) in which the inflation system can no longer keep pace and a low tire pressure warning is given.

4.1.3 Loaded Test at High Speed

This test examines the effects of tire heating, due to sustained high-speed driving, on the warning indicator/light of the systems.

4.1.4 Failure Modes Test

This test phase determines whether, for automatic inflation systems, a large or catastrophic air leak depletes the air supply for the pneumatic brakes or forces the system to run continuously without giving the driver a warning that a tire has lost air. For systems where tires are interconnected (dual-tire equalizing and central inflation system technologies), the purpose is to ensure that loss of inflation pressure in a single tire does not affect the interconnected tires.

4.1.5 Disablement Test

This test determines the system's ability to provide a warning or some type of indication if/when it is disabled either by an intentional act or as a result of a failure of a system or component. At least five modes, in which each system could be disabled, were tested.

4.1.6 Operator Interface Evaluation

This test is a qualitative evaluation of the effectiveness of the driver interface.

4.1.7 Gate Reader Evaluation

This test evaluates the performance and reliability of the drive-thru gate readers used with tire-mounted monitoring systems. The objective was to determine the speed and consistency of the gate readers in capturing pressures of all 18 tires.

4.2 Data Collection Process

The Link DAS system received information from 16 individual channels at a frequency of 10 Hz. Exhibit 3.13 provides a complete list of channels. A key stroke on the laptop activated the DAS at the beginning of each test run. Data was collected until the vehicle reached a complete stop. A memory cache built into the DAS recorded one second of data prior to the start of data recording.

The actual data from each test run was stored in individual files on a Windows-based laptop computer installed in each test vehicle in turn. The average TPMS test lasted about 10 to 30 minutes and generated approximately 5,000 to 10,000 data points. In total, the testing program generated approximately 450 Mb of data.

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

CHAPTER 5. TEST RESULTS

This chapter presents a summary of the results from the test program and offers some observations regarding the accuracy, sensitivity, and applicability of various TPMS technologies for determining tire pressure deficiencies.

Due to the very large volume of data generated (450 Mb), it is not practical to plot data from all test runs and/or perform comprehensive comparisons among all TPMS for all test scenarios in this report. Therefore, this chapter presents analyses performed to assess the operational characteristics and limitations of the various TPMS technologies.

The project team developed a test plan to address the various performance parameters of the TPMS technologies, which was reviewed by the project sponsor, TRC engineers and, where appropriate, by TPMS vendors. The initial test plans followed proposed test procedures. The final test plans produced a test matrix that more efficiently utilized track time and incorporated modifications to the test procedures related to characteristics of the selected TPMS technologies.

The results and observations presented in this chapter are not exhaustive; however, extensive data was collected and supports significant additional statistical analyses. Other tire researchers may wish to examine the data and draw independent conclusions on TPMS performance and the utility of the various systems examined in this program.[14]

This chapter is organized as follows:

- An analysis of the data collected from the dual tire equalizers
- An analysis of the data collected from the tire pressure monitoring systems
- An analysis of the data collected from the central tire inflation systems

5.1 Dual Tire Equalizers

The following tests were performed on the dual tire equalizers:

- Static and dynamic functionality tests
- Threshold warning tests
- Failure modes tests
- Disablement modes tests
- Operator interface evaluation

These tests and the test results are described in detail in the following subsections.

[14] Data can be obtained from the Federal Motor Carrier Safety Administration (FMCSA), Office of Bus and Truck Standards and Operations (MC-PSV), 400 7th Street, SW, Washington, DC 20590-0001.

5.1.1 Static and Dynamic Functionality Tests

The static and dynamic functionality tests assess the ability of tire equalizers to equalize between tires of a dual installation as well as to isolate a good tire from a tire that has experienced a significant or total loss of pressure. The systems were tested both statically to determine basic functionality and dynamically to determine the effect of the vehicle operation on the equalizer system's performance.

Exhibit 5.1 summarizes the dual tire equalizer functionality test procedure. Although equalizers can be installed on motorcoaches and trucks, the two equalizer systems were tested on the tractor-trailer because the larger number of dual wheel installations on the vehicle facilitated and improved efficiency of the testing.

Exhibit 5.1 – Dual Tire Equalizer Functionality Test Procedures

Step Number	Procedure
Static Functionality Check	
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
2	Set Manifold to Proper Positions
3	Start Data Recorder, sample at 10 Hz
4	Deflate RROD tire to 85 psi, using manifold
5	Stop recorder when pressures have equalized for at least 1 minute or up to 10 minutes have elapsed.
6	Record file name and stop number
7	Examine display at wheel, Take digital photo, Record Photo File Name
8	Re-inflate "giving" tire to 100 psi, Deflate RROD additional 10 psi below previous setting
9	Repeat 1-8 until pressure reaches 55 psi or tires no longer equalize pressures
10	Repeat 1-9 for LFID, and RFIT and LROT
Dynamic Functionality Check	
11	Set all tires to Cold Inflation Pressure (CIP=100psi), Create new test file
12	Set Manifold to Proper Positions
13	Start Data Recorder, sample at 10 Hz
14	Deflate RROD tire to 85 psi, using manifold
15	Drive vehicle at 45 mph for 10 minutes (1 lap), stop vehicle in pit
16	Stop Data Recorder
17	Record file name and stop number
18	Examine display at wheel, Take digital photo. Record Photo File Name
19	Re-inflate "giving" tire to 100 psi, Deflate RROD additional 10 psi below previous setting
20	Repeat 11-19 until pressure reaches 55 psi or tires no longer equalize pressures
21	Repeat 11-20 for LFID, RFIT, and LROT

Exhibit 5.2 shows the Link equalizer equalizing a dual installation during a static test in which the left front inner drive (LFID) tire's pressure was dropped to 75 psi and the corresponding left front outer drive (LFOD) tire was set at 100 psi. The low pressure and spikes in the LFID trace are due to the high rate of deflation and intermittent checking of the pressure by the test engineer during the deliberate reduction to 75 psi. Due to the location of the transducer relative to the position of the exhaust valve used to deflate the tire, the pressure reads lower than actual tire pressure during high deflation rates. The exhaust valve must be closed intermittently during

deflation to check the pressure in the tire being deflated. The tires begin to equalize immediately on the reduction of pressure as evidenced by the LFOD trace. The data show that the tires equalized at approximately 81 psi. The temperatures of both tires also show a decrease as their pressures dropped (as would be expected). The spike in the marker trace indicates the point where the LFID reached the 75 psi test point.

Exhibit 5.2 – Link Equalizer Static Equalizer Functionality Test LFID 75 psi

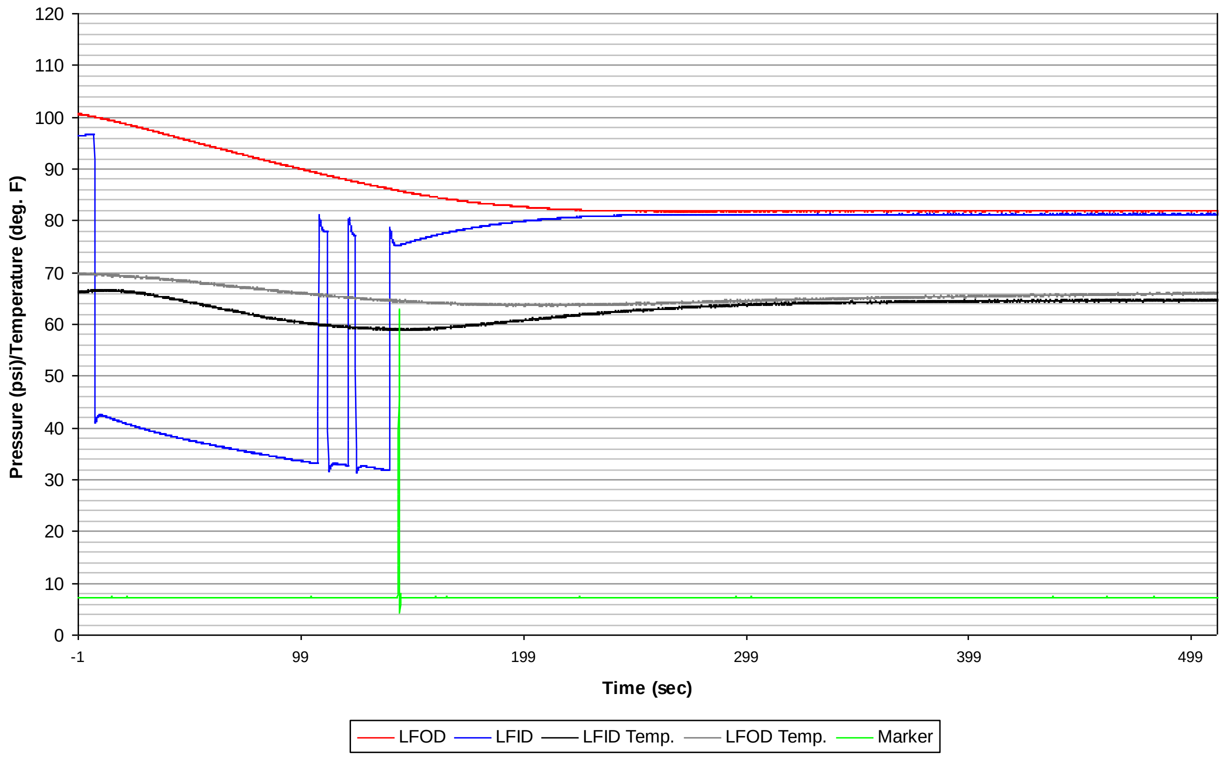


Exhibit 5.3 shows the Link equalizer equalizing a dual installation during a static test in which the LFID tire's pressure was dropped to 55 psi and the corresponding LFOD tire was set at 100 psi. The low pressure and spikes in the LFID trace are due to the high exhaust rate and intermittent checking of the pressure by the test engineer during the deliberate reduction to 55 psi. The tires begin to equalize immediately on the reduction of pressure as evidenced by the LFOD trace. The data show that the tires do not equalize but remain isolated by the check valve in the system. The LFID remains at approximately 58 psi and the LFOD remains at approximately 80 psi. The temperatures of both tires again decrease as their pressures drop. The spike in the marker trace indicates the point where the LFID reached the 55 psi test point.

Exhibit 5.3 – Link Equalizer Static Equalizer Functionality Test LFID 55 psi

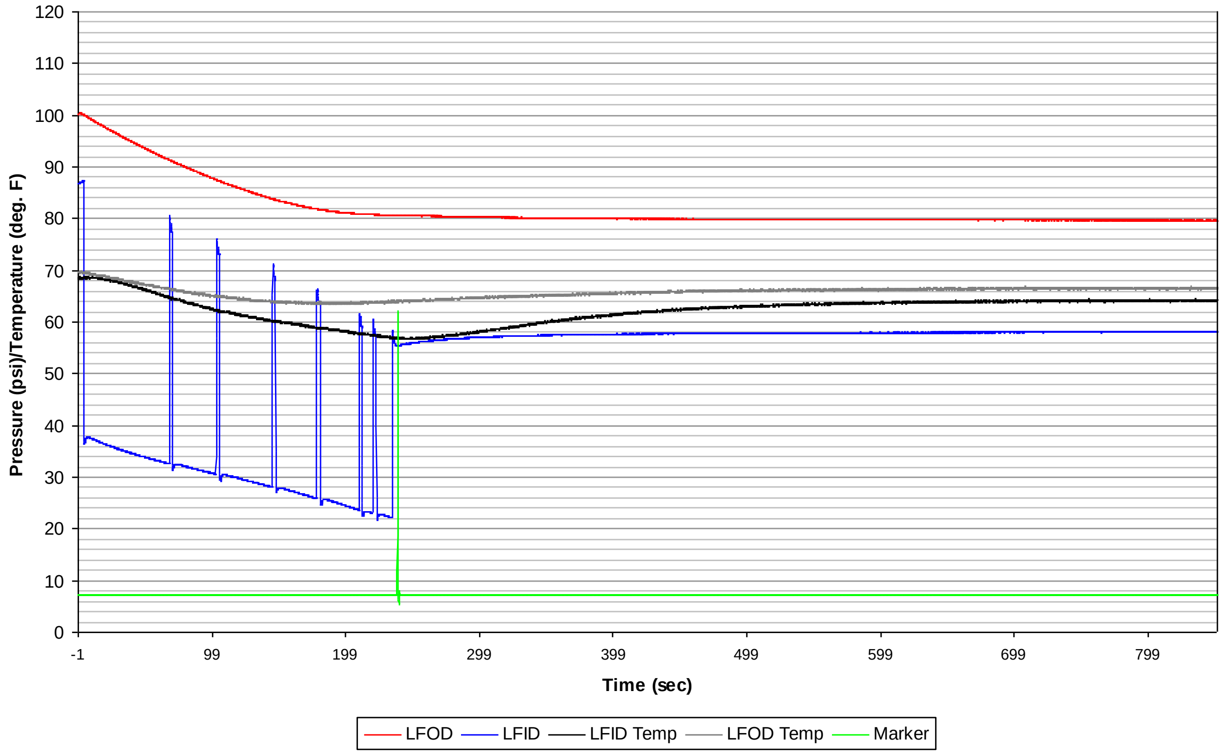


Exhibit 5.4 summarizes the data from the Link equalizer static functionality testing. The system appears to equalize the pressure of the tire experiencing air loss until it decreases to approximately 80 psi. When a leaking tire deflates below 80 psi, the system will stop pressure equalization when the pressure of the intact tire reaches 80 psi to prevent the total loss of pressure in both tires of a dual installation.

Exhibit 5.4 – Link Equalizer Static Functionality Test Data

Tire Set	Initial Pressure	Equalized Pressures	Isolated Pressures
RROD/RRID	85/100	90/90	-
	75/100	82/82	-
	65/100	79/79	-
	55/100	-	74/80
LFID/LFOD	85/100	90/90	-
	75/100	82/82	-
	65/100	-	70/78
	55/100	-	58/80
RFIT/RFOT	85/100	86/86	-
	75/100	78/78	-
	65/100	-	66/80
	55/100	-	55/80
LROT/LRIT	85/100	89/89	-
	75/100	85/85	-
	65/100	79/79	-
	55/100	-	62/82

Exhibit 5.5 summarizes the data from the V-Tech equalizer static functionality testing. Similar to the Link equalizer, the system appears to equalize pressures down to slightly below 80 psi. However, the equalizer on the LFID/LFOD tire set did show a tendency to isolate the intact tire at pressures in the mid 90 psi range when presented with a larger pressure differential. Similar to the Equalizer System #1, when a tire deflates below 80 psi, the system will stop pressure equalization from the intact tire 80 psi to prevent the loss of pressure in both tires of a dual installation.

Exhibit 5.5 – V-Tech Equalizer Static Functionality Test Data

Tire Set	Initial Pressure	Equalized Pressures	Isolated Pressures
RROD/RRID	95/100	98/98	-
	90/100	95/95	-
	85/100	92/92	-
	80/100	89/89	-
	75/100	86/86	-
	70/100	85/85	-
	65/100	79/79	-
	60/100	78/78	-
	55/100	-	74/79
LFID/LFOD	85/100	92/92	-
	75/100	86/86	-
	65/100	-	77/84
	55/100	-	56/96
RFIT/RFOT	85/100	92/92	-
	75/100	86/86	-
	65/100	78/78	-
	55/100	-	71/75
LROT/LRIT	85/100	93/93	-
	75/100	85/85	-
	65/100	79/79	-
	55/100	-	62/82

Exhibit 5.6 shows the V-Tech equalizer equalizing a dual installation, during a dynamic test at 45 mph. During this test, the LFID tire's pressure was dropped to 85 psi while the corresponding LFOD tire was initialized at 100 psi. The low pressure and spikes in the LFID trace are due to the high exhaust rate and intermittent checking of the tire pressure during the deliberate reduction to 85 psi. The tires begin to equalize immediately on the reduction of pressure as evidenced by the LFOD trace. The data show that the tires equalized at approximately 92 psi. This result was similar to the equalization pressure in the static functionality test. The temperatures of both tires also show an initial decrease as their pressures dropped and then an increase as the vehicle was driven at a constant speed of 45 mph. This is indicated by the spike in the marker trace.

Exhibit 5.6 – V-Tech Equalizer Dynamic Equalizer Functionality Test LFID 85 psi

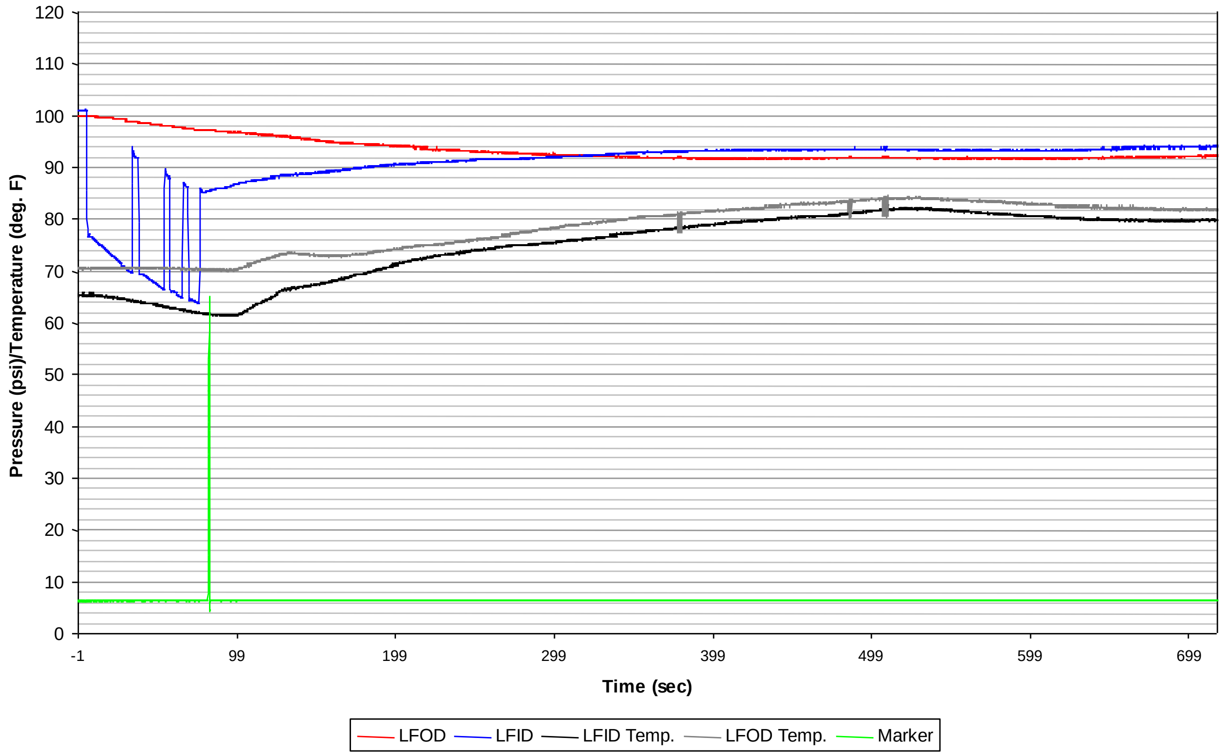


Exhibit 5.7 shows the V-Tech equalizer equalizing a dual installation during a dynamic test at 45 mph. In this test, the LFID tire's pressure was deliberately reduced to 55 psi and the corresponding LFOD tire was initially set at 100 psi. Similar to the results shown in Exhibit 5.3, the low pressure and spikes in the LFID trace are due to the high exhaust rate and intermittent checking of the tire pressure by the test engineer during the deliberate reduction to 55 psi. The tires begin to equalize immediately when the reduction of pressure was detected, as shown by the LFOD trace. The data trace indicates that the pressures between the dual tires do not equalize, but that they remain isolated by the check valve in the system. The LFID pressure was increased to approximately 55 psi at the beginning of the equalization period and increased gradually to 56 psi. The LFOD dropped to approximately 96 psi at the beginning of the equalization sequence and gradually increased to approximately 97 psi. The isolation pressures were similar to the pressures observed in the static functionality tests for this case. The temperatures of both tires initially decrease as their pressures drop, but begin to increase as the vehicle is driven. The slight increase in pressure after the start of the test, as indicated by the spike in the marker trace, is due to the temperature increase in the tires as the vehicle is driven.

Exhibit 5.7 – V-Tech Equalizer Dynamic Equalizer Functionality Test LFID 55 psi

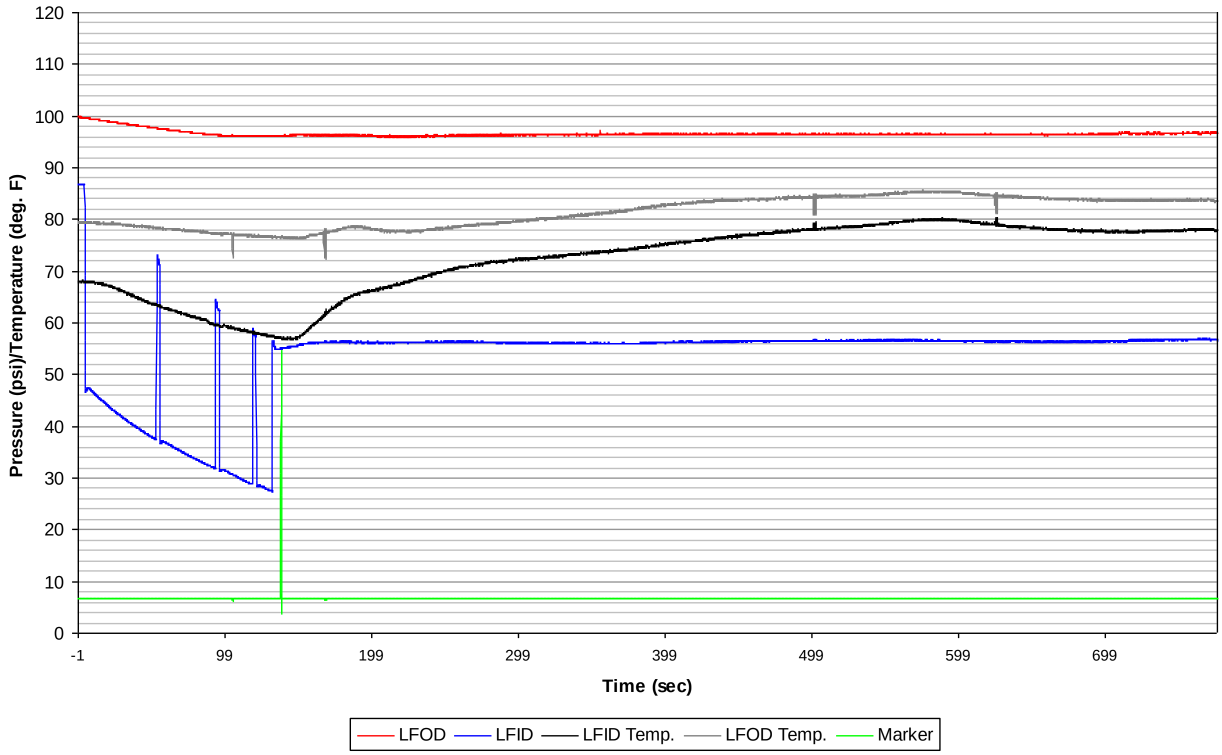


Exhibit 5.8 summarizes the data from the Link equalizer dynamic functionality testing. Similar to its static test behavior, the system appears to equalize pressures down to approximately 80 psi. However, the equalizers on the RROD/RRID and LROT/LRIT tire sets isolated the intact tires at pressures just below 90 psi when the low tire's pressure set to 65 psi and 75 psi respectively. Again as in the static tests, when a tire deflates below approximately 80 psi, the system will halt pressure equalization from the intact tire at approximately 80 psi to prevent the loss of pressure in both tires of a dual installation.

Exhibit 5.8 – Link Equalizer Dynamic Functionality Test Data

Tire Set	Initial Pressure	Equalized Pressures	Isolated Pressures
RROD/RRID	85/100	91/91	-
	75/100	82/82	-
	65/100	-	66/88
	55/100	-	71/80
LFID/LFOD	85/100	90/90	-
	75/100	81/81	-
	65/100	-	70/78
	55/100	-	58/80
RFIT/RFOT	85/100	89/89	-
	75/100	80/80	-
	65/100	-	69/79
	55/100	-	59/82
LROT/LRIT	85/100	89/89	-
	75/100	-	76/89
	65/100	80/80	-
	55/100	-	63/83

Exhibit 5.9 summarizes the data from the V-Tech equalizer dynamic functionality testing. Similar to its static test behavior, the system appears to equalize pressures down to approximately 80 psi. However, the equalizers on the LFID/LFOD tire set isolated the intact tires at 96 psi when the other tire dropped to 55 psi.

Exhibit 5.9 – V-Tech Equalizer Dynamic Functionality Test Data

Tire Set	Initial Pressure	Equalized Pressures	Isolated Pressures
RROD/RRID	95/100	97/97	-
	90/100	95/95	-
	85/100	92/92	-
	80/100	89/89	-
	75/100	86/86	-
	70/100	85/85	-
	65/100	79/79	-
	60/100	78/78	-
	55/100	-	74/79
LFID/LFOD	85/100	92/92	-
	75/100	86/86	-
	65/100	-	78/84
	55/100	-	56/96
RFIT/RFOT	85/100	92/92	-
	75/100	85/85	-
	65/100	82/82	-
	55/100	-	69/75
LROT/LRIT	85/100	93/93	-
	75/100	86/86	-
	65/100	80/80	-
	55/100	-	63/83

5.1.2 Threshold Warning Tests

The threshold warning tests evaluate the ability of tire equalizers to equalize inflation pressures between the two tires of a dual installation at slow leak rates, as well as to isolate an intact tire from a tire that has experienced a slow leak that results in a total loss of pressure. The systems were tested both statically to determine basic functionality and dynamically to determine the effect of the vehicle operation on the equalizer system's performance. Exhibit 5.10 presents the dual tire equalizer threshold warning test procedures.

Exhibit 5.10 – Dual Tire Equalizer Threshold Warning Test Procedures

Step Number	Procedure
Static Slow Leak	
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
2	Start Data Recorder, sample at 10 Hz
3	Begin slowly leaking RROD tire pressure at approximately 1.5 psi/min*
4	Allow tire to deflate until pressure reaches 60 psi, stop deflation
5	Stop Data Recorder
6	Record file name and stop number

Step Number	Procedure
7	Repeat 1-6 for LFID, and RFIT and LROT
Dynamic Slow Leak	
8	Start Data Recorder, sample at 10 Hz
9	Begin slowly leaking LROT tire pressure at approximately 1.5 psi/min*
10	Drive vehicle at 45 mph, until LROT tire pressure reaches 60 psi, or two hours have elapsed.
11	Stop Data Recorder, Stop Leak
12	Record file name and stop number
*Do not exceed 40% below CIP for drive/trailer tires, or 25% below CIP for steer tires	

Exhibit 5.11 shows the Link equalizer equalizing a pair of duals during a static test. During this test, the LRIT tire's pressure slowly dropped due to an induced leak of approximately 1.5 psi per minute and the corresponding LROT tire was set at 100 psi. The tires begin to equalize immediately on the reduction of pressure as shown by both the LRIT and LROT traces. The LROT tire stabilized at approximately 78 psi, while the LRIT tire continued to deflate at a slightly higher rate because the check valve activated and discontinued the equalization process. The temperatures of both tires remained relatively constant during the slow leak process.

Exhibit 5.11 – Link Equalizer Static Slow Leak Test

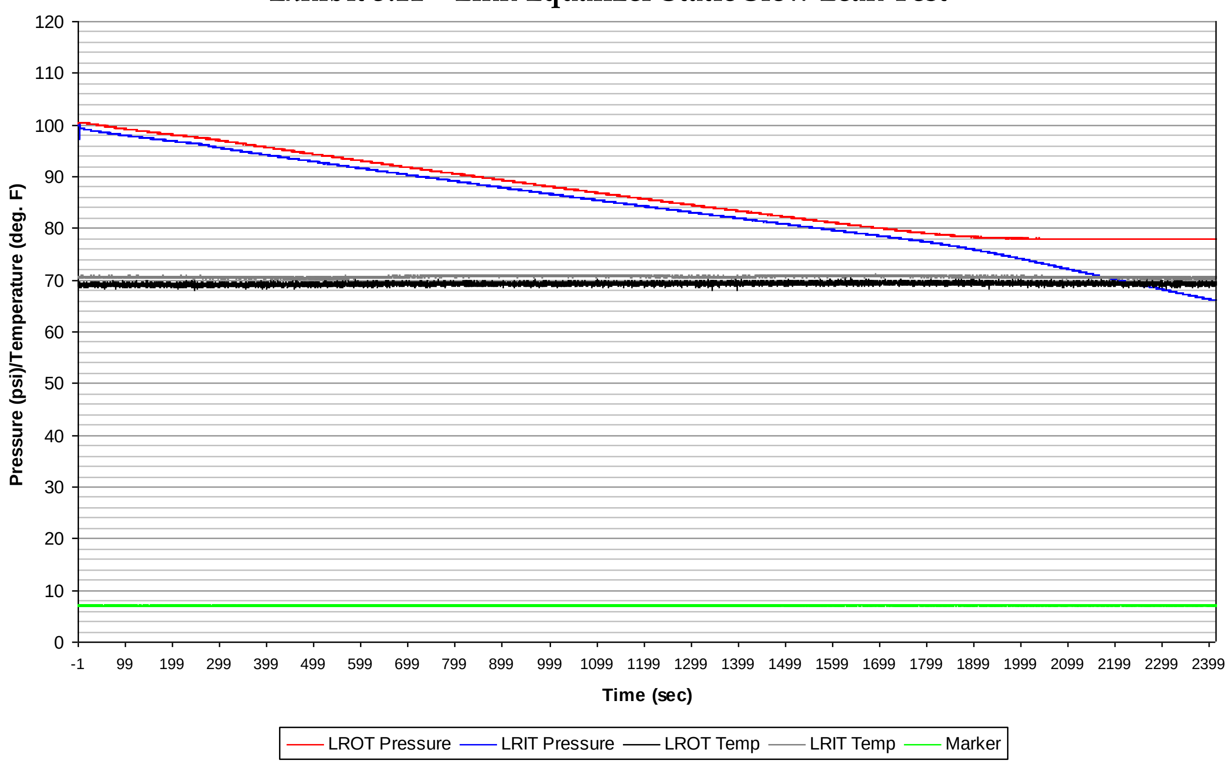


Exhibit 5.12 shows the Link equalizer equalizing a dual installation during a dynamic test at 45 mph. Here, the LRIT tire's pressure slowly dropped due to an induced leak of approximately 1.5 psi per minute, while the corresponding initial LROT was set at 100 psi. The tires begin to equalize immediately on the reduction of pressure as evidenced by both the LRIT and LROT traces. The data show that the LROT tire stabilized at approximately 75 psi, while the LRIT tire

continued to deflate at a slightly faster rate. As in the previous test, the check valve activated and discontinued the equalization process. The temperatures of both tires gradually increased during the slow leak process due to the heating induced by driving the vehicles.

