Advanced Sensors and Applications: Commercial Motor Vehicle Tire Pressure Monitoring and Maintenance

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

February 2014

FOREWORD

This project was completed as a follow-on to several projects performed under the provisions of Section 5117 of the Transportation Equity Act for the 21st Century (TEA-21). The primary objectives of this project were to provide vital cost and benefit information for the implementation of tire pressure monitoring systems (TPMSs) and automatic tire inflation systems (ATISs) to improve tire performance and safety and to influence maintenance intervals and practices. The work performed under the project included:

- Updating and expanding the Federal Motor Carrier Safety Administration's (FMCSA's) past market research studies on tire inflation maintenance and monitoring systems.
- Selecting TPMSs that were representative of currently available products in the marketplace.
- Arranging for field testing of these systems with a commercial fleet, in a normal "everyday" service environment.
- Developing data collection and analysis plans.
- Installing systems on test vehicles.
- Preparing for and conducting the field test.
- Analyzing the data and observations collected during the field test.
- Developing a report that summarizes the results of the analysis including observations and conclusions.

NOTICE

Technical Report Documentation Page

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16. Abstract

This study evaluated the costs and benefits of tire pressure monitoring and maintenance systems for commercial fleets by conducting a yearlong field test. Specifically, the study's goal was to determine whether these systems could influence maintenance intervals and practices and improve performance and safety.

The team evaluated tire pressure monitoring systems (TPMSs) and automatic tire inflation systems (ATISs) on two private fleets. The first fleet, CLI Transport, monitored 24 married tractor-tanker pairs at their maintenance terminal in Altoona, PA. The team installed Wabco's Integrated Vehicle Tire Monitoring (IVTM) System on 12 tractors and Meritor's Tire Inflation System by Pressure Systems, Inc. (PSI) on 12 tankers. The second fleet, Gordon Food Service (GFS), monitored 24 tractors, 30 standard 50-foot trailers, and 20 refrigerated pup trailers (reefer pups). The team installed HCI Corporation's (HCI's) Tire-SafeGuard on 12 tractors and 15 standard 50-foot trailers. GFS ensured the equipment would operate together during the entire field test. In addition, the team installed Meritor's Tire Inflation System by PSI on 20 reefer pups.

The team used fuel logs, maintenance records, and technician failure/inspection reports to analyze the impact of the equipment on maintenance practices, performance, and safety. The field test results showed the use of TPMS/ATIS equipment reduced the operational costs of the fleet and improved the driver's awareness of the tractor-trailer tires. The test fleets experienced a 1.4-percent improvement in fuel economy over the control fleet. The test fleet equipped with TPMS/ATIS equipment exhibited an increase in the life of the drive tires by 19 percent compared to the control fleet. Using the analysis results, the team estimated the equipment costs would be recovered in less than 18 months. The return on investment (ROI) dropped to less than 6 months as the cost of fuel and tires increased. The findings from the field test and the ROI calculations confirm that the use of TPMS/ATIS equipment will reduce fleet operating costs.

17. Key Words **Commercial motor vehicle, field test, fuel, monitor, monitoring, mi/gal, tire pressure, tires, TPMS**	18. Distribution Statement **No restrictions**

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SI* (MODERN METRIC) CONVERSION FACTORS

TABLE OF APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
Ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME	1,000 L shall be shown in m^3	
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE	Temperature is in exact degrees	
°F	Fahrenheit	5 × (F-32) ÷ 9 or (F-32) ÷ 1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fL	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

TABLE OF APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
Mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
M	meters	1.09	yards	yd
Km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
G	grams	0.035	ounces	oz
Kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE	Temperature is in exact degrees	
°C	Celsius	1.8C + 32	Fahrenheit	°F
		ILLUMINATION		
Lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fL
		Force & Pressure Or Stress		
N	Newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009).

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ABS	antilock braking system
ATIS	automatic tire inflation system
CLI	CLI Transport
CMV	commercial motor vehicle
DDU	driver display and tractor ECU
ECU	electronic control unit
FMCSA	Federal Motor Carrier Safety Administration
FOT	field operational test
GFS	Gordon Food Service
HCI	HCI Corporation
IVTM	Integrated Vehicle Tire Monitoring
MHz	megahertz
mi/gal	miles per gallon
MTIS	Meritor Tire Inflation System
psi	pounds per square inch
PSI	Pressure Systems Inc.
reefer pup	refrigerated pup trailer
RF	radio frequency
ROI	return on investment
TPMS	tire pressure monitoring system

EXECUTIVE SUMMARY

OBJECTIVES

The Federal Motor Carrier Safety Administration's (FMCSA's) Research and Technology program, defined by 49 U.S.C. 31108, includes activities that improve "…the safety and efficiency of commercial motor vehicles (CMVs) through technological innovation and improvement." Within that context, this project assesses the value of tire monitoring and automatic inflation systems. This study consisted of a yearlong field test on two tire pressure monitoring systems (TPMSs) and an automatic tire inflation system (ATIS). The study's goal was to determine whether these systems could influence maintenance intervals/practices and improve performance and safety.

Prior to this field test, preliminary studies were conducted on the following:

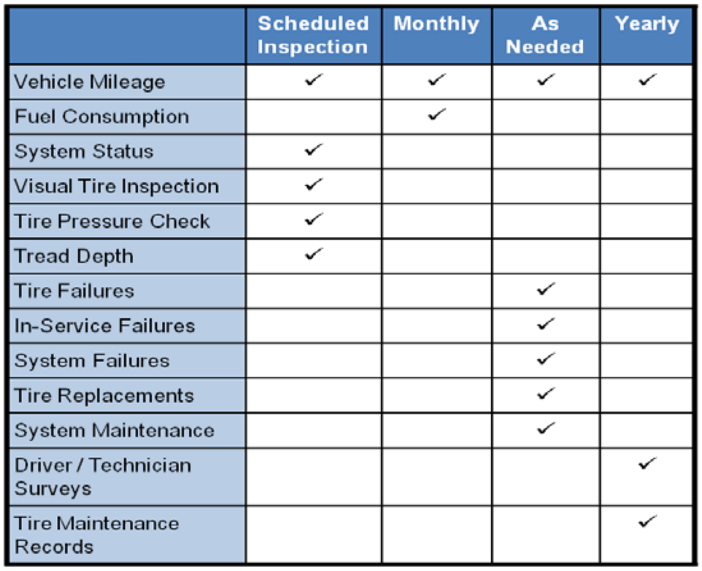
- The impacts of tire inflation practices.
- The equipment reliability of the TPMS and the ATIS on a controlled test track.
- The performance and reliability of TPMS equipment in revenue service.

FIELD TEST PLAN

The outline for the field test included the following five hypotheses:

- TPMS or ATIS use will increase the tire life.
- TPMS or ATIS use will reduce fuel consumption of tractors.
- TPMS or ATIS use will reduce road calls for damaged/flat tires of tractor-trailers.
- TPMS or ATIS will accurately measure the tire pressure of tractor-trailers.
- TPMS or ATIS use will not introduce unscheduled maintenance that adversely affects day-to-day fleet operations.

The authors developed a data collection plan to minimize the impact of the field test on the technicians' daily maintenance responsibilities. The plan, outlined in Figure 1, identified the collection cycle for each data source.



	Scheduled Inspection	Monthly	As Needed	Yearly
Vehicle Mileage	✓	✓	✓	✓
Fuel Consumption		✓		
System Status	✓			
Visual Tire Inspection	✓			
Tire Pressure Check	✓			
Tread Depth	✓			
Tire Failures			✓	
In-Service Failures			✓	
System Failures			✓	
Tire Replacements			✓	
System Maintenance			✓	
Driver / Technician Surveys				✓
Tire Maintenance Records				✓

Figure 1. Grid. Example of data collection schedule.

FIELD TEST FINDINGS

Overview

Two private fleets participated in the field test. The first fleet, CLI Transport (CLI), monitored 24 married tractor-tanker pairs. The research team installed Wabco's Integrated Vehicle Tire Monitoring (IVTM) System on 12 tractors and Meritor's Tire Inflation System by Pressure Systems, Inc. (PSI) on 12 tankers. The second fleet, Gordon Food Service (GFS), monitored 24 tractors, 30 standard 50-foot trailers, and 20 refrigerated pup trailers (reefer pups). The team installed HCI Corporation's (HCI's) Tire-SafeGuard on 12 tractors and 15 standard 50-foot trailers. GFS ensured the equipment would operate together during the entire field test. In addition, the team installed Meritor's Tire Inflation System by PSI on 20 reefer pups.

CLI conducted the field test for 13 months. During the test period, the fleet traveled more than 3.8 million miles and consumed more than 600,000 gallons of diesel fuel. Each tractor-tanker married pair averaged 14,000 miles per month. The technicians conducted 324 inspections to measure tread depth and verify system operation. Between the test fleet and the control fleet, CLI replaced 160 tires for wear and identified 38 tire incidents.

During the 18-month test with GFS, the tractors traveled approximately 3.4 million miles and consumed more than 500,000 gallons of diesel fuel. The tractors averaged 7,900 miles per month. The trailers traveled approximately 5.5 million miles and averaged 4,300 miles per month. The technicians replaced 278 tires for wear and identified 77 tire incidents.

Findings from the field test for each fleet were thoroughly analyzed for fuel consumption, tire maintenance actions, tire wear, system accuracy, system reliability, and user feedback. Each of the 5 hypotheses was analyzed independently for the 2 fleets under test (resulting in a total of 10 hypotheses).

HYPOTHESIS ANALYSIS

The field test validated the assumptions outlined in 6 of the 10 hypotheses. No hypotheses were proven invalid. Previous experience and subjective data gleaned during the field test suggest that an extended field test might have provided sufficient data to prove the inconclusive hypotheses valid. Table 1 presents the results.

Table 1. Analysis of field test hypotheses.

No.	Hypothesis	Analysis	CLI	GFS
1	The use of TPMS and ATIS will increase the life of TPMS/ATIS-equipped tires.	Analyze tread wear per mile. Analyze based on tire location (steer, drive, trailer).	Valid	Inconclusive
2	The use of TPMS and ATIS will reduce the fuel consumption of equipped tractor-trailers.	Analyze average miles per gallon (mi/gal).	Valid	Valid
3	The use of TPMS and ATIS will reduce road calls for damaged/flat tires for equipped tractor-trailers.	Analyze overall road calls. Analyze tire failures.	Inconclusive	Valid
4	TPMS and ATIS will accurately display the tire pressure of equipped tractor-trailers at the driver interface.	Analyze accuracy of equipment.	Inconclusive	Inconclusive
5	TPMS and ATIS will not introduce unscheduled maintenance that will affect the day-to-day fleet operations.	Analyze unscheduled maintenance actions.	Valid	Valid

COST-BENEFIT ANALYSIS

The findings from this report may encourage fleets to use TPMS or ATIS equipment due to their potential to reduce CMV operating costs. Researchers conducted a cost-benefit analysis to estimate the fleets' expected return on investment (ROI). The cost of fuel, the cost of tires, and the average mileage traveled influenced the ROI for the TPMS and ATIS equipment. For example, CLI operates a high-mileage fleet with wide-based single tires (a high-cost consumable supply). As shown in Figure 2, CLI would recover the costs of the TPMS and ATIS equipment in less than a year. Although fuel savings offer the highest incentive for TPMS and ATIS use, the high cost of wide-based tires further shortens CLI's expected ROI. In comparison, GFS operates a lower-mileage fleet with standard tires. In addition, the size of GFS's fleet reduces the need to dispatch the entire trailer fleet daily. The annual savings for GFS are less than half of the savings for CLI. At the mid-2011 cost of $3.98 per gallon of diesel fuel, CLI would save $3,160 per year for each tractor-trailer, compared to $1,327 per year at GFS.

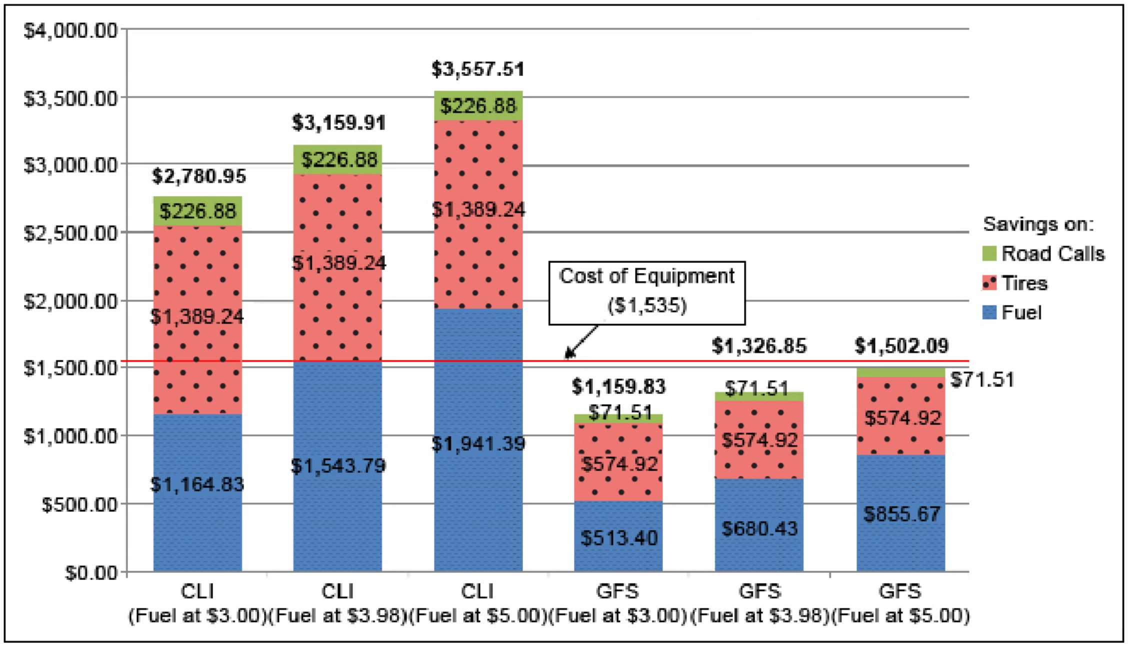


Figure 2. Chart. Annual savings on road calls, tires, and fuel per TPMS/ATIS-equipped tractor-trailer.

While CLI would recover the cost of the TPMS and ATIS equipment in less than 6 months with the cost of fuel at $3.98 per gallon, GFS's cost recovery period would be twice as long. GFS would recover the TPMS and ATIS purchase cost within 14 months with fuel priced at $3.98 per gallon (as shown in Figure 3).

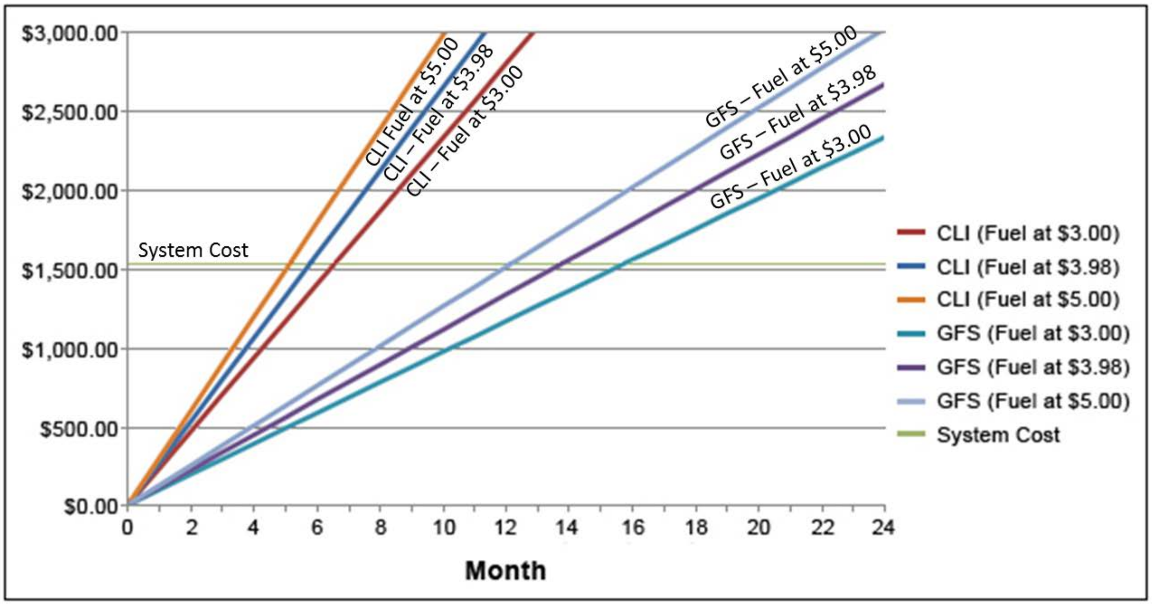


Figure 3. Graph. Accumulated monthly savings per TPMS/ATIS-equipped tractor-trailer.

The findings from the field test and ROI calculations confirm that the use of TPMS/ATIS equipment is very likely to reduce the operating costs of a fleet. The time required for the ROI decreases as the cost of diesel fuel increases. Fleets that use TPMS and/or ATIS equipment will not only reduce their operating costs, but will improve their tire pressure maintenance programs. The use of such equipment encourages mechanics and drivers to monitor tire pressures and report abnormal tire conditions. Interviews with drivers confirmed their acceptance of the equipment and a desire to expand use to the entire fleet.

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1. INTRODUCTION AND BACKGROUND

This section is organized as follows:

- Background on the Commercial Vehicle Safety Technology Diagnostics and Performance Enhancement Program.
- Rationale and objectives for this research project.
- Overview of approach.

1.1 BACKGROUND

A study conducted by the Federal Motor Carrier Safety Administration (FMCSA) in 2003(1) identified potential safety benefits for properly inflated tires, identified and validated the equipment available to the industry, and identified the durability of selected systems. The study found that a significant portion of fleet operators do not regularly perform tire pressure maintenance to the standards recommended by tire manufacturers, and suggested that improper inflation increases total tire-related costs, including lifecycle cost of individual tires, and unscheduled service calls on tractor-trailer combinations. As a result of these findings, FMCSA also performed a cost-benefit analysis of tire pressure maintenance systems (TPMSs). The analysis found that the cost of many of the TPMSs on the market at that time averaged between $1,000 and $1,500 per tractor-trailer. Conservative assumptions about the effectiveness of such systems in motivating changes in tire pressure maintenance practices assume that the payback period for many fleets is less than 2 years. Further, the 2003 report found that the market penetration of tire pressure maintenance equipment has remained low due to the lack of objective, accurate, real-world test data concerning the effectiveness of current and emerging technologies. Most of the cost and benefit data on such systems are not well documented, lack proper baseline testing, and/or are anecdotal in nature.

From the findings of the first study, FMCSA sponsored two additional studies to expand on the cost and benefit of TPMSs and automatic tire inflation system (ATIS) equipment—a track test and a field test. The second study, published in 2006,(2) evaluated dual-tire equalizers, TPMSs and ATIS equipment for overall performance. The study tested vehicles under controlled conditions on a test track at the Transportation Research Center (TRC) in Columbus, Ohio. The study examined the accuracy, responsiveness, resolution, and reliability of the various tire pressure inflation and monitoring systems on a tractor-trailer and a motorcoach. The majority of the equipment performed as advertised by the manufacturer. No catastrophic equipment failures were introduced during the track testing.

In the third study,(3) researchers conducted a field test of a TPMS on commercial heavy-duty buses operating under real-world conditions. The transit bus platform provided a severe urban stop/start duty cycle—an environment that accelerates tire wear, thus allowing the sensor systems to be heavily "exercised" over the study period. After testing identified a limited number of manufacturing flaws, the systems held up to the rigors of an urban city environment. Key challenges associated with the introduction of the sensor systems included implementation of proper training for maintenance staff and disciplined tracking of the installed sensors to ensure that equipment was not lost during routine and non-routine maintenance.

From the results of these three studies, FMCSA sponsored an additional field operational test (FOT) to further explore the technologies using over-the-road commercial tractors/trailers. The goal of the FOT was twofold: to provide solid, credible evidence of the utility and cost-effectiveness of the tested tire pressure monitoring system (TPMS) and ATIS, and to highlight the potential operational, safety, and productivity benefits associated with the two systems. The findings from this FOT are reported here.

1.2 RATIONALE AND RESEARCH OBJECTIVES

TPMS and ATIS technologies show significant promise for improving safety and reducing costs in the commercial vehicle industry. Improved tire pressure management directly relates to improved vehicle stability, reduced tire wear and damage, better braking, improved fuel efficiency, and fewer roadside breakdowns—and thus, enhanced safety and cost effectiveness. Improved tire pressure maintenance and general tire management can have a direct and substantial impact on carrier productivity as it relates to downtime and road calls.

FMCSA contracted the authors to perform an FOT to determine whether the systems could influence tire maintenance practices and reduce the need for frequent tire maintenance. The test was also conducted to help determine system costs and benefits, as well as system reliability and accuracy.

Researchers originally planned to collect test data for 1 year. However, due to minor issues with the equipment and the installation process, data collection ended up lasting 13 months for CLI Transport (CLI) and 18 months for Gordon Food Service (GFS). Researchers designed the field test to have minimal impact on routine operations and maintenance performed by the selected fleets; researchers also designed the field test so that it would not alter established fleet practices related to reporting road calls and tire failures. Fleet technicians continued regular maintenance practices as outlined in the company's standard operating procedures. Additionally, fleet drivers continued to perform U.S. Department of Transportation (USDOT) pre-trip condition assessments and post-trip inspections without demonstrating further vigilance on non-equipped vehicles.

1.3 OVERVIEW OF APPROACH

The study team's approach to implementing a comprehensive FOT included the following tasks:

- Conduct a market research study to supplement the study completed in 2003 through the following steps:
  - Identify all current and future (within 2 years) TPMS and ATIS technologies offered to the industry. Outline the changes to the TPMS/ATIS market from the previous market study.
  - Conduct a detailed analysis of each system to determine application, installation requirements, maintenance requirements, unit and installation costs, system performance factors, system operational characteristics, and other general knowledge on system operation and industry penetration.
  - Outline findings from previous track and field tests to highlight potential hurdles and lessons learned.
  - Evaluate identified systems for use in the FOT using an evaluation matrix to rank each system.
- Select candidate TPMS/ATIS technologies based on the evaluation matrix, commercial availability, willingness to participate in a sponsored field test, and FMCSA approval.
- Identify a commercial fleet operator (or "host" fleet) with characteristics that would allow for effective and fair evaluation of systems and technologies, including:
  - An operating environment and duty cycle that are representative of the industry in terms of tire wear and annual mileage.
  - Homogeneity of the fleet in terms of vehicle type, make, and model to eliminate the potential for the vehicles to influence the evaluation.
- Perform a field test, including test plan development, system installation, test monitoring, and data collection.
- Conduct a data analysis and present the findings in a final report.

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2. DESCRIPTION OF THE FIELD TEST

This section provides additional information on the following:

- Host fleets.
- Technologies under evaluation.
- Fleet test plan.

2.1 HOST FLEETS

Based on experience with previous research, several criteria were established for selecting the host fleet(s) for the FOT. The selection criteria included:

- **Private Fleet:** In previous field tests, the use of a privately-owned fleet ensured a close, direct relationship with fleet management. This relationship is essential to ensure the timely exchange of collected data and support for the installation of equipment, etc.
- **Matched Tractor-trailer Pairs:** In previous FOTs, the use of non-matched tractor-trailer sets proved to be cumbersome. Fleet operators were not able to consistently return the fleet to a facility for data collection. In particular, fleets that operated a "drop-trailer" could not guarantee when the trailer would return to the maintenance facility and could not track the location of the trailer throughout the field test.
- **Daily Return to Central Facility:** Ideally, the equipment would return to the same maintenance facility daily. This would ensure that the FOT-trained maintenance personnel would track all maintenance and equipment failures. The fleet could also operate from various depots, but all maintenance would be performed at a single facility to ensure no data loss.
- **Interest in Innovative Technologies:** Although not essential, the fleet's interest in tire pressure maintenance technologies would enhance participation. With management buy-in, the field test would run more smoothly, as management would encourage staff to collect accurate data, communicate failures to the project team, and install equipment in a timely manner.
- **Single Company/Single Site:** To ensure reliable data, the test fleet should operate from a single maintenance facility. Training a single facility to collect data would ensure a consistent collection method and accurate analysis. Although ideal, it would not be essential to use a single company. If multiple companies were used, the data from each fleet would be analyzed separately to ensure that the analyses accurately reflected the fleet operation.

Using these criteria, two commercial motor vehicle (CMV) fleets were identified—CLI and GFS. Each fleet brings unique characteristics to enhance industry acceptance of the test results. CLI offers tanker trucks that operate on wide-based single tires. As the industry gradually adopts the use of these tires, results from this FOT will provide information for fleet operators considering the adoption of these technologies and will confirm the basic reliability, durability, and inflation monitoring features of the tested TPMS and ATIS technologies. GFS offers accelerated-wear tires with inner-city distribution networks and highway operations. Additionally, the use of 50-foot refrigerated trailers in the field test offers information on the adaptability of TPMS technologies during the connection and disconnection of trailers.

2.1.1 CLI Fleet

CLI is a dedicated transportation company for a large, privately-owned gas and convenience store chain based in Altoona, PA. CLI operates 90 state-of-the-art petroleum tanker trucks out of 7 major terminals.

The field test was conducted at CLI's Altoona terminal. The facility has 26 domiciled, married pairs that return to the facility daily. The tanker pairs operate an average of 450 miles per day. The vehicles are outfitted with wide-base single tires on tractors' drive axles and on the tankers. The fleet provided a unique operating environment as tires were exposed to maximum and minimum load thresholds during a single shift.

CLI manages the drivers. The drivers operate in two shifts with three drivers assigned to each tractor. A separate maintenance contractor provides full-time maintenance technicians who are responsible for periodic and unscheduled maintenance. In addition, they conduct service calls when a vehicle breaks down while in service.

Table 2. CLI tractor and tanker specifications.

Specification	Details
Tractor Model	Freightliner Columbia
Tractor Model Year	Test: 2007 (9), 2008 (1), 2009 (1) Control: 2006 (5), 2007 (3), 2008 (1), 2009 (5)
Tractor Engine	Mercedes-Benz 4000
Tractor Transmission	Eaton FRO-15210C
Tractor Wheelbase	170 inches
Tractor GVWR	80,000 pounds
Trailer Model	Heil
Trailer Model Year	Test: 2004 (1), 2006 (1), 2007 (3), 2008 (5) Control: 2004 (4), 2005 (1), 2006 (3), 2008 (1)
Trailer Type	406 Tanker
Trailer Length	44 feet 5 inches
Trailer Wheelbase	49 inches
Trailer GVWR	80,000 pounds

Table 3. CLI tractor and tanker tire specifications.

Specification	Steer Tire Details	Drive Tire Details	Tanker Tire Details
Tire Manufacturer	Michelin	Michelin	Michelin
Tire Make/Type	XZE2, XZA (1, 2, & 3)	XDA-HT, MD400	XTE
Tire Size	275/80R22.5	445/50R225	445/50R225
Tire Pressure (in pounds per square inch [psi])	110	110	110

2.1.2 GFS Fleet

GFS is the largest family-owned food service distributor in the U.S. It provides a wide variety of food, beverage, and paper products to restaurants, hotels, and other institutions. Headquartered in Grand Rapids, MI, GFS operates 9 distribution centers and 132 stores in 14 States, including most of the Midwest and Florida, as shown in Figure 4.

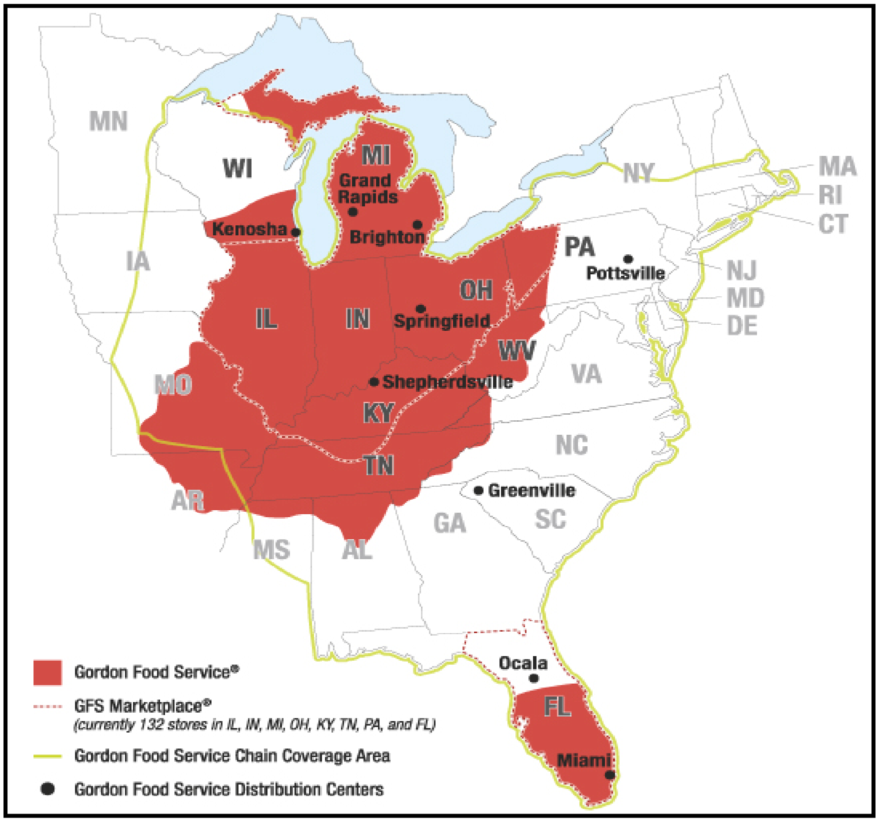

Figure 4. Map. GFS distribution network.

The maintenance terminals operate 28-foot reefer pups and 50-foot refrigerated trailers. The trucks under test exclusively pull the 50-foot trailers. The reefer pups operate over highway and local roads, delivering to areas with limited maneuverability (e.g., loading docks, alleys). The tires experience highway wear, local wear, and scuffing due to the operation of the trailers. The standard trailers primarily operate on highway routes.

The Grand Rapids maintenance facility conducted the field test. It employs a full maintenance crew to perform periodic and unscheduled maintenance. The facility maintains 233 tractors and 324 trailers. The facility employs a tire service company for changing and repairing tires. The tire service company is also responsible for service calls.

Table 4. GFS tractor specifications.

Specification	Tractor 1 Details	Tractor 2 Details
Model	Volvo VNM42T200	IHC 8600A 6X4
Model Year	Test—2005 (1), 2008 (9) Control—2008 (12)	Test—2007 (2)
Engine	Volvo D-11	Cummins ISM
Transmission	Eaton FR13210B	Meritor M14G104A

Table 5. GFS trailer specifications.

Specification	Standard Trailer Details	Pup Trailer Details
Model	Great Dane	Great Dane
Model Year	Test—2006 (15) Control—2006 (5), 2007 (6), 2008 (4)	Test—2006 (14), 2007 (6) Control—1998 (13), 2006 (7)
Trailer Type	Straight	Straight
Length	50 feet	28 feet
Wheelbase	N/A	265 inches
GVWR	39,000 pounds	39,000 pounds

Table 6. GFS tractor and trailer tire specifications.