Exhibit 5.12 – Link Equalizer Dynamic Slow Leak Test

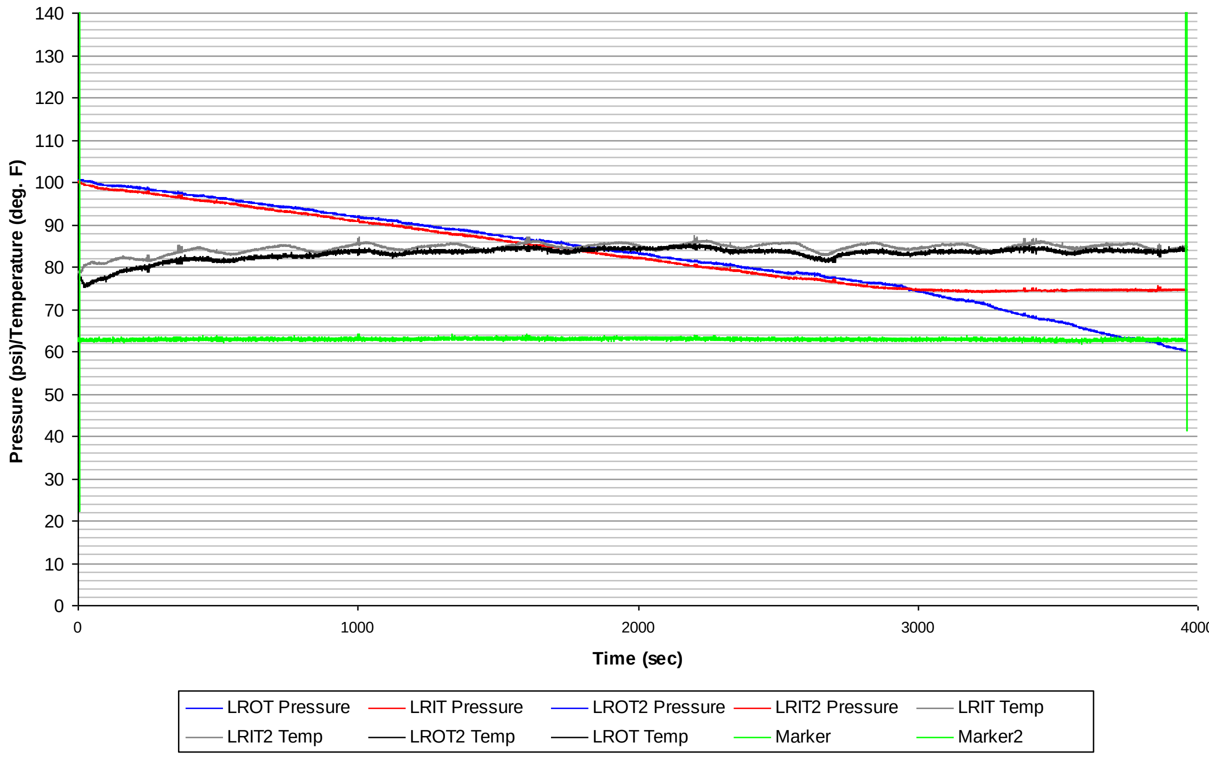


Exhibit 5.13 summarizes the data from the Link equalizer threshold warning testing. During the static and dynamic testing with a slowly leaking tire, the system appears to equalize pressures down to approximately 80 psi, although the pressures of the isolated tires were in the mid to upper 70 psi range. Because the air loss rates were low, the equalizers on the RROD/RRID and LFID/LFOD equalized but did not isolate the intact tire of the dual pair during the test period.

Exhibit 5.13 – Link Equalizer Threshold Warning Test Data

Tire Set	Initial Pressures	Equalized Pressures	Isolated Pressures
Static			
RROD/RRID	100/100	87/87	Test Period Expired
LFID/LFOD	100/100	75/75	Test Period Expired
RFIT/RFOT	100/100	-	Continued Leak/79
LROT/LRIT	100/100	-	Continued Leak/78
Dynamic			
RROD/RRID	100/100	-	Continued Leak/74

Exhibit 5-14 summarizes the data from the V-Tech equalizer threshold warning testing. During the static and dynamic testing with a slowly leaking tire, the system appears to equalize pressures down to approximately 80 psi. Similar to the Link equalizer, the pressures of the isolated tires were also in the mid to upper 70 psi range.

Exhibit 5.14 – V-Tech Equalizer Threshold Warning Test Data

Tire Set	Initial Pressures	Equalized Pressures	Isolated Pressures
Static			
RROD/RRID	100/100	-	Continued Leak/78
LFID/LFOD	100/100	-	Continued Leak/78
RFIT/RFOT	100/100	-	Continued Leak/73
LROT/LRIT	100/100	-	Continued Leak/74
Dynamic			
LROT/LRIT	100/100	-	Continued Leak/74

5.1.3 Failure Modes Tests

The failure modes tests for tire equalizers evaluate their ability to equalize between two tires of a dual installation at rapid leak rates as well as to isolate an intact tire from a tire that has experienced a rapid leak that results in total loss of pressure. The systems were tested both statically to determine basic functionality and dynamically to determine the effect of the vehicle operation on the equalizer system's performance. Exhibit 5.15 details the dual tire equalizer failure modes test procedures.

Exhibit 5.15 – Dual Tire Equalizer Failure Modes Test Procedures

Step Number	Procedure
Static Rapid Leak	
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
2	Start Data Recorder, sample at 10 Hz
3	Initiate air loss from RROD tire at the maximum rate (approximately 20 psi/min.)
4	Wait until pressure in RROD reaches 0 psi and RRID pressure stabilizes for 1 minute
5	Stop Data Recorder
6	Record file name and stop number
Dynamic Rapid Leak	
7	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
8	Start Data Recorder, sample at 10Hz
9	Initiate air loss from RROD tire at maximum rate (approximately 20 psi/min.)
10	Drive vehicle at 45 mph, until RROD tire pressure reaches 60 psi
11	Stop Data Recorder, Stop air loss
12	Record file name and stop number
*Do not exceed 40% below CIP for drive/trailer tires, or 25% below CIP for steer tires	

Exhibit 5.16 shows the V-Tech equalizer equalizing a dual installation during a static test in which the LFID tire's pressure rapidly dropped due to an induced leak of 20 psi per minute. Both the LFID and corresponding LFOD tires were initially set at 100 psi. The tires begin to equalize immediately on the reduction of pressure as evidenced by both the LFID and LFOD traces. The data show that the LFOD tire stabilized at approximately 95 psi, while the LFID tire continued to deflate at a slightly faster rate because the check valve activated and discontinued the equalization process. The temperatures of the LFID tire initially dropped due to the decrease in pressure, while the temperature of the LFOD tire remained relatively constant. The large initial drop and relatively low pressure of the LFID trace is due to the effect of the large induced leak on the pressure transducer installation.

Exhibit 5.16 – V-Tech Equalizer Static Rapid Leak LFID Test

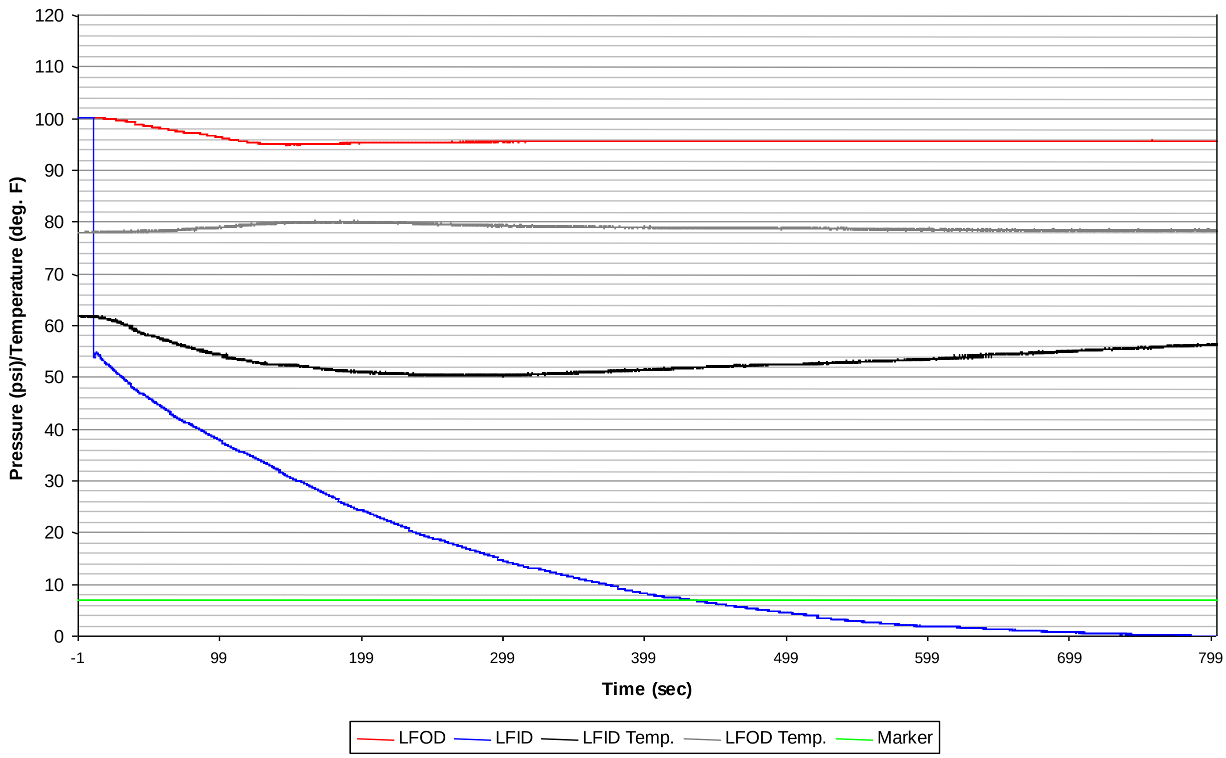


Exhibit 5.17 shows the performance of the V-Tech equalizer on a dual installation during a dynamic test at 45 mph where the LFID tire's pressure rapidly dropped due to an induced leak of approximately 20 psi per minute. Both the LFID and the corresponding LFOD tires were initially set at 100 psi. The tires begin to equalize immediately on the reduction of pressure as evidenced by the LFOD trace. The data show that the LFOD tire stabilized at approximately 95 psi, while the LFID tire continued to deflate until testing was terminated when the LFID tire reached 60 psi. The temperatures of both tires initially dropped due to the decrease in pressure and then gradually increased due to heat generated from driving the vehicle. As mentioned previously, the large initial drop and relatively low pressure of the LFID trace is due to the effect of the high induced leak rate on the pressure transducer installation, while the spikes are due to intermittent checks of the tire pressure.

Exhibit 5.17 – V-Tech Equalizer Dynamic Rapid Leak LFID Test

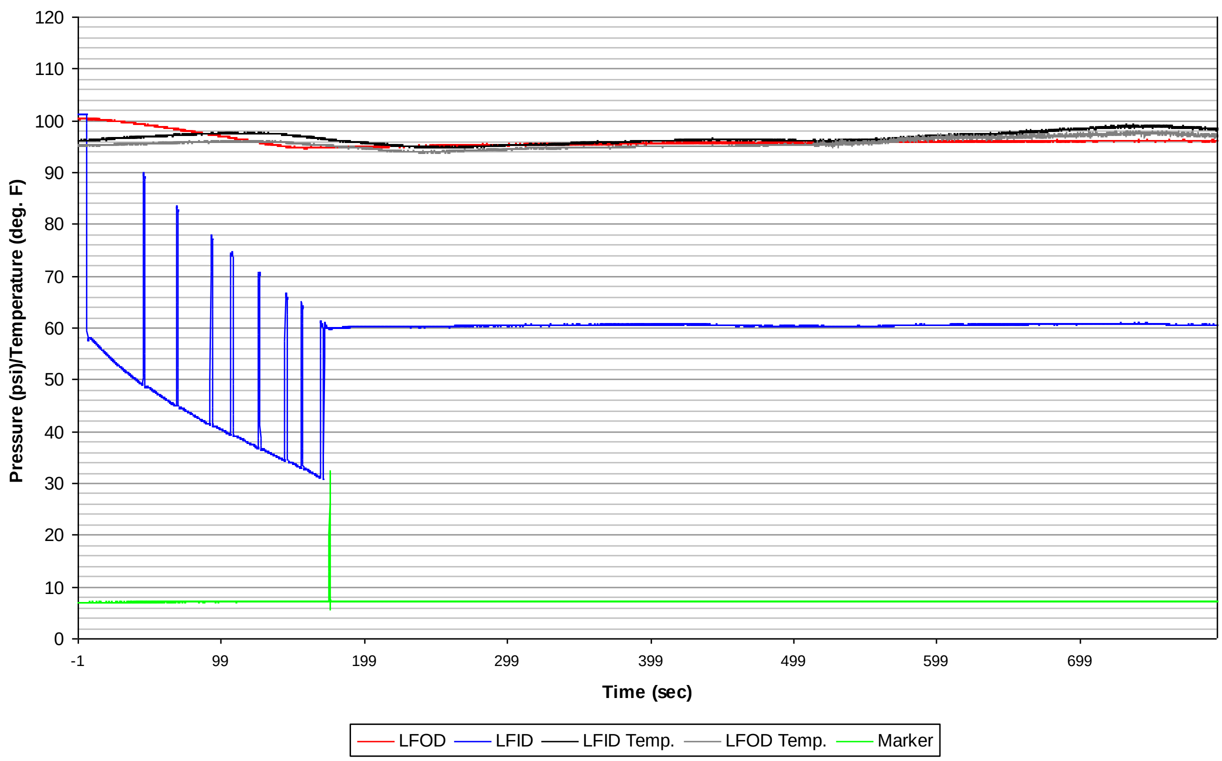


Exhibit 5.18 summarizes the data from the Link equalizer failure mode testing. During the static and dynamic testing with a rapidly leaking tire, the system appears to equalize pressures down to approximately 80 psi in the LFID/LFOD and RFIT/RFOT tire pairs. The RROD/RRID and LROT/LRIT pairs, however, stopped equalizing when the pressures of the isolated tires were in the high-80s psi range.

Exhibit 5.18 – Link Equalizer Failure Mode Test Data

Tire Set	Initial Pressures (psi)	Isolated Pressures (psi)
Static		
RROD/RRID	100/100	Continuing Leak/88
LFID/LFOD	100/100	Continuing Leak/80
RFIT/RFOT	100/100	Continuing Leak/80
LROT/LRIT	100/100	Continuing Leak/89
Dynamic		
RROD/RRID	100/100	Continuing Leak/89
LFID/LFOD	100/100	Continuing Leak/78
RFIT/RFOT	100/100	Continuing Leak/80
LROT/LRIT	100/100	Continuing Leak/88

Exhibit 5.19 summarizes the data from the V-Tech equalizer failure mode testing. During the static testing of a rapidly leaking tire in a pair, the system appears to equalize pressures down to a range of 88 to 95 psi. During dynamic testing of a rapidly leaking tire in a pair, the system appears to equalize pressures down to a range of 90 to 95 psi. Safety requirements prevented continuing the dynamic testing beyond the point where the pressure of an affected tire went

below 60 psi. Thus, we were not able to test the equalization pressures when the affected tire was isolated in the RROD/RRID, RFIT/RFOT, and LROT/LRIT tests. The LFID/LFOD tire set did reach the isolation point of 95 psi during both the dynamic and static tests.

Exhibit 5.19 – V-Tech Equalizer Failure Mode Test Data

Tire Set	Initial Pressures (psi)	Isolated Pressures (psi)
Static		
RROD/RRID	100/100	Continuing Leak/92
LFID/LFOD	100/100	Continuing Leak/95
RFIT/RFOT	100/100	Continuing Leak/88
LROT/LRIT	100/100	Continuing Leak/88
Dynamic		
RROD/RRID	100/100	60/95 (Test Terminated at 60 psi)
LFID/LFOD	100/100	Continuing Leak/95
RFIT/RFOT	100/100	60/90 (Test Terminated at 60 psi)
LROT/LRIT	100/100	60/90 (Test Terminated at 60 psi)

5.1.4 Disablement Tests

The purpose of this test is to determine the ability of the system to protect the tire(s) from loss of air pressure in the event of damage or failure of the system components. Components of the system were purposely damaged or removed to simulate damage or loss due to road debris, curb strikes, vandalism, etc. These tests were performed statically due to concerns about driver, vehicle, and track safety if a tire failed on a moving vehicle. Exhibit 5.20 presents the test procedures for the dual tire equalizer failure modes.

Exhibit 5.20 – Dual Tire Equalizer Failure Modes Test Procedures

Step Number	Procedure
Disablement	
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
2	Start Data Recorder, sample at 10 Hz
3	Disable the TPMS according to disablement Mode #1
4	Examine display at wheel, Take digital photo, Record Photo File Name
5	Record response of system & if/when a warning/indicator of disablement is observed
6	Wait until response has stabilized for 1 minute
7	Stop Data Recorder
8	Record file name and stop number
9	Examine display at wheel, Take digital photo, Record Photo File Name
10	Repeat 1-9 for each mode of disablement
Possible Modes of Disablement	
1	Unscrew equalizer hose from RROD equalizer housing
2	Unscrew equalizer hose from RROD valve
3	Fracture sight glass on RROD equalizer housing
4	Cut hose between valve and RROD stem

As summarized in Exhibit 5.21, the two TPMS tested responded somewhat differently to the four disablement modes, but both isolated the good tire from the tire with the induced failures.

Exhibit 5.21 – Dual Tire Equalizer Failure Modes Test Data

Disablement Mode	Initial Tire Pressure (psi) RROD/RRID	Disablement Tire Pressure (psi) RROD/RRID
Link Equalizer		
Mode 1	100/100	0/100
Mode 2	100/100	100/100
Mode 3	100/100	100/100
Mode 4	100/100	0/100
V-Tech Equalizer		
Mode 1	100/100	100/100
Mode 2	100/100	100/100
Mode 3	100/100	0/100
Mode 4	100/100	0/90

Mode 1 tested the responses of the systems to a hose unscrewing from the equalizer block. For the Link equalizer, this resulted in the total loss of air from the affected tire while the system isolated the intact tire (similar to the previously discussed leak tests). For the V-Tech equalizer, which uses a check valve on the equalizer block, the check valve actuated and no air was lost from either tire.

Mode 2 tested the check valve in the tire valve and the check valve in the equalizer block. During Mode 2 tests, both systems' check valves actuated in the equalizer block, and the tire valves held the "fault" tire at 100 psi. There was no loss of pressure from either tire in the Link or V-Tech equalizers. The systems isolated the tire on the intact side at 100 psi, and the tire valve held the "fault" tire at 100 psi.

Mode 3 tested the responses of the systems to a fractured cover glass on the visual indicator. The two systems reacted differently in this failure mode. For the Link equalizer, there was no leakage from either tire. However, the V-Tech equalizer behaved as if there was a tire failure resulting in loss of tire pressure in the RROD, and isolated the RRID tire.

Mode 4 essentially tested the reactions of the systems to a catastrophic tire failure by cutting the hose between the equalizer block and the tire valve. Both systems responded with the check valve in the equalizer block activating and isolating the side with the intact tire (or, in this case, the intact valve) from the tire with the cut hose as its pressure dropped to 0 psi.

5.1.5 Operator Interface Evaluation

The pressure gauge for the Link equalizer is a yellow-and-black display on the air valve. When the display is all yellow, it indicates the tire pressure is within +/- 2 percent of the target inflation pressure. Exhibit 5.22 displays the range of motion of the gauge. As pressure drops, a vertical black line appears in the center of the display. The bright yellow eye opens gradually as pressure drops, and the display becomes completely black if dual tire pressure drops approximately 10 psi below the specified level. The technicians and drivers at TRC stated that the yellow indicator gauge was easy to see during the walk-around inspection and gave a positive indication of the tire pressures.

Exhibit 5.22 – Link Equalizer Pressure Gauge

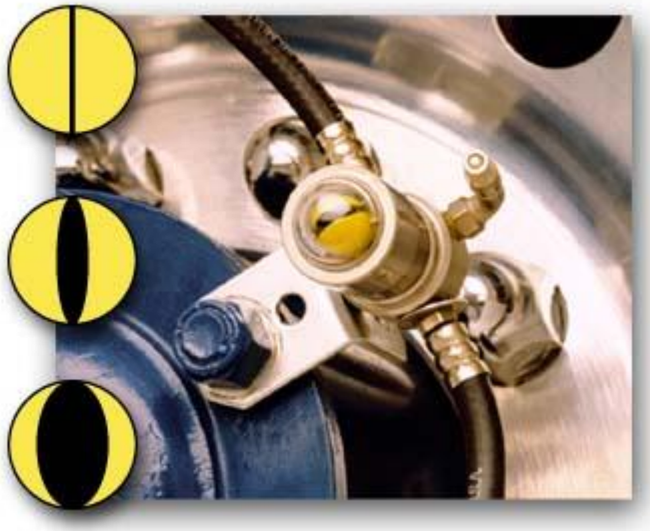
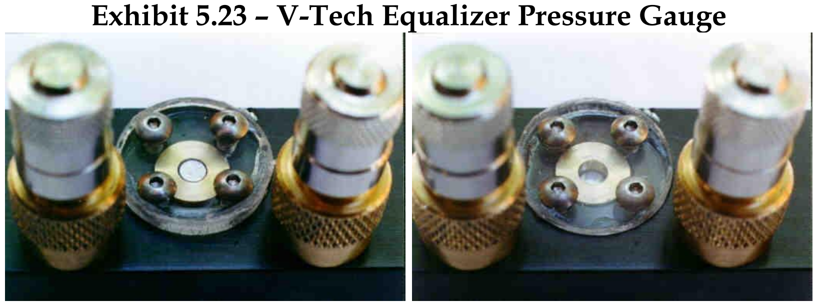


Exhibit 5.23 displays the V-Tech equalizer gauge, which consists of a pin that moves within a hole in the equalizer block. The tire pressure is in the target range when the pin is flush with the surface of the hole. The pin retracting into the hole indicated a pressure problem. TRC drivers and technicians stated that, while the gauge did provide a positive indication of the tire pressure condition, it could be difficult at times to observe the pin position due to the small size and limited travel of the pin.

Exhibit 5.23 – V-Tech Equalizer Pressure Gauge



5.2 Tire Pressure Monitoring Systems

Three types of tire pressure monitoring systems were evaluated:

- **Valve-Stem-Mounted Tire Pressure Monitors,** connected to the exterior of the tire at the valve stem
- **Wheel-Mounted Tire Pressure Monitors,** connected to the wheel, internal to the tire, typically using a metal band-strap
- **Tire-Mounted Tire Pressure Monitors,** connected to the tire itself, either molded into place or using a mounting similar to a tire patch

These systems use devices mounted on the wheel or tire that monitor the tire pressure and transmit an RF signal to a console containing a receiver and display, which is located in the tractor cab or is readable by an external handheld or drive-by gate reader.

Many systems also monitor temperature and convert the actual hot tire pressure to cold pressure so that meaningful data is related to the user. This temperature monitoring also has the added benefit of compensating for tire temperature increases due to sustained driving—thus, theoretically maintaining a low-pressure warning even as the pressure increases in the tire due to excess heat buildup.

5.2.1 Functionality Test

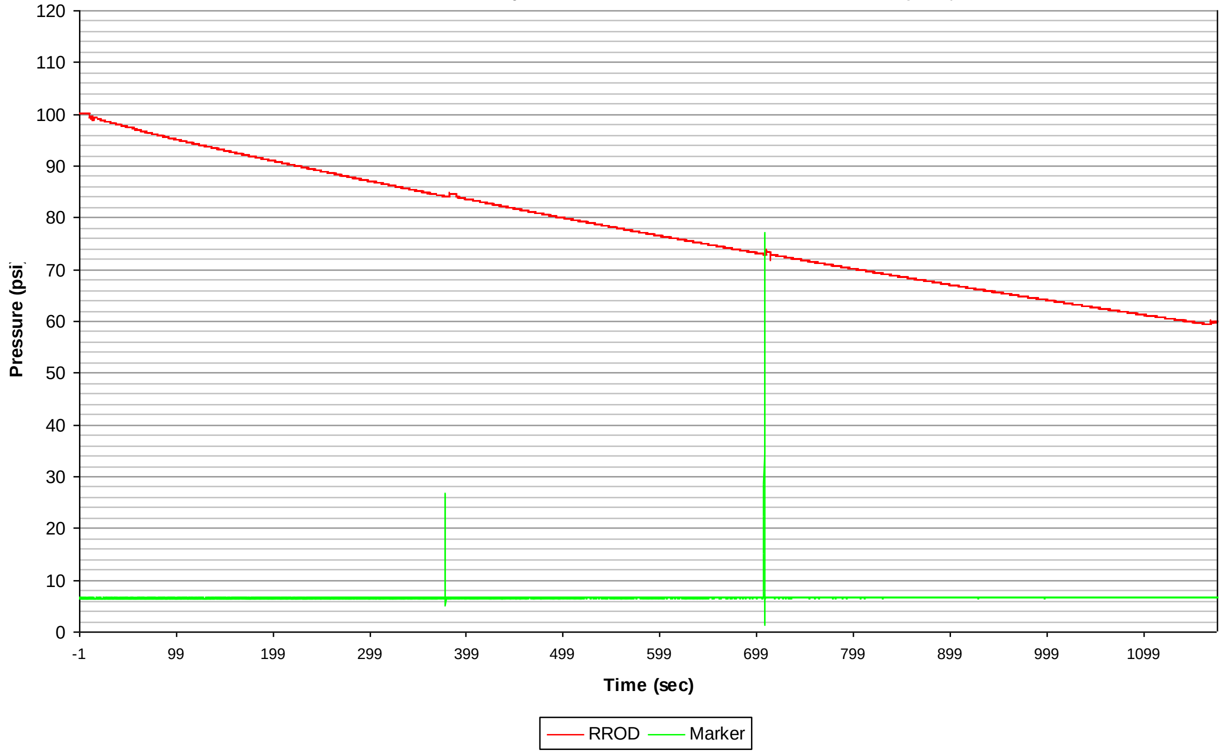
To understand how the TPMS technologies respond to slow air leaks, both static and dynamic functionality tests were performed. These tests involved initiating a slow leak (approximately a 1.5 psi/min initial leak rate) in a test tire while monitoring the inflation pressure through the DAS and recording warnings from the TPMS. This test was performed both statically (vehicle not in motion) and dynamically (at 45 mph around the high-speed test track). The test procedure in Exhibit 5.24 was used to perform this test of the TPMS.

Exhibit 5.24 – TPMS Functionality Test Procedures

Step Number	Procedure
Static	
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test data file
2	Set manifold to proper positions
3	Start Data Recorder, Sample at 10 Hz
4	Record Starting Tire Temperatures
5	Begin Slowly reducing RFS tire pressure at approximately 1.5 psi/min; do not exceed 40% below CIP for drive/trailer tires, or 25% below CIP for steer tires
6	Press marker switch when system indicates low tire pressure (for those systems which have multiple warning levels, mark when each level is met)
7	Stop Data Recorder
8	Record file name and stop number
9	Repeat 1-8 for LFID, RROD, RFIT, and LROT
Dynamic	
10	Set all tires to Cold Inflation Pressure (CIP=100psi), Create new test data file
11	Set manifold to proper positions
12	Start Data Recorder, Sample at 10 Hz
13	Record Starting Tire Temperatures
14	Begin Slowly reducing RFS tire pressure at approximately 1.5 psi/min
15	Drive vehicle at 45 mph until RFS reaches 40% below CIP for drive/trailer tires or 25% below CIP for steer tires or 2 hours have elapsed if those pressures are not reached.
16	Press marker switch when system indicates low tire pressure (for those systems which have multiple warning levels, mark when each level is met)
17	Stop Data Recorder
18	Record file name and stop number
19	Wait 30 minutes, or until tires return to temperatures recorded in Step 13
20	Repeat 10-19 for LFID, RROD, RFIT, and LROT

Exhibit 5.25 shows the results of the static functionality tests on a valve-stem-mounted TPMS.

Exhibit 5.25 – Static Functionality Test of Valve-Stem-Mounted TPMS (RROD)



For this system, Exhibit 5.25 shows that an initial leak rate of 1.5 psi/minute on the RROD resulted in the initial warning indicating at 84 psi and a second warning indicating at 72 psi, as shown by the Marker channel. These readings generally correspond to the manufacturer's specification of an initial warning indicator at 12.5 percent below CIP (87.5 psi for our test) and a second indicator at 25 percent below CIP (75 psi for our test).

Exhibit 5.26 shows the results of the dynamic functionality test for this same system. The initial warning was indicated at 86 psi (marker signal not shown) and a second warning indicator given at 74 psi (marker shown), which correspond to the manufacturer's warning specifications of 87.5 psi and 75 psi respectively for our test CIP.