Specification	Steer Tire Details	Drive Tire Details	Trailer Tire Details
Tire Manufacturer	Michelin	Michelin	Michelin
Tire Make/Type	XZE, XZE2	XDA, XZE, XDN2	XZE, XZE2
Tire Size	295/75R22.5	295/75R22.5	295/75R22.5
Tire Pressure (psi)	95	95	95

2.2 TECHNOLOGIES UNDER EVALUATION

The team used two main criteria to select the TPMS and ATIS for this study: documented successful performance under controlled testing and commercial availability. The systems selected were:

- Wabco’s IVTM System.
- HCI’s Tire-SafeGuard.
- Meritor Tire Inflation System (MTIS) by Pressure Systems Inc. (PSI).

2.2.1 Wabco Integrated Vehicle Monitoring System

2.2.1.1 General Description

Wabco (in conjunction with Michelin) developed and launched the IVTM system in 2003. The IVTM system consists of three main components, shown in Figure 5:


Tire Pressure Sensor Wheel Module
Display Unit
ECU

Figure 5. Grouped photo. Wabco tire pressure sensor wheel module (left), display unit (center), and electronic control unit (right).

In the IVTM system, each tire and wheel assembly is equipped with a sensor unit, which contains a pressure transducer and a transmitter. A built-in lithium battery with a 5-year service life supplies power for the sensor unit. The sensor unit is secured to the wheel rim at a location adjacent to the valve stem using the two closest lug nuts. A pneumatic hose runs between the sensor and valve stem (as shown in Figure 6).

Figure 6. Photo. Wabco IVTM sensor unit mounting system.

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

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

The main ECU is hardwired to a display unit that is designed to mount on the dashboard. The display unit warns the driver visually and acoustically of low tire pressures. A yellow lamp indicates a slow rate of pressure loss or slight decrease in pressure, and a red lamp indicates extremely low pressure. The yellow and red lights are located at the lower edge of the display. Using an on-screen menu, the driver can select the position of any instrumented tire and can query its inflation pressure. If all tires are within an appropriate inflation pressure range, the display is blank. If a tire has low pressure, the display screen shows the location of the tire and its pressure. For example, Figure 7 shows a low-pressure reading of 5.9 bar (85 psi) on the right rear tag-axle tire.

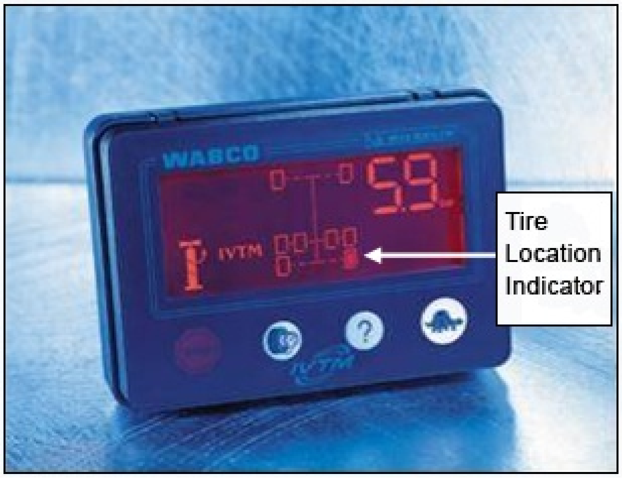

Figure 7. Photo. Wabco IVTM system indicating tire location and low pressure reading.

2.2.1.2 Installation

The Wabco IVTM system was installed on 10 tractors at CLI. Installation was led by a Wabco service engineer.

The tractors used in this field test had six tires (standard-width tires on the steer axle and wide-base single tires on each drive axle); thus, six sensor units had to be installed.

To install the sensor unit, the pneumatic hose was first connected to the sensor module and then connected to the tire’s valve stem. With the hose connected to the valve stem, the sensor unit was slipped over the wheel lugs and secured in place with the cap nuts. The quickest way to mount the wheel module to the steer tires was to attach the sensor unit to the valve stem with the short hose before securing it to the wheel. Figure 8 illustrates the wheel-module installation process on a steer tire. As shown in the photos, the steer tires required mounting a counterweight onto the tire, opposite the sensor. The weight countered the effect the sensor had on the rotation of the wheel. Because the sensors were installed near the wide-base single tires' center of gravity, the drive and trailer tires did not require a counterweight.

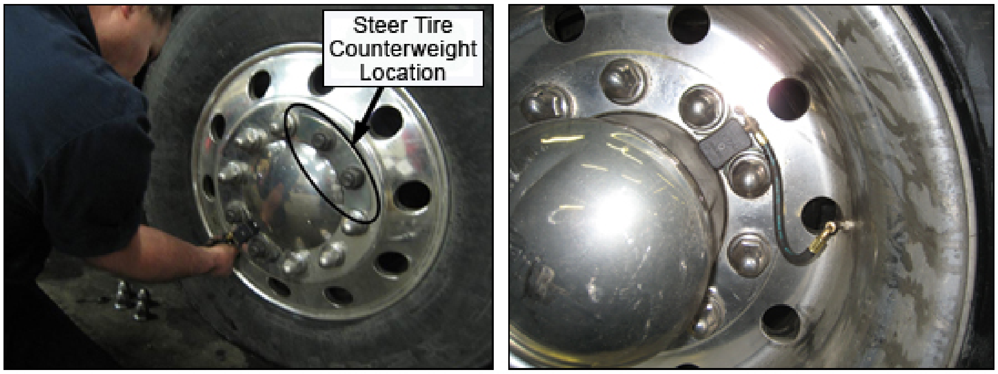

Figure 8. Grouped photo. Module installation of steer wheel (left) and drive wheel (right) with steer tire counterweight location.

The ECU must be mounted in a centralized location relative to the tire sensors. The ECU was bracket-mounted to the rear cross-member of the cab, equidistant from each of the six sensor locations. The display unit, hardwired to the ECU, was mounted within reach of the driver on the cab's dashboard, as shown in Figure 9. The display was electrically protected by mounting an inline 5-ampere fuse in the glove box.

Figure 9. Grouped photo. ECU (left) and display unit (right) installations.

After installation of the IVTM hardware components, the system was programmed in accordance with the manufacturer's instructions. The IVTM ECU was equipped with a diagnostic data port that could be accessed with a laptop so that technicians could communicate with the ECU via Wabco's IVTM diagnostic software. The diagnostic software shows tire pressure readings and system messages. During installation, the software was used to monitor the tire pressures at each wheel location.

2.2.2 HCI's Tire-SafeGuard

2.2.2.1 General Description

HCI manufactures the Tire-SafeGuard TPMS. For the FOT, the team installed the internal rim-mounted model, which consisted of the following components:

- **Wheel Module—**Monitors internal tire pressure and temperature.
- **Driver Display and Tractor ECU (DDU)—**Establishes communication with the connected trailer's ECU. Processes RF signals transmitted from the tractor and trailer wheel modules. Displays the condition of tires at all wheel locations.
- **Trailer ECU—**Performs wireless "handshaking" with the DDU to establish communication. Relays RF signals transmitted from the trailer's wheel modules to the DDU via the tractor antenna.
- **Tractor Antenna—**Relays the RF signals transmitted from the tractor's wheel modules and the trailer ECU to the DDU.

Figure 10 shows a wheel module secured to a wheel by a steel band (top left), the dash-mounted DDU (top right), the trailer's chassis-mounted ECU (bottom left), and the tractor's chassis-mounted antenna (bottom right).

Figure 10. Grouped photo. HCI Tire-SafeGuard components.

The wheel module includes an integrated pressure-temperature transducer, an RF transmitter, and an internal battery to supply power to the unit for more than 5 years. The wheel module (or sensor) is strapped to the hub of the wheel inside the tire. It continuously transmits the tire's pressure, temperature, wheel position, and tire status to the trailer ECU using RF signals. The wheel modules transmit the tire condition based on several factors, including vehicle movement. If the vehicle is stationary, the module will revert to transmitting the tire condition every 2 hours to maximize battery life. If a tire pressure change has been detected, an immediate RF signal is transmitted to the ECU.

The DDU processes the RF signals received via coaxial cable from the tractor-mounted antenna, which is mounted at a location equidistant between the front and rear axles. The DDU alerts the driver of low-pressure situations by providing the location, temperature, and pressure readings via display icons and an audible signal. Figure 11 shows the wheel-mounted sensor (right) and the DDU (left). The default display screen shows the tire pressures of all "located" tires. (A tire is "located" when the DDU has successfully received communication from the wheel sensor at a specific tire location.) The user can cycle through the display modes to view the tire pressure and temperature at a single tire location. The display automatically returns to the default mode after 8 seconds. The system uses two 12-volt power sources for operation. A keyed source provides power to the display. A second, non-keyed source provides power to the ECU. As a result, the cab display is only active while the vehicle is keyed, but the ECU operates continuously.

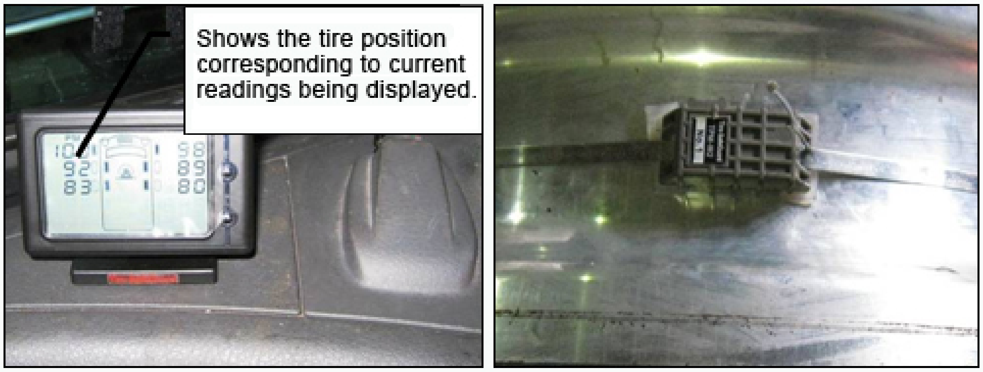

Figure 11. Grouped photo. HCI Tire-SafeGuard TPMS: DDU displaying tire position (left) and the wheel-mounted sensor (right).

The trailer ECU includes a receiver and a transmitter. It receives the RF signals from the trailer wheel modules and wirelessly transmits the signals to the DDU via the tractor-mounted antenna. Unlike previous versions of the equipment, the version used in the FOT automatically detected equipped trailers. It did not require the tractor to be married to a specific trailer. A handshake signal from the DDU (when the tractor is keyed-up and trailer power is restored) initiates the linkage between the DDU and the trailer ECU. The DDU links to the appropriate trailer through one of two processes—a keying sequence at startup or an elimination process after key-up. In the first case, the driver initiates a key-up/key-down sequence, which resets the internal clock of the DDU and the trailer ECU. After the third power-up cycle, the DDU links to the trailer ECU with an identical clock cycle. In the second case, if the operator does not initiate a keying cycle, the DDU monitors the surrounding RF signals to identify ECUs with similar startup clock cycles. The DDU links to the trailer ECU with a similar clock cycle, since both were reset during the key-up. The linkage period for the second scenario could take up to 5 minutes. In both cases, after establishment of the initial link, the DDU stores the trailer ECU information and eliminates the need for future initiation cycles.

2.2.2.2 Installation

A team of engineers and GFS technicians installed the Tire-SafeGuard TPMS on 13 tractors and 15 trailers. The team followed the instruction manual provided by HCI. For ease of installation, HCI provided installation kits for tractors and trailers. The kits included wheel modules with pre-assigned locations and a programmed DDU or ECU to recognize the supplied wheel modules.

Engineers installed a wheel module on the tractor and trailer at each assigned location. With the tire removed from the wheel, engineers strapped the sensor to the wheel at the lowest point of the drop-center well using metal strapping. Once the sensor was secured, the tire was remounted to the wheel and inflated. The right photo in Figure 11 shows a tire pressure sensor strapped to a wheel. The team mounted the wheel sensor near the wheel's valve stem port to prevent damage to the sensor unit when changing the tire. If the paddle arm of the tire-changing machine were to contact the wheel module, it could damage it. By placing the module in a specific location (at the valve stem in this case), the tire changers had a reference point for the module when removing the tire casing from the rim and avoided contact with the paddle arm.

Engineers installed two receivers for the system (shown in Figure 12). An antenna was mounted in front of the rear axles on the truck frame using a magnetic base, and a coaxial cable was used to connect the antenna to the dash-mounted DDU. The trailer ECU was mounted to the trailer's cross beam (between the trailer tires). Using an antilock braking system (ABS) connector, engineers connected the ECU to the trailer's 12-volt power source.

Figure 12. Grouped photo. HCI Tire-SafeGuard antennas.

The DDU (as shown in Figure 13) was installed on the dashboard of the tractor. A coaxial cable connected the DDU and the antenna by routing the cable through an existing access port in the dashboard. HCI programmed the DDU to assign each wheel module to a specific location and set the warning threshold for the tire pressure to 103 psi (approximately 10 percent below the 115 psi set tire pressure). Upon powering the DDU, the team tested the system to ensure that each of the wheel modules was communicating with the DDU and properly reading the tire pressures.

The DDU was also used to verify operation of the trailer unit. When the DDU was within range of the trailer, it would detect and display the trailer's wheel module data. With the DDU preprogrammed for the tire locations, the team did not have to program the location of each wheel module. The DDU has the capability to recognize the location of wheel modules after a tire rotation or tire change-out. The wheel modules do not have to remain in the preprogrammed location.

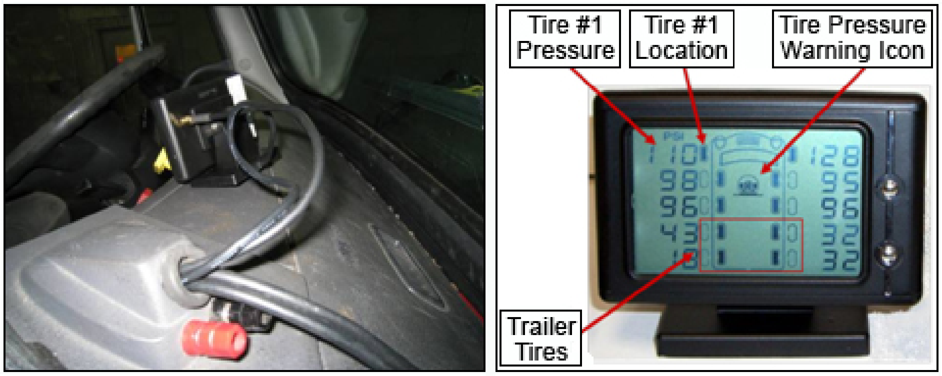

Figure 13. Grouped photo. DDU installation: coaxial cables connecting DDU (left) and the DDU displaying tire location and pressure data (right).

2.2.3 MTIS System by Pressure Systems, Inc.

2.2.3.1 General Description

The MTIS distributed by Pressure Systems, Inc. (PSI) consists of the following six components:

- **Pressure Protection Valve—**Maintains trailer air system at 80 psi in the event of a tire or inflation system failure (Figure 15).
- **Control Unit—**Controls the pressure distributed to each axle end and illuminates indicator light.
- **Press Plug—**Used with hollow axles to seal pressurized axle interior from wheel end (shown in Figure 16).
- **Stator and Through-tee—**Rotary union assembly delivers air from the pressurized axle to the wheel end.
- **Indicator Light—**Illuminates when airflow within the system has been detected.

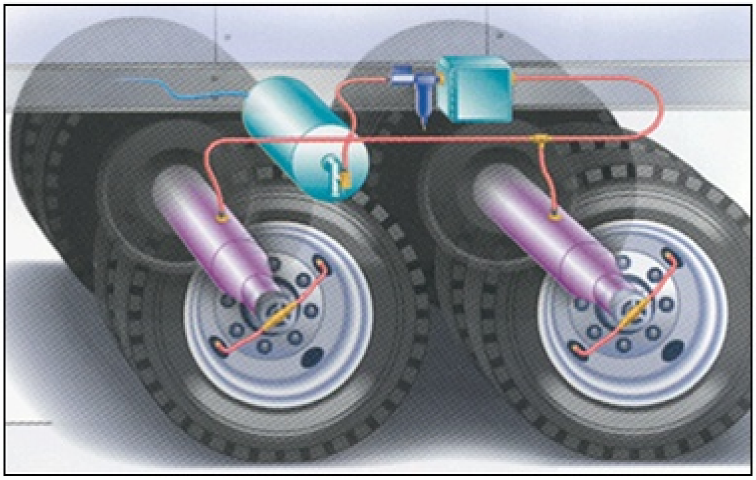

Figure 14. Graphic. Components of the MTIS.

The inflation system (shown in Figure 14) uses compressed air from the trailer's air system to inflate any tire that falls below the predefined target pressure. Air for the inflation system is routed from the existing trailer supply tank to the control box. A pressure protection valve (see Figure 15) regulates the air supplied to the inflation system. If the supply pressure falls below 80 psi, the pressure protection valve inhibits the flow of air to the inflation system.

Figure 15. Photo. Pressure protection valve (CLI).

The control unit includes a system filter, a shut-off valve, and a control box. The filter prevents contaminants from entering the system. The shut-off valve isolates the inflation system from the air system. The control box regulates the air pressure to the wheel ends and illuminates the indicator light when airflow is detected. Inside the control box, a regulator valve is factory set according to a fleet's recommended tire pressure, which can be adjusted in the field. In addition, the control box has a flow-detection switch. If airflow is moving through the system, the switch illuminates the indicator light to alert the driver of a tire issue.

The hollow, pressurized trailer axle carries air from the control box to a rotary union at each wheel end (Figure 16). A hose connected to the rotary union routes the air to the wheel. A one-way check valve located in the hose protects each tire against air pressure loss. If a puncture results in the loss of air pressure, the check valve prevents loss of pressure in the other tires.

Figure 16. Grouped photo. MTIS, rotary units on wheel ends.

2.2.3.2 Installation

The installation procedure for the inflation system was similar at both test sites. The only differences were in the location of the control box and the use of two hoses on the GFS fleet (because CLI uses wide-base tires on the tanker, only one hose is needed). PSI provided a field technician to demonstrate and assist in the installation of the inflation systems. The team installed 30 inflation systems—10 systems on CLI's tankers and 20 systems on GFS's reefer pups.

The installation began with preparation of the axles and wheel ends. A hole was drilled and tapped at the center point of each axle, and the axle air fitting was installed. The hubcaps and Welsh plugs were removed to provide access to the interior of the axle. Using compressed air, a cleaning wand removed debris and metal shavings from the axle. After clearing the debris from the axle, a press plug was inserted into each wheel end to seal the axle. The stator was threaded into the press plug (as shown in Figure 17, left) and a hubcap designed for use with the MTIS was bolted onto the wheel end.

The through-tee assembly was attached to each trailer hubcap. For the CLI fleet, the through-tee included a single output port (as shown in Figure 17, right). For the GFS fleet, the through-tee included two output ports. A hose was connected between the output port and the wheel valve stem to deliver the pressurized air from the axle to each wheel.

Figure 17. Grouped photo. Wheel end assembly with press plug and stator (left) and through-tee (right).

The installation of the system air components included installing the pressure protection valve, mounting the control box, and routing the hose. The pressure protection valve was installed on the spare port of the trailer's air tank. A hose was routed from the valve to the input of the control box. The GFS control box was mounted on the trailer's crossbeam, forward of the rear axles (as shown in Figure 18, right). The CLI tanker did not have crossbeams under the tanker. For this reason, the CLI control box was mounted at the rear of the tanker in a recessed area between the taillights (as shown in Figure 18, left). From the control box output, a tee split the hosing to deliver air to each of the axle fittings.

Figure 18. Grouped photo. CLI and GFS control box installation between taillights (right) and on tanker's crossbeam (left).

The final component of the PSI inflation system is the indicator light. The indicator light was installed in a location that allowed the driver to see the light through the driver's side mirror. On the CLI fleet, the light was mounted on the fender of the tanker (as shown in Figure 19, left). On the GFS fleet, a mounting bracket was fabricated to allow the light to be mounted on the underside of the reefer pup, forward of the axles (as shown in Figure 19, right). The operation of the indicator light required a constant supply of 12-volt power. The CLI fleet used the tanker's seven-way box, and the GFS fleet accessed the ABS wiring via a pigtail connector. Electrical wiring was routed from the indicator light through the identified power source to the electrical contacts of the flow-sensing switch in the control box.

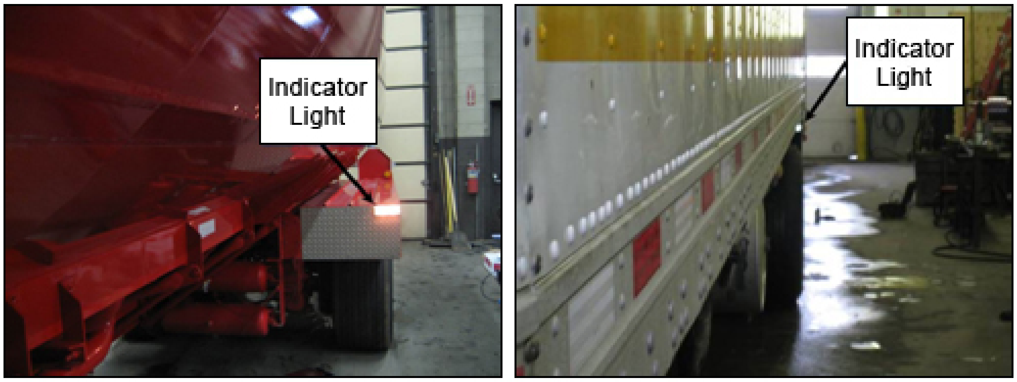

Figure 19. Grouped photo. CLI and GFS indicator light installation on the fender (left) and underside of the reefer pup (right).

2.3 TEST PLAN

The study team developed a test plan to address the requirements of the field test. The test plan was divided into the following sections:

- Objectives.
- Team members' roles and responsibilities.
- Equipment.
- Schedule.

2.3.1 Objectives

FMCSA identified a list of important factors to consider in the development of the test plan. Chief among the factors was the capability of the field test to generate the data, observations, and insights needed to validate or refute key questions and hypotheses regarding the efficacy and performance of TPMS and ATIS devices and systems. FMCSA's factors included:

- **Scheduled Maintenance—**Frequency of scheduled TPMS and ATIS maintenance.
- **Reliability Measures—**Frequency of unscheduled TPMS and ATIS maintenance; accuracy of TPMS and ATIS units.
- **Maintenance Considerations—**Interference with routine truck maintenance (e.g., tire changes, tire rotations, brake inspections and repair, RF data links); influence on tire inventory management (increased predictability of tire life).
- **Lifecycle Costs—**Cost savings for implementing a TPMS and an ATIS (e.g., tire inspection costs, tire life, retread life, fuel, road calls).
- **Driver Impact—**Improved driver productivity; improved driver satisfaction.
- **TPMS and ATIS Perception—**Viewed favorably by drivers and technicians; improved image with shippers/customers.

- **Safety Benefits—**Impact on braking performance, vehicle stability, and vehicle handling; tire maintenance (e.g., decreased blowouts, less roadside tire debris); and CMV crashes, injuries, and fatalities.

From these factors, the study team identified five key test objectives, as shown in Table 7. The study team broke down each hypothesis to identify the required sources to conduct a thorough analysis to prove/disprove the hypothesis. Because of the relative infrequency of catastrophic tire failures, a hypothesis of the impact these systems would have on braking performance, vehicle stability, and vehicle handling and the resultant crashes, injuries, and fatalities was not included. Section 3 describes the data collection process.

Table 7. Test objectives/methods.

Hypothesis	Description	Analysis	Source(s)
The use of TPMS and ATIS will increase the life of TPMS/ATIS-equipped tires.	Prove the tires on equipped vehicles will experience less tread wear per mile as compared to non-equipped vehicles.	Analyze tread wear per mile. Analyze based on tire location (steer, drive, trailer).	Vehicle mileage, periodic inspections, and maintenance records.
The use of TPMS and ATIS will reduce the fuel consumption of equipped tractors.	Prove the equipped vehicles will experience improved fuel mileage as compared to non-equipped vehicles.	Analyze average mi/gal.	Vehicle mileage, fuel records.
The use of TPMS and ATIS will reduce road calls for damaged/flat tires for equipped tractor-trailers.	Prove road calls and tire failures for equipped vehicles will be reduced as compared to the control vehicles.	Analyze overall road calls. Analyze tire failures.	Failure reports, maintenance records.
TPMS and ATIS will accurately display the tire pressure of equipped tractor-trailers at the driver interface.	Prove the monitoring systems provide accurate tire pressure values at the display. Prove the inflation system maintains the tire pressure at the proper setting.	Analyze accuracy of equipment.	Maintenance records, questionnaire.
TPMS and ATIS will not introduce unscheduled maintenance that will affect the day-to-day fleet operations.	Prove the equipped vehicles will not introduce additional unscheduled maintenance as compared to the control vehicles. Prove the equipped vehicles experience few unscheduled maintenance calls due to tire failures.	Analyze unscheduled maintenance actions.	Failure reports, questionnaire.

2.3.2 Roles and Responsibilities

The success of the field test depended on a clear understanding of the roles and responsibilities for each of the participating parties—the study team, the host fleets, and the vendors.

The test coordinators, in conjunction with FMCSA, identified the host fleets and secured a fleet agreement. They developed the field test plan, procured the TPMS equipment and spares, and oversaw the system installations. The test coordinators also developed and maintained a test database for storing all data collected during the field test. In addition, the test coordinators conducted educational sessions for the maintenance technicians and the drivers participating in the field test. The presentations used in these educational sessions described the purpose of the field test, the systems being tested, and the responsibilities of the personnel.

The test coordinators worked with the host fleets to develop a memorandum of understanding. The document outlined the responsibilities of the host fleet during the field test. The responsibilities included providing use of the tractor-trailers for 1 year; providing maintenance support for system installation, data collection, and system monitoring; and providing maintenance data on vehicle mileage, tire repairs, equipment failures, and fuel logs.

The vendors supported the field test by providing system documentation, overseeing initial system installations, and demonstrating proper installation, maintenance, and operation. Each vendor provided ongoing engineering support and component spares as necessary.

2.3.3 Equipment

Table 8 shows the distribution of the technologies between the host fleets. The MTIS was installed on 10 tanker trailers and 20 reefer pups. The IVTM system was installed on 10 tractors. The Tire-SafeGuard system was installed on 12 tractors and 15 standard trailers.

Table 8. Technologies under evaluation.

Vehicle Type	Total Fleet Size	Control Fleet	IVTM	Tire-SafeGuard	MTIS
CLI Tractor	25	14	11	–	–
CLI Tanker	19	9	–	–	10
GFS Tractor	240	12	–	12	–
GFS Trailer	400	15	–	15	–
GFS Reefer Pup	263	20	–	–	20

Each host fleet identified tractors and trailers that would be used for the control fleet. For CLI, the entire fleet was tracked during the field test. GFS personnel identified the control fleet based on tractors and trailers that would experience driving conditions and mileage similar to the test fleet.

2.3.4 Schedule

The field tests operated for a period of approximately 1 year from the installation of the equipment on the fleet. The length of the field test permitted operation of the equipment in various weather conditions and operating environments.

The study team visited the CLI facility on March 3, 2008 to assist in equipment installation, provide presentations to drivers and technicians on the test expectations, and meet with vendor representatives. The maintenance technicians continued to install the equipment through April 2008. The technicians also collected baseline readings on the control fleets' mileage and tire depth in April 2008. The field test began in May 2008 and continued for a period of 13 months. An extra month was added to the field test to account for the data variability experienced during the initial data collection period (May 2008).

The study team visited GFS on November 5, 2008 to present an overview of the field test to the maintenance technicians. This included data collection requirements, a system overview, and GFS's roles and responsibilities. PSI and the study team installed the inflation system on

December 2 and 3, 2008. The study team visited GFS on February 17, 2009 to demonstrate the installation of the Tire-SafeGuard equipment. The maintenance technicians installed most of the systems by June 2009. The field test began in May 2009 and continued through November 2010.

3. DATA COLLECTION

The study team identified the sources of data necessary for a successful field test. Based on the five hypotheses outlined in the previous section, the study team determined that the following five parameters were required to address the objective of the field test:

- Tire wear.
- System reliability.
- Tire failures.
- Fuel consumption.
- System functionality/usability.

The information was obtained from periodic maintenance inspections, tractor and trailer maintenance records, fuel logs, staff interviews, and wrap-up surveys.

3.1 PERIODIC MAINTENANCE INSPECTIONS

At the beginning of the field test, every control and test unit was baselined by recording unit mileage, tread depth, and tire make and model. In addition, the technicians recorded the serial numbers of the TPMS sensors installed on the test vehicles.

During the field test, the technicians regularly collected unit data according to an inspection schedule established at the beginning of the field test. CLI conducted test inspections during the scheduled periodic maintenance. CLI’s periodic maintenance occurs every 9,000 miles (approximately every 3 weeks). GFS conducted test inspections either when the units were on site for maintenance/storage or every 6 weeks, whichever occurred first. GFS’s periodic maintenance schedule could not be used to track the field test accurately, as periodic maintenance did not occur regularly at the test facility and could have extended beyond a 2-month cycle.

The technicians recorded vital statistics on the tractors, tankers, and trailers used in the FOT. They used a single form to record the periodic inspection and failure data. A form unique to their operation was provided to each fleet. The forms recorded:

- Date.
- Tractor and tanker/trailer number.
- Tractor and tanker/trailer mileage.
- Vehicle type (test or control).
- System-displayed tire pressures.
- Gauged tire pressures.

- Tire condition (damaged, scuffed, etc.).
- Mounting/physical condition of sensors.
- Tire changes.

The data collection forms also recorded infrequent tire maintenance activities, including tire replacement, TPMS or ATIS system failure, and tire failure. For system and component failures, the technicians reported the unit mileage, component failure, failure location, and detailed failure data (e.g., component failed, action taken to resolve discrepancy). For tire replacement, the technicians reported the unit mileage, tread depth, and location of the tire removed, as well as the tread depth, tire model, and location of the tire installed. For the GFS operation, the data collection form also noted whether the tire installed was a retread, and if possible, the number of times the tire casing had been retreaded.

3.2 MAINTENANCE RECORDS

The maintenance records provided oversight on the data collected by the technicians during the field test and ensured that all tire actions were recorded. The study team inspected the fleet's vehicle maintenance system at the completion of the field test to collect data on tire maintenance incurred by the fleet throughout the test period. The team identified tire replacements, tire changes, tire failures, and road calls that occurred.

3.3 FUEL RECORDS

The host fleets provided monthly fuel logs for the test and control tractors. The logs included vehicle usage and fuel consumption during a monthly period. At CLI, the drivers recorded the vehicle mileage and fuel consumed to the tractor's log. The terminal manager assembled the data and submitted the findings to the fleet manager. CLI provided the study team with a monthly summary of mileage traveled and fuel consumed. At GFS, the study team downloaded fuel logs from the maintenance database.