Exhibit 5.26 – Dynamic Functionality Test of Valve-Stem-Mounted TPMS (RROD)

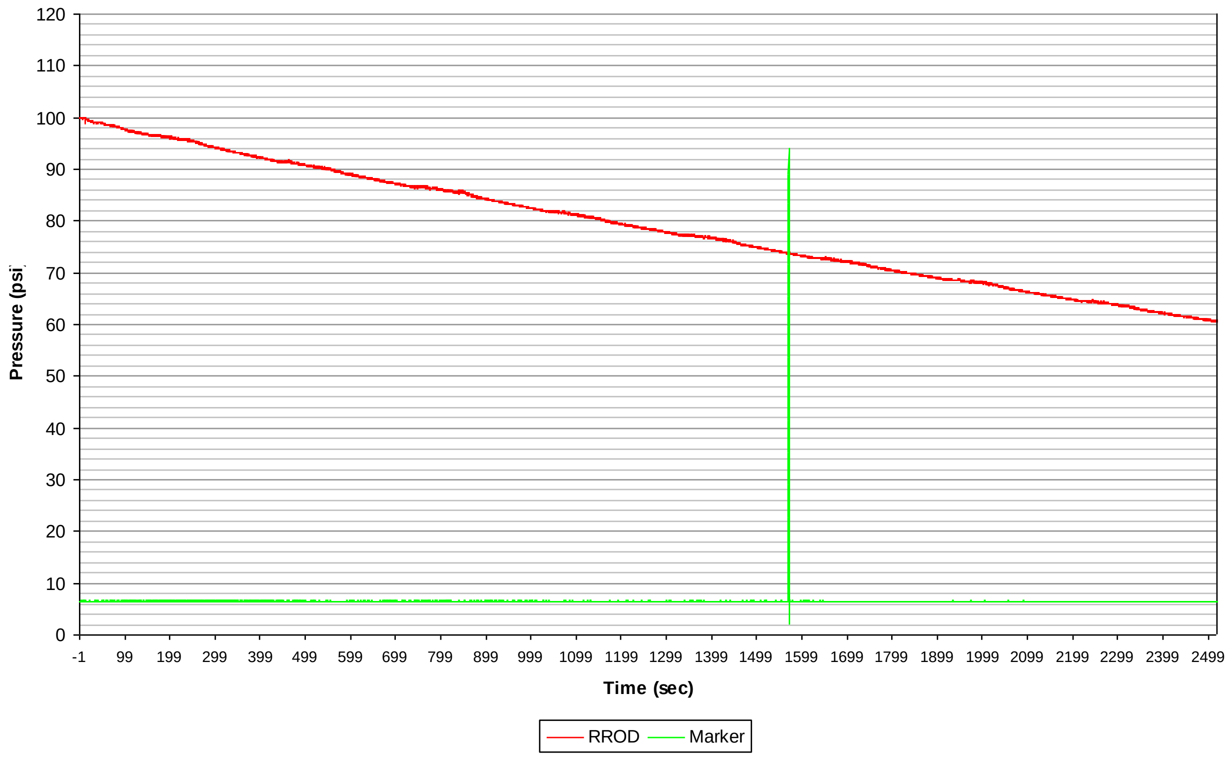


Exhibit 5.27 shows similar results for a static functionality test of a wheel-mounted TPMS. With this system, the manufacture sets an initial “slow air leak” warning to be indicated when the pressure in the tire decreases by 3 psi. A second warning for “low pressure” is set to indicate a warning when the tire pressure reaches a user-adjustable level, in our case set at 20 psi below CIP (or 80 psi). The measurements in Exhibit 5.27 generally correspond to the manufacturer’s specification with an initial warning indicator at 98 psi in our test and a second indicator at 79 psi in our test.

Exhibit 5.27 – Static Functionality Test of Wheel-Mounted TPMS (RROD)

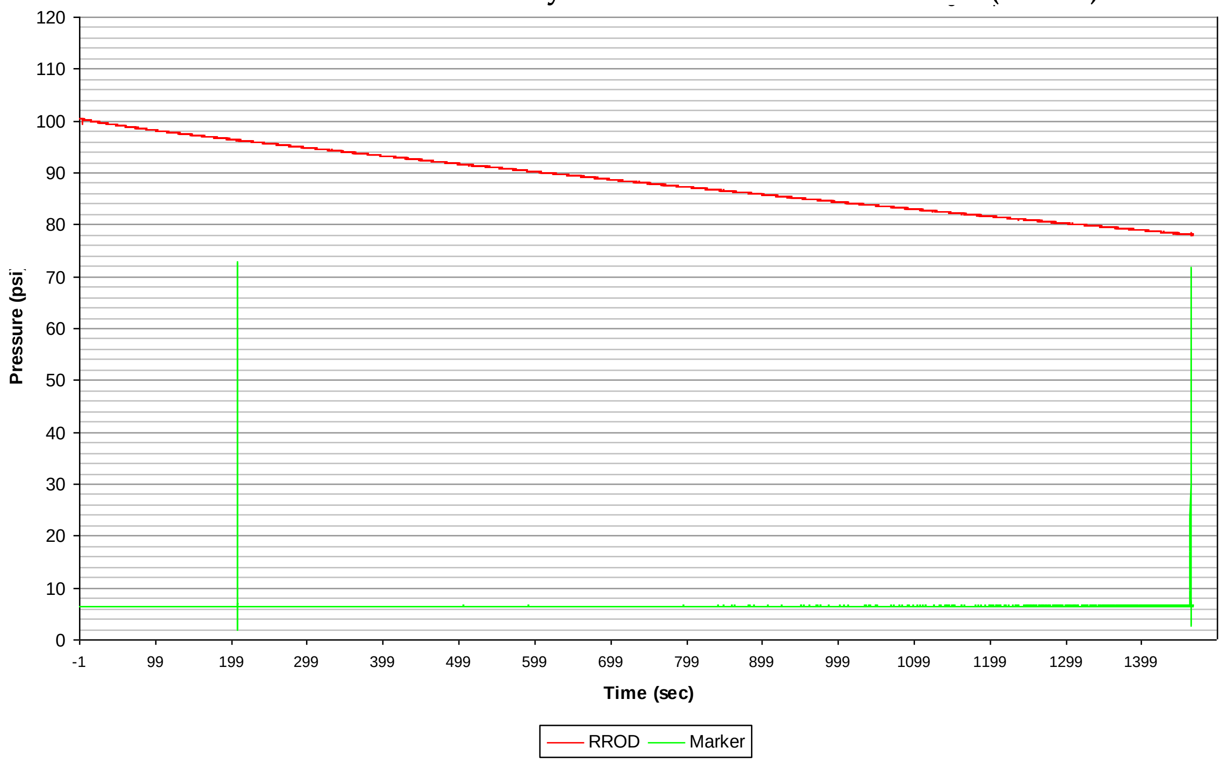
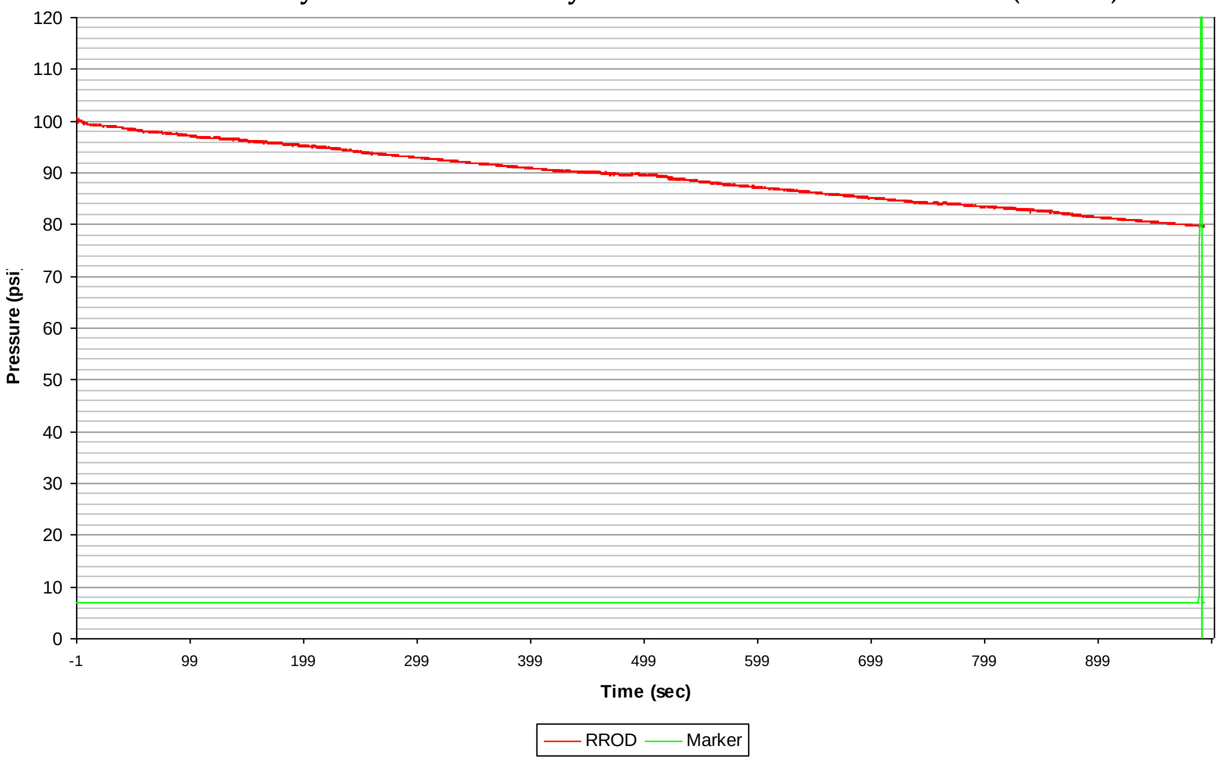


Exhibit 5.28 shows the results of a dynamic functionality test for the same wheel-mounted TPMS in Exhibit 5.27. In this test, an initial warning is indicated for a "slow leak" at 98 psi (not indicated by the marker) and a "low pressure" warning is indicated at 80 psi (as noted above, the specification from the manufacturer called for the first warning at 3 psi below target and a second warning at 20 psi below target).

Exhibit 5.28 – Dynamic Functionality Test of Wheel-Mounted TPMS (RROD)



In general, each system tested, valve- or wheel-mounted, had the base-level functionality expected based on their individual designs. All provided warnings, although the deviation from the expected warning pressure varied from system to system and tire to tire given a slow leak (approximately 1.5 psi/min initial rate). The exact deviations from the expected warning thresholds were tested and analyzed in the warning threshold level tests in the next section.

Static and dynamic functionality tests were not performed on the tire-mounted TPMS because the systems tested did not use in-cab displays to provide a real-time warning of under-inflation of the tires. As described earlier in the report, they use a handheld or drive-through gate reader to measure and record individual tire pressures.

5.2.2 Threshold Warning Level Test

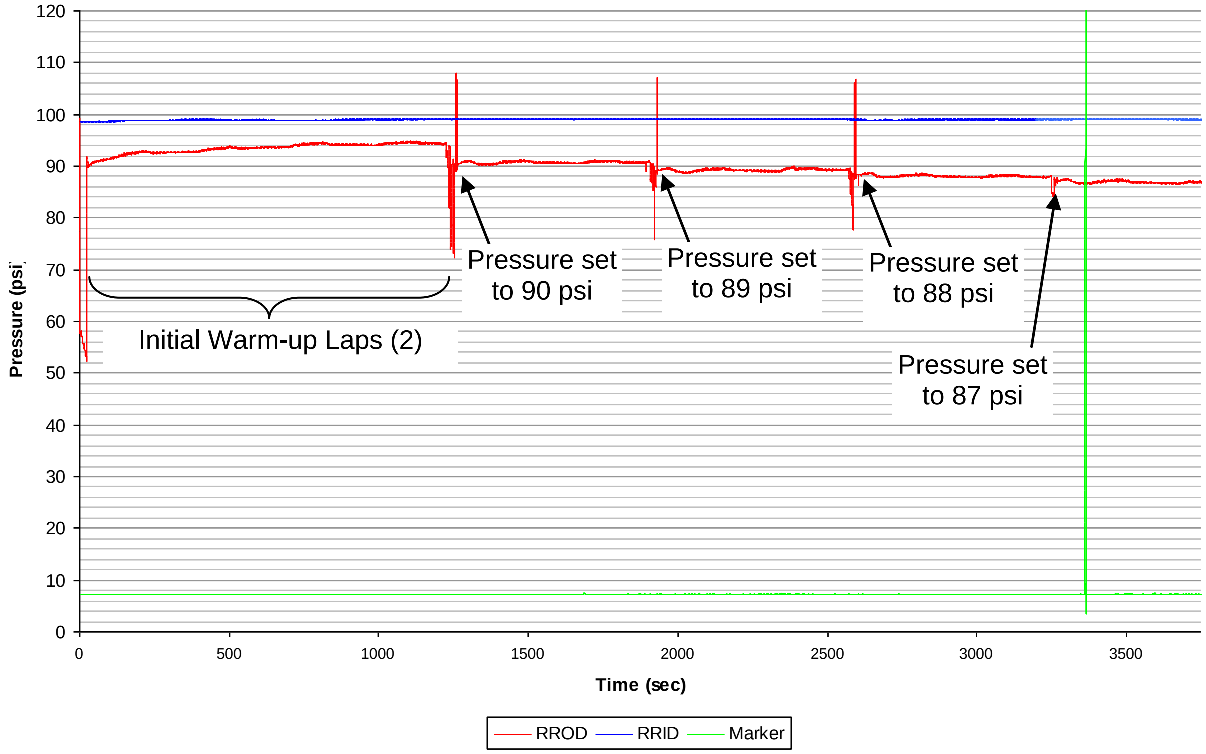
The objective of the threshold warning level tests was to understand the threshold levels at which TPMS indicate a low tire pressure warning. For the testing of each TPMS, the test procedure in Exhibit 5.29 was used.

Exhibit 5.29 – TPMS Threshold Warning Level Test Procedures

Step Number	Procedure
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test data file
2	Set test manifold to proper positions
3	Start Data Recorder, Sample at 10 Hz
4	Record Starting Tire Temperatures
5	Deflate RFS tire to 2 psi above expected warning threshold as indicated by the manufacturer.
6	Drive vehicle at 45 mph for 20 minutes (2 laps) around the high speed track
7	Stop Vehicle
8	Reset test tire pressure to 2 psi above expected warning threshold
9	Drive vehicle at 45 mph for 10 minutes (1 lap) around high speed track
10	Press marker switch when system indicates low tire pressure
11	Stop vehicle
12	If no warning observed, decrease tire pressure 1 psi below previously set value
13	Repeat 9-12 until warning is observed or tire pressure reaches 40% below CIP for drive/trailer tires or 25% below CIP for steer tires (for those systems which have multiple warning levels, repeat until all warning level thresholds are met)
14	Stop Data Recorder
15	Record file name and stop number
16	Wait 30 minutes, or until tires return to temperatures recorded in Step 4
17	Repeat 1-16 for LFID, RROD, RFIT, and LROT

Exhibit 5.30 shows the results of a threshold warning level test on an Advantage PressurePro valve-stem-mounted TPMS installed on the tractor-trailer vehicle platform.

Exhibit 5.30 – Advantage PressurePro Valve-Stem-Mounted TPMS Threshold Warning Level Test



As shown in Exhibit 5.30, the test tire was set at 90 psi (2 psi above the expected warning threshold). The test vehicle was driven at 45 mph for two laps (7.5 miles each) around the test track. The pressure was then reset at 90 psi (down from a hot inflation pressure of 96 psi) and the vehicle was driven for another lap at 45 mph. The system did not indicate any warning during that lap; therefore, the pressure was reduced an additional 1 psi, and an additional 45 mph lap was driven. This process was repeated until a warning was indicated at 87 psi just after beginning the fourth test lap, as indicated in Exhibit 5.30 by the Marker channel. Additional tests were performed on the RFS, LFID, RFIT, and LROT tires for this system, and on another valve-stem-mounted system (IVTM) installed on the motorcoach platform. The results are shown in Exhibit 5.31.

Exhibit 5.31 – Valve-Stem-Mounted TPMS Threshold Warning Level Tests Results

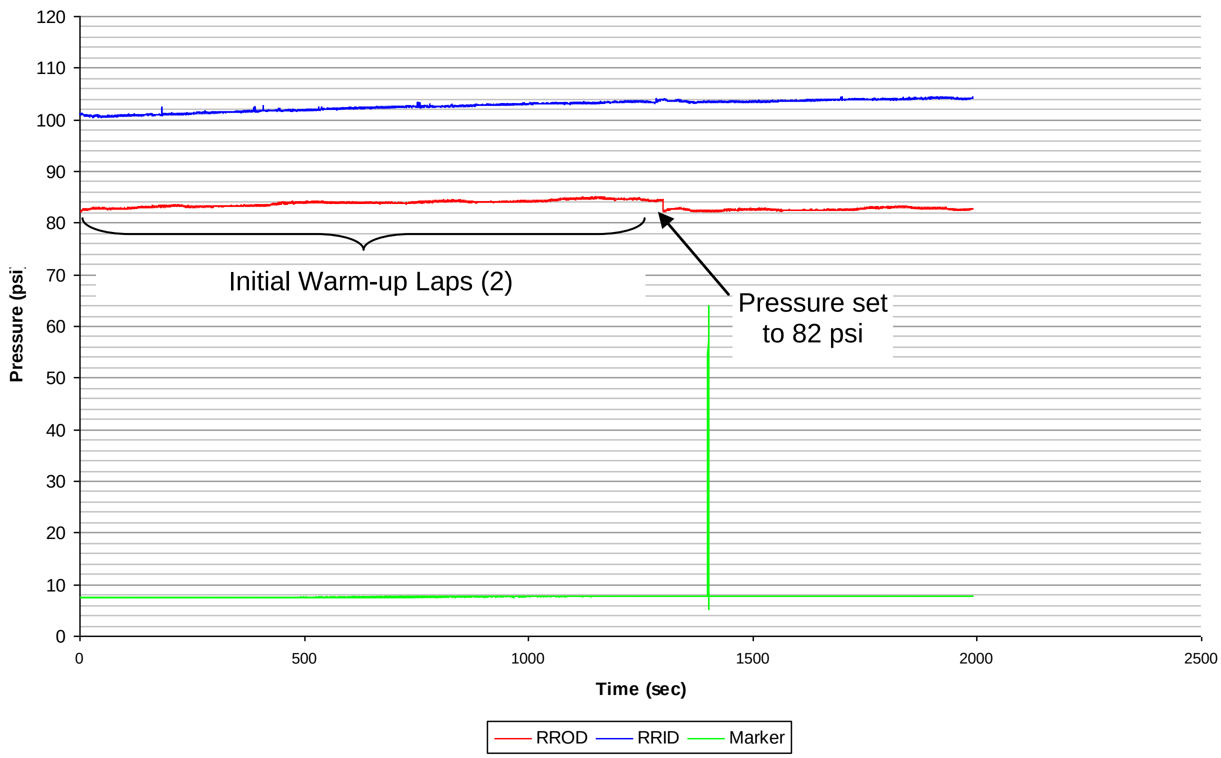
Advantage PressurePro – Tractor-Trailer	
Tire Position	1st Warning Threshold (psi)
RFS	88
LFID	87
RROD	87
RFIT	88
LROT	87

IVTM – Motorcoach		
Tire Position	1st Warning Threshold (psi)	2nd Warning Threshold (psi)
RFS	88	74
LFID	87	75
RTAG	86	77

The results in Exhibit 5.31 show that for each system, the warning thresholds were consistent across all of the tires tested. The Advantage PressurePro TPMS installed in the tractor-trailer was set up to provide an initial warning at 12.5 percent below CIP (or 87.5 psi), which is consistent with the data collected.[15] The TPMS installed in the motorcoach provided an initial low-pressure warning between 86 and 88 psi and a second low-pressure warning between 74 and 77 psi.

Exhibit 5.32 provides a chart of a threshold warning level test for a wheel-mounted TPMS installed on the tractor-trailer vehicle platform.

Exhibit 5.32 – Wheel-Mounted TPMS Threshold Warning Level Test



[15] A second warning was also available from this system, but the threshold where this warning occurred was not tested due to an initial failure to record the warning with the data acquisition system, which was later corrected.

As shown in Exhibit 5.32, the wheel-mounted TPMS tested initiated a warning at 82 psi. This occurred during the first 45-mph lap run after the two initial warm-up laps. Additional tests were performed on the RFS, LFID, RFIT, and LROT tires for this system, and on a different wheel-mounted system installed on the motorcoach platform. The results are shown in Exhibit 5.33.

The expected warning threshold for the TPMS installed in the tractor-trailer platform was the default setting of 80 psi (20 psi below CIP) for the tractor tires and 70 psi (30 psi below CIP) for the trailer tires.[16] The expected warning threshold for the TPMS installed in the motorcoach platform was 90 psi (20 psi below CIP), also the default setting.[16]

Exhibit 5.33 – Valve-Stem-Mounted TPMS Threshold Warning Level Tests Results

Tire-SafeGuard– Tractor-Trailer	
Tire Position	1st Warning Threshold (psi)
RFS	84
LFID	81
RROD	82
RFIT	71
LROT	71

SmarTire – Motorcoach	
Tire Position	1st Warning Threshold (psi)
RFS	89
LFID	91
RTAG	90

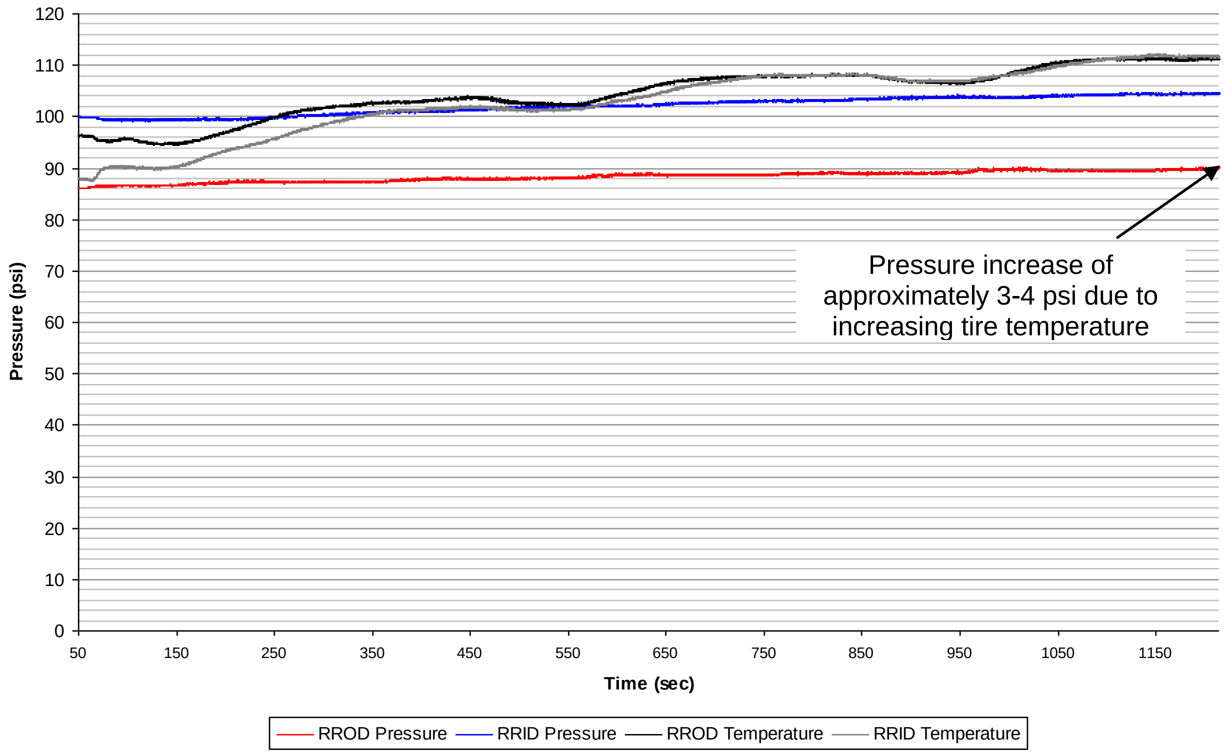
Each of the four TPMS tested provided warnings with a very good correlation with the expected values and between the tire assemblies tested.

5.2.3 Loaded Test at High Speed

This test examined the effects of tire heating, due to sustained high-speed driving, on the warning indicator of the TPMS. As vehicles are driven, heat builds up in the tire due to a number of factors—mostly as a result of rolling friction with the road surface, but also due to flexing the sidewall of the tire (which is increased if the tire is under inflated), heat from braking and other radiant sources, and tire scrubbing during turning and cornering. This increase in heat results in an increase of pressure inside the tire. Exhibit 5.34 shows an example of this effect.

[16] This value is configurable by the vehicle operator.

Exhibit 5.34 – Example of Pressure Increase Due to Sustained High-speed Driving



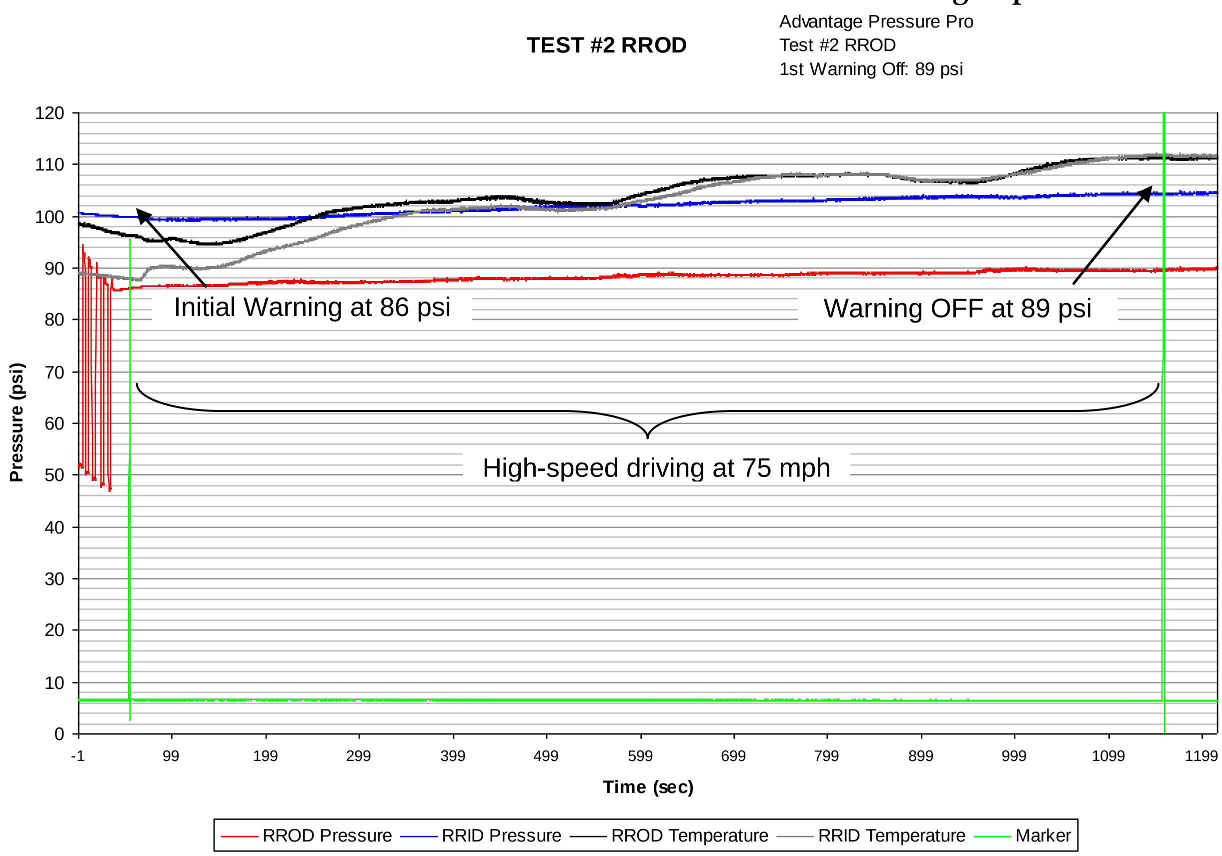
To accommodate this effect, some TPMS measure the tire temperature and compensate for the increased pressure by calculating an equivalent CIP. This test is designed to determine, for the TPMS technologies selected for testing here, whether they compensate for the increased pressure as a result of sustained high-speed driving. Exhibit 5.35 shows the general test procedures performed.

Exhibit 5.35 – TPMS Loaded Test at High-Speed Test Procedures

Step Number	Procedure
1	Set all tires to Cold Inflation Pressure (CIP=100 psi), Create new test file
2	Set manifold to proper positions
3	Start Data Recorder, Sample at 10 Hz
4	Record Starting Tire Temperatures
5	Deflate RFS tire to 2 psi below the average warning threshold determined in Test #1
6	Drive the vehicle at 45 mph for 10 minutes (1 lap) around HST
7	Press marker switch when system indicates low tire pressure
8	If no warning observed, stop vehicle, reduce tire pressure an additional 2 psi, repeat Steps 6-7 until a warning is observed or tire reaches 40% below CIP for drive/trailer tires or 25% below CIP for steer tires
9	Drive vehicle at 75 mph for 22.5 miles (3 laps) around HST
10	Press marker switch again if/when low tire pressure indicator is extinguished
11	Stop Data Recorder
12	Record file name and stop number
13	If the low tire pressure warning is maintained, restore tire to 100 psi
14	Drive vehicle at 45 mph around HST until warning indicator is extinguished
15	Wait 30 minutes, or until tires return to temperatures recorded in Step 4
16	Repeat 1-15 for LFID, RROD, RFIT, and LROT

Exhibit 5.36 illustrates the pressure changes over time for a valve-stem-mounted TPMS on the tractor-trailer vehicle platform.

Exhibit 5.36 – Valve-Stem-Mounted TPMS Loaded Test at High Speed



In Exhibit 5.36, the pressure in the RROD tire was deflated to 86 psi, triggering a warning indicator by the valve-stem-mounted TPMS. The fully loaded vehicle then was driven at 75 mph around the high-speed test track for three laps. Exhibit 5.36 shows that the temperature for both the RROD and the RRID increase during this sustained high-speed driving. As shown in Exhibit 5.36, the warning indicator was extinguished when the temperature increased sufficiently to cause an increase in tire pressure to 89 psi.

Additional tests were performed on the RFS, LFID, RFIT, and LROT tires for this system, and on a valve-stem-mounted system installed on the motorcoach platform. The results are shown in Exhibit 5.37.