3.4 MAINTENANCE STAFF AND DRIVER INTERVIEWS

Maintenance technicians and supervisors were interviewed informally throughout the test period. The intent of these interviews was to gather information about the technicians' and supervisors' experiences with maintaining the systems, the ease of the data presentation, and the usefulness of the equipment.

3.5 MAINTENANCE STAFF AND DRIVER QUESTIONNAIRES

Questionnaires were distributed to the technicians and the drivers at the completion of the field test. The questionnaires collected subjective feedback on the use of TPMS and ATIS equipment. The questions addressed a number of issues, including:

- **Driver Time Savings—**Did the addition of the equipment reduce the need for tire inspections during a pre-trip inspection?
- **Driver Satisfaction—**Did the addition of the equipment provide the driver with valuable information (during driving) that was not previously available? Was the driver comfortable with the operation and intent of the equipped systems?
- **Fleet Image—**Did the addition of the systems improve the image of the fleet with shippers, customers, or fellow truck drivers?
- **Maintenance Requirements—**Did the systems require additional maintenance beyond verifying that the components were secure?
- **Unscheduled Maintenance—**Did the systems have a high number of failures during the test?
- **Ease of Failure Diagnosis—**Were the system/tire failures difficult to diagnose? With identified failures, were technicians able to quickly repair the failure and return the vehicle to service?
- **Accuracy—**Did the systems provide false information to the drivers or technicians? Did the drivers and technicians rely on the data reported by the system?
- **Impact on Normal Maintenance—**Did the systems decrease the amount of work required during tire inspections? Did the systems result in increased maintenance times during tire rotations, tire replacement, brake system maintenance, and brake inspections?
- **Driver/Technician Perception—**Did the systems improve tire life? Did the systems reduce road calls? Did a failure occur that would not have been found without the system?
- **Overall Perception—**What is the user’s overall perception of the system, including the effect on operations, confidence in the system, preferred features, and likes/dislikes of installed systems?

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4. FIELD TEST DATA ANALYSIS

This section analyzes the data collected during the field test, including vehicle total miles traveled, total maintenance actions performed, and fuel consumed. Specifically, the section analyzes the following:

- Fuel consumed.
- Tire maintenance actions, including tire failures and road calls.
- Tire wear.
- System accuracy.
- System reliability.
- Driver/technician feedback.

4.1 CLI

As stated previously, the field test at CLI took place from May 2008 through June 2009. During this time, CLI operated two delivery shifts per day, averaging 450 miles per day per truck. The 25 trucks under test operated a total of 3,856,337 miles during the field test (Table 9). The technicians completed 324 inspections, with the vehicles averaging 12,831 miles between inspections.

Table 9. Total field test mileage (CLI).

Fleet	Mileage Under Test	Number of Inspections	Miles Per Inspection
Test Fleet	2,028,631	197	10,360
Control Fleet	1,827,706	127	14,772
Total	**3,856,337**	**324**	**12,831 (Average)**

4.1.1 Fuel

The study team tracked fleet fuel consumption using monthly fuel logs distributed by the terminal manager. The fuel logs tracked monthly mileage and fuel consumed. The fuel logs were generated using an automated fuel tracker system that recorded the fuel added to the tractor at the beginning of each shift.

The fleet consumed a total of 632,870 gallons of fuel during the 13-month field test, with an average fuel economy of 6.10 mi/gal. As shown in Table 10, the test fleet averaged 6.19 mi/gal, and the control fleet averaged 6.04 mi/gal. The test fleet had a 3.06-percent improvement in fuel economy above the control fleet.

Table 10. Fleet fuel consumption (CLI).

Tractors	Mileage Under Test	Fuel Consumed	Average mi/gal
Test Tractors	2,028,631	327,774	6.19
Control Tractors	1,827,706	305,096	6.00
Total	**3,856,337**	**632,870**	**6.10 (Average)**

The monthly fuel logs were used to track the fuel economy of the test fleet and the control fleet, with the fuel economy of the test fleet consistently surpassing the control fleet. As shown in Figure 20, the test fleet averaged a 3.2-percent improvement in fuel economy, with the largest improvement occurring in December 2008.

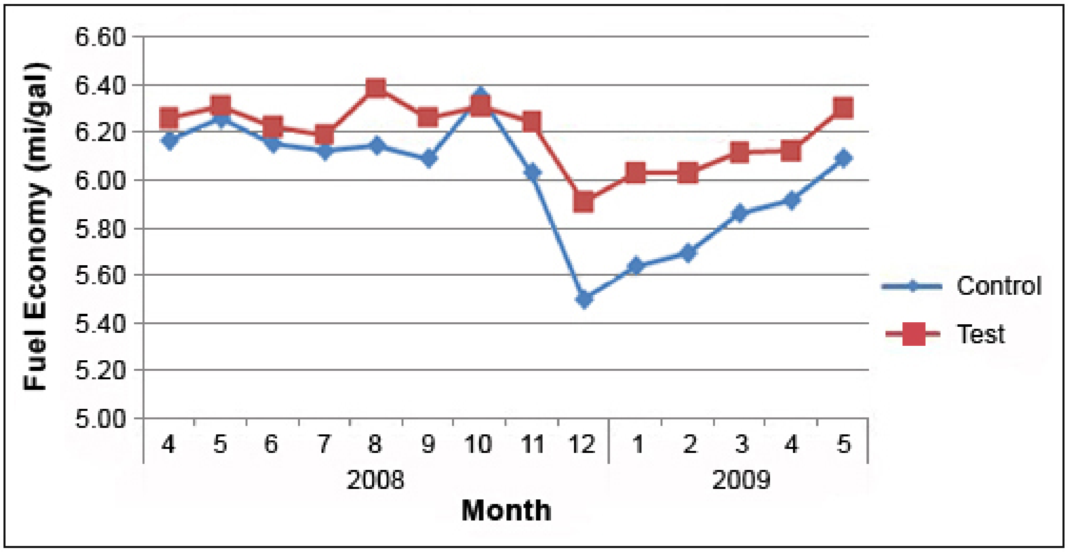


Figure 20. Graph. Monthly average fuel economy (CLI) for control and test fleets.

The control fleet's fuel economy dropped by approximately 0.53 mi/gal between November 2008 and December 2008 (as shown in Figure 20). Although decreases in fuel economy are expected during the winter months, the 8.8-percent drop in fuel economy between November and December cannot be associated with adverse weather conditions during the month. CLI noted that six of the oldest vehicles in its fleet were replaced with new 2009 Freightliners. New vehicles require an engine break-in period prior to obtaining their optimal fuel economy and may have had differing engine and emission control packages, which could have affected their fuel economy.

Removing the new tractors from the analysis eliminated the drop in fuel economy due to new equipment. Without the new tractors, the test fleet demonstrated a 1.39-percent improvement in fuel economy over the control fleet (as shown in Figure 21). As shown in the chart, when the new tractors were removed from the analysis, the fuel economy dropped by only 1.7 percent between November 2008 and December 2008. Thus, it appears that the large drop in fuel economy shown in Figure 20 can be attributed to the new tractors.

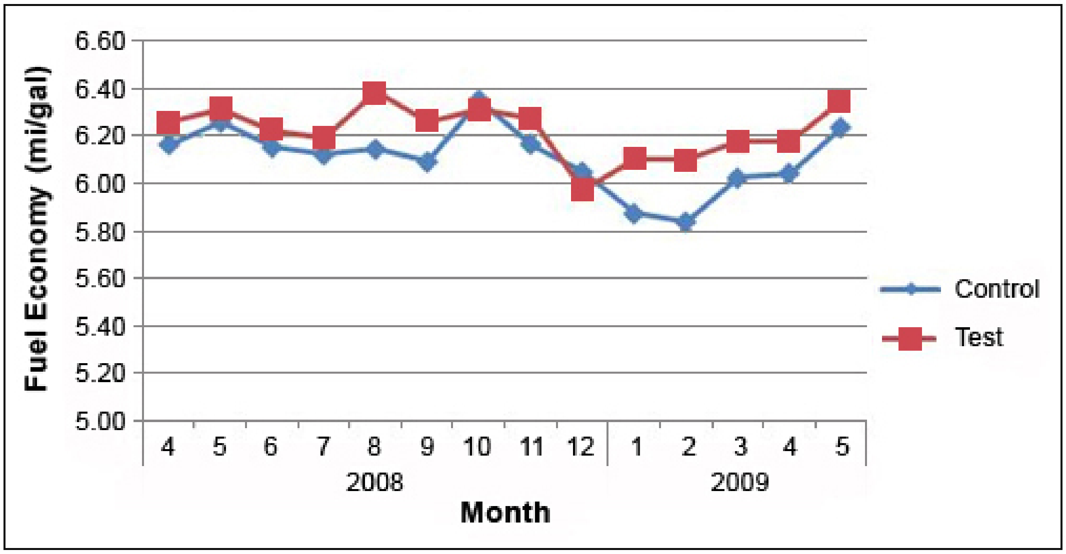


Figure 21. Graph. Monthly average fuel economy, original tractors (CLI).

4.1.2 Tires

During the periodic maintenance inspections, technicians recorded the tire depth at each of the 10 tire locations on the tractor-tanker. Technicians measured the tire depth from the center tread of the tire, ensuring that the measurement was not taken on a wear bar.

CLI's tire replacement policy did not allow the retreading of any tires in the fleet. The steer tires and drive tires were usually replaced with new tires. The tanker tires were replaced with either used drive tires or new tires. New steer tires had an average depth of 18/32nds of an inch. New wide-base single tires had an average depth of 27/32nds of an inch. CLI moved drive tires to the tanker axles to obtain the maximum life of the tire. If a tire was moved from the drive axle to the tanker axle, the average tire depth was 16/32nds of an inch.

The following sections discuss maintenance actions (the replacement of tires due to wear or failure) and tire wear (the analysis of tire depth measurements as a function of miles traveled).

4.1.2.1 Tire Maintenance Actions

A "tire maintenance action" was the act of replacing or repairing a tire. The actions included replacing a tire due to wear or failure, repairing a tire due to penetration of a foreign object, or conducting a road call due to a catastrophic failure during service. The host fleet submitted 198 reports of tire actions during the field test, as shown in Table 11. Tire action reports included failure reports submitted by drivers, failure reports submitted by technicians, and periodic inspections that included a tire change-out. During the field test, CLI completed 160 tire wear replacements, 16 tire failure replacements, 16 tire repairs, and 6 road calls.

Table 11. Tire maintenance actions (CLI).

Fleet	Tire Wear	Tire Failure	Repair Only	Road Call	Total Tire Actions
Test Fleet	102	11	12	4	129
Control Fleet	58	5	4	2	69
Total Tire Actions	**160**	**16**	**16**	**6**	**198**
Percent	**81%**	**8%**	**8%**	**3%**	**N/A**

The largest contributor to tire maintenance actions was the replacement of tires due to tire wear (81 percent). The technicians replaced 160 tires due to wear during the field test. Table 12 breaks down the distribution of the tire replacements per million miles. Tankers had the highest number of tires replaced. The tanker tires did not necessarily experience more wear, but they were routinely replaced with used drive tires. Therefore, the tires were replaced more frequently due to the lower starting tire depth. The following section provides more detail on tire wear patterns.

Table 12. Maintenance actions per million miles, by axle (CLI).

CLI	Tire Wear	Tire Failure	Repair Only	Road Call	Total Tire Actions
Test Fleet Steer Axle	12.3	0.5	0.5	0.0	13.3
Test Fleet Drive Axle	13.8	2.0	3.5	1.5	20.7
Test Fleet Tanker Axle	24.2	3.0	2.0	0.5	29.6
Total (Test Fleet)	**50.3**	**5.4**	**5.9**	**2.0**	**63.6**
Control Fleet Steer Axle	6.0	0.0	0.0	1.1	7.1
Control Fleet Drive Axle	10.9	1.6	0.5	0.0	13.1
Control Fleet Tanker Axle	14.8	1.1	1.6	0.0	17.5
Total (Control Fleet)	**31.7**	**2.7**	**2.2**	**1.1**	**37.8**
Average Maintenance Actions between Fleets	**41.5**	**4.1**	**4.1**	**1.6**	**51.3**

Tire failures, tire repairs, and road calls accounted for the remainder of the tire maintenance actions. Drivers and mechanics submitted 38 failure reports during the field test. Table 13 provides a breakdown of the control fleet’s failure reports. The technicians and drivers submitted 11 failure reports on the control fleet.

Table 13. Control fleet failure reports (CLI).

Incident	Number of Events	System Warning	Drove to Garage	Road Call	Comment
Tractor Foreign Object Detected	2	N/A	Yes	No	Drivers identified a bolt in the tread.
Tractor Pre-trip Inspection	2	N/A	No	No	Drivers identified a tire bulge and a tire leak (due to a slice on the inner sidewall).
Tractor Tire Failure	2	N/A	No	Yes	Report of tire blowout and nail in tire.
Total Tractor Events	**6**	**–**	**–**	**–**	**–**
Tanker Low Air	2	N/A	Yes	No	Drivers identified low air.
Tanker Foreign Object Detected	2	N/A	Yes	No	Drivers identified a nail and a bolt in the tread.
Tanker Pre-trip Inspection	1	N/A	No	No	Driver identified a slice in the sidewall.
Total Tanker Events	**5**	**–**	**–**	**–**	**–**
Grand Total	**11**	–	–	–	–

In one instance, two drivers submitted reports for low pressure in a tanker tire. The drivers added air to the tires and continued their shift. After the second report, the technicians inspected and pulled a bolt from the tire. The tire was repaired, and the tractor-tanker unit returned to service. (If this were a test unit, the light would have illuminated, the tire pressure would have been maintained, and maintenance would have been notified of the impending tire failure at the start of a shift.)

In two instances, the tanker tires had significantly low tire pressures (more than 30-percent loss in recommended pressure) during service. In both instances, drivers observed the low pressure due to the significant loss in tire pressure. (If this were a test unit, the tire pressure would have been maintained, but the driver would have been notified of the system refilling the tires. A driver would not have had to add air to the tires during service.)

Table 14 provides a breakdown of the test fleet’s failure reports. The technicians and the drivers submitted 27 failure reports. The test fleet had a significantly higher number of failure reports. The test fleet may not necessarily have had more failures, but the systems increased the visibility of the failures.

Table 14. Test fleet failure reports (CLI).

Incident	Number of Events	System Warning	Drove to Garage	Road Call	Comment
Tractor Low Air	3	Yes	Yes	No	–
Tractor Leaking Valve Stem	2	Yes	Yes	No	–
Tractor Foreign Object Detected	5	Yes	Yes	No	Drivers identified screwdriver, bolts, and nails.
Tractor Pre-trip Inspection	3	Yes	No	No	Identified prior to trip. Included a broken belt, an air leak, and torn tread.
Tractor Tire Failure	3	Yes	No	Yes	Reports on only 2 incidents: at service station, nail in tire; at truck scale, faulty tire valve.
Total Tractor Events	**16**	**–**	**–**	**–**	**–**
Tanker Foreign Object Detected	8	Yes	Yes	No	Drivers identified screws, nails, and bolts. System maintained air.
Tanker Pre-trip Inspection	2	No	No	No	Drivers identified tire separation and nail during pre-trip inspection. Identified prior to failure. Fixed prior to shift.
Tanker Tire Failure	1	No	No	Yes	Tire blowout. System could not maintain air.
Total Tanker Events	**11**	**–**	**–**	**–**	**–**
Grand Total	**27**	**–**	**–**	**–**	**–**

In three instances, the IVTM system warned the driver of low pressure in the tractor tires. The driver continued the service deliveries while monitoring the tire pressures on the in-cab display. In two instances, the driver specifically noted that the system warned of the low tire pressure at 95 psi. No low-pressure warnings were issued for the tanker tires. It is likely that low pressures were not noted for the tanker tires because the inflation system properly maintained the tire pressures. The failure reports noted four instances in which the inflation system was adding air to the tires. In each of these instances, the technician identified a foreign object in the tire and serviced the tire accordingly.

The IVTM system warned the driver of a low tire pressure problem with a tractor tire in four of the five foreign object events. The driver was able to continue servicing his route, while monitoring the tire pressure. Upon returning to the terminal, the driver reported the warning to the technicians, who then serviced the tire accordingly.

In one instance, a tire on the front drive axle picked up a nail in the tread while the driver was pulling into a station for delivery. Before continuing the delivery route, the IVTM system issued a STOP warning to the driver, indicating that the tire pressure was dangerously low. The driver was able to request a service call prior to returning to service and potentially causing a catastrophic failure while driving.

The MTIS maintained the tire pressure in all eight foreign object events. The system light warned the driver or technician of a potential failure at the tire and provided supplemental air to maintain the tire pressure. When the vehicle returned to the terminal, the driver or technician identified a foreign object in the tire. The system maintained the tire pressure during the shift, and all tires were replaced at the terminal. None of the tire events on the trailer resulted in a road call.

The tire failures on the test vehicles were either catastrophic failures or failures of the tire casing. One failure required an out-of-State road service to replace the tire. Failure information on this tire was not available. The remaining failures were the result of a broken belt, a sidewall bulge, and the tread separating from the tire. The systems did not warn of these instances, as the tires had not experienced loss of air prior to discovery.

Finally, faulty tire valves accounted for two of the failure reports. Each system identified leaks at the valve stems due to the loss of air in the affected tire. In one case, the driver identified the leak while at the scale house. The tire pressure dropped to 55 psi in a drive tire and required the replacement of a bad valve stem while in service. In the other cases, the driver identified and corrected the leaking valve stem without removing the vehicle from service. The control vehicles did not identify any tire valve failures.

4.1.2.2 Tire Wear

The technicians collected 362 tire depths as part of the field test through tire replacement actions or end-of-test measurements. The test tractors had 193 tire depth measurements, and the control tractors had 169 tire depth measurements. Table 15 breaks down the distribution of the tire depths by vehicle type and axle location. The analysis measured tire wear between initial tire installation and tire removal. Due to the low tire wear between inspection intervals, tire wear was difficult to track throughout the life of the tire.

Table 15. Number of tire wear measurements (CLI).

CLI	Steer Axle	Drive Axle	Tanker Axle	Total
Test Fleet	44	72	77	193
Control Fleet	39	75	55	169
Total	**83**	**147**	**132**	**362**

Figure 22 and Figure 23 show tire wear per mile for the control vehicles and the test vehicles, respectively. The data points chart axle location (steer, drive, or tanker), and the trend lines show the average rate of wear for each axle location. As the slope of the trend line decreases (i.e., becomes “shallower”), the life of the tire increases (more miles per 32nd-inch of wear). Each exhibit shows consistency in tire wear by location. The drive tires for the control and test vehicles had the highest wear rates and were replaced more frequently. The tanker tires had the lowest wear rates.

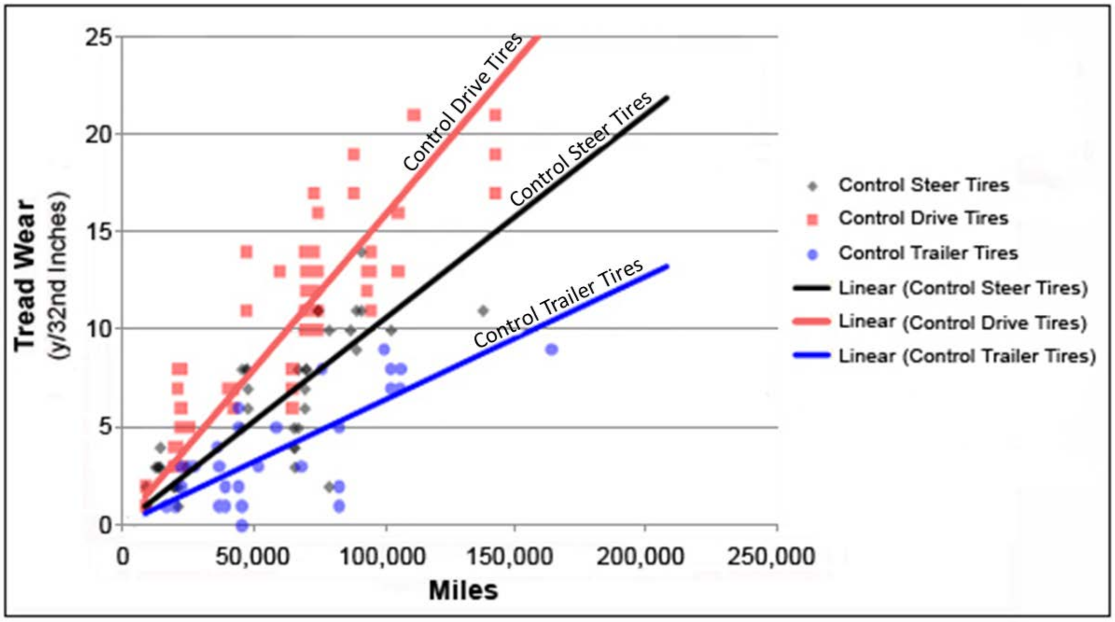


Figure 22. Graph. Tread wear of control fleet tires (CLI).

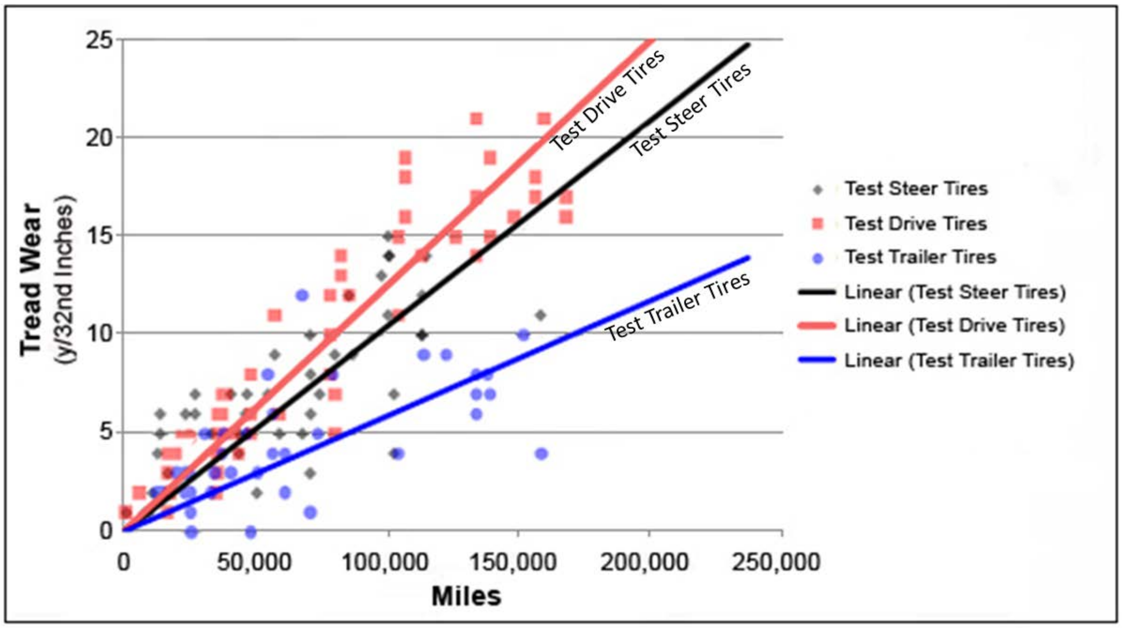
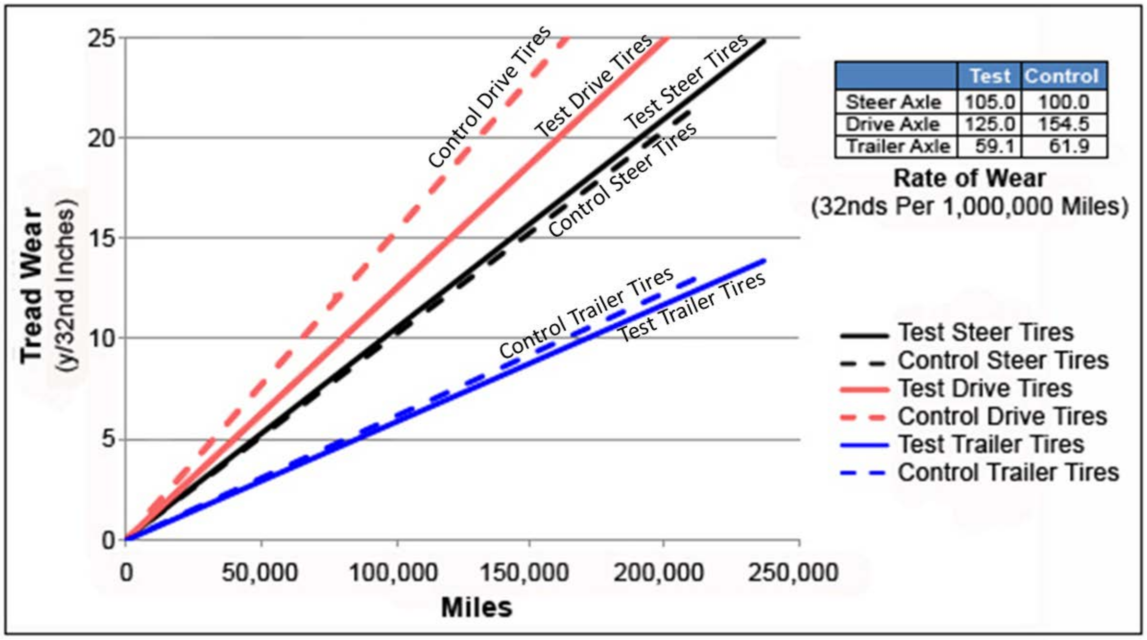


Figure 23. Graph. Tread wear of test fleet tires (CLI).

Figure 24 presents trend lines from the test and control vehicles in a single chart to compare the tire wear between the two datasets. The solid lines represent the test vehicles, and the dashed lines represent the control vehicles. TPMS and ATIS improved the tire wear for tires installed on the test fleet's drive and tanker axles.



	Test	Control
Steer Axle	105.0	100.0
Drive Axle	125.0	154.5
Trailer Axle	59.1	61.9

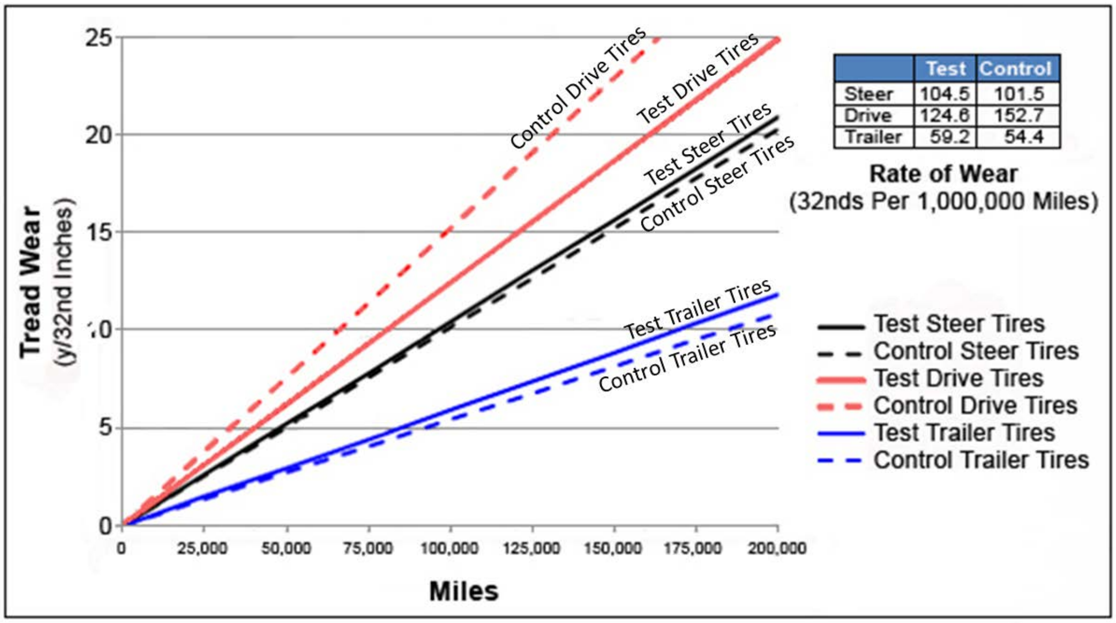
Figure 24. Graph. Tread wear per mile, steer, drive, and trailer axles: control versus test tires (CLI).

The use of TPMS resulted in a 19-percent improvement in the wear rate of the tires on the test vehicles' drive axles. The drive tires had a wear rate of 125/32nds of an inch of wear per million miles on the test tires and 154.5/32nds of an inch of wear per million miles on the control tires.

The use of ATIS resulted in a 5-percent improvement in the wear rate of the tires on the test vehicles' tanker axles. The tanker tires had a wear rate of 59.1/32nds of an inch of wear per million miles on the test tires and 61.9/32nds of an inch of wear per million miles on the control tires. Due to the wear patterns of tanker tires, the small improvement is expected. CLI routinely installed worn drive tires onto the tanker axles, limiting the overall wear rate at this tire location. As stated earlier, worn drive tires that were moved to the tanker axles averaged 16/32nds of an inch of tread depth remaining.

The use of TPMS did not improve the wear rate of the tires on the test vehicles' steer axles. According to the trend lines, the control vehicles actually had a 5-percent improvement over the test vehicles, but the data analysis showed that this result was not statistically significant. A review of tire maintenance practices concludes that the tire wear at the steer axles is very similar among the test and control vehicles. Maintenance technicians closely monitor the wear and tire inflation at the steer tires due to the belief that steer tire failures will result in higher damage liability to the fleet.

The authors conducted a regression analysis of the scatter plots to determine the statistical significance of the data (as shown in Figure 25). The findings for the drive and steer axles are nearly identical to the trend lines plotted as part of the scatter plot. According to the analysis, the tanker tires on the control vehicles had a lower wear rate as compared to the test vehicles, but the result of the analysis showed that this difference was not statistically significant. The team attributes this discrepancy to the minimal difference in wear rates between the test and control fleets. The trend lines for the tire wear rate validated that the test fleet's drive tires experienced a slower rate of wear than the control fleet's drive tires. In addition, the wear rate calculations further validate the rate of wear identified for the drive and steer axles. Statistical analysis confirmed the wear rate of the drive tires to be statistically significant at the 95-percent confidence level (t = 38.4 [Mileage] and 5.8 [Variable A]). **Note:** Variable A = Tractor Mileage (x-axis) * (1 if test, 0 if control).



	Test	Control
Steer	104.5	101.5
Drive	124.6	152.7
Trailer	59.2	54.4

Figure 25. Graph. Regression analysis of tread wear per mile (CLI): control versus test tires.

4.1.3 System Accuracy

During the analysis, the team identified two conditions that resulted in inaccurate tire pressure readings—technicians recorded system tire pressure readings after adjusting pressure at the tire, and the monitoring system sensors inaccurately displayed tire pressures. A review of the data shows that when a technician measured a lower tire pressure, he frequently added air to the tires before recording the pressures at the in-cab display. As a result, the data analysis inaccurately represents the valid tire pressure measurements. The team could not determine whether the discrepancy between the measured tire pressure and the in-cab display's tire pressure readings was due to inaccuracy of the in-cab display or to the data collection procedure. In addition, the technicians continuously reported reliability issues with the wheel sensors. When the wheel sensor failed, the in-cab display would display an incorrect tire pressure. The technicians identified tire pressure differentials of up to 30 psi. In these situations, the technicians verified that the tire pressures were correct using a manual tire pressure gauge. The technicians reported the tire sensor failure, but continued to complete periodic inspections with the invalid wheel sensor. The team conducted a review of the data, discarding any readings that appeared to meet these conditions, and identified consistent tire pressure measurements between the manual measurement and the system measurement with minor tire pressure differentials of no more than 2 psi.