Exhibit 5.37 – Valve-Stem-Mounted TPMS Loaded Test at High Speeds Results

Tire Position	Initial Warning Pressure (psi)	Temperature Change (degrees F)	Warning Status After Driving (ON/OFF)	Final Pressure (psi)
Advantage PressurePro – Tractor-Trailer				
RFS	86	+21	OFF	89
LFID	86	+16	OFF	88
RROD	86	+15	OFF	89
RFIT	86	+20	OFF	89
LROT	86	+14	ON	89
IVTM – Motorcoach				
RFS	76	+33	ON	82
LFID	75	+13	ON	72*
RTAG	76	+30	ON	80

* Note: Although this test was conducted on the same day as the RFS and RTAG, the ambient temperature for the LFID test fell to 11 degrees F – due to the sunset, possibly resulting in erroneous readings by the data collection equipment.

As shown in Exhibit 5.37, the valve-stem-mounted TPMS installed on the tractor-trailer platform did not compensate for increased tire pressure due to heating, which resulted in warnings being extinguished once the pressure exceeds the warning threshold. However, the valve-stem-mounted TPMS installed on the motorcoach platform shows that the warning indicators remained on during the test. The manufacturer indicated the use of two methods to compensate for this effect. First, the manufacturer uses a hysteresis effect where a warning is only extinguished once the pressure exceeds the warning threshold by a specific amount. According to the manufacturer:

> "For example, if the pressure falls down below the under inflation threshold of -20% and then the tire is filled up again, the pressure must be above -15 %. 100 psi ref. pressure -> pressure drop to 80 psi -> filling up to 85 psi -> warning disappears. The wheel module transmits an actual pressure value when the new measured value is at least a 4 psi change than the last transmitted value. Then the wheel module will constantly update the ECU until the pressure is stabilized."[17]

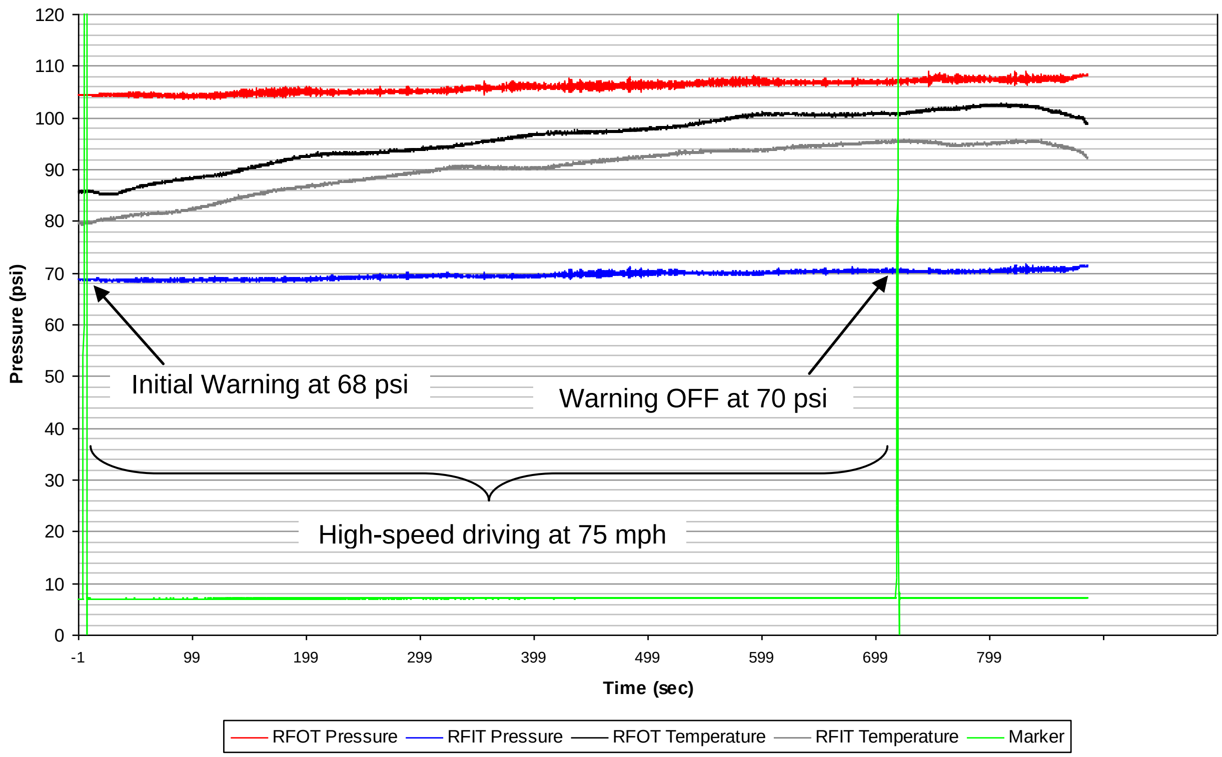
To translate, in a vehicle with a target pressure of 100 psi deflating the tire to 80 psi triggers a warning indicator. This warning indicator would not be extinguished until the pressure increased above 85 psi. Secondly, the manufacturer compensates for temperature by a proprietary algorithm:

[17] McNamee, Thomas, e-mail to the authors, December 16, 2005.

> "We have on the ECU an algorithm designed to determine when a vehicle is starting out cold, then when pressure increases which causes the tire to run hot. This prevents false alarms and accurate reporting of over and under inflation and address the issue of temperature pressure relationships."[17]

Exhibit 5.38 shows a loaded test at high speed for a wheel-mounted TPMS on the tractor-trailer vehicle platform.

Exhibit 5.38 – Wheel-Mounted TPMS Loaded Test at High Speed



As shown in Exhibit 5.38, the wheel-mounted TPMS also exhibited increased pressure effects due to tire heating, but the warning indication was discontinued once the pressure reached the warning threshold.

Additional tests were performed on the RFS, LFID, RFIT, and LROT tires for this system, and on a wheel-mounted SmarTire system installed on the motorcoach platform. The results are shown in Exhibit 5.39.

Exhibit 5.39 – Wheel-Mounted TPMS Loaded Test at High Speeds Results

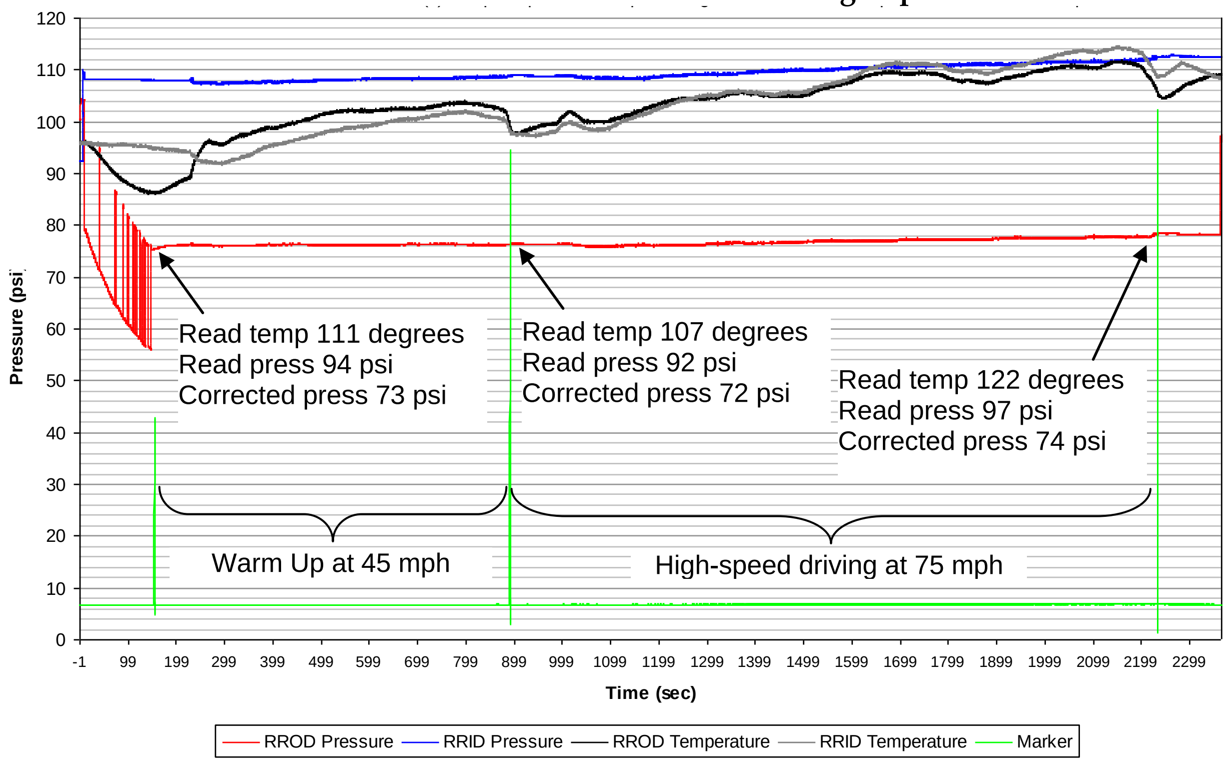
Tire Position	Initial Warning Pressure (psi)	Temperature Change (degrees F)	Warning Status After Driving (ON/OFF)	Final Pressure (psi)
Tire-SafeGuard – Tractor-Trailer				
RFS	78	+20	ON	82
LFID	78	+12	OFF	81
RROD	78	+3	OFF	79
RFIT	68	+16	OFF	70
LROT	68	+22	ON	72
SmarTire – Motorcoach				
RFS	88	+16	OFF	93
LFID	88	+26	ON	92
RTAG	88	+24	OFF	94

In Exhibit 5.39, the wheel-mounted system on the tractor-trailer platform showed a significant amount of variation in the results. The warning indicator remained on during the tests on the RFS and LROT—there was a significant increase in temperature and an increase in pressure above the warning thresholds of 80 psi on the tractor tires and 70 psi on the trailer tires. In contrast, the warning indicator was extinguished on tests of the LFID, RROD, and RFIT, which had lower temperature increases and resulting lower pressure increases. This might be a result of the ability of the compensation algorithm employed to detect and compensate for large and rapid increases in temperature but not for the more gradual increases.

The TPMS installed in the motorcoach platform also exhibited some variation in the test results, with the RFS and RTAG warning indicators being extinguished in their respective tests, but the LFID warning indicator not being extinguished in its test. However, as Exhibit 5.16 shows, the pressure in the LFID only reached 92 psi (as opposed to 93 psi and 94 psi for the RFS and RTAG) before the test time expired. Therefore it is unknown whether the warning indicator would be extinguished during further driving.

Exhibit 5.40 shows the loaded test at high speed of an eTire TPMS installed on the tractor-trailer platform. As we noted, the eTire TPMS selected for this test program did not have an in-cab display available, but relied instead on a handheld or gate reader to capture pressure readings. There was no practical way to observe while the CMV was being driven on the track when warnings were or were not indicated, so the test procedures for this system were modified slightly to enable manual reading of the test tire. The test tire's sensor patch was read with the manual reader before the test, after the warm-up lap, and again after completing three 75 mph laps around the test track. Exhibit 5.40 shows the data collected from this test on the RROD tire.

Exhibit 5.40 - eTire TPMS Loaded Test at High Speed



In Exhibit 5.40, the handheld reader recorded the temperature read by the sensor, the pressure read by the sensor, and the corrected pressure as a result of the sensor compensating for the temperature inside the tire. Exhibit 5.40 shows that the eTire TPMS sensor compensated for the increased temperature and pressure due to sustained high-speed driving. Exhibit 5.41 show the results of each of the tests for the tire-mounted TPMS.

Exhibit 5.41 – eTire TPMS Loaded Test at High Speeds Results

eTire – Tractor-Trailer									
	Start			After Warm Up			After High-Speed Driving		
Tire Position	Read Temp. (deg. F)	Read Press. (psi)	Corrected Press. (psi)	Read Temp. (deg. F)	Read Press. (psi)	Corrected Pressure (psi)	Read Temp. (deg. F)	Read Press. (psi)	Corrected Press. (psi)
RFS	Not Recorded			95	98	80	131	107	**81**
LFID	87	96	78	89	96	79	107	98	**76**
RROD	111	94	73	107	92	72	122	97	**74**
RFIT	93	91	73	98	95	75	105	97	**75**
LROT	95	91	71	96	92	72	107	94	**73**

Exhibit 5.41 shows that the eTire TPMS appears to compensate effectively for the increased tire temperatures and pressures as a result of tire heating due to sustained high-speed driving.

5.2.4 Disablement Test

This test determines the system's ability to provide a warning indicator if/when it is disabled either by an intentional act or as a result of a failure of a system or component. Based on experience with each system, the specific configuration of the system, and the possible ways the system might be disabled intentionally or non-intentionally, several disablement modes were tested for each system.

Exhibit 5.42 shows the disablement modes tested for the valve-stem-mounted TPMS installed on the tractor-trailer vehicle platform.

Exhibit 5.42 – Advantage PressurePro Disablement Results

Advantage PressurePro – Tractor-Trailer			
Mode #	**Purpose**	**Description**	**Result**
1	Simulate Loose Sensor	Slightly unscrew sensor from RROD valve stem (ensure air leakage can be heard)	No response from system
2	Simulate Disconnected Sensor	Completely unscrew sensor from LROT valve stem	Display indicated warning of 0 psi immediately
3	Simulate Disconnected Trailer Antenna	Completely unscrew antenna from outside rear of tractor cab	System lost signal from RROT and RRIT sensors
4	Simulate Disconnected Display Antenna	Completely unscrew antenna from display unit in cab	System lost signal with all tires except RFS, RFS, and RROD
5	Simulate Swapped Sensors	Swap RROD and LFID sensors	System swapped pressure readings
6	Simulate Lost Sensor	Quickly remove RROD sensor and throw it > 100 ft	Display indicated warning of "---" immediately
7	Simulate Impact from Hammer	Strike LFID sensor with hammer once	No response from system

Exhibit 5.42 shows the requirement for utilizing remote antenna assemblies on the rear of the tractor and attached to the display—because disconnecting these antennas resulted in loss of signal from several sensors. The test also showed that the system is able to detect a lost or disconnected sensor and displays this as a reading of 0 psi.

Exhibit 5.43 shows the disablement modes tested for the valve-stem-mounted TPMS installed on the motorcoach platform.

Exhibit 5.43 – IVTM Disablement Results

IVTM – Motorcoach			
Mode #	**Purpose**	**Description**	**Result**
1	Simulate Swapped Sensors	Switch RROD and LROD sensors	System switched pressure readings for tires
2	Simulate Loose Sensor	Slightly unscrew sensor from RFS valve stem (ensure air leakage can be heard)	Display indicated low pressure with "STOP" light illuminated
3	Simulate Disconnected Sensor	Completely unscrew sensor from RFS valve stem	Tire leaked slowly and display indicated low pressure with "STOP" light illuminated
4	Simulate Severed Hose	Cut hose connecting the RFS sensor to the RFS valve stem	Tire leaked and display indicated low pressure with "STOP" light illuminated
5	Simulate Impact from Hammer	Strike RFS sensor with hammer once	No affect on system

In Exhibit 5.43, the system displayed a "STOP" indicator when it detected a disconnected or loose sensor, or when it detected a disconnected input hose. This result was expected.

Both valve-stem-mounted systems in Exhibits 5.42 and 5.43 display sensor readings when the sensors have been switched between tires but pressures indicated correspond to the incorrect tire position. Although expected, this highlights an issue with valve-stem-mounted systems as they are often removed to replace tires, inspect brakes, or perform other vehicle maintenance. Therefore, either careful records must be kept as to which sensor goes on which tire, or the systems must be "retrained" after the maintenance is performed. While sounding straightforward, in a maintenance garage with many tire technicians mechanics or in a shop where some of the technicians are not familiar with the TPMS, this could prove difficult.

Exhibit 5.44 shows the disablement modes tested for a wheel-mounted TPMS installed on the tractor-trailer vehicle platform.

Exhibit 5.44 – Tire-SafeGuard Disablement Results

Tire-SafeGuard – Tractor-Trailer			
Mode #	**Purpose**	**Description**	**Result**
1	Simulate Fractured Sensor Due to Damage by Tire Mounting Machine	Install sensor which was accidentally damaged by the tire mounting machine during installation.	System indicated 104 psi with 100 psi in tire
2	Simulate Disconnected Tractor Antenna	Completely unscrew tractor antenna cable from tractor receiver	No readings from sensors
3	Simulate Disconnected Trailer RX Antenna	Completely unscrew RX antenna cable from trailer receiver	No readings from sensors
4	Simulate Disconnected Trailer TX Antenna	Completely unscrew TX antenna cable from trailer receiver	No readings from sensors
5	Simulate Swapped Trailer Sensors	Switch LFOT wheel/tire with RRIT wheel/tire (do not re-train)	System indicated pressure of new tire position in original tire position
6	Simulate Swapped Sensors Between Tractor and Trailer	Switch LFOT wheel/tire with LROD wheel/tire (do not re-train)	System indicated pressure of new tire position in original tire position
7	Simulate Loss of Battery Power	Disconnect battery, wait 10 minutes, reconnect battery.	System functioned normally

Exhibit 5.45 shows the disablement modes tested for the wheel-mounted SmarTire TPMS installed on the motorcoach platform.

Exhibit 5.45 – SmarTire Disablement Results

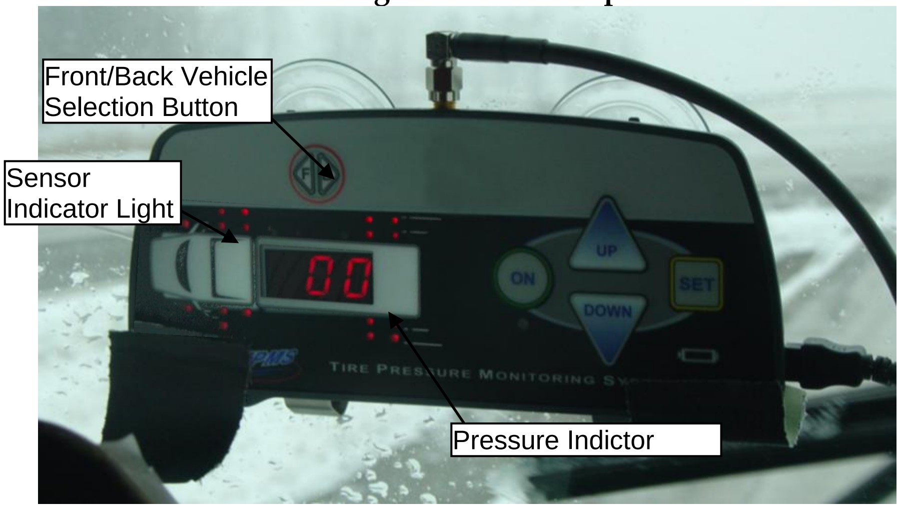
SmarTire – Motorcoach			
Mode #	**Purpose**	**Description**	**Result**
1	Simulate Fractured Sensor Due to Damage by Tire Mounting Machine	Install sensor which was accidentally damaged by the tire mounting machine during installation.	No response from system, system continued to read normally.
2	Simulate Disconnected One Antenna While Stationary	Completely unscrew one antenna cable from receiver	System functioned normally
3	Simulate Disconnected Both Antennas	Completely unscrew both antennas from receiver and drive at 45 mph	"E1" Message Displayed
4	Simulate Disconnected One Antenna While In Motion	Completely unscrew antenna #1 from receiver and drive at 45 mph and initiate a leak in RFS and RTAG	Display indicated warning of low pressure in RFS.
5	Simulate Disconnected One Antenna While In Motion	Completely unscrew antenna #2 from receiver and drive at 45 mph and initiate a leak in RFS and RTAG	Display indicated warning of low pressure in RTAG.

In Exhibit 5.45, the system responded with an error message when it could not receive signals from any sensors due to disconnection of the antennas. When only the front antenna was disconnected, the RFS sensor did not record a low-pressure warning, but the RTAG sensor did (Mode #5). Conversely, when the rear antenna was disconnected, the RTAG sensor did not record a low-pressure warning, but the RFS sensor did (Mode #4).

5.2.5 Operator Interface Evaluation

Advantage PressurePro used an aftermarket-type display interface that attached by suction to the windshield of the cab, as shown in Exhibit 5.46. The display had a graphic of a tractor and trailer with an LED display for the pressure and warning lights for each of the tires. If more than one tire sensor provides a warning, the system cycles through each affected tire. A flashing warning light and an audible alarm alerts the driver to low pressure. The light flashes on the LED display once per second for the first alert level (12.5 percent below set CIP) and twice per second for the second alert level (25 percent below set CIP). The system also provides alerts for low sensor batteries, missing sensors, and reminder alerts beyond the initial warning for low pressure. In addition, the display unit includes a number of buttons to control various functions of the system. Of interest, the up/down arrow keys allow the operator to check individual tire pressures, and the F/B button allows the operator to monitor only the front or back vehicle in the case of combination units or on an RV towing a vehicle.

Exhibit 5.46 – Advantage PressurePro Operator Interface



The IVTM used an LCD display in conjunction with a large "STOP" light, a "SLOW" light with a turtle icon, and an audible alarm. Moderate inflation problems result in a "SLOW" or turtle light illumination and an audible signal that sounds for a period of 10 minutes. Pressing the "?" button multiple times displays in sequence the position of the affected tire, tire pressure, and an action graphic on the LCD of either a wrench (system maintenance required) or tire pump (inflation required). An additional LCD graphic indicates a creeping pressure loss. A major inflation issue results in a "STOP" light illumination and a one-minute audible signal similar to the 10-minute audible signal, except for duration. In the event of multiple warnings, the system cycles through each affected tire. The operator can inspect the status of any sensor-equipped tire by pressing an inspection button (magnifying glass and tire icon). Exhibit 5.47 shows this display.

Exhibit 5.47 – IVTM Operator Interface

The test drivers commented that the interface in Exhibit 5.47 for the IVTM was difficult to read in the daytime. The black and red display, in addition to the "STOP" and "SLOW" lights, was not bright enough to overcome the high-light conditions during the daytime. However, this display worked exceptionally well during the nighttime testing.

The operator interface for Tire-SafeGuard, shown in Exhibit 5.48, includes an LCD display designed to be mounted onto the dashboard. It uses a single LCD screen for both the tractor and trailer displays (cycling through the tires on each in turn) in conjunction with an audible alarm. In the event of an inflation problem, the system sounds an alarm for 8 seconds and displays the location of the tire, an icon indicating the warning type (low pressure, slow air leak, high tire pressure, or high temperature), the measured tire pressure, and the tire temperature. In the event of multiple warnings, the system cycles through each affected tire continuously until the condition is remedied. Warnings could be temporarily cleared using a small button on the front panel, but the underlying condition persisted. The warnings reappeared during the next tire pressure data transmission cycle.

Exhibit 5.48 – Tire-SafeGuard Operator Interface

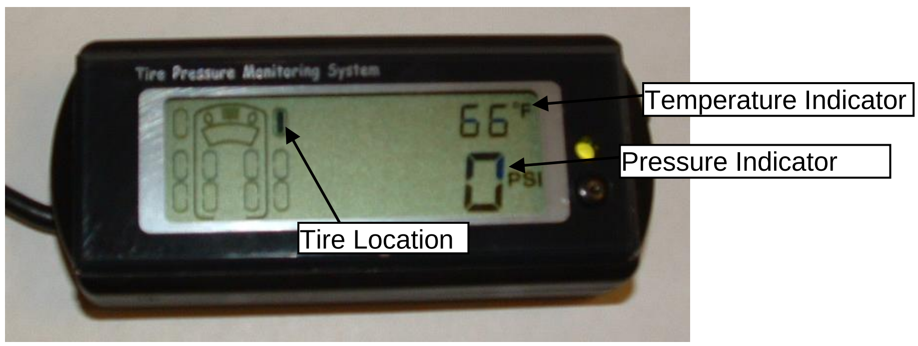
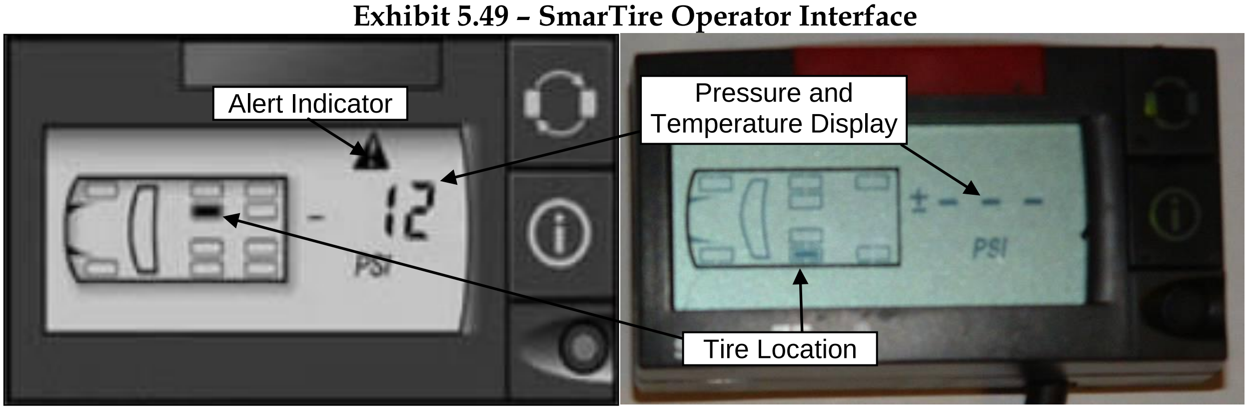


Exhibit 5.49 shows the operator interface for SmarTire. It includes an LCD with the image of a motorcoach and an audible alarm. A low pressure or a deviation in pressure results in the illumination of the alert indicator, sounding of an audible alarm, and (in the case of low pressure) illumination of a low-pressure warning light (image of a flat tire). The driver can acknowledge and turn off the audible alarm, but the alert remains active until tires are properly re-inflated. A driver can inspect the tire pressures, temperature, and pressure deviation readings at any time.

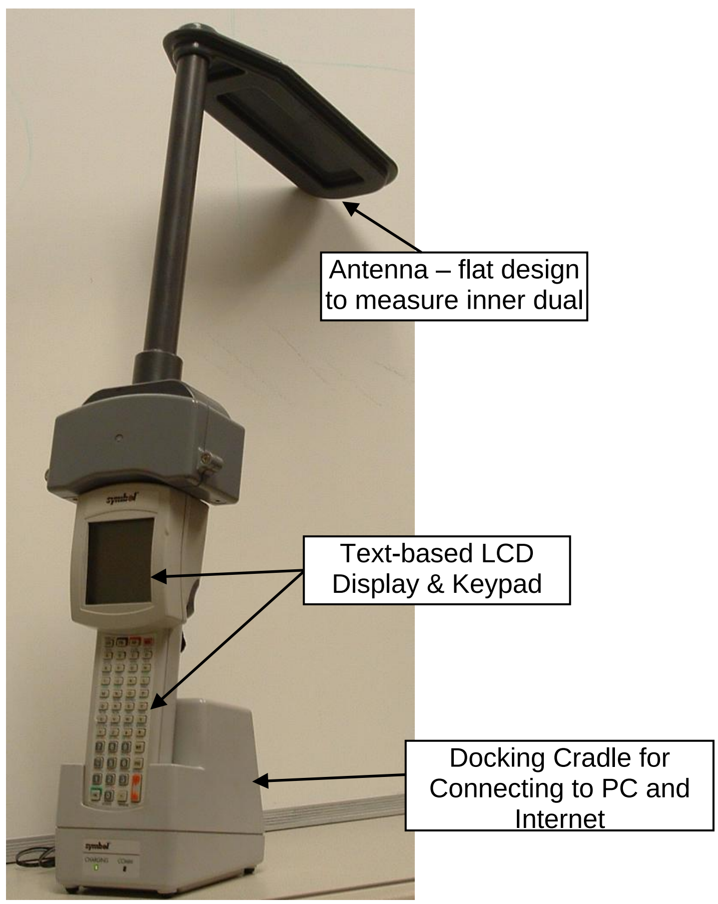
Exhibit 5.49 – SmarTire Operator Interface



The eTire was a tire-mounted TPMS, which did not use an in-cab display. Instead, maintenance personnel would use a handheld reader to upload the data, or the vehicle could be driven through a gate reader that uploaded the tire pressure to an on-line tire management database (the gate reader is evaluated in the next section). However, the handheld reader assembly was used for the track testing. The handheld reader, shown in Exhibit 5.50, was designed with a flat antenna on the end of a 1 ½-foot pole and an LCD display and keypad on the other. Because the range of the sensors' transmission was only a few inches, this design was necessary to place the antenna between the tires of a dual assembly to be able to read the tag of the inner dual.

To inspect tires by hand, maintenance personnel would navigate to the proper "inspection" menu on the reader and "swipe" a tire's tag by placing the flat antenna end 2 to 3 inches from the tire at the specific location of the tag along the sidewall (as indicated by an affixed decal). They would read the pressure and temperature of the tire from the reader's LCD display. The reader could then be replaced in the docking station, which (if connected to the Internet) would upload the reading from the unit to the maintenance management database operated by the system manufacturer for the fleet.

Exhibit 5.50 – eTire Handheld Reader Interface



The technicians and test engineers found the handheld reader cumbersome in operation and required a significant learning curve to use. The software was text-based and the data entry from the handheld unit required that its cradle be connected to a computer with Internet access.

However, per our discussions with the fleet that operated the gate reader assembly used in our tests (see Section 5.2.6), the maintenance personnel were pleased with the handheld reader's performance.

5.2.6 Gate Reader Evaluation

This test evaluates the performance and reliability of the drive-through gate readers used with tire-mounted monitoring systems. The objective was to determine the speed and consistency of the gate readers in capturing pressures.

Only one system tested used an external gate reader, the eTire TPMS. Due to the cost of installing a gate reader at the TRC test facility in Columbus, the team used an existing gate reader facility operated by a fleet in Indianapolis, IN, to perform this test. The fleet operator graciously allowed the team to use this reader for 2 days in April 2005.

Exhibit 5.51 shows a photograph of the gate reader setup at the fleet in Indianapolis.

Exhibit 5.51 – Photo of Gate Reader Installation in Indianapolis, IN

In Exhibit 5.51, the gate reader sensors are protected by concrete posts to prevent accidental damage by vehicles. The eTire TPMS tested used a passive tire tag (i.e., the tag was not powered, but received its power from the measuring sensor), which resulted in a very short transmission range. This required the sensors and concrete posts to be very close to the wheel assemblies. This tight clearance limited the speeds that the test tractor, with externally mounted rotary union test equipment, could run through the gate reader to about 3 to 4 mph. Therefore, an additional test to determine the vehicle speeds at which this system could accurately record tire pressures was not performed.