4.1.4 System Reliability

CLI submitted 99 failure reports concerning the operation of the tested systems. The failure reports included 38 driver reports and 61 technician reports. The drivers and the technicians submitted failure reports to document abnormalities in the operation of the systems under test. Failures included loss of communication with the cab display, pressure warnings, oil leaks at the wheel ends, and abnormal operation of the system. This section divides the analysis of the system reliability into two parts: the monitoring system and the inflation system.

4.1.4.1 Monitoring System

The monitoring system accounted for all of the driver failure reports and 85 percent of the technician failure reports. As shown in Table 16, the majority of the failure reports were due to failed wheel modules.

Table 16. IVTM system failure reports (CLI).

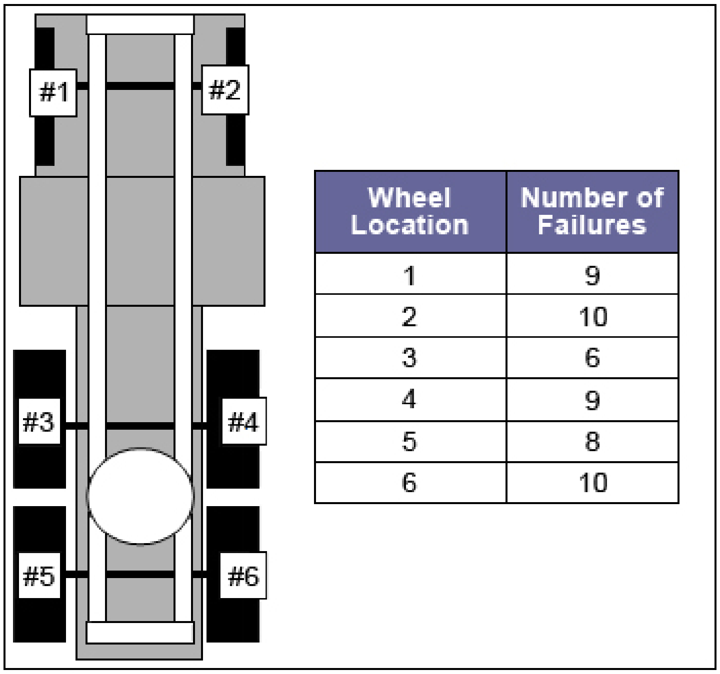
System Failures	Driver Report	Technician Report
Wheel Module Failure	15	39
Air Leak	8	6
Operator Error	1	0
Communication Failure	3	0
Hardware Failure	0	4
Unknown	11	3
Total	**38**	**52**

Wheel Module Failures

At the beginning of the field test, technicians installed 121 wheel modules. Of those original modules, all but 14 were replaced. An additional 52 wheel modules had to be replaced during the field test. According to the driver and technician failure reports, the wheel modules were removed for one of two reasons: loss of communication with the in-cab display, or invalid tire pressure shown on the in-cab display.

During the field test, the authors and Wabco worked together to identify the cause of the wheel module failures. The team identified four possible scenarios for the failures: wheel module-to-antenna separation, specific tractor influences, external electromagnetic interference, or equipment failure.

As shown in Figure 26, the team could not identify a failure pattern based on the distance between the wheel module and the antenna. The wheel module failures were evenly distributed among the six wheel locations. A failure pattern could not be determined based on axle or wheel location. The data showed that the failures were not the result of an installation issue, the location of the antenna was not inhibiting communications, and the drive wheels did not block RF communications.



Wheel Location	Number of Failures
1	9
2	10
3	6
4	9
5	8
6	10

Figure 26. Diagram. Wheel module failure locations and number (CLI).

Similarly, the failure analysis did not show failures grouped to any particular tractor or group of tractors (as shown in Table 17). The tractors averaged 5.2 wheel module failures during the test period. One tractor, 7495, only had a single wheel module failure, caused by operator error.

Table 17. Wheel module replacement by tractor and location (CLI).

Tractor	Tire Location 1	Tire Location 2	Tire Location 3	Tire Location 4	Tire Location 5	Tire Location 6	Total
7375	1	0	0	1	2	2	6
7376	2	1	2	1	1	1	8
7377	1	2	1	2	1	2	9
7378/75	1	1	1	1	1	0	5
7379	0	2	0	0	0	2	4
7380	1	1	1	2	0	0	5
7381	1	1	0	0	1	1	4
7385	1	1	0	1	1	2	6
7386	1	1	1	0	1	0	4
7495	0	0	0	1	0	0	1
Total	**9**	**10**	**6**	**9**	**8**	**10**	**52**

Wabco, CLI, and a representative for the authors met at the Altoona terminal in January 2009 to review the sensor failures to date, to discuss failure scenarios, and to review Wabco's proposal to correct the wheel sensor failures. By January 2009, CLI had replaced 16 wheel modules; 11 of the modules were replaced between October 2008 and January 2009. During the meeting, Wabco presented the next version of the IVTM equipment, which included a second-generation wheel module (as shown in Figure 27). The new equipment, when paired with the new in-cab display, would enhance the driver's interface with the IVTM system. Wabco requested that the team replace the first-generation modules to improve the communication within the system. The second-generation modules were 100-percent compatible with the original IVTM equipment installed for the field test.

The second-generation modules included notable modifications. First, the modules "stood off" the mounting brackets. As shown in Figure 27, the new modules were not installed between the tire lugs, as they were in the previous generation. Instead, the mounting bracket incorporated an extended metal standoff to prevent the module from lying between the tire lugs, possibly improving the system communications. Second, the technician determined the length of the air tubing during installation, instead of using a predetermined single length during manufacture. The technician identified the required length of tubing and trimmed the excess prior to completing the installation. The technician inserted and locked the trimmed end into the wheel module. The new design permitted the air hose to be adjusted and allowed the use of longer air hoses to ease removal and installation of wheel modules during tire changes.

First-Generation Module (Steer)

Second-Generation Module (Steer)

Figure 27. Grouped photo. Wabco wheel modules, side-by-side comparison of first-generation and second-generation modules.

Wabco provided 30 second-generation wheel modules to equip 5 tractors with new equipment. CLI retrofitted two tractors by replacing all the first-generation wheel modules on each tractor. CLI used the remaining second-generation wheel modules as spares to replace failed wheel modules. The spare wheel modules replaced an additional 26 first-generation wheel modules that failed between January and July. At the end of the field test, the failure rate for the first-generation wheel modules equaled 47 percent, with only 14 of the original modules functioning throughout the entire field test. The failed wheel modules were returned to Wabco for failure analysis. At the time of the report, Wabco had preliminary failure reports identifying three potential issues: no failure found, premature battery failure, and failure under investigation. Wabco did not provide a summary on the final analysis of the equipment. At the time this report was prepared, the team was unable to discern whether the high failure rate was directly attributable to premature battery failure.

The second-generation wheel modules experienced a lower failure rate (27 percent). Of the seven modules that were replaced, one failure was due to improper maintenance. The fill valve of the wheel module (as shown in Figure 28) did not allow users to add air to the tire using traditional methods. A low-clearance tire chuck had to be used in order to access the fill valve properly. When this particular module required additional air, the user did not use a low-clearance tire chuck. Instead, a stick tire chuck was used to fill the tire, and the stick chuck likely was used as a lever: when the stick could not fully engage the fill valve, a large force was applied as a lever, breaking the fill valve on the wheel module.

Figure 28. Grouped photo. Second-generation wheel module (fill valve) failure.

Unknown Failures (Potential Wheel Module Failures)

Drivers and technicians submitted 14 reports that did not include detailed descriptions of the failures. In the majority of the cases, the technicians replaced the wheel module during the next periodic inspection. Each of the unknown failure reports likely was due to a wheel module failure. When the wheel module was replaced, the IVTM equipment began to correctly monitor the tire pressure at the affected location again. The replacement of these wheel modules was accounted for in the total replacement discussed above.

Air Leak

As described earlier, the wheel modules monitor the tire pressure through a hose connection to the valve stem (as shown in Figure 29). With the hose connected to the valve stem, the tire valve is held in the open position to permit monitoring of the internal tire pressure. As a result, the tires will lose air if the hose-to-valve stem connection is not securely fastened.

Figure 29. Photo. IVTM wheel module installation.

At the beginning of the field test, loose hose connections contributed to 14 reported incidents that resulted in the IVTM system issuing low-pressure warnings. Upon investigation, the driver or technician identified an air leak at the hose connection. In two instances, the tire pressure dropped below 80 psi. As the field test progressed, reports of air loss at the hose connections decreased.

4.1.4.2 Inflation System

The drivers did not report any failures of the MTIS equipment, and the technicians reported only nine failures of the MTIS equipment. As shown in Table 18, rotary-tee failures were the largest single cause of failures of the inflation system. In addition, technicians reported single failures caused by air leaks, hardware failures, and oil leaks.

Table 18. PSI failure reports (CLI).

System Failures	Driver Report	Technician Report
Rotary Tee	0	5
Air Leak	0	1
Hardware Failure	0	1
Oil Leak	0	1
Unknown	0	1
Total	**0**	**9**

Rotary Tee Failures

In July 2008, CLI requested additional rotary tees to replace tees that were slinging oil from the wheel end. CLI suspected the rotary tees had faulty seals that were allowing oil to escape from the wheel end. CLI removed the rotary tees and returned the components to PSI for analysis.

PSI tested the returned components on a test bench in an effort to replicate the failure. No failure was found. PSI stated that the failure was likely due to overfilled or leaking wheel ends. When filling the wheel ends with oil, a sight window on the hubcap provides an indication of the least and the most oil allowed in the wheel end. With a non-MTIS-outfitted hubcap, the level of oil is not a large concern. Overfilling the wheel end will not cause leaks. The PSI-outfitted hubcap includes vents at the center of the hubcap to allow the release of air in the event of a system failure. If oil is added above the “maximum fill” line, the oil will encroach on the hubcap vents and escape from the wheel end. In addition, oil has been known to leak from the windows on specific hubcaps manufactured to accept the MTIS equipment. PSI recommended that CLI ensure oil was not added beyond the maximum fill line and recommended the replacement of the faulty hubcaps with a proven alternative. After these actions were taken, there were no more reports of incidents of slinging oil.

Other Failures

The remaining failure reports were single occurrences, including an air leak, a hardware failure, and an oil leak.

Air Leak: In July 2008, a technician identified an air leak at the line nut between the pressure regulator valve and the flow-sensing switch. The technician tightened the line nut, resolving the air leak. The test fleet did not have any additional air leaks at this location. The failure was a one-time occurrence.

In addition, the CLI field representative reported several air leaks during the first month of the field test that were not recorded in the failure reports. CLI stated that the system had air leaks at the connection between the hose and the tire’s valve stem (as shown in Figure 30). The MTIS equipment inflates the tires in a manner similar to the way the IVTM system monitors the tires. A hose connects between the T-fitting at the hubcap and the tire stem. The technicians disconnected the hose from the valve stem to measure the tire pressures during the periodic inspections. Similar to the IVTM air leaks, the MTIS air leaks occurred at the connection between the hose and the tire’s valve stem. Similar to the IVTM equipment, the technicians properly tightened the hose connections, stopping the air leaks at this location. PSI stated that the inflation system does not require regular measurements of the tire pressure. The regular tire pressure measurements occurred during the field test to collect data on the accuracy of the tire inflation system. PSI recommends verifying the system pressure during the annual inspection of the inflation system.

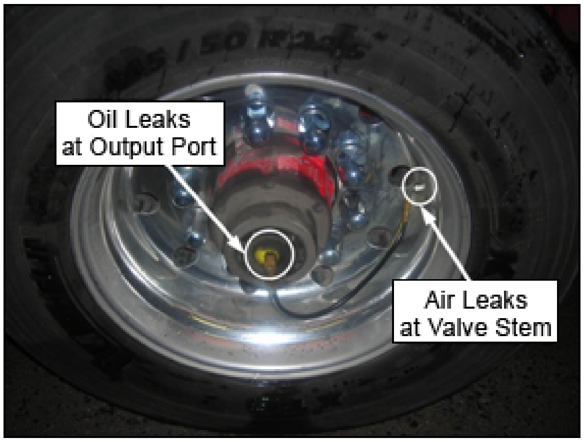


Figure 30. Photo. PSI equipment on tire: oil leaks at the output port and air leaks at the valve stem.

Hardware Failure: In April 2008, a technician identified an air leak at the T-connection near the rear axle. The connection splits the air line to supply air for the front and rear axles. The hardware failure occurred within 1 month of the initial installation of the MTIS equipment. No other hardware failures to the T-connection were reported during the field test. The failure was attributed to either a manufacturing or an installation flaw that resulted in a leak at the T-connection. After identification and repair of the leak, there were no further reports of air leaks.

Oil Leak: In June 2008, a technician identified oil leaking at the face of the hubcap at wheel location #8. The MTIS equipment did not contribute to the failure. The PSI representatives reviewed the failure report and the installed equipment. The representatives stated that the hubcap used by CLI had a history of oil leaking from the oil fill window. PSI recommended that CLI replace the hubcaps with others from a different manufacturer. After replacing the equipment, CLI did not experience any more oil leaks at the hubcaps.

4.1.5 Driver Feedback

The study team conducted a driver's survey at the completion of the field test. The survey addressed three areas of interest—driver knowledge, driver display experience, and field test experience. CLI distributed the surveys to the entire driver pool, with 100 percent of the drivers returning completed surveys (59 responses). Drivers of the TPMS-equipped tractors and ATIS-equipped tankers represented 64 percent of the survey responses. The remaining survey responses represented the control vehicle drivers.

4.1.5.1 Driver Knowledge

The drivers answered a series of questions on their exposure to and opinion of TPMS and ATIS technologies. Figure 31 breaks down the "Driver Knowledge" survey responses. The drivers had limited experience with TPMS and ATIS technologies. The survey responses showed that the majority of the drivers did not have previous knowledge of (83 percent) or driving experience with (92 percent) TPMS or ATIS technologies. Therefore, prior to starting the field test, the majority of the drivers stated that their perception of the technology was either neutral (20 percent) or they had no previous knowledge (64 percent). After completion of the field test, the drivers' perception of TPMS and ATIS technologies improved significantly. The positive/slightly positive perception of TPMS and ATIS improved to 72 percent of the drivers surveyed. No drivers had a negative perception of the equipment.

During the surveys, one driver stated that he had worked with ATIS equipment while enlisted in the Army Reserves. He stated that the technology was a high-maintenance item with minimal benefits. In his opinion, the technology did not work very well on the Army's vehicles. After driving an equipped vehicle for the field test, the driver stated that the technology was very useful (positive perception). The driver did not have any tire-related issues after installation of the technology.

Although some drivers did not have previous exposure to the technology, they believed the technology would cause more maintenance without any benefit for the driver. At the completion of the test, these drivers also stated that they believed the technology was very useful. One driver stated that the technology warned him of a slow leak on his vehicle before he left the terminal at the start of his shift.