The particular system tested used an on-line Web-based tool and backend tire tag tracking system run by the TPMS manufacturer to log the pressure readings from the gate reader or handheld reader. The gate reader connected to a remote terminal located in the motor carrier's maintenance office, where the tire pressure readings could be displayed to personnel immediately. The data was then also forwarded via the Internet to the backend tracking system run by the system manufacturer. These tools enabled maintenance and management personnel to search a Web-based system to find the status of vehicles and tires, add and remove tires from the system, and manage the fleet's inventory of tires.

Exhibit 5.52 shows the results of the test runs conducted on the gate reader.

Exhibit 5.52 – Gate Reader Evaluation Results

Vehicle	Passes Through Gates	Potential Tires Read	Actual Tires Read	Percentage Read
Tractor	13	130	127	98%
Trailer	13	104	103	99%

Exhibit 5.52 shows that of the 26 passes through the gate reader, all but 4 of the potential 234 tires were recorded. The limited speed at which the test vehicle could traverse through the gate reader has significant effects on the ability of the system to record signals from the tire tags. Therefore, it is highly likely that these results were skewed due to the test setup. However, in the project team's discussions with the maintenance fleet, they did not express any issues related to poor tire read rates, but stated they were satisfied with the system's performance and effectiveness.

5.3 Central Inflation Systems

Central tire inflation systems use air from the reservoirs on the vehicle that are filled by the engine-powered compressor. These systems provide an on-board capability to monitor and inflate tires to proper pressures. They also provide some ability to continue to operate with small levels of leakage until repairs can be made. The systems use check valves that isolate tires with severe pressure loss or catastrophic failures to prevent the total loss of pressure from the primary and secondary reservoirs. This protects the braking system from a total loss of pressure, but will still allow the transfer of air between the reservoir and the tires with moderate pressure differentials. The systems also protect tires on a common fill circuit (i.e., an entire axle) from individual tire failures and allows the tires on each circuit to be monitored with visual indicator gauges.

The manufacturer of the Vigia CIS tested in this study advises that the CIS will inflate tires if the preset tire pressure in any tire drops 3 psi from its calibrated level. If the tire continues to lose air, it will maintain the calibrated pressure until the vehicle stops and the engine is shut off. In the case of catastrophic air loss, the CIS are equipped with check valves that prevent the vehicle's air supply from falling below 70 psi. The installation requirements of the Vigia CIS required an alteration of the instrumentation because it uses a rotary union on the outboard side of each axle. The study's instrumentation system, as described in previous sections, also used a rotary union to transfer pressure and temperature data. Because it is not possible to use two separate rotary unions simultaneously, the pressure transducers on the DAS were connected with tees into the air lines of the Vigia CIS. Tire temperatures could not be recorded without the use of the DAS' instrumentation rotary unions, and therefore do not appear in the data for the Vigia CIS.

Central tire inflation systems can be installed on motorcoaches, straight trucks, and tractor-trailers. The PSI CIS was designed for truck trailers only, while the Vigia CIS was designed for tractor-trailers or motorcoaches. The PSI CIS was installed and tested on the trailer of the tractor-trailer vehicle. The Vigia CIS was installed and tested on the motorcoach.

5.3.1 Functionality Tests

The static and dynamic functionality tests for central tire inflation systems evaluate their ability to inflate a low tire as well as to isolate an intact tire from a tire that has experienced a significant or total loss of pressure. The systems were tested both statically to determine basic functionality and dynamically to determine the effect of the vehicle operation on the equalizer system's performance. Exhibit 5.53 summarizes central tire inflation system functionality test procedures.

Exhibit 5.53 – CIS Static/Dynamic Functionality Test Procedures

Step Number	Procedure
Static Functionality Check	
1	Set Manifold to Proper Positions
2	Start Data Recorder, Sample at 10 Hz
3	Deflate RFS (or RFIT on trailer-only systems) tire 5 psi
4	Flip Marker Switch when tire reaches 100 psi
5	Stop Data Recorder
6	Record File Name
7	Repeat 8-14 but deflate in additional 5 psi increments until tires reaches 75 psi on steer/60 psi on drive/trailer
9	Start Data Recorder, Sample at 10 Hz
10	Completely deflate RFS (or RFIT on trailer-only systems) to 0 psi
11	Flip Marker Switch when tire reaches 100 psi
12	Stop Data Recorder
13	Record File Name
Dynamic Functionality Check	
14	Set all tires to Cold Inflation Pressure (CIP=105 psi)
15	Deflate RFS (or RFIT on trailer-only systems) tire 5 psi
16	Drive vehicle at 45 mph for 10 minutes (1 lap) around HST
17	Flip Marker Switch when tire reaches 105 psi
18	Stop Data Recorder
19	Record File Name

20	Repeat 14-19 but deflate in additional 5 psi increments until tires reaches 75 psi on steer/60 psi on drive/trailer
21	Repeat 1-20 for LFOD and RTAG (or LROT on trailer-only systems)

Exhibit 5.54 summarizes the Vigia CIS static functionality test data. The system inflated all tires to target pressures over a wide range in time; the longest time required was less than 8 minutes with some tires requiring well under a minute. The data is seemingly scattered due to the effect of the air system/compressor supplying the air reservoirs on the vehicle. During static testing, "shop air" was used to reduce the variability of the engine-driven compressor output pressure cycles. However, the shop compressor duty cycle was also somewhat variable. The inflation systems inflated tires much faster during the periods when the compressor was charging the system.

Exhibit 5.54 – Vigia CIS Static Functionality Test Data

Tire Set	Initial Pressure (psi)	Final Pressure (psi)
RFS/Steer Axle		
	100	102
	95	103
	90	103
	85	103
	80	103
	75	103
	0	103
LFOD/Drive Axle		
	100	106
	95	105
	90	105
	85	106
	80	106
	75	106
	70	107
	65	106
	60	104
RTAG/Tag Axle		
	100	106
	95	106
	90	106
	85	107
	80	107
	75	107
	70	107
	65	108
	60	108

Exhibit 5.55 displays the inflation times for the Vigia CIS used on the RTAG tire for a range of initial tire pressures. These rates are typical of the static test of the other tire positions. In general, it takes longer to inflate tires from lower initial pressures; however, the reservoir pressure has a large effect on the inflation rates as discussed above. Also the pressures rises very quickly at the beginning of the inflation test due to the need to tee in the pressure transducer on the system fill line because of the system's use of its own rotary union. This location of the transducer shows a pressure that starts at 0 psi and an artificially high pressure in the early portion of the inflation test because it is actually measuring the fill line pressure during inflation. All of the tests appear to reach or nearly reach the target inflation pressures within 3 minutes or less.

Exhibit 5.55 – Vigia CIS RTAG Static Functionality Test

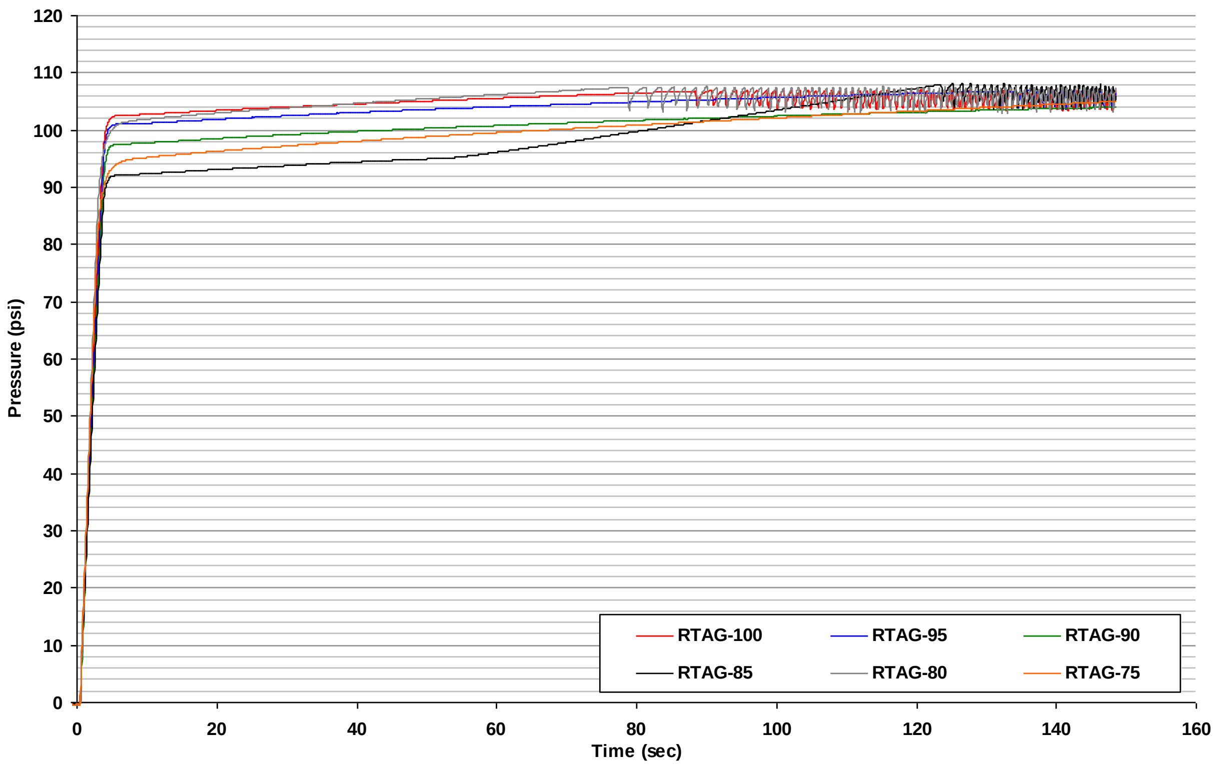


Exhibit 5.56 summarizes the Vigia CIS dynamic functionality test data. The data show that the system is capable of inflating tires from pressures ranging down to 40 psi below the target inflation pressure of approximately 105 psi in several minutes or less. Again, there is tremendous variability in the inflation rates due to the cycling of the vehicle compressor, primary reservoir, and secondary reservoir pressures so that the resulting inflation times did not reflect the initial starting pressures. The RFS tire was not tested below 80 psi while driving on the test track for safety reasons.

Exhibit 5.56 – Vigia CIS Dynamic Functionality Test Data

Tire Set	Initial Pressure (psi)	Final Pressure (psi)
RFS/Steer Axle		
	100	103
	95	103
	90	103
	85	103
	80	103
LFOD/Drive Axle		
	100	108
	95	108
	90	108
	85	108
	80	108
	75	108
	70	104
	65	104
	60	104
RTAG/Tag Axle		
	100	102
	95	105
	90	105
	85	105
	80	105
	75	104
	70	104
	65	104
	60	104

Exhibit 5.57 displays the test data from the Vigia CIS dynamic functionality test. The data show that the system is capable of inflating all tires from pressures ranging from 45 psi below the target pressure of 105 psi within a few minutes and at times considerably less. Again, the data show a high degree of variability due to the vehicle's compressor loading cycles.

Exhibit 5.57 – Vigia CIS LFOD Dynamic Functionality Test

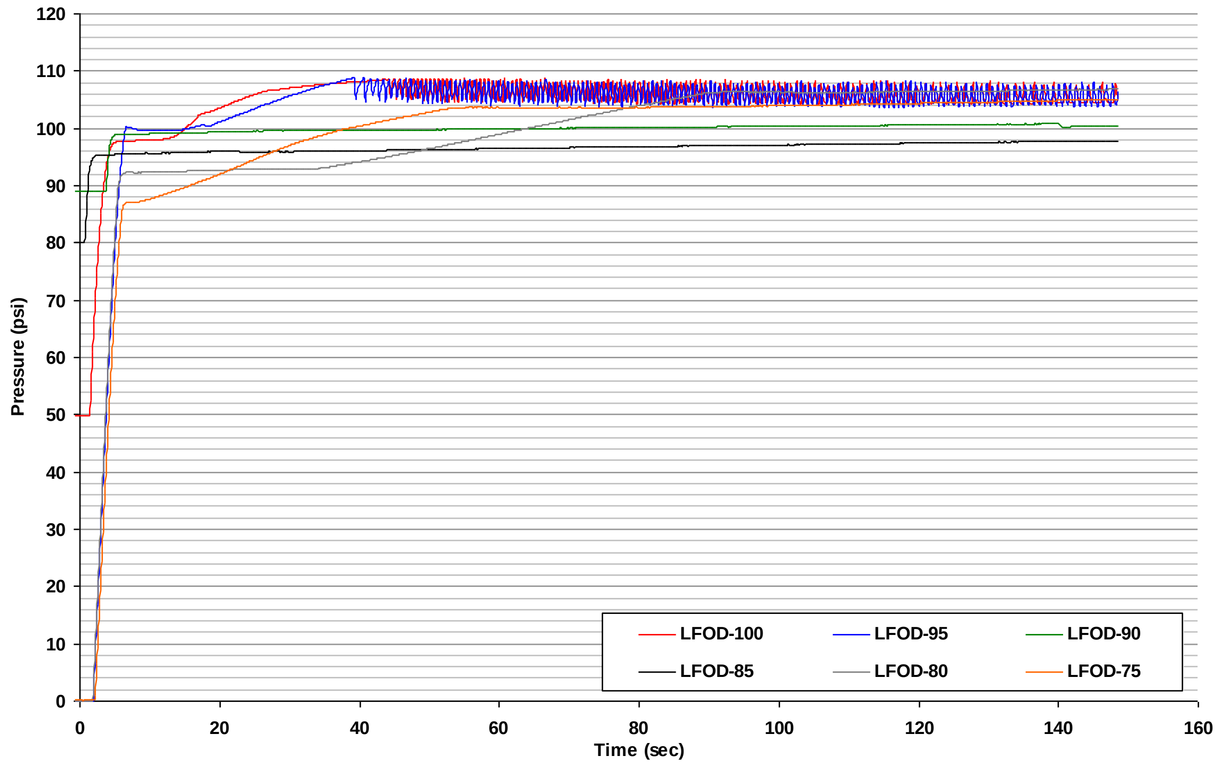
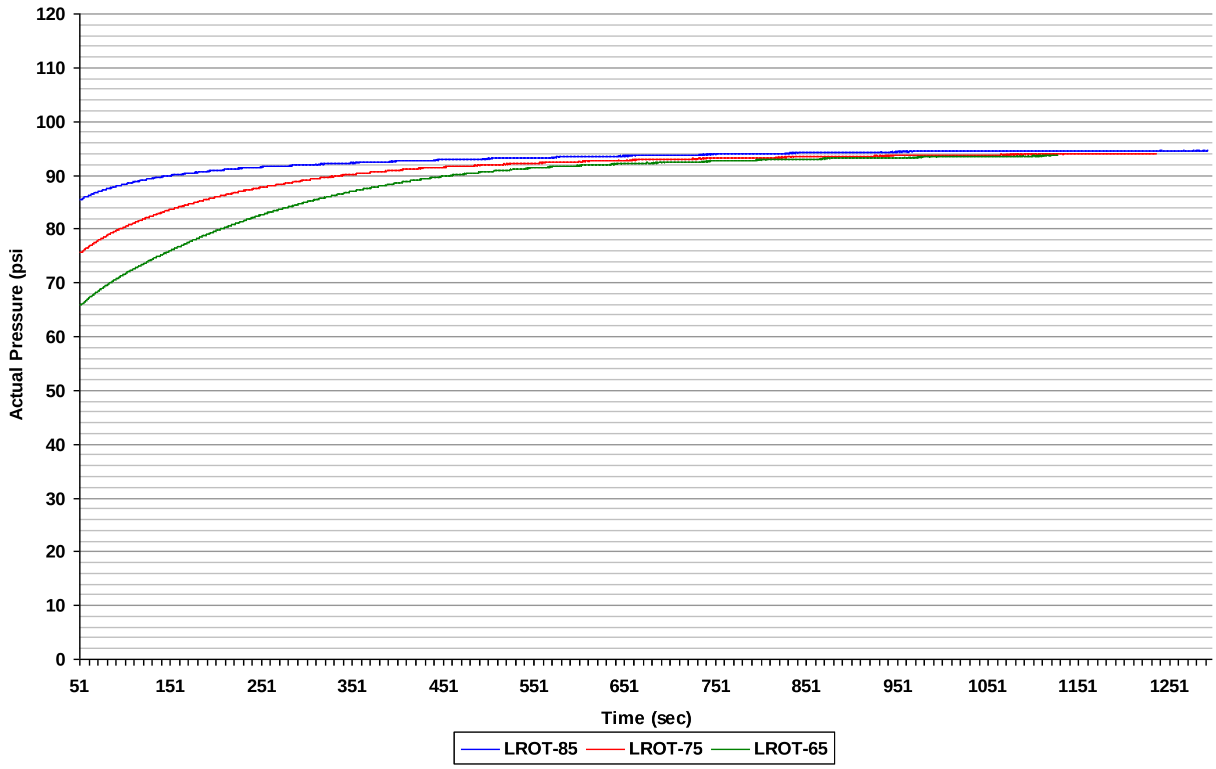


Exhibit 5.58 shows the static functionality test of the PSI CIS.

Exhibit 5.58 – Static Functionality Test of PSI CIS



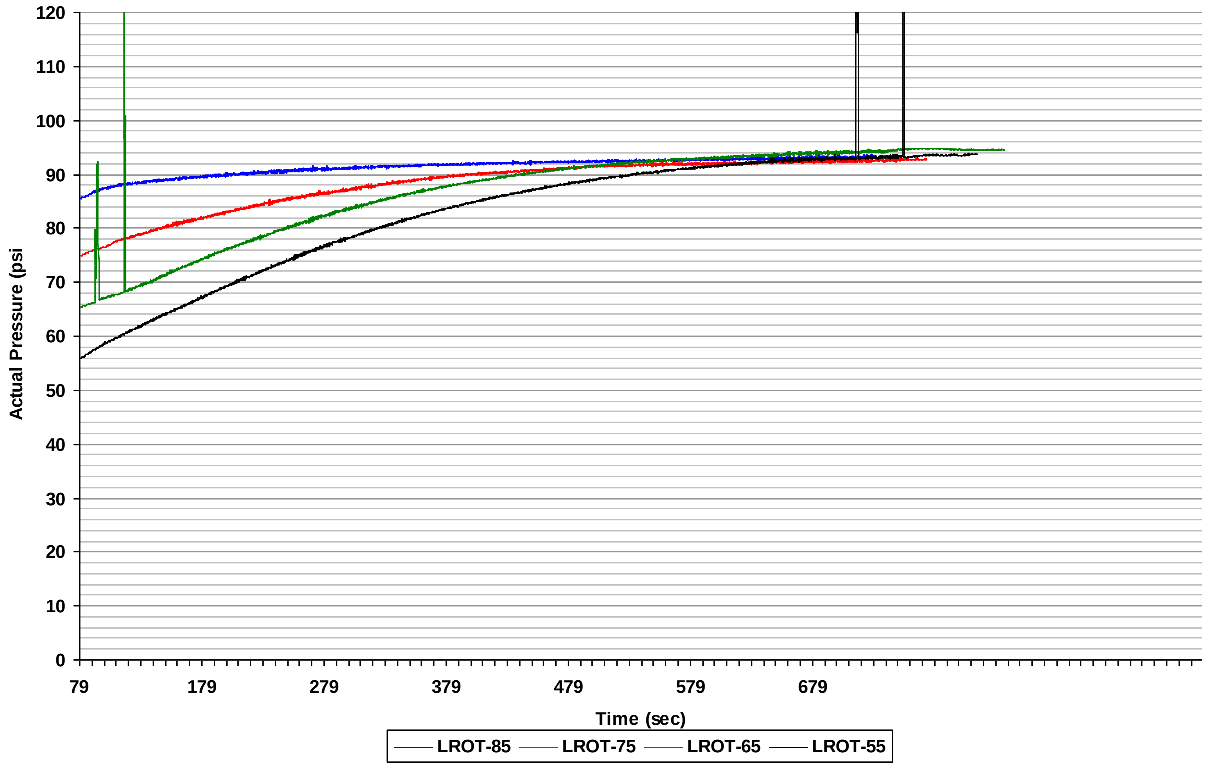
As shown in Exhibit 5.58, the PSI CIS inflates under-inflated tires (from 85, 75, and 65 psi) up to 94 to 95 psi, which was the system pressure set by the manufacturer's installers who outfitted the test trailer. This is as expected based upon the intended functionality of the system and the system pressure setting set by the manufacturer. The same test series was performed for this system on the RFIT tire, which exhibited similar results within a 2- to 3-psi range, as shown in Exhibit 5.59.

Exhibit 5.59 – Static Functionality Test Results for PSI CIS

CIS #1 – Trailer-Only		
Tire Set	Initial Pressure (psi)	Final Pressure (psi)
RFIT	86	93
RFIT	76	93
RFIT	68	93
RFIT	63	92
LROT	85	95
LROT	76	94
LROT	66	94

Exhibit 5.60 shows the results of the dynamic functional test performed on the PSI CIS.

Exhibit 5.60 – Dynamic Functionality Test of PSI CIS



As shown in Exhibit 5.60, the PSI CIS performed similarly under the dynamic test as it did under the static test—inflating tires (from 86, 73, 63 psi) up to 93 to 95 psi. The spikes in the LROT-65 trace are due to noise in the data. These same test series were performed on the RFIT tire, which experienced similar test results as shown in Exhibit 5.61.

Exhibit 5.61 – Dynamic Functionality Test Results for PSI CIS

CIS #1 – Trailer-Only		
Tire Set	Initial Pressure (psi)	Final Pressure (psi)
RFIT	86	94
RFIT	76	93
RFIT	70	92
RFIT	58	91
LROT	86	93
LROT	73	93
LROT	65	95
LROT	56	94

Exhibits 5.58 through 5.61 show that the PSI CIS responded as expected to under-inflated tires from 85 to 56 psi, inflating them to within 2 to 3 psi of the targeted 95 psi.

5.3.2 Threshold Warning Level Tests

The threshold warning tests for CIS evaluates their ability to continue to inflate a tire with a constant leak and determine the level when a low tire pressure warning is given. The systems are also tested for their ability to isolate intact tires from failed tires. The systems were tested both statically to determine basic functionality and dynamically at 45 mph to determine the effect of the vehicle operation on the inflation system performance. The inflation system threshold warning test procedures are detailed in Exhibit 5.62.

Exhibit 5.62 – CIS Threshold Warning Test Procedures

Step Number	Procedure
Threshold Warning Level	
1	1 Set all tires to Cold Inflation Pressure (CIP=100 psi)
2	Set Manifold to Proper Positions
3	Start Data Recorder, Sample at 10 Hz
4	Initiate slowly leaking RFS (or RFIT on trailer-only systems) tire pressure at a rate of approximately 1.5 psi/min*
5	Drive vehicle at 45 mph for 10 minutes (1 lap)
6	Flip Marker Switch when system indicates low tire pressure
7	If no warning observed after 1 lap, increase leak rate by approximately 0.5 psi/min*
8	Repeat 5-7 until low pressure warning is observed
9	Stop Data Recorder
10	Record File Name
11	Record Set Leak Rate
12	Wait 30 minutes
13	Repeat 1-12 for LFOD and RTAG (or LROT on trailer-only systems)

Exhibit 5.63 displays a summary of the Vigia CIS threshold warning data. The system provides a warning almost immediately after the start of the leak. The system was able to keep up with a constant leak rate of 1.5 psi/minute. The system experienced a continued loss of tire pressure during the testing period with a 5-psi-per-minute leak, but may be able to continue over a longer period and stabilize at a slightly lower pressure. Ultimately, the size and duty cycle of the vehicle's compressor and air system determine the maximum sustainable leakage rate.

Exhibit 5.63 – Vigia CIS Threshold Warning Test (45 mph) Data

Tire Set	Initial Pressure (psi)	Final Pressure (psi)	Leak Rate (psi/min)	Warning (Yes/No)
RFS/Steer Axle				
	106	106	1.5	Yes
	108	Continued pressure loss	5	Yes
LFOD/Drive Axle				
	103	103	1.5	Yes
	104	Continued pressure loss	5	Yes
RTAG/Tag Axle				
	104	104	1.5	Yes
	104	Continued pressure loss	5	Yes

Exhibit 5.64 displays the data from the Vigia CIS threshold warning test of the RFS tire. The system shows its ability to maintain tire pressure with a 1.5-psi-per-minute leak rate as

evidenced by the 1.5 psi trace. With a leak rate of 1.5-psi-per-minute, the RFS tire pressure drops over time from 106 psi to about 104 psi. The inflation system then begins to fill the tire as evidenced by the trace oscillating as the system cycles its inflation valve open and closed. Over the period of the test with a 5-psi-per-minute leak, the RFS tire continuously lost pressure as evidenced by the 5-psi-per-minute trace dropping steadily from 108 psi to 92 psi over the 500 seconds of the test. The inflation system cycled briefly at the beginning of the 5-psi-per-minute leak and then left the inflation valve open. During the 5-psi-per-minute leak, the vehicle compressor did not load and charge the reservoir, which would have allowed some level of recovery of the RFS tire pressure. The yellow warning light was illuminated, and the steer axle gauge indicated below-target pressure from the start of the leaks.

Exhibit 5.64 – Vigia CIS RFS Threshold Warning Test

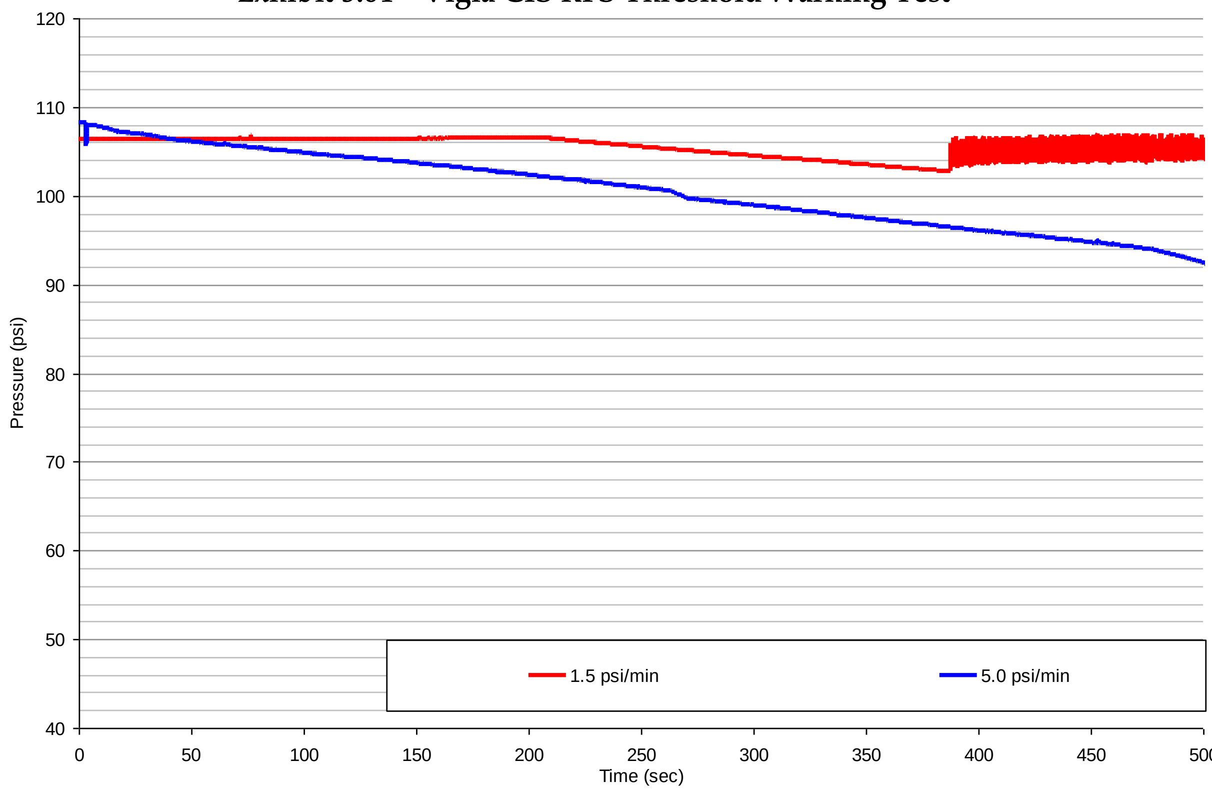
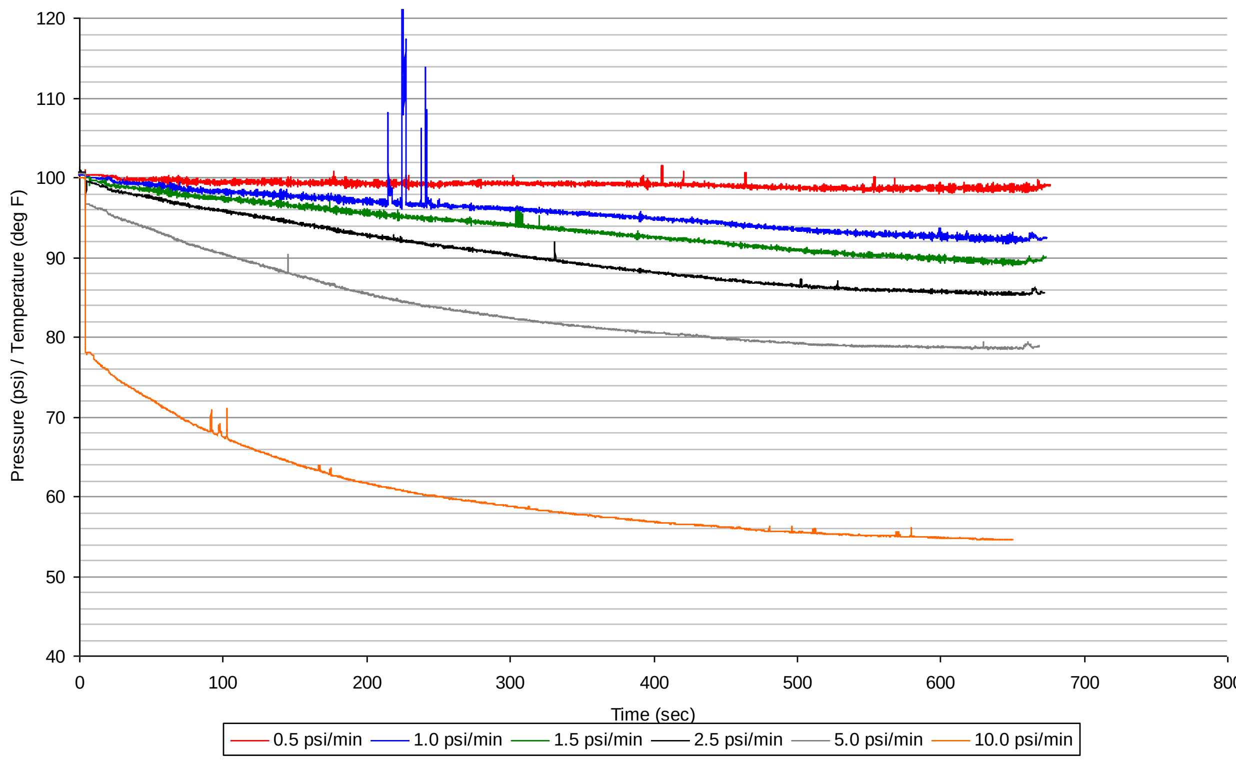


Exhibit 5.65 shows the threshold warning level test of the PSI CIS.

Exhibit 5.65 – Threshold Warning Level Test of PSI CIS



As shown in Exhibit 5.65, initial leak rates from 0.5 psi per minute to 10.0 psi per minute were set using the pressure control manifold, and the vehicles were driven at 45 mph around the test track. The spikes in the 1.0 psi/min trace are due to noise in the data. It should be noted that an initial leak rate (psi/min) was set using the metering valve in the control manifold, which yielded a fixed orifice size for the leak. Therefore, as the pressure dropped, the leak rate decreased, shown by the asymptotic graphs in Exhibit 5.65, as the rate reached a point at which the inflation system could maintain the flow of air into and out of the tire.[18] Exhibit 5.66 shows complete results of the PSI CIS for the test runs on the RFIT and LROT tires.

[18] It should also be noted that for the leak rates of 5.0 and 10.0 psi/min, the initial sharp decrease in pressure is not a result of rapid loss of tire pressure, but rather of the pressure transducer being plumbed into the same air line as the leak orifice—the high rate of flow through the line appears to the pressure transducer as a lower pressure.

Exhibit 5.66 – Threshold Warning Test Results for PSI CIS

CIS #1 – Trailer-Only			
Tire Set	Leak Rate (psi/min)	Initial Pressure (psi)	Final Pressure (psi)
RFIT	0.5	100	99
RFIT	1.0	100	92
RFIT	1.5	100	90
RFIT	2.5	101	86
RFIT	5.0	101	79
RFIT	10.0	100	55
LROT	1.5	100	92
LROT	2.5	100	90
LROT	5.0	101	81
LROT	10.0	100	64

In general, the results in Exhibit 5.66 show that the PSI CIS is capable of supplying air to refill the trailer tires, but a leak orifice that has an initial leak rate of more than 0.5 psi/min results in a lower sustained tire pressure than the system's set pressure. An initial leak rate above 5.0 psi per minute yields a sustained final tire pressure of 20 psi below target—considered a serious under-inflation issue.

5.3.3 Loaded Test at High Speed

The loaded dynamic tests at high speed for central inflation systems evaluate their ability to continue to inflate a tire with a constant leak and determine the level when a low tire pressure warning is given. The systems are also tested for their ability to isolate intact tires from failed tires. The systems were tested at the vehicle's gross vehicle weight rating and at 75 mph to determine the effect of the vehicle operation on the inflation system performance. Exhibit 5.67 details the procedures for the inflation system loaded dynamic test at high speed.

Exhibit 5.67 – CIS Loaded Dynamic Test at High-Speed Test Procedures

Step Number	Procedure
Loaded Test at High Speed	
1	Set all tires to Cold Inflation Pressure (CIP=105 psi)
2	Set Manifold to Proper Positions
3	Start Data Recorder, Sample at 10 Hz
4	Begin leaking RFS tire at the threshold rate determined in Test #1
5	Drive the vehicle at 45 mph for 10 minutes (1 lap) around HST
6	Flip Marker Switch when system indicates low tire pressure
7	If no warning observed, stop vehicle, increase leak rate by an additional 0.5 psi/min, Repeat 5-6
8	Drive vehicle at 75 mph for 22.5 miles (3 laps) around HST
9	Flip Marker Switch when low pressure warning is extinguished
10	If the low tire pressure warning is maintained, repeat 8-9 once.
11	If the low tire pressure warning is maintained, stop vehicle, wait until tire reaches CIP
12	Drive vehicle at 45 mph for 10 minutes (1 lap) or until warning indicator is extinguished
13	Stop Data Recorder
14	Record File Name
15	Wait 30 minutes
16	Repeat 1-15 for LFOD and RTAG

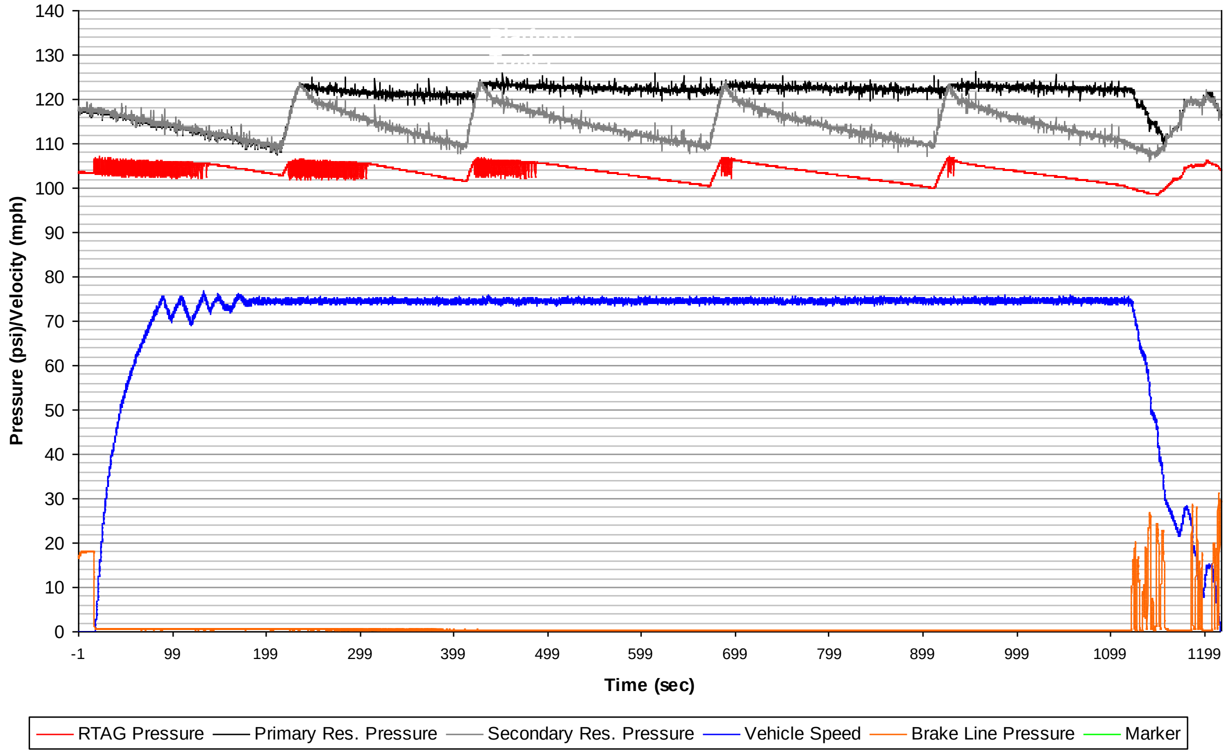
The Vigia CIS is limited more by the compressor and air system on the vehicle than the inflation system components. The system sensor is sensitive to 2 to 3 psi for activation. The maximum tire leakage rate that can be accommodated is typically 5 to 8 psi per minute, with 120 to 140 psi pressure in the reservoir tank. With this rate of leakage, the pressure on the lines/tires will be maintained at 96 to 105 psi. Exhibit 5.68 is a summary of the data for the Vigia CIS loaded test at high speed. The data show that the system can re-inflate the tires back to the target pressure of 105 psi with leakage rates of 5 to 6 psi per minute. However, the tires do not maintain 105 psi, and cycle up and down with the vehicle air compressor loading cycles. The test of the LFOD/Drive Axle did not have a compressor cycle during the test time period, and the system was not able to re-inflate the tire until after the test when the compressor loaded.

Exhibit 5.68 – Vigia CIS Loaded Test at High Speed (75 mph) Data

Tire Set	Initial Pressure (psi)	Peak Recovery Pressure (psi)	Leak Rate (psi/min)
RFS/Steer Axle	105	105	5
LFOD/Drive Axle	105	93 (compressor did not load during test.)	6
RTAG/Tag Axle	105	105	6

Exhibit 5.69 displays the data from the test of Vigia CIS RTAG tire loaded at high speed. The exhibit shows that the system is able to re-inflate the RTAG tire back to its initial pressure of 105 psi, but the tire only reached the target pressure during periods of compressor loading, as evidenced by the traces of the primary and secondary reservoirs. During the test period, as the vehicle was operating at 75 mph, the compressor cycled on and off as the trace for the secondary reservoir pressure increased and decreased. The inflation system is connected to the secondary reservoir that supplies the front brakes to isolate the primary reservoir that supplies the rear brakes, which provide most of the braking force of the vehicle. Interestingly, as the test progressed, the system maintained the target inflation pressure for shorter durations. This appears to be due to the interaction of the primary and secondary air reservoir pressure switches and the control logic that cycles the compressor loading.

Exhibit 5.69 – Vigia CIS RTAG Loaded High-Speed Test with Rapid Leak



The PSI CIS installed in the test trailer had a malfunctioning warning indicator light. The cause of the fault could not be determined by the manufacturer representative on site; therefore, no loaded test at high-speed procedures was performed on the PSI CIS.

5.3.4 Failure Modes Test

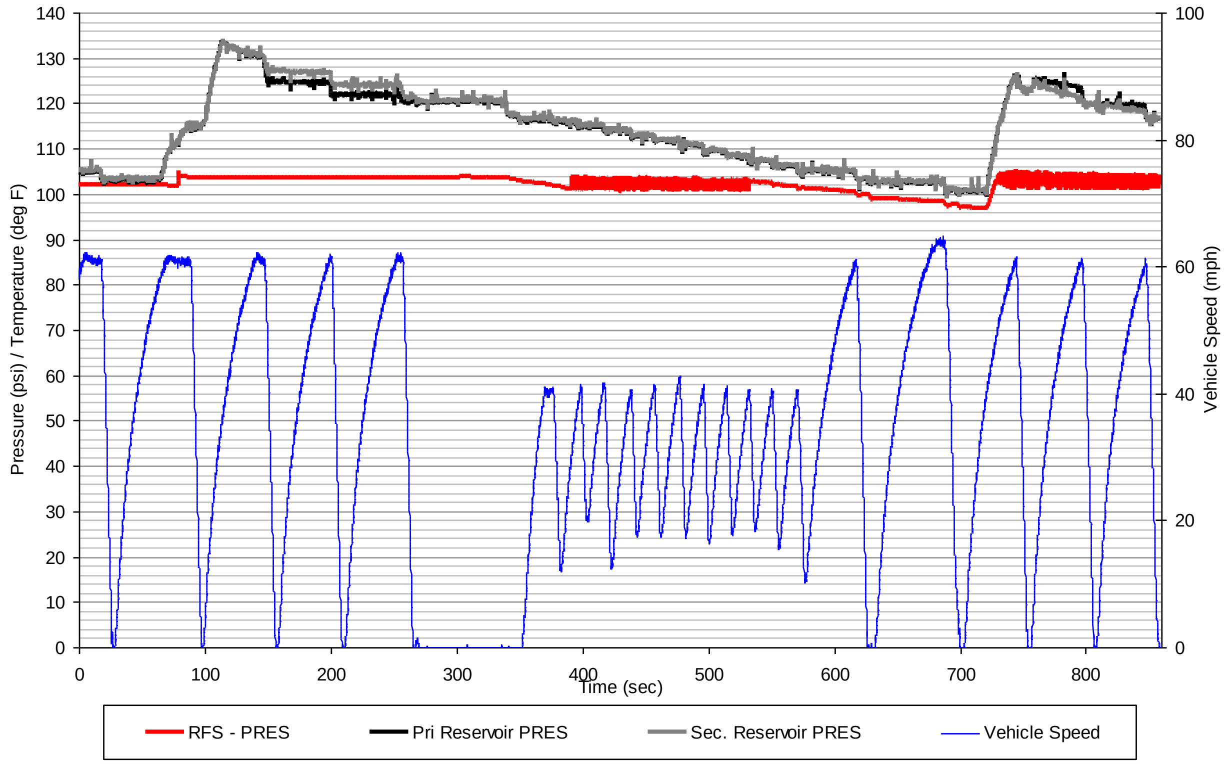
The failure modes test for CIS primarily evaluates the potential of a large air leak to deplete the air brake system reservoir. The failure modes test also determines whether an air leak will cause the system to run constantly without giving the driver a warning of a flat tire. Finally, the failure modes where tires are interconnected are investigated to ensure that loss of inflation pressure in a single tire does not affect the interconnected tires. Exhibit 5.70 details the CIS failure modes test procedures.

Exhibit 5.70 – Failure Modes Test Procedures

Step Number	Procedure
Failure Modes	
1	Set all tires to Cold Inflation Pressure (CIP=105 psi)
2	Set Manifold to Proper Positions
3	Start Data Recorder, Sample at 10 Hz
4	Perform 5 brake stops (60 to 0 mph @ max deceleration rate)
5	Initiate rapidly leaking RFS (or RFIT on trailer-only systems) tire at a rate of approximately 6 psi/min*
6	Perform 10 braking stops from 40 to 20 mph @ 10 ft/sec^2, every mile
7	Flip Marker Switch when system indicates low tire pressure
8	Perform 5 brake stops (60 to 0 mph @ max deceleration rate)
9	Stop Data Recorder
10	Record File Name
11	Wait 30 minutes
12	Repeat 1-11 for LFOD and RTAG (or LROT on trailer-only systems)

Exhibit 5.71 displays the data from the Vigia CIS RFS tire failure modes test. The vehicle was put through a series of 5 brake snubs from 60 mph to 0 mph and a 6 psi/minute leak was initiated, followed by 10 brake snubs from 40 to 20 mph, followed by another 5 brake snubs from 60 to 0 mph. This placed a high level of stress on the braking system, and would not be experienced in normal operations of the motorcoach. As indicated by the traces for the primary and secondary reservoirs, the vehicle compressor loaded twice during the test and maintained acceptable pressure in the reservoirs for adequate braking performance. The RFS tire pressure was also maintained by the inflation system as shown by the RFS pressure trace. During the test, the warning light on the console was illuminated when the system was inflating the tire, and the pressure of the RFS tire was indicated on the steer axle gauge. The test of the other tires on the vehicle yielded similar data.

Exhibit 5.71 – Vigia CIS RFS Failure Modes Test



In Exhibit 5.72, the supply line between the control console on the Vigia CIS and the secondary reservoir was cut to examine the potential of a catastrophic failure of the system to drain the reservoirs of the vehicle. Due to safety concerns, the vehicle was not driven for this test. The trace for the primary reservoir remains constant, while the secondary reservoir drains down to 83 psi where it is isolated by a check valve from the inflation system. During this test, the red system failure warning light illuminated and the gauges all read 0 psi. The tires were all protected by check valves and remained at 105 psi.

Exhibit 5.72 – Vigia CIS Failure Modes Test Total System Air Loss

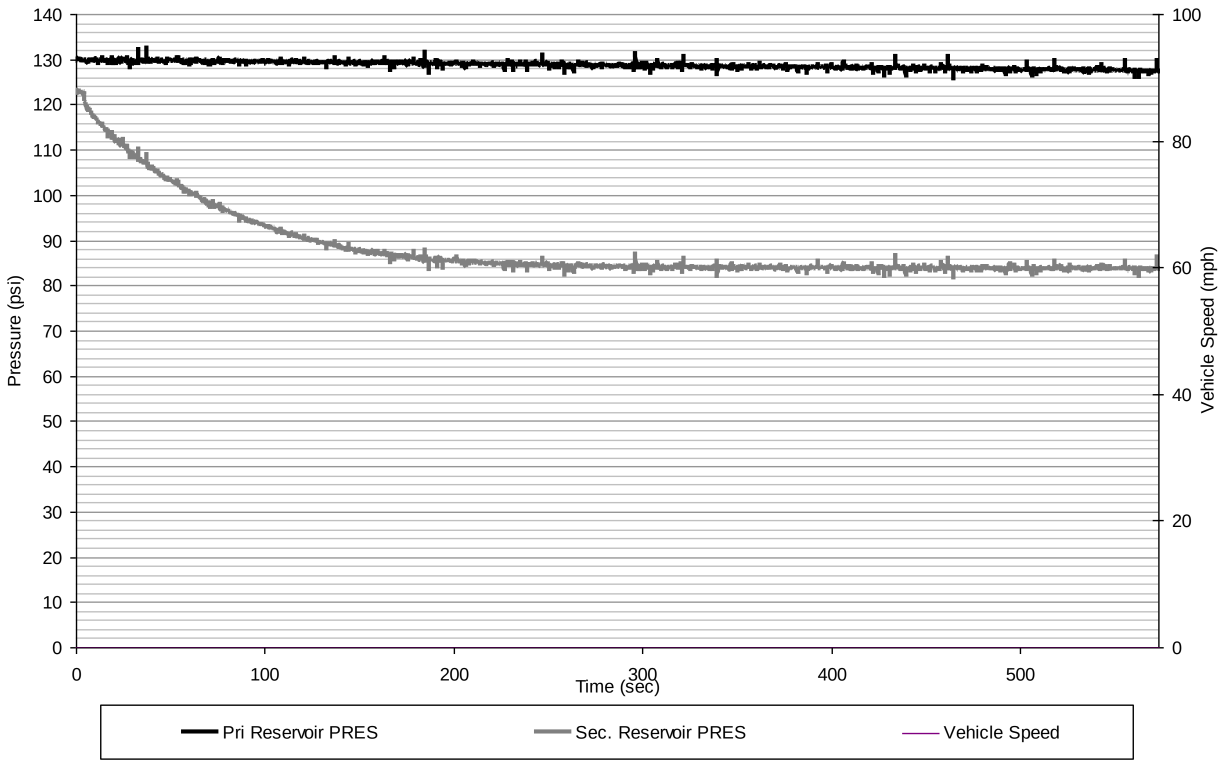
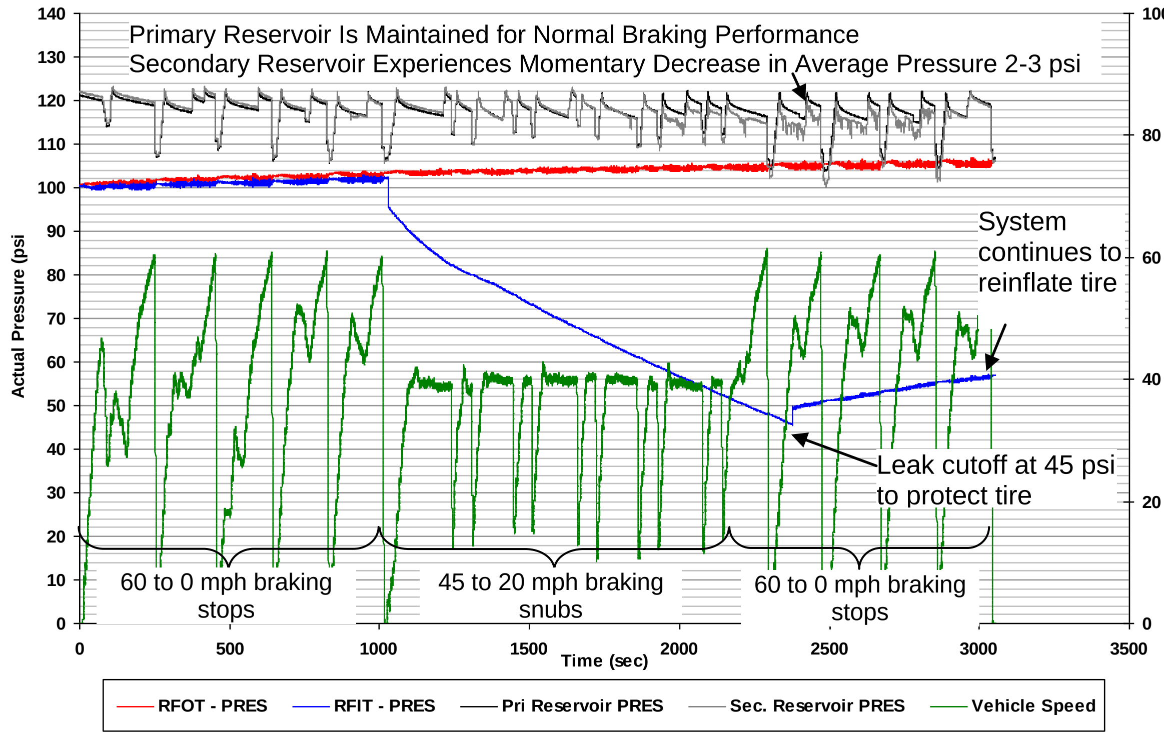


Exhibit 5.73 shows a failure modes test of the PSI CIS.

Exhibit 5.73 – Failure Modes Test of PSI CIS



In the test shown in Exhibit 5.73, the vehicle performed five braking stops from 60 to 0 mph, then a leak was initiated in the RFIT tire at a rate of 6 psi/min. A series of 10 braking snubs was performed from 45 to 20 mph, followed by another 5 braking stops from 60 to 0 mph. As shown in Exhibit 5.73, the rapid leak rate resulted in a significant pressure drop in the RFIT despite the presence of the CIS. The low pressure ultimately resulted in the test engineer needing to terminate the leak once pressure reached 45 psi.

Exhibit 5.73 shows that the primary air reservoir maintained necessary air pressure for braking throughout the test procedure—a consistent pattern for the period before the leak and the period after the leak. The secondary air reservoir showed a momentary loss of only 2 to 3 psi during the final braking stops, but this was only temporary. The test series performed on the LROT tire showed similar results to those in Exhibit 5.73 in which no braking performance issues resulted from operation of the CIS.

5.3.5 Disablement Test

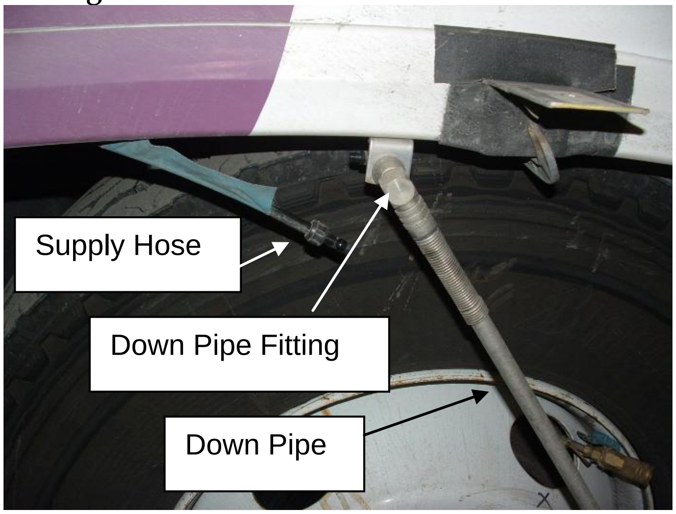
The disablement modes test determine whether the inflation system is designed to provide a warning indicator if/when it is disabled and to determine the ability of the system to protect the tire(s) from loss of air pressure in the event of damage or failure of the system components. Components of the system were purposely damaged or removed to simulate damage or loss due to road debris, curb strikes, vandalism, etc. These tests were performed statically due to safety issues related to tire failures while driving the vehicle. Exhibit 5.74 details the test procedures for the disablement modes test.

Exhibit 5.74 – CIS Disablement Modes Test Procedures

Step Number	Procedure
Failure Modes	
1	Set all tires to Cold Inflation Pressure (CIP=105 psi)
2	Start Data Recorder, sample at 10 Hz
3	Disable the TPMS according to disablement Mode #1
4	Examine display, Take digital photo, Record Photo File Name
5	Record response of system & if/when a warning/indicator of disablement is observed
6	Stop Data Recorder
7	Record file name
8	Examine display, Take digital photo, Record Photo File Name
9	Repeat 1-9 for each mode of disablement
Possible Modes of Disablement (Vigia CIS)	
1	Disconnect hose from down line fitting, equivalent to cutting hose from console to down pipe
2	Disconnect quick disconnect on down pipe
3	Break rotor cover
4	Cut rotor feed hose
5	Disconnect down pipe
6	Break rotor support
7	Deflate LFOD to simulate flat/blowout with engine off to prevent inflation
8	Repeat 7 but with engine running to attempt inflation of flat/blowout tire
9	Disconnect hose at console
Possible Modes of Disablement (PSI CIS)	
1	Detach LROT inflation hose on system-side; Attached cut replacement hose to system-side
2	Detach LROT inflation hose on tire-side; Attached cut replacement hose to tire-side
3	Fully open valve at output side of system box under trailer.
4	Drill and Tap RFIT system hubcap, Inject with 100 psi shop air. Record if release vents (orange ring) open
5	Cut hose leading from system box to trailer air reservoir

Vigia CIS Disablement Mode 1 was a condition where the hose from the control console was disconnected from the down pipe fitting. The RFS and LFS tires were protected by check valves; the console indicated no pressure on the steer axle and the yellow warning light illuminated. Exhibit 5.75 shows the physical damage to the system and the effect of the severed supply line to the RFS down pipe (Mode 1).

Exhibit 5.75 – Vigia CIS Disablement Mode 1 Test Inflation System #2



In Exhibit 5.76, the console reads 0 pressure on the steer axle, and the instrument panel shows that the primary and secondary reservoirs were also protected and retained pressure.

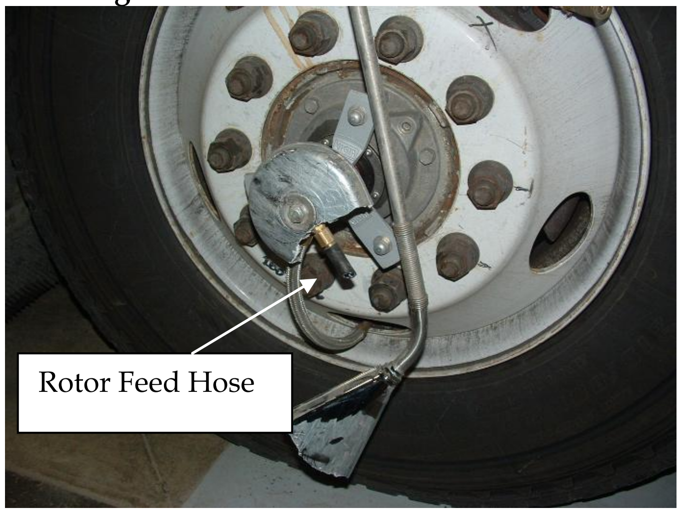
Exhibit 5.76 – Vigia CIS Disablement Mode 1 Test System Console and Instrument Panel

Vigia CIS Disablement Mode 2 differed from Mode 1 in that the quick disconnect sealed off the line from the console. The hose check valve protected the RFS tire from deflation. The system indicated normal pressure in the LFS tire and functioned normally, but it could only inflate the LFS tire.

Vigia CIS Disablement Mode 3 involved breaking the RFS rotor cover. The rotor cover is cosmetic in nature and designed to break away to prevent damage to the rotary union. The damage to the rotor cover had no effect on the system.

Vigia CIS Disablement Mode 4 was a cut RFS rotor feed hose. This failure was similar to Mode 1. The RFS and LFS tires were protected by check valves, and the console indicated the steer axle had no pressure and the yellow warning light illuminated. Exhibit 5.77 displays the damage in Disablement Mode 4.

Exhibit 5.77 – Vigia CIS Disablement Mode 4 Rotor Feed Hose Cut



Vigia CIS Disablement Mode 5 was, in effect, similar to Mode 2. The RFS down pipe was disconnected from the system at the rotor and at the quick disconnect. The RFS and LFS tires were protected by check valves, and the RFS circuit was isolated from the system by the quick disconnect. The console indicated 105 psi and functioned normally, but was only monitoring the LFS tire.

Vigia CIS Disablement Mode 6 involved breaking the RFS rotor support. The tire and the system were protected by the check valves. The RFS tire remained at 105 psi, and the system console indicated 105 psi for the steer axle.

Vigia CIS Disablement Mode 7 tested the system by setting a large leak in the LFOD tire to simulate a flat or blow out. With the engine off to prevent re-inflation of the LFOD tire, all of the air was dumped from the LFOD tire. The system isolated all of the other tires on the vehicle with check valves, and they remained at 105 psi.

Vigia CIS Disablement Mode 8 was similar to Mode 7, but with the engine running. The compressor frequently cycled on to refill the secondary reservoir as the tire continued leaking. The console indicated approximately 60 psi as the system attempted to inflate the leaking tire and the yellow warning light illuminated. All other tires on the vehicle remained at 105 psi.

Vigia CIS Disablement Mode 9 entailed disconnecting the steer axle hose at the console. The RFS and LFS tires were protected by check valves and remained at 105 psi. The console indicated 0 psi on the steer axle, and the yellow warning light illuminated.

Exhibit 5.78 provides a summary of the results for the Vigia CIS disablement mode tests. In the disablement tests, the initial tire pressures were recorded before the disablement procedure and after the failure was created. The console gauge pressures for the affected tire/axle were recorded after the failure to identify the different system failure indications to the driver.

Exhibit 5.78 – Vigia CIS Disablement Mode Test Results

Disablement Mode	Initial Tire Pressure (psi)	Tire Pressure (psi)	Console Pressure (psi)
Mode 1 (RFS)	105	105	0
Mode 2 (RFS)	105	105	105
Mode 3 (RFS)	105	105	105
Mode 4 (RFS)	105	105	0
Mode 5 (RFS)	105	105	105
Mode 6 (RFS)	105	105	105
Mode 7(LFOD)	105	0 (105 in all other tires)	0/
Mode 8 (LFOD)	105	0	60
Mode 9 (RFS)	105	105	0

Exhibit 5.79 shows the disablement modes tested for the PSI CIS.

Exhibit 5.79 – PSI CIS Disablement Results

PSI CIS			
Mode #	Purpose	Description	Result
1	Simulate Failed Inflation Hose – System Perspective	Detached LROT inflation hose on system-side; Attached cut replacement hose to system-side	System lost air pressure, indicator light was illuminated, tire and connected dual was protected.
2	Simulate Failed Inflation Hose – Tire Perspective	Detached LROT inflation hose on tire-side; Attached cut replacement hose to tire-side	Tire lost air pressure, system and connected dual was protected from pressure loss.
3	Simulate Failed output hose	Fully open valve at output side of system box under trailer.	System lost pressure, indicator light illuminated, tires and air reservoir were protected from pressure loss.
4	Simulate Failed Internal Seal	Drill and tap RFIT system hubcap, Inject with 100 psi shop air. Record if release vents (orange ring) open	Release vents opened properly to vent air.
5	Simulate failed input hose	Cut hose leading from system box to trailer air reservoir	Pressure protection valve protected the trailer air reservoir.

Exhibit 5.79 shows that a failure of the fill hose located at the wheel end resulted in a loss of air both in the affected tire and in the system. However, the associated dual was protected from the failure, as was the air reservoir. Failure of the internal seal in the hubcap resulted in proper venting of system air by the pressure release vents. Additionally, the pressure protection valve on the air reservoir protected the reservoir against a failure in the inflation system or the input hose.

5.3.6 Operator Interface Evaluation

The operator interface for the Vigia CIS consists of a console with three pressure gauges, three warning lights, a red system warning light, and a green power light. Exhibit 5.80 shows the console unit of the Vigia CIS. The only operator control is a power switch on the console. If the air supply to the unit falls to 70 psi, the Vigia CIS discontinues taking air from the tank, while the control panel flashes a red light alerting the driver of a system problem. The gauges are read directly by the driver and correspond to the pressure of the tires in each axle.

Exhibit 5.80 – Vigia CIS Operator Interface

When the system is adding air to a tire/axle, a yellow indicator light flashes and an audible clicking sound is heard. If the system is inflating a low tire, the yellow indicator light is on and the tire pressure can be read from the gauge as it inflates. When the system is within 3 psi of full inflation, it begins to turn on and off rapidly and a series of clicks is heard until the calibrated pressure setting is reached. The test drivers and mechanics commented that the console was somewhat large, but the gauges were easy to read and the pressure information was clearly presented. The combination of audible clicks and flashing yellow lights effectively attracted the drivers' attention when the system was active.

Exhibit 5.81 shows a photograph of the warning indicator for the PSI CIS.

Exhibit 5.81 – Warning Indicator for the PSI CIS

As shown in Exhibit 5.81, the PSI CIS relies on a simple trailer-only blue indicator light. The light should be mounted in such a way as to allow the vehicle operator to see it through the left-side mirrors. In the test setup, the indicator light did not function consistently and the manufacturer representative present could not find the source of the fault.

CHAPTER 6. OBSERVATIONS AND CONCLUSIONS

This chapter outlines the key observations and conclusions presented in previous chapters regarding the performance and operational characteristics of the various TPMS and their ability to detect tire pressure abnormalities.

6.1 Dual Tire Equalizers

Dual tire equalizers from two different manufacturers were installed on the tractor-trailer test platform. Both units were installed on both test vehicles without incident. Dual tire equalizers can be installed on any vehicle with dual tires assemblies. Because the tractor-trailer had eight dual tire sets as opposed to just two on the motorcoach, both of the dual tire equalizer systems were installed on the tractor-trailer for testing. This permitted more efficient use of test resources because four axles on the tractor-trailer could be instrumented, as opposed to only one axle on the motorcoach. The following are some key observations and conclusions related to dual tire equalizers:

- Dual tire equalizers are effective in balancing the pressures between the two tires. The equalization technologies function as designed under both static and dynamic conditions.
- The two equalization systems were effective in isolating a tire with no leaks from an adjacent tire with a major leak. The isolation pressures vary with leakage rate and system characteristics. The two equalizer systems appear to have isolation pressures that are nominally set at about 80 psi. When exposed to a high pressure differential due to a high rate of leakage in one tire (e.g., from a severely damaged tire or a blowout), the equalizer systems tended to isolate the intact tire at higher pressures compared to slow leaks.
- During disablement testing, cutting a hose to simulate damage from road debris resulted in a total loss of air from one dual, but the other tire was protected by a check valve. Simulated physical damage to the visual indicator/check valve assemblies of both units resulted in one system losing pressure in one tire, while the other system maintained pressure in both tires. Both systems prevented the loss of pressure in one or both tires in every failure mode implemented.
- The two equalizers include a visual indicator that can provide a gross indication of tire pressure. They provide an indication that the tire pressure is within its target range; however, if the pressure falls below this range, they only show a “low” pressure condition and do not indicate the degree of under-inflation.
- While the indicators provide a good visual indication of tire pressure, they can be difficult to read because they are mounted to the wheel and can become obscured by dirt.

6.2 Tire Pressure Monitoring Systems

The team tested five different tire pressure monitoring systems for this study project. They included two valve-stem-mounted, two wheel-mounted, and one tire-mounted tire pressure monitoring system. The following are some key observations and conclusions on the TPMS technology.

General TPMS Observations

- The tire pressure monitoring systems tested in this project were generally accurate to within 2 to 3 psi from the values measured by the test instrumentation. In general, each system tested (valve-, wheel-, or tire-mounted) had the base-level functionality expected of their individual designs.
- Low-pressure warning thresholds are "factory set" on some systems, but user-configurable on others. For those systems with factory settings, different warning levels ranging from 12 percent to 25 percent below target pressure were observed. Further, all systems tested were generally within a 2- to 3-psi range of the expected warning threshold (whether set at the factory or by the user). The systems tested had similar performance both statically (vehicle not in motion) and dynamically (vehicle driven at 45 mph around the test track).
- Many of the TPMSs tested used RF communications to transmit data between the sensors and the display unit or ECU. The relatively long length of typical CMVs means that additional on-board antennas are required for some of the systems to receive the sensor signals from trailer or tag axle tires. Disconnected or damaged antennas can lead to loss of signal from the sensors.
- The operator interface for the TPMS tested varies significantly, but all used in-cab visual displays and audible alerts (except the tire-mounted TPMS) to warn the operator of inflation issues.

Valve-Stem-Mounted TPMS Observations

- One of the systems tested initiated a warning when the pressure fell below a preset value (approximately 20 percent below target); however, the warning remained active until the tire was inflated to a higher value (approximately 15 percent below target). In other words, this system incorporates a "hysteresis effect" by having different pressure settings for when a warning is initiated versus when the warning is cancelled (or turned off).
- Initially, it was thought that valve-stem-mounted technology typically does not compensate for increases in tire pressure as a result of increased tire temperature from high-speed driving. Therefore, as tire pressures increase due to increasing temperature, any low-pressure warnings that may have been active when the tire was cold would be cancelled as the tire temperature increased. However, the valve-stem-mounted technology tested on the motorcoach disproved this hypothesis during the testing and was shown to include temperature compensation. The manufacture used the hysteresis effect described above in conjunction with a proprietary algorithm to determine when tires are increasing pressure as a result of tire temperature.
- Valve-stem-mounted systems are susceptible to loss and possibly theft because they have to be removed during wheel mounting and dismounting for vehicle maintenance and inspection. Reinstalling these systems on the proper wheel is also critical for maintaining the proper programming in the display units (swapped sensor locations lead to swapped sensor readings).

Wheel-Mounted TPMS Observations

- An initial project hypothesis was that wheel-mounted technology included temperature compensation, and typically provided the best performance for correcting for tire temperature. However, during the high-speed testing, both wheel-mounted systems tested had active warnings cancelled when the pressure increased in the tire as a result of increased tire temperature. This occurred intermittently between the various test runs on different axles, although it appears from the test data that the systems were able to compensate for large increases in tire temperature (greater than 20 degrees F) a majority of the time, but smaller increases with corresponding pressure increases were not compensated for.
- It was discovered during the TPMS installations that the wheel-mounted technologies are vulnerable to damage during tire mounting/demounting.

Tire-Mounted TPMS Observations

- The tire-mounted technology tested included temperature compensation, which when read by the handheld reader, displayed temperature-corrected pressure along with the uncorrected pressure and the tire temperature.
- The tire-mounted technology tested required handheld or gate reader devices to inspect tires—no in-cab display was available. In addition, the system was designed to provide an Internet-based tire maintenance and tracking database application hosted by the system manufacturer. This allowed data from the gate reader to be uploaded automatically to the Web database where a complete history of that tire/tire tag is stored. The handheld reader (used typically by maintenance personnel) could be docked with a cradle to upload scans of tire tags to the same Web database.
- For the tire-mounted units, the gate reader clearance requirement dictated very slow vehicle speed, less than 5 mph. This limited the practical ability to test varying speeds through the gate reader. However, since the reader, according to the manufacturer, typically requires a 5- to 10-mph speed, the clearance is beneficial for the fleet in that it forces drivers to negotiate the gate reader slowly, thus ensuring complete reads of sensors.

6.3 Central Inflation Systems (CIS)

CIS are available for motorcoaches, straight trucks, and tractor-trailer vehicles. In this test, one system was tested on the motorcoach and one was tested on the trailer of a tractor-trailer. The Vigia CIS used externally routed air lines to each wheel end on the vehicle. The PSI CIS used the hollow axles to route the air to the wheel ends. The requirement of a rotary union for the Vigia CIS precluded the use of the rotary union for the test instrumentation, somewhat limiting the range of performance tests. Key observations and conclusions on the CIS include the following:

- The tested CIS generally perform as designed and specified by the manufacturer. The systems performed well in both static and dynamic conditions.
- During the testing involving leak rates, the Vigia CIS was able to keep up with leak rates up to 5 to 8 psi/min. Ultimately, this system was limited by the vehicle’s air compressor duty cycle and air system design.

- Trailer-only systems use internal axle passages for supplying air to the wheel ends. This system kept most of the system components and lines out of sight and protected from potential damage.
- The CIS tested on the trailer could maintain adequate tire pressure with slow leak rates (less than 1.0 psi/min), but would not maintain adequate tire pressure for higher leakage rates. This system appeared to be limited by its ability to flow air to the tires more than by the on-board compressor and air system.
- During testing with heavy braking and simultaneous tire leaks, the vehicles' primary (rear brakes) and secondary (front brakes) air reservoirs did not become significantly depleted. The compressor had no difficulty recharging the reservoirs without having to run continuously. The test data suggests that the vehicles would likely have braking problems due to over-heating of the brakes before they would encounter problems with insufficient air pressure. During the tests, there were no adverse effects on braking performance observed with either CIS subjected to high leakage rates
- Both CIS tested protected the "intact" tires from deflating if/when a catastrophic air leak was experienced in one of the other tires in the system. In this regard, the systems functioned in a manner similar to the dual tire equalizers' isolation circuits.
- The PSI CIS used pressure release vents to protect the wheel hub from a failed internal seal. Without these vents, there is a potential to "blow out" the grease from the wheel end through the hub if an internal air seal fails in the axle. This type of failure would seriously damage the axle and could present a safety hazard. During the disablement modes tests (Section 5.3.5), the hubcap of a test axle was drilled to fit a shop air hose and 100 psi of shop air was applied to the hole simulating a failed internal seal. The PSI CIS vents in the hubcap properly opened releasing the pressurized air and preventing possible damage to the axle end and bearings. In a real failure of the internal seal, this could result in significant damage if there were no vents or if the vents failed to open as designed. While it is likely that this type of failure may not have an immediate safety impact, should the axle or bearings be damaged, handling of the vehicle might be compromised.
- The Vigia CIS used an external rotary union assembly to provide air to the steer, drive, and tag axles. This exposed assembly could be prone to damage from road debris or impacts during CMV operations. The design of the trailer-only system (specifically, the use of the axle to deliver air pressure) prevents its application to drive and steer axles because they do not provide a hollow internal path to the wheel ends.

6.4 General System Performance and Test Observations

Observations and conclusions about brake system performance and the testing in general are as follows:

- The central tire inflation pressure testing revealed an interaction between the high leakage rates and the vehicle air systems. High leakage rates cause increased compressor loading cycles resulting from the depletion of the secondary air reservoir by the CIS. The CIS are plumbed into the secondary reservoir to isolate the primary reservoir supply to the braking system. The primary air system supplies the rear brakes of the CMV, which provide the majority of the braking power of the vehicle. The secondary air reservoir supplies the front brakes of the vehicle, which require less air for operation and produce less braking power than the rear brakes. Vehicle air systems are not optimized to support a CIS with high leakage rates; therefore, the functionality of the CIS is often limited by the vehicle's air system. Additionally, there may be some long-term impact to the air system of the vehicle when exposed to a high leakage rate from the secondary reservoir including a significant increase in the duty cycle of the compressor and subsequent impacts on durability.

- Installation time for systems vary, but in general valve-stem-mounted TPMS and dual tire equalizers were less time consuming to install, followed by wheel-mounted TPMS and tire-mounted TPMS, with CIS taking significant time for installation.
- Temperature compensation in TPMS requires further refinement. During high-speed driving, the warning indicators would energize intermittently on some systems.
- The Vigia CIS precluded the use of the custom rotary union that was used in the instrumentation set up for all the other systems tested. Future tests of CIS that incorporate rotary unions in their designs will need to use instrumentation such as wheel-mounted RF-type systems to transmit tire pressures and temperatures wirelessly to the data acquisition equipment. In the test of the Vigia CIS, the pressure transducers had to be plumbed into the pressure lines of the system being tested in order to monitor tire pressures. This is not an optimal condition as the pressure being measured is the inflation line pressure and not the tire pressure under conditions when there are high rates of inflation. The inability to use the instrumentation rotary unions also prevented the ability to monitor the tire temperatures via the installed thermocouples.

6.5 Recommended Future Research

This project has provided comprehensive baseline assessments of a variety of state-of-the-practice tire pressure monitoring and inflation systems. The project team performed these assessments under controlled test track conditions. Between test sequences, the team checked and recalibrated various sensors and systems as needed. In the "real world" of CMV operations, inspection and maintenance are generally performed at much longer intervals—for CMVs operating in interstate commerce, the mandatory periodic inspection interval is 12 months. Furthermore, the useful operating life of a heavy-duty truck or motorcoach can be 10 to 12 years or longer, and the operating environment is much more severe than on the test track. Therefore, there is a need to subject tire pressure monitoring and maintenance sensors and systems to the rigors of operation that a CMV would experience during the course of revenue service.

An FMCSA-sponsored FOT involving the use of a transit bus fleet or commercial trucking fleet would serve as a long-term test bed for new equipment and maintenance practices. Data collected during the FOT could be used to determine tire pressure monitoring and maintenance systems ease of installation, ergonomics and functionality, accuracy and sensitivity for detecting pressure changes, serviceability, reliability, and overall customer acceptance. The utility of these systems could also be evaluated with the help of the fleet operator to determine the potential of using the systems for reducing maintenance costs, increasing performance and safety, and reducing vehicle downtime for scheduled or unscheduled maintenance and repair.

APPENDIX A – TIRE PRESSURE MONITORING AND INFLATION SYSTEMS AND PRODUCTS

Dual Tire Pressure Equalizers

Tire pressure equalizers are designed to make tire pressure maintenance a bit easier and equalize the pressure between two tires of a dual assembly. Equalizing the tire pressure reduces irregular tire wear and decreases rolling resistance, which improves fuel economy.

Tire pressure equalizer systems constantly monitor tire pressure and equalize dual tire pressure by allowing air to transfer from one tire to another as they run down the road. This is accomplished by the use of two hoses that are plumbed to a check valve and each attached to the valve stem of a dual tire. The check valve is attached to the hub. The valve opens to allow airflow between the tires, but closes and shuts the air off in case of an instantaneous air loss, which prevents both tires from going flat. In a slow leak situation, the valve isolates both tires after a pressure drop of approximately 10 psi. Since a central valve is located in these devices, a single airing point is provided that eliminates the need to remove the hoses to add air to the tires and makes airing the tires easier since both tires in the assembly are aired at the same time. These systems also provide a visual indicator of air pressure conditions in the tires that can be seen from about 20 feet away. They do not provide actual inflation pressures, but do provide different types of go/no-go gauges that can indicate whether the tires are under-inflated, over-inflated, or at the correct pressure. This display feature is the primary difference between these systems.

One problem with tire pressure equalizers is that after a year or two the accuracy of the valves deteriorates as the internal diaphragms wear. Hose breakage is also a maintenance item.

Link Manufacturing, Ltd. produces the ***Cat's Eye Tire Pressure Maintenance System***. The Cat's Eye Tire Gauge works in the same manner as the Tire-Knight-S, but has a different display for inflation condition. A 100-percent solid yellow display on the air valve indicates that the tire pressure is +/- 2 percent of the recommended inflation level. As the pressure drops, a vertical black line appears in the center of the display. This is the "Cat's Eye." As pressure drops further, the line widens until an all-black display indicates that tire pressure is approximately 10 psi below the specified level. The display is factory set for a specific pressure and is non-adjustable. This system currently costs about $50 an axle end with rubber hoses, and $60 an axle end with stainless steel hoses. The company has been marketing the Cat's Eye Tire Pressure Maintenance System since 1990, and has sold conservatively 125,000 units to date. It now sells approximately 30,000 annually. *Link Manufacturing, Ltd., 223 15th Street, N.E., Sioux Center, IA 51250-2120, (800) 222-6283, Pat Coghlan, National Sales Director, www.linkmfg.com.*

V-Tech International, Inc. produces the ***Tire-Knight-S*** for dual-truck tires. It is similar to other equalizer systems in that the check valve assembly is mounted onto the wheel and the hoses are attached to the valve stems of both dual tires. However, each tire is connected to its own chamber and has its own valve for individual inflating and pressure checking in the unit. A bypass connects and equalizes the pressure in both tires when a piston opens or closes the bypass. (The piston is the only moving part in the unit.) The piston opens the bypass if both tires have a pressure greater than 85 to 90 psi. The piston closes the bypass if one tire blows out, one hose is unhooked or cut, or both tires have a pressure of less than 80 to 85 psi. The position of the piston can be checked at a glance, although the indicator is not very clear. The bypass is designed to allow minimal air flow. In case of a leak, there will be a pressure difference between the dual tires. Both tires would have to be gauged to determine which is leaking. V-Tech is currently developing an integrated new sensor/indicator that will produce a radio frequency (RF) or infrared transmission signal (thus, improving upon V-Tech's current piston indicator). The signal would be sent to a gate reader or in-cab monitor. The prototype for this RF device will be available in June. V-Tech has sold around 100 to 200 units locally in the Wisconsin area including some to Schneider National. The price per unit is $80, or $640 for 16 positions. *V-Tech International, Inc., 227 Barbie Drive, West Bend, WI 53090, (262) 306-1708, Gottfried Hoffmann, President, www.vtechint.com.*

Tire Pressure Monitoring Systems

There are several types of tire pressure monitors. These systems can be categorized into the following types:

1. Valve-Stem-Mounted Tire Pressure Monitors
2. Wheel-Mounted Tire Pressure Monitors
3. Tire-Mounted Tire Pressure Monitors

All of these systems monitor tire pressure through a device that senses the pressure and forwards an RF signal to a display of some kind, which is located in the tractor cab or in a more remote location. Many systems also monitor temperature and convert the actual hot tire pressure to cold pressure so that meaningful data is related to the user.

Valve-Stem-Mounted Tire Pressure Monitors

Advantage PressurePro LLC markets ***PressurePro*** (formerly Tire Mate). The company began its entry into the tire pressure monitor market in 1992 with Tire Mate, a product that fits over the valve stem like a valve cap and transmits an RF signal indicating the tire pressure. The product was not reliable, as it frequently failed to work in high humidity and rainy conditions. It had a two-percent failure rate on the sensors, and did not have the ability to notify users when it was not functioning properly.

The company's newest product is called PressurePro. It is approximately 1 inch in diameter and ¾ inch in length, weighs 0.25 ounce, is completely sealed, and fits over the valve stem. There is no RF "cross-talk" between systems on adjacent wheels as each sensor signal is uniquely identified by its own serial code. The sensors check tire pressure every 15 seconds. The PressurePro system can monitor 1 to 34 tires with pressure from 10 to 150 psi. The receiver/monitor is battery operated. The monitor is 6 inches wide by 3 inches tall and 0.5 inch thick, and weighs just under 8 ounces. When tire pressure drops below the low trigger pressure set by the user, the monitor triggers an alert that displays tire location, low-pressure reading, and battery power in the sensor. An audio and visual alert comes on when a tire is 10 percent below target pressure, and a more aggressive alert identifies a tire that is 20 percent below. The driver can scroll through the display to check all tires on demand as well. The battery life in the valve-stem sensors is expected to be 5 years in automobiles, 3 to 3 ½ years in RV applications, and 2 years on commercial trucks. The life of the battery is dependent upon mileage since the sensor is activated by tire rotation. The RF signals from the trailer tires are linked to the tractor receiver with a relay box that fits on the front of the trailer and sends an RF signal to the cab. Alternatively, a handheld receiver called the PressurePro Wand can read sensors within one foot of the tire. A gate reader will be added to the product line as well. PressurePro is currently being field tested. The company states that it has 600 units installed on a variety of commercial vehicles. The cost for an 18-wheel, tractor-trailer combination will be around $1,075 for the sensors and on-board receiver. Between 35,000 and 40,000 Tire Mate units were sold primarily to the RV industry and owner operators. Advantage has about 600 to 800 of the new PressurePro units operating on commercial vehicles at this time. *Advantage PressurePro LLC, Inc., 205 Wall Street, Harrisonville, MO 64701, (800) 959-3505, Phil Zaroor, President, www.advantagepressurepro.com.*

The **AIR CHEX Equipment Co., Inc.** is developing the ***Air Chex*** system, which is a monitoring system that includes a pressure sensor/transmitter, pressure gauge, valve stem, and connecting braided hoses. The hose connects to the valve stem and has a pressure sensor attached to the end. Air pressure is constantly monitored. The sensor can be fitted with either a red LED that lights when the battery is low or a buzzer that sounds on the wheel. A display is attached to the dash. The Aero Disc is designed for dual wheels and has pressure gauges on the disc face and valve stems. Behind the disc is the pressure sensor/transmitter and connecting braided hoses to the valve stems. The company claims the disc reduces turbulence around the wheel and improves fuel economy by 4 percent. The cost of this system is projected to be under $30/wheel. *AIR CHEX Equipment Co., Inc. 27 New Street, Nyack-on-Hudson, NY 10960, (845) 358-8179, Fax (845) 358-4804, Mark Wallach, CEO.*

Meritor WABCO and **Michelin** developed the ***WABCO Integrated Vehicle Tire Pressure Monitoring (IVTM) System*** for commercial vehicles. Each tire and wheel assembly is equipped with a wheel module that is attached to the outside of the wheel rim using two wheel bolts and nuts. It is connected to the tire valves using pneumatic hoses. The system checks pressure constantly and transmits tire pressure via an RF signal every 15 minutes to the electronic control unit (ECU), and every 30 seconds in case of a significant pressure variation. Operating frequency is 433 MHz. Power is supplied from a built-in lithium battery with a five-year service life. The IVTM ECU is mounted on the vehicle chassis attached equidistant between the front/rear axles and contains a built-in antenna to receive the pressure data from all tires. This location eliminates the need for additional antennas in the wheel modules themselves. Trailers are equipped with their own ECU/transmitter, which sends the tire inflation pressure RF signals to the ECU on the tractor.

The dashboard display warns the driver optically and acoustically whenever the inflation pressure of a tire on the tractor or trailer has reached a critical value. A yellow lamp indicates a slight pressure loss; a red lamp indicates a critical pressure loss. The position of the concerned tire and its current inflation pressure can be queried on the display at the push of a button. Under normal circumstances, there is no pressure display as this system only displays exceptions. *WABCO GmbH, Vehicle Control Systems, Am Lindener Hafen 21, D-30453, Hanover, Postfach 91 21 62, Germany, 49-511-922-2144, www.ivtm.com.*

The **Bigfoot Tire Alert Company** sells a pressure monitor system called the ***Bigfoot Tire Alert*** that attaches large dial gauges to the ends of the valve stems with hoses. The gauges are attached to the outside of the wheels with the wheel studs. Adaptors are available for hub piloted, stud piloted, and spoke wheel/demountable wheel systems. Tire pressure is monitored by walking around the vehicle. The company has been manufacturing and selling this product since June 2003 and has sold approximately 450 units to date. The cost of the Bigfoot Tire Alert is $100 Canadian. The monitors are sold in packages of four. *Bigfoot Tire-Alert Co., 4532 6th Street, N.E., Calgary, Alberta, Canada T2E 327, (403) 276-7948, www.bigfoot-tirealert.com.*

Colorado Enterprise International is developing a remote tire pressure sensor for medium-duty trucks called the ***C.E.I. Tire Monitor***. Its remote pressure sensor continually monitors the pressure of each tire on a vehicle and provides the driver with a real-time display of this information. The device is made up of two components. The first is a small radio transmitter assembled into a modified tire valve assembly. This valve is also equipped with a simple pressure switch that is configured to activate at a predetermined threshold. Once activated by low pressure, the transmitter will immediately transmit to the unit on the dash the unique sensor identity code for that wheel position. The unit on the dash will receive the code and match it against the codes it has stored for the tires on that vehicle. If a match is found, an enunciator will sound and an indicator will show which wheel is generating the signal. A small standard lithium coin cell battery that is estimated to provide more than 4 years of operation powers the transmitter module. Once depleted, it can be replaced by the user. (The company is exploring the possibility of powering the unit with centrifugal force.) To provide notification of sensors that have failed, are missing, or whose batteries have been depleted, the transmitters are configured to periodically send a brief message to the dash unit to confirm they are operational. If the dash unit does not receive the periodic update, a different warning message is provided to the driver. The company claims that the sensors attached to wheel assemblies on doubles trailers can successfully transmit their signals to the dashboard receiver. List price for this system is about $500 ($27/monitor) for an 18-wheeled vehicle. *Colorado Enterprise International, 20 Lanning Blvd., Suite 215, East Windsor, NJ 08520, (609) 918-9646, Edward Neefeldt, President.*

Doran Manufacturing LLC sells the ***Doran Tire Pressure Monitoring System***. This system is made up of a sensor that screws onto the valve stem of each tire and a receiver that fits into a standard gauge hole in the dash. The sensors weight 25.7 grams and require the user to adjust the pressure setting. The sensor comes apart to show a pressure scale that has a range from 18 to 125 psi. The desired pressure is set using a screwdriver. The sensor sends a “soft” alarm when the pressure drops to 10 percent below the setting and a more urgent audible alarm when the pressure drops by 25 percent. Each sensor on the truck/tractor is marked with the wheel position so that the system can tell the driver which tire has low pressure. In addition, the system has unique codes for each sensor so that trucks do not receive signals from each other in the yard. However, all trailer sensors are coded the same, which allows for drop and hook operations. Sensor batteries normally last 2 to 3 years since the sensor only sends a signal when there is a low-pressure tire. However, if no action is taken to correct the under-inflation condition, the sensor sends the alarm continuously and the battery will last only to 2 weeks. The receiver in the dash indicates which tire is low with a graphic display. The appropriate position is indicated visually, a “Low Tire” signal is shown, and an audio signal is heard. The receiver needs three wires that attach to the battery, ignition, and ground. An antenna is required to receive signals from trailer tire sensors. This antenna is a wire that attaches to the back of the receiver and runs under the cab to the back of the tractor. The Doran Tire Pressure Monitoring System can monitor up to 34 tires. This product has been available since January 2004. The price to equip an 18-wheel unit is around $900 and a 6-wheel unit is $300. The company anticipates that they will develop a gate reader in the near future. Also available is the use of a "Repeater" unit (like that used by Advantage PressurePro) that will send the new codes for a new trailer hooked up to a tractor to the monitor so it will recognize the new trailers sensors. *Doran Mfg., LLC, 2851 Massachusetts Avenue, Cincinnati, OH 45225, (866) 816-7233, Fax (513) 681-5604, www.doranmfg.com.*

Fleet Specialties Company produces ***Tire Sentry*** for all classes of trucks, buses, and RVs. Microchip wheel sensors attach to each valve stem to continuously monitor tire pressure mechanically and transmit a coded signal to the dash instrument when a loss of tire pressure is detected. A warning light and audible alarm on the dash display shows which tire is losing pressure. The Tire Sentry wheel sensors incorporate a pressure sensor and a microchip transmitter powered by two standard watch batteries and are set to the user's individual tire pressure requirements. The user can change pressure settings when desired without the need of special equipment. The wheel sensors that are installed on each tire valve stem weigh less than 1 ounce and can transmit their coded signal up to 50 feet to the antenna located near the drive axle of the tractor. Tire Sentry's coding system prevents "cross-talk" to other vehicles. The display module is wired into the vehicle's power source. Tire Sentry's operating range is 50 feet. It operates on 303 or 418 MHz frequency, has an air pressure range of 18 to 125 psi, and has a battery life of two to three years. The cost of a Tire Sentry system for an 18-wheel vehicle is about $750 to $965 depending upon fleet size, and for a 6-wheel bus is $395 or less depending upon fleet size. Fleet Specialties has been developing Tire Sentry since 1995 and has been marketing it since 1997. It has sold "several thousand" units. *Fleet Specialties Co., PO Box 4575, Thousand Oaks, CA 91361, (818) 889-1716, Bill James or Bill Shore, www.tiresentry.com.*

REA Technologies has patented the ***Integrated Tire Pressure Audio Alarm***. Although not yet on the market, this tire pressure warning device consists of a long-life battery, a pressure sensing switch, and an audio alarm. The device can be designed as either a discrete thread-on (to an existing valve stem) unit or as a unit that would completely replace a standard valve stem. Either design could be made with a replaceable battery or as a throwaway unit after the battery is completely drained. In the thread-on version, the device would simply thread onto an existing valve stem, replacing the valve cap and providing an intermittent audio warning, which could be heard within a few feet of the device when a pre-determined, low-pressure threshold is reached. The device is cylindrical, about 3/8 inch in diameter and approximately one inch in length that essentially looks like a valve-stem extension. The valve-stem version is designed to completely replace the standard valve stem. This unit would perform just like a standard valve stem except it provides the appropriate low-pressure warning. Both units incorporate a small sensor/switch at its base and a battery/sounder module. Since the units are under pressure, pressure is constantly monitored. It does not have an in-cab display, but could provide an LED display on the end of the valve stem. Depending on the specific production model, pressure range, and features, the product is priced at under $10 per unit, or $180 for a tractor-trailer combination. *REA Technologies, Inc., 815 Brookmead Drive, O-Fallon, MO 63366, (636) 272-3770, Stephen Blakely, Director, Technology Commercialization.*

Sensatec, LLC is developing a tire pressure and temperature sensor system. The system alerts drivers to impending tire, bearing, and brake problems by generating an audible, visual, and digital alert when any increase in tire temperature or decrease in tire pressure occurs. It provides constant monitoring of changes in tire pressure and temperature on any vehicle. Tire Safe can be coupled to a satellite transmitter to relay information to a central control facility. The system includes sensors on each tire valve and a portable dash unit that consists of a liquid-crystal display that is either battery powered, wired into the vehicle's electrical system, or plugged into the cigarette lighter. The tire sensor is a 1 x 2 inches cylinder that has a special universal mounting sleeve, which allows it to fit on most valves stems. The sensors are battery powered, and battery life is between 9 to 24 months depending on battery type, frequency of interrogation, and amount of use. The user can accept factory default conditions or program a variety of performance monitoring features such as variable pressure, temperature, frequency of reading, and alarm settings. The operator can set the level at which the tire pressure and temperature measurements will activate the audible and visual warning and alarm features. The display unit continuously displays each tire's position and its conditions. Green is normal, amber is a warning condition, and red is an alarm condition. The display unit includes buttons for power and setup menus and an optional computer connection for downloading of tire condition history. A communication control relay box is available for trailers that allows a single tractor to connect to any so equipped trailer. The system operates on 900-950 MHz frequency. Market introduction is expected in 2007. The price for the Tire Safe system will be about $1,200 for an 18-wheeled tractor-trailer unit and $400 for a 6-wheeled bus. *Sensatec, LLC, 4 Woodbine Avenue, Greenwood Lake, NY 10925, (845) 477-0200, Keith Yeates, www.sensatecllc.com.*

TireGuard has a valve-stem-mounted tire pressure monitor called the ***TireGuard***. The valve cap-like monitor is available in pressure ranges from 26 to 120 psi and as such is being marketed to the automobile/light truck and motorcycle markets as well as the recreational vehicle and commercial vehicle markets. The cost is $7.50 per wheel retail with discounts being offered to fleets. A typical fleet can equip all their wheels for around $4/wheel or $72 for an 18-wheeled tractor-trailer unit. This product has had problems with leakage that causes tires to lose air and go flat, as experienced by the author. *TireGuard, 1501 E. Orangethorpe Ave., Suite 170, Fullerton, CA 92831, (714) 773-4300, Fred Wiseman, www.tireguard.net.*

Wheel-Mounted Tire Pressure Monitors

Beru Group introduced its ***Tire Safety System (TSS)*** as standard OEM equipment for commercial vehicles in July 2003 in Europe. The TSS consists of a central control unit and a set of battery-powered wheel electronics attached to each wheel as well as a high frequency receiver for each axle group. The sensors measure the tire pressure and temperature at frequent intervals. These values are sent by radio communications to the antennas where they are then converted into a digital signal and sent to the central control unit for analysis. The control unit analyzes the data, and converts tire air pressure to standard pressure. The target tire pressure is set by the driver at the press of a button or at the factory. Should a sudden drop in tire pressure occur, a warning appears in the instrument panel display that says "Flat tire, stop immediately." In the case of a slow loss of pressure, a warning is displayed for the driver to increase the tire pressure at the next opportunity, which is repeated each time the ignition is turned on. This warning first appears when pressure has dropped 6 psi. If the pressure falls 12 psi, the warning is displayed at a higher urgency level in red instead of yellow. If the pressure loss occurs when the vehicle is stationary, the driver is warned before he starts his trip. The service life of the wheel electronics is 3 years, and they operate at tire temperatures ranging from -40 to 120 degrees. This system has been linked to satellite-aided telemetry in Europe. It is understood that Beru has recently been talking to truck OEMs in the United States. *Beru Group, Morikestr. 155, D-71636 Ludwigsburg, Germany, 49- 7141-132- 233, www.beru.com.*

HCI Corporation sells the ***Tire-SafeGuard*** tire pressure monitoring system. This system alerts drivers of low-pressure situations by providing the location, temperature, and pressure readings via a display unit and an audible signal. It monitors tire pressure continuously with detection of abnormal tire pressure even while the vehicle is parked. The Tire-SafeGuard product for commercial vehicles (TPM-S206) uses a sensor mounted onto the wheel rim inside the tire. The low-pressure and temperature warning is user adjustable and has a range of 18 to 130 psi. The sensor transmitter automatically switches on when the vehicle is moving faster than 15 mph and reports pressure readings to the receiver using an RF signal. Pressure measurement accuracy is +/- 1 psi. The module has an operating temperature range of -40 to 250 degrees and a battery life of over 5 years. The receiver for the display can be plugged into the auxiliary power outlet or can be directly hardwired to the main power source. It is 3 ½ x 1 $^{1}/_{8}$ x $^{5}/_{8}$ inches in size and weighs 1.5 ounces. The cost to equip a tractor (10 positions) is $650. The company has also developed a receiver to mount onto trailers that will transmit signals from the trailer tires to the in-cab monitor in the tractor. *HCI Corporation, 11245 E. 183rd Street, Cerritos, CA 90703, (562) 926-7123 x 212, Tim Glassford, Sales Manager, www.tiresafeguard.com*.

SmarTire Systems, Inc.'s currently marketed technology uses wireless communications to monitor the air pressure and temperature in tires. A small sensor is strapped on each wheel and collects temperature and pressure data every 7 seconds. This data is transmitted via radio frequency to a receiver display located inside the vehicle that indicates individual tire pressure and temperature. The transmitted tire data is captured by the receiver which in turn sends the information to the display unit. The display unit allows the driver to toggle through each wheel position and to select the type of information being displayed: tire pressure, temperature, or pressure deviation. The display incorporates a bright red LED light, which is activated whenever a tire pressure irregularity is detected or when the temperature of a tire goes above a preset level. SmarTire currently sells tire-monitoring products for the RV market and for the CMV market. These products monitor pressures up to 188 psi and accommodate up to 20 wheel positions. *SmarTire Systems, Inc., Suite 150 – 13151 Vanier Place, Richmond, BC, Canada V6V 2J1, (604) 276-9884 x 308, John Bolegoh, Product Manager, www.smartire.com.*

Yokohama Tire Corp. has also developed a chip technology for truck and bus tires. Yokohama's has named its tire pressure monitoring system ***Hi-Technology Tire Engineering System (HiTES***). This system uses a sensor that is mounted onto the tire rim and reports pressure and temperature to a receiver and display unit in the cab of the truck. Also, near the driver is an LED indicator that uses color changes to show air pressure status. This allows drivers to confirm air pressure in real time, reducing the time needed to conduct checks before they begin a trip. Yokohama also has a handheld monitor. Data is automatically transmitted to Yokohama's host computer where it is managed along with information gained through periodic checks of tire wear, damage, and distance traveled. This information can be analyzed and provided to the customer via the Internet, enabling customers to precisely calculate the appropriate times for tire changes and rotations. According to Yokohama, it has been testing this technology in both OTR tires as well as medium truck tires for several years. No price is yet available for this system. HiTES was commercialized in Japan in July 2003 and is expected to be marketed in limited quantities to trucking firms and bus companies through Yokohama's tire sales subsidiaries throughout the world including the United States. Yokohama is offering the system exclusively to users of Yokohama tires. To date, the product has not been introduced to the U.S. market. (One vehicle was equipped for test at the Port of Tauranga, New Zealand in January 2004.) Yokohama plans to develop a range of systems and products as part of its Tire Management System program. *Yokohama Tire Corp., 1500 Indiana Avenue, PO Box 3250, Salem, VA 24153, (540) 389-5426, www.yokohamatire.com.*

Tire-Mounted Tire Pressure Monitors

CrossLink, Inc. was licensed by Bridgestone/Firestone to market the ***TreadLink*** system that is designed for trucks and other heavy equipment vehicles, after 5 years of development. The TreadLink system uses 1–inch, square, 915 MHz passive tags that have a read range of up to 30 feet. Each tag holds 8 kilobits of data, including a unique serial number, temperature and pressure readings, and the maximum temperature of a tire during its lifetime. The pressure-sensing chip is permanently installed on a patch inside the tire**.** The RFID transponder sends data on the temperature-adjusted pressure of each vehicle's tires to readers placed on the truck or at a terminal entrance or exit. These readers are connected to PCs with special software to record the information. Fleet operators can also scan the tags with a handheld reader. The company says it is working on reusable tags as well as a similar system that tracks tires and links them to the truck as part of a larger vehicle-monitoring system. The TreadLink system will be available in early 2004 for trucks, buses, tankers, trailers and off-road heavy equipment vehicles over 6,000 pounds gross vehicle weight rating. The tags are expected to be priced at around $30 each. Fixed readers will run about $1,000. On-board and handheld readers will cost about $300 to $400. *CrossLink,Inc., 6185 Arapahoe Avenue, Boulder, CO 80303, (303) 473-9232, Gary Zarlengo, President, www.crosslinkinc.com.*

D.H. Products is developing a tire pressure monitoring system called the ***Flat Alert System*** that is placed inside the tire, although not mounted to the tire. This system uses a silicone-covered, 2–inch, 2-ounce ball, which rolls inside the tire as the tire runs. It has an expected life of 250,000 miles. A handheld reader is used to read the pressure and a display/receiver is also located in the cab of the vehicle. It is expected to retail at $612 for an 18-wheeled unit ($450 for fleets). *D.H. Products, 2231 Riviera Place, Longmont, CO 80501, (303) 772-7902, Dusty Hill, President.*

Michelin North America introduced its **eTire** system for medium-duty trucks in October 2002. The eTire system uses Michelin's battery-less InTire Sensors that can be applied to any commercial truck tire using the sidewall-mounted SensorDocks, which are molded rubber pieces that chemically cure to the inside of the sidewalls in the same fashion as tire repair units. The sensor unit slips over a knob on the rubber dock and locks into place. Once installed, the sensors remain throughout the entire life of the tire including retread processes. The sensor is removable and can be reattached to a new truck tire with a new SensorDock. The sensors measure temperature and pressure on demand and communicate this information along with wheel position, and a programmable identification number for its respective tire, to drive-by and handheld readers that power the sensors. Other sensors located on the tractor and trailer provide vehicle identification information at the same time. The sensors include an RF transmitter, pressure and temperature sensors, and an antenna, which are encased in impact- and heat-resistant plastic. The unit measures 4 x 1.5 inches and weighs less than an ounce. The vehicle must be traveling about 5 mph or less past a gate reader for the reader to receive the information from all the tires including the inside duals. The reader picks up about 95 percent of the sensor information when a vehicle drives by. The sensors included temperature compensation. The information gathered is reported in a fleet specific manner via an Internet server to Michelin's

BIBTRACK Web site, which is home to BIBTRACK software that tracks tires and provides recommended actions for problem tires. Fleets can get up-to-date information on their tires, track tire costs, and monitor inventories around the clock by going on-line. No data is stored on the sensors themselves. This system does not have an in-cab display. The InTire Sensors do not have 360-degree read capability, so the handheld reader must be positioned over the sensor to read it. Michelin has an eTire label installed on the outside of the tire that visually locates the sensor. Each sensor unit costs about $30, but actual fleet cost will vary based on fleet size. Handheld readers are approximately $6,000, and gate readers are approximately $10,000 to $12,000. No unit sales numbers are available. *Michelin North America Inc., PO Box 19011, Greenville, SC 29602, (864) 458-5476, Randy Clark, Vice President of Marketing, Truck Tire Unit, www.michelintruck.com.*

Tire Pressure Maintenance Systems

There are basically two types of tire inflation systems. The first type uses air from the vehicle's air system to inflate the vehicle's tires. These systems are generally referred to as central tire inflation systems. The second type uses a pump of some kind that is separate from the vehicle's air system to generate air. These systems are referred to as continuous tire pressure pumps.

Central tire inflation systems take the air that is stored in the air brake wet tanks on a vehicle and use it to supply air to the tires. This can be done on demand or automatically triggered through sensors that monitor tire pressure. These systems can be broken down into two types—constant and variable. Constant systems maintain tire pressure at a single preset level. They eliminate the need to check tire pressure manually and allow a vehicle to remain in-service despite small air leaks in one or more of its tires. Constant tire inflation systems have no involvement from the driver. They automatically sense the pressure in the tires and inflate as necessary when they lose air. A drawback to these systems is that the external hoses can get damaged and render the systems ineffective and may even deflate tires. Seal life in the axle ends of systems under contact pressure is reduced. Also, tires with undetected nail holes can develop separations over time.

Variable central tire inflation systems can raise or lower tire pressures during vehicle operation to compensate for varying load and road conditions in addition to maintaining tire pressure. These systems allow the driver to interact with the system and change tire pressure on demand. They are expensive and are usually used for on-off road operations such as logging, construction, mining, gravel hauling, concrete, exploration, and military.

Variable Central Tire Inflation Systems

CM Automotive Systems, Inc. manufactures the ***Central Tire Inflation System (CTIS)***, which is designed for all terrain operations more so than over-the-road operations. CM Automotive's targeted market is military trucks and transports, fire and rescue vehicles, logging operations, and dump trucks. The CTIS allows the driver to maintain traction and mobility over wide variations of terrain by adjusting the tire pressures. The tire adjustments can be made while the vehicle is in motion. The system components are the manifold, controller, wheel valve, and harness. The manifold adjusts pressure that goes to or out of the system. The controller is the display located in the cab that allows the driver to operate the system. The wheel valve attaches to the valve stems and allows for the air to enter or escape the tires, and the harness provides the electronic controls to the system. The cost of this system on a tractor–trailer combination ranges from $1,200 to $2,500 depending on vehicle/axle configuration. *CM Automotive Systems, Inc., 120 Commerce Way, Walnut, CA 91789, (909) 869-7912, www.cmautomotive.com.*

Tire Pressure Control International, LTD. (TPC International) manufactures and distributes the ***TIREBOSS Tire Pressure Control System***. This system integrates with the existing air supply on the vehicle. It is comprised of five component assemblies: a priority valve that protects air brake system integrity, control air valves, air lines to and from the control valves, and axle end rotary union hardware that transmits air into and out of the rotating tires. In use, the driver selects an appropriate setting on the operator control panel, which sends a signal through the computer to either the inflate or deflate control valves. Air from the vehicle brake wet tank is drawn into the tire pressure control system to inflate tires through the inflate valves, while air from the tires is exhausted through the deflate valves. Priority safety switches make sure that air is available for tire inflation only when the vehicle system air brake pressure is above a safe level, typically 90 psi. The computer continuously monitors tire pressure and controls the inflating, deflating, or maintaining of a pre-selected target tire pressure. The system also monitors vehicle speed. If it detects the rig is going too fast for the selected tire pressure and risking tire damage, visual and audible alerts warn the operator to reduce speed or choose another pressure setting. Should the driver fail to respond to these alerts, the computer is programmed to automatically select a pressure suitable for higher speeds. The operator control unit is easy to read allowing the driver to monitor the status of the TPCS at a glance. Four buttons control and program the system's functions, which include four driving modes (i.e., highway loaded, highway unloaded, off-highway loaded, and off-highway unloaded) as well as three secondary function modes. This system is used primarily in on-off road applications such as forestry and concrete operations where mobility in sand or soft ground is required. The cost for this system starts at about $8,000 to equip the tandem drive axles on a tractor. *Tire Pressure Control International Ltd., 15803 – 121 A Avenue, Edmonton, Alberta, Canada, T5V 1B1, (888) 338-3587, www.tirepressurecontrol.com.*

Dana Corporation, Spicer Heavy Axle & Brake Division, markets the ***Tire Pressure Control System***. Dana's Tire Pressure Control System is designed specifically to allow the operator to adjust tire pressure to match the conditions on and off the road while the vehicle is in motion or is stationary. This system is the commercial version of the Eaton Central Tire Inflation System used in military applications. This system regulates tire pressures through a series of electro-pneumatic controls that feed air to each wheel end through wheel valves. The driver operates a dash-mounted graphic control panel, which commands the system to adjust tire pressures, and tells the driver what functions the system is currently performing. A pressure switch prevents the system from consuming air unless the vehicle's brake system is fully charged. This system has three distinct settings: a highway setting for high speed travel on paved surfaces, an off-highway setting for operation on secondary roads, and an emergency setting to help free vehicles that are stuck in muddy terrain or to help drivers negotiate difficult grades. Two modes accommodate both loaded and unloaded trucks. The cost for this system on a tractor-trailer unit is about $7,000 to $13,000. Eaton first introduced this to the truck market in 1990. No sales numbers are available for this product. *Dana Corporation, Spicer Heavy Axle & Brake Division, Advanced Chassis Control Unit, PO Box 4097, Kalamazoo, MI 49003-4097,(800) 826-4357, www.roadranger.com.*

Constant Central Tire Inflation Systems

Air Fender Systems, Inc. has just developed its ***Rotary Air Chamber*.** This system is designed for tractor (including steer tires) and trailer tires and supplies air to them while traveling down the road. The Rotary Air Chamber does this by taking air from the brake system air tank and passing it into an internal air chamber that is bolted on to the axles and rotates with the tires. The air then passes through a small tunnel hole in the rotator shaft and comes out via a 'T' connection that has two hoses connected to the valve stems of the dual tires. The housing of the air chamber is held stationary by Air Fender's fender panel. Tire pressure can be visually read by examining a small pressure gauge on the hose lines that constantly measures the actual tire pressure. Pressure is maintained at 100 psi, and air is exhausted from the tires when pressures exceed 120 psi. This system costs about $80 an axle end. *Air Fender Systems, Inc., 322 Northpoint Parkway, Suite J, Acworth, GA 30102, (800) 527-7729, John Becker, President, www.airfenders.com.*

AIRGO Systems Inc. brought out a new central tire inflation system in July 2003 called the ***AIRGO System***. The company founder, Tony Ingram, was formerly with Pressure Systems International. The trailer central tire inflation system has a light on the trailer nose that indicates when the system is supplying pressure to the tires. The AIRGO System offers constant tire monitoring and when necessary automatic re-inflation. When a tire loses pressure due to a puncture or other leakage, the system's sensor check valve automatically detects the loss. It immediately draws air from the vehicle's reserve pneumatic system, and directs air flow to each tire requiring air. This air pressure is delivered via the trailer's hollow axle housing, through the hub assembly and into the tires. The system uses an externally located rotation design for venting outside of the hub, which eliminates potential internal pressure leaks and debris that can cause damage to internal hub components. Eight cubic feet per minute of air flow is supplied to a leaking tire via a large transfer tube. The external location of the rotating unit allows for fast installation and service and no custom hubcaps are required. The rotary seal this system uses is guaranteed to last 5 years. The suggested retail price is $795 for a tandem axle trailer. OEM and distributor pricing is available. *AIRGO Systems, PO Box 727, Edmond, OK 73034, (405) 844-5825, Tony Ingram, CEO, Julie Leidner Marketing, (617) 422-0045.*

Arvin Meritor distributes **Pressure System International's (PSI's)** ***Tire Inflation System***. This system currently addresses only trailer tires, but the company is working on developing a system for tractors as well. The Tire Inflation System uses compressed air from the trailer to inflate any tire that falls below pre-defined specifications. Air from the existing trailer air supply is routed to a control box and then into each axle. Acting as a conduit, the axles carry the air through a rotary union assembly at the spindle end, which then distributes the air to each tire as needed. Tire pressure is constantly monitored. When a tire experiences a leak, an indicator light mounted onto the trailer comes on to signal air delivery and that tires are being inflated. A one-way check valve located in the hose connected to the valve stem protects each tire against air pressure loss. If a tire is punctured during operation and loses air pressure, the check valve prevents loss of pressure in the other tires. A pressure protection valve located between the shut-off valve and the reservoir allows air to flow to the tire inflation system only when the brakes have sufficient pressure to operate correctly. The cost for this system is approximately $700. *Arvin Meritor Commercial Vehicle Systems, Meritor Heavy Vehicle Systems, LLC, 2135 West Maple Road, Troy, MI 48084, (800) 435-5560, www.arvinmeritor.com. Pressure Systems International, 3023 Interstate Drive, San Antonio, TX 78219, (210) 222-1926, Frank Sonzala, Executive Vice President.*

Dana Corporation, Spicer Heavy Axle & Brake Division, produces the ***Tire Maintenance System for Trailers***. This system constantly monitors tire pressure and provides air pressure automatically to trailer tires that experience air loss. (It does not address tractor tires.) This system detects and responds to low tire pressure by directing air as needed and alerting the operator with a yellow light located on the left front corner of the trailer. It also retains evidence of low pressure tires in its memory for recall during vehicle maintenance. The system uses a main power harness, an ECU, and a pneumatic control valve to regulate air pressure to the tires. Air flows through conduits inside the axle to wheel end seals. The price for this system on an eight-wheeled trailer is $900. This system was introduced in 1999-2000. No unit sales numbers are available for this product. *Dana Corporation, Spicer Heavy Axle & Brake Division, Advanced Chassis Control Unit, PO Box 4097, Kalamazoo, MI 49003-4097, www.roadranger.com.*

Gio-Set Corporation produces the ***Vigia Automatic Tire Pressure System*** for tractors-trailer combinations and RVs**.** This system continuously reports and automatically regulates the tire pressure. When the pressure falls minimally in one or more tires, the Vigia system reports the existence and location of the problem to the driver. At the same time, the inflation process starts to maintain the appropriate pressure in the tires. In case of a tire blowout, the equipment automatically shuts down to protect the operation of the other air-powered components on the vehicle such as the brakes, clutch, suspension, etc. Air pressure is supplied from the auxiliary air reservoir. A dedicated air filter absorbs the impurities in the air. Once the air is filtered, it reaches the control panel and from there is redistributed to the tires. A small control panel in the truck cab controls all the functions in the system. The lights indicate the normal function of the equipment, the loss of pressure in tires, the air circuit where the loss is taking place, and the low air pressure of the compressor. A separate control panel is placed on the front corner of the trailer so that the driver can readily see it. This system costs $2,300 to $3,200 depending on the axle setup for a tractor and trailer combination. *Gio-Set Corporation, 37 Landing, Laguna Niguel, CA 92677, (949) 412-9393, Ruben Giosa, Distributor. www.gio-set.com.*

Hendrickson International began marketing its ***Hendrickson Tire Inflation System*** **(HTIS)** for its INTRAAX and VANTRAAX trailer suspension systems in 2002. This responsive tire maintenance system maintains inflation to a specified level. The system checks tire pressure every 10 minutes, detects low tire pressure, and alerts the operator to the occurrence. It responds by directing air when a tire dips below a predetermined pressure level. HTIS activates only when needed—constant air pressurization to the tires is ***not*** required—reducing air demand and prolonging system life. Air travels from the supply tank through air lines inside the axle to the wheel-ends. A rotary union allows air to flow from a non-rotating axle spindle to the rotating hubcap fitting. Hoses connect from a hubcap tee to the tires. A warning light alerts the operator to system status and maintenance activity and the system records episodes of low tire pressure for retrieval during servicing. Check valves help prevent tire pressure loss back through the system. Manual fill and pressure checks may be accomplished at the hose end. HTIS connects all tires to the trailer air supply and may be combined with any of an extensive array of wheel end configurations and spindles available for INTRAAX and VANTRAAX suspensions only. A laptop computer can be used to download tire inflation history from the system. The system was jointly developed by Hendrickson and Spicer over a 2 ½ - to 3-year period, and was introduced to the market in May 2002. Approximately 1,000 systems are currently in use. Hendrickson sells this system only to trailer OEMs who price it competitively with other similar systems on new trailers. As a result, Hendrickson does not control the price.

Hendrickson introduced a new tire inflation system in 2003 called ***TIREMAXX*** that has less record-keeping features but is less costly. This system is governed by an ECU that detects low tire pressure and signals the operator. It responds by directing air from the trailer tank to one or more tires when the pressure dips below the pre-set level. It only pressurizes the air lines when needed, which protects seals and wheel ends. A lamp is mounted onto the trailer to alert the driver to the system status. An optional handheld programmer featuring a 32-character display accesses status information and, using convenient system-check routines, reduces guesswork when troubleshooting. This convenient maintenance tool reprograms target pressure to settings from 70 to 130 psi in 5-psi increments and helps prevent system tampering. *Hendrickson International, Trailer Suspension Systems, 2070 Industrial Place SE, Canton, OH 44707-2641, (866) 743-3247, Rick Bevington, Marketing Manager, Tire Inflation Systems, www.hendrickson-intl.com.*

Reineke Company Inc. manufactures the ***PressureGuard Automatic Tire Maintenance System*** (which it purchased from Innovative Transportation Products Inc. (ITP) in 2003). The PressureGuard system routes air from the trailer's supply tank through the axle to the hub and then to the tires so they maintain pressure at preset levels. The system is always under pressure so tire pressure is constantly monitored. If there is a tire blowout or system leak, PressureGuard's valve-stem-mounted check valve keeps air in the remaining tires. If a sudden drop in pressure occurs, the system protection valve closes to prevent air loss out of the reservoir so the rest of the trailer air system including brakes remains unaffected. When a sudden loss of air occurs, a trailer-only warning indicator alerts the driver. The cost of the PressureGuard System for one trailer is about $600. ITP worked on developing this product for over a year before it introduced it to the market in October 1999. Since then, it has sold around 20,000 units. Reineke Company has been working with Tire-SafeGuard to offer a tire monitoring system that will work in conjunction with the Pressure Guard Automatic Tire Maintenance System, which will include a display in the cab that advises the driver of individual tire air pressures

Reineke is also developing a drive axle tire inflation system. The ***Drive Axle TIS*** uses a rotary union that can be adapted to fit an array of drive shaft designs. The system was designed for use without complicated electronic components and to maintain correct tire pressure at a preset level (inflate only). The cost for this system is expected to be between $2,000 and $3,000.

PressureGuard TIS for wide base tires is also under development. This system uses a valve stem adapter that is inserted in a hole drilled into the wheel and eliminates the need for hoses. The cost of this system is expected to be from $600 to $700 per trailer. *Reineke Company Inc., 1025 Faultless Drive, Ashland, OH 44805,(419) 281-5800, Matt Reineke, President, www.pressureguard.com.*

Continuous Tire Pressure Pumps

The **Cycloid Company** produced the ***Cycloid Model 2000 Continuous Tire Pressure Maintenance System***. This system was different from the other tire inflation systems as it did not use the air system on the vehicle to supply air to the tires, but rather generated its own compressed air with a small pump mounted onto the end of each axle. The rolling motion of the wheel (centrifugal force) continuously powered the Cycloid self-contained pump compressor. It attached to the hub of a dual wheel assembly and hoses connected the pump to the tire valve stems. Inner and outer tire pressures could easily be checked from a centralized hub-mounted valve stem. An option was available that provided visible pressure gauges to indicate the exact pressure in the tire assemblies. The pump was set at the factory with the maximum pressure to which the tire would be inflated so it would not over-inflate or deflate the tires. The pump constantly monitored tire pressure. When a tire experienced an air leak, the pump supplied air independently to that tire. It did not equalize pressure between the dual tires. Due to overall width limitations on commercial vehicles, the pump could only be installed on dual wheel combinations and could not be placed on steer axle ends. The pump weighed 2 lbs. and pumped 6 psi an hour to tires that experienced air loss. The cost of a Cycloid Model 2000 Pump ranged from $200 to $250 an axle end depending upon the accessories chosen.

In 2001, Cycloid signed an exclusive distribution contract with Euclid Industries for sale of their truck tire pump. However, on the same day, Euclid was purchased by Arvin Meritor, which already had an exclusive agreement with Pressure Systems International for distribution of its Tire Inflation System. As a result, Cycloid decided to exit the commercial truck market and concentrate on the automotive market with its pump through its ties with Arvin Meritor. At this moment, the company does not sell pumps for commercial trucks. Cycloid began developing its Continuous Tire Pressure Maintenance System in 1992 and introduced it to the market in 1997. It has sold 7,000 pumps in the trucking industry. *Cycloid Company, 301 Commerce Park Drive, Cranberry Township, PA 16066, (724) 742-1780, Mervyn Carse, President and CEO.*

Other Technologies

With the advent of the Firestone recall in 2000, new and innovative technologies are being explored to address the problem of tire failures. Some of these technologies do not fit the general category of tire pressure monitors, but do address detection of tire failures. One such technology is described below.

Radian Inc. has developed the ***Thermal Imaging Inspection Station (TIIS)***. This system uses thermal imagery to detect tire faults that result in tire failures due to heat buildup inside a tire. In tires, most tire failures begin with separation in the plies. Air eventually seeps into these areas of separation and heats up and expands when the vehicle is moving. The air trapped in the separations becomes hotter than the air in the tire, which causes the separations to expand until a chunk of rubber breaks off and causes a blowout. The pattern of heat that builds up can be viewed with a thermal imager (camera) that takes temperature sensitive snap shots of tires. The TIIS detects these separations that show up as red in the photographs and is programmed to recognize the thermal signatures associated with separations to give advanced warning of an impending failure. The TIIS can be used in any location where vehicles have been in operation at highway speeds. Weigh stations on interstate highways and the entrance into maintenance yards are good sites for inspecting tires. Vehicles can be moving at speeds up to 15 mph while going through the TIIS inspection. The TIIS can also be mounted in a vehicle and a handheld unit may be available in the future too. In addition, this system can be used to detect overheating brakes and bearings. The cost of the TIIS is currently about $90,000 to $100,000. Radian, however, is working on making a smaller, handheld version that will have a target price of around $20,000. *Radian, Inc., 5845 Richmond Highway, Alexandria, VA 22303, (703) 329-9300, www.radianinc.com.*

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

Report No. FMCSA-PSV-07-001

For more information on the Federal Motor Carrier Safety Administration, check out our website at www.fmcsa.dot.gov.