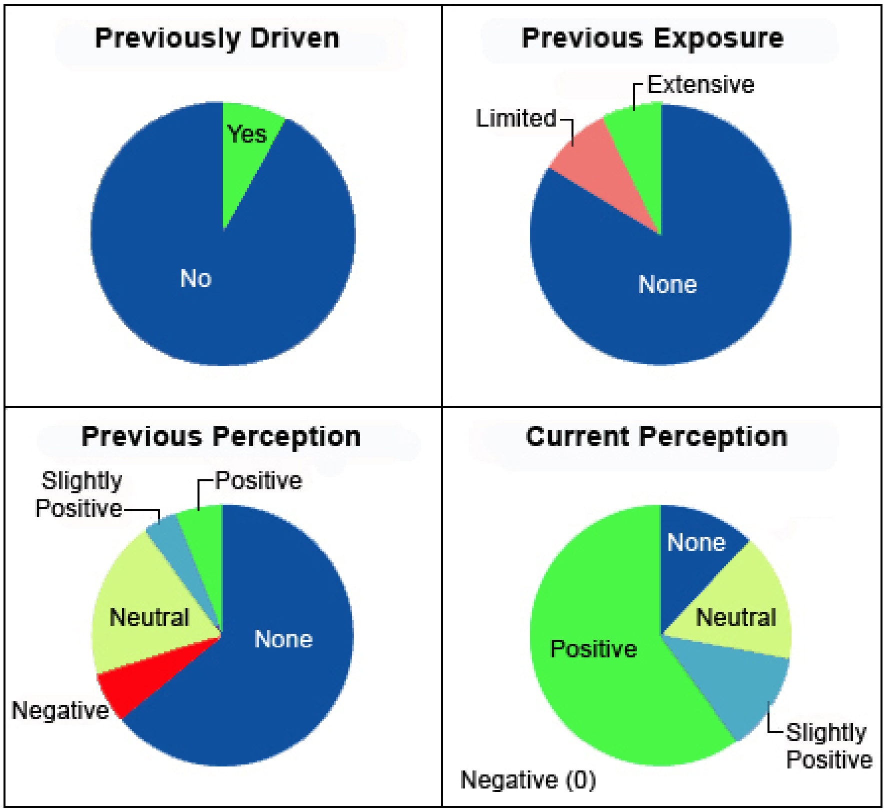


Figure 31. Pie charts. Driver survey results: driver knowledge (CLI).

Overall, the drivers' opinions of the TPMS and ATIS technologies improved after completion of the field test. Several drivers stated that the equipment warned them of a tire failure before a road call was required. In addition, the drivers of the control vehicles requested expanding the installation of the TPMS and ATIS equipment to the entire fleet. The drivers believed the TPMS and ATIS technologies were very useful for tracking the status of the tires.

4.1.5.2 TPMS and ATIS Display Experience

The team surveyed the drivers to document their opinions on the TPMS and ATIS displays. As stated previously, the tractor display and the tanker display offered different interfaces. The tractor display was mounted on the dashboard to the right of the driver. The display allowed the driver to scroll through each tire position to monitor the tire pressures. In addition, the display alerted the driver with an audible and visual warning when a tire dropped below a preset tire pressure. The tanker display was an indicator light that the driver could view through his side mirror mounted on the fender of the tanker. The light illuminated when air was being added to the tanker tires.

The charts in Figure 32 highlight the drivers' responses to the accuracy, location, and functionality of the tractor display. The majority of the drivers (74 percent) stated that the tractor display was accurate "most of the time." From comments received during the survey, the authors linked the lower rating to the wheel sensor failures. As stated earlier, if a wheel sensor failed, the tire pressures at the in-cab display would be invalid. The majority of the drivers (72 percent) stated that the tractor display never interfered with the operation of the vehicle. The survey did identify a single driver who stated that the displays always interfered with vehicle operation. A review of this driver's responses found that he was very receptive to the TPMS and ATIS technology and offered only positive feedback on both systems. Therefore, it was assumed that the driver responded inaccurately to this question. Finally, most drivers (62 percent) found the interactive display very easy to use. As shown in the exhibit, the drivers had only positive feedback on the display's ease of use.

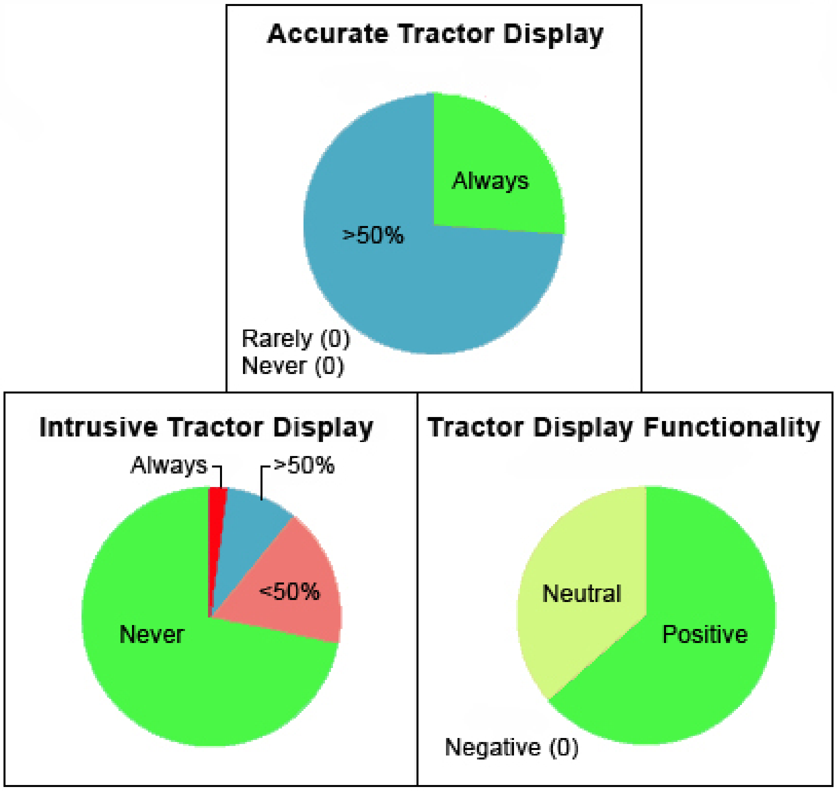


Figure 32. Pie charts. Driver survey results: TPMS tractor display experience (CLI).

The charts in Figure 33 highlight the drivers' responses to the accuracy and location of the tanker indicator light. The drivers' opinions of the accuracy of the MTIS fault indicator did not reflect the written and verbal reports delivered to the team. The survey results showed that only 47 percent of the drivers found the tanker display to be accurate. An additional 29 percent of the drivers stated that the tanker display was accurate "most of the time" (more than 75 percent accurate). Although the combined responses result in a satisfactory rating for more than 76 percent of the drivers, the results do not reflect the verbal comments received. In addition, approximately 24 percent of the drivers ranked the fault display unit as less than satisfactory (i.e. inaccurate more than 25 percent of the time or never accurate).

A review of the survey comments did not clarify the reason for the lower rankings. The team identified several possibilities for the discrepancy, including misunderstanding of the survey question, misunderstanding of rank severity (high versus low), or misunderstanding of the capability of the MTIS indicator light (i.e., it does not provide an actual pressure reading). When asked to rank the location of the tanker display, 77 percent of the drivers stated that the display never interfered with vehicle operation. Although 77 percent of the drivers responded positively to the location of the tanker display, an additional 17 percent of the drivers stated that the tanker display was intrusive either all the time or most of the time. These drivers offered no reasoning for rating the display location so low. Again, the study team believes these drivers may have misunderstood the ranking for the survey question. Because the fault indicator for the tanker inflation system was installed on the tanker's fender, it would be unlikely for the indicator to interfere with vehicle operation.

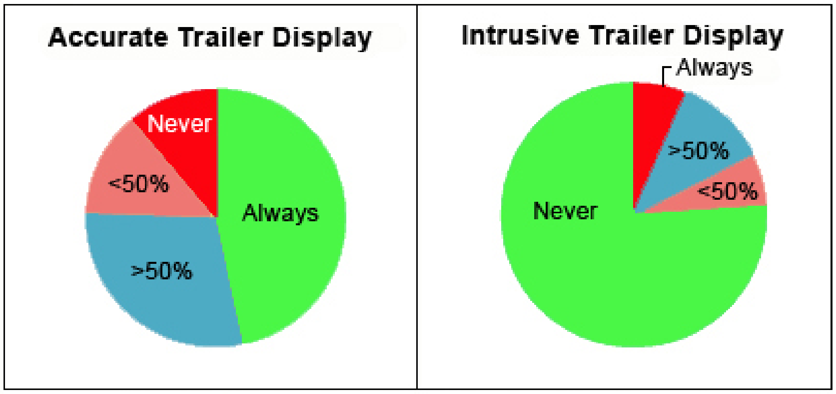


Figure 33. Pie charts. Driver survey results: ATIS tanker display experience (CLI).

4.1.5.3 Field Test Experience

The team surveyed the drivers to document events that occurred during the field test, including tire failures and system failures. The drivers answered questions on the frequency of tire failures on the tractors and the tankers.

The majority of the drivers experienced fewer than five tire failures during the field test. The drivers identified more failures on the tractor (55 percent) than on the tanker (41 percent), as shown in Figure 34. In all but one case, the displays accurately alerted the drivers of the tire failure. In this single case, the driver stated that the display did not accurately show the fault location. The screen indicated a tire warning for the right front drive tire. Upon inspection, the tire failure was found on the right rear drive. The test team did not witness this failure but suspects the failure was the result of one of two maintenance events: the sensors were not returned to their original locations after a tire rotation, or the sensor locations were not properly assigned during installation. Therefore, the failure was likely the result of improper maintenance rather than equipment failure.

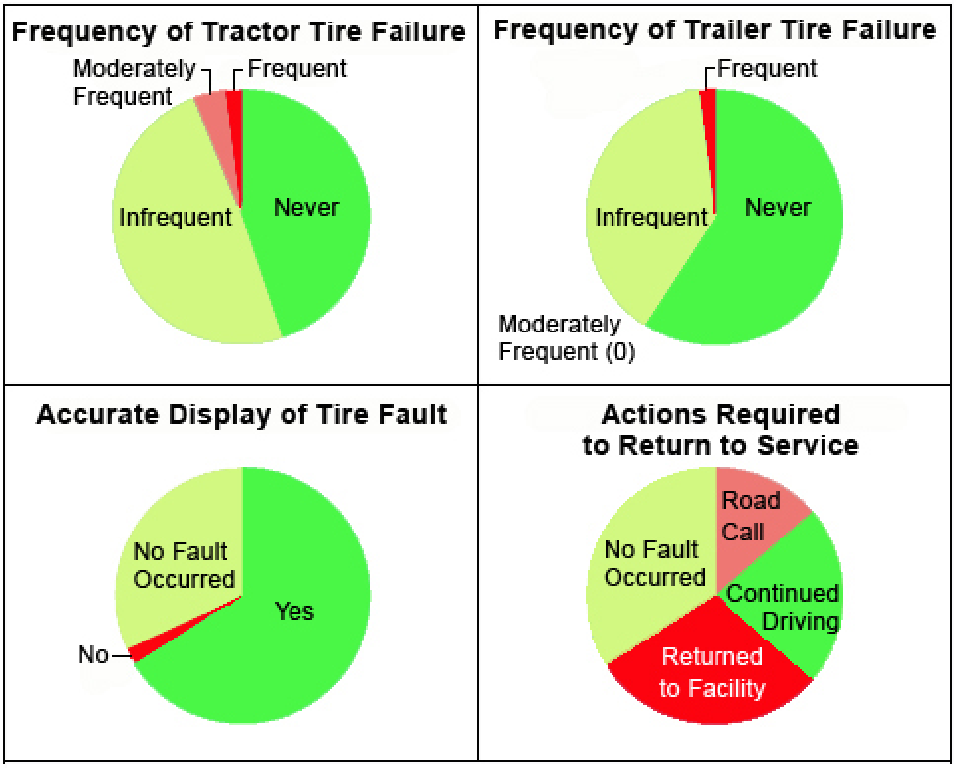


Figure 34. Pie charts. Driver survey results: tire failure experiences (CLI).

The chart labeled “Actions Required to Return to Service” in Figure 34 breaks down the steps that had to be taken after identifying a tire failure. Most of the drivers (66 percent) identified at least a single tire failure during the field test. In most cases, the drivers were able to either continue driving their route or return to the maintenance facility without requiring a road call. Six drivers required a road call because of the tire failure. In these cases, the catastrophic tire failure would not allow the driver to continue operation (e.g., sidewall blowout, failed valve stem, nail in the tread). In two cases, the drivers identified a leak in the tanker tires and were able to maintain proper tire pressure to return to the facility. In seven cases, the system warned of a leak, and the driver identified the source and determined he could safely return to the facility before taking any maintenance actions. The drivers stated that the use of the TPMS and ATIS equipment in these cases saved the tire casing and prevented a road call.

The drivers answered questions on the reliability of the tractor TPMS and tanker ATIS equipment. The survey divided the failures into three categories—never, infrequent (less than five failures), moderately frequent (less than one per month), and frequent (more than one per month). As stated earlier, the tractor TPMS equipment experienced a high number of sensor failures. As a result, the majority of the drivers experienced infrequent tractor TPMS failures (as shown in Figure 35). Although the number of failures may appear insignificant, 18 drivers made at least one comment on the sensors failing during the field test. Only nine drivers, of whom five regularly drove the test vehicles, reported no system failures during the field test.

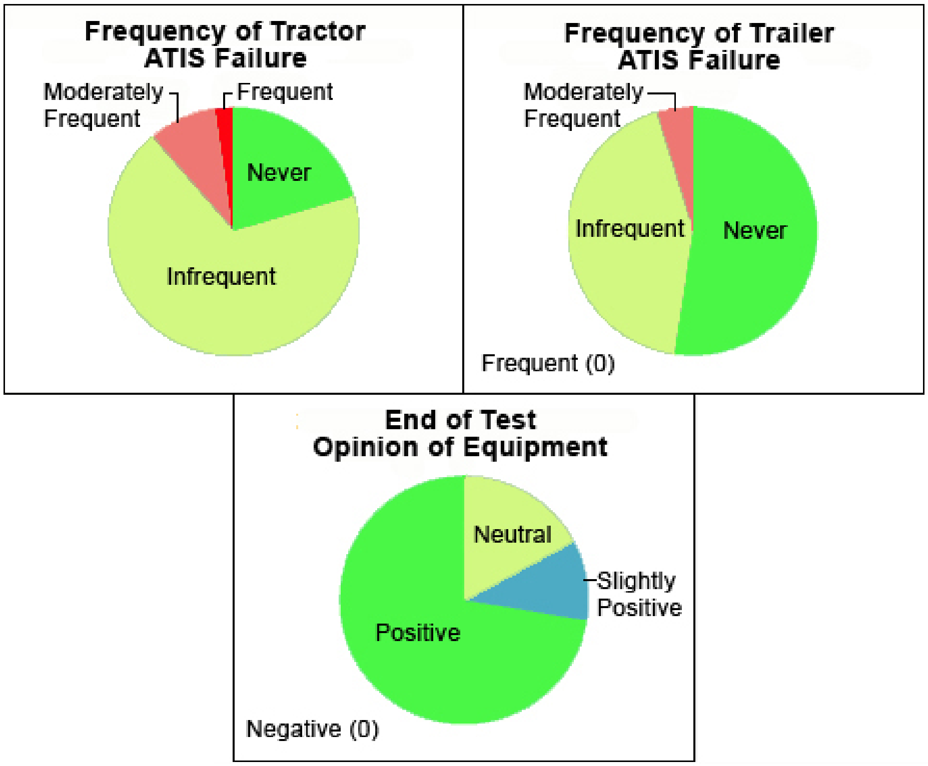


Figure 35. Pie charts. Driver survey results: system failures experience (CLI).

The drivers experienced far fewer failures on the tanker ATIS equipment. The majority of the drivers (52 percent) did not experience a single system failure during the field test. The drivers offered little insight into the system failures for the MTIS equipment. Drivers commented on loosening hoses, a “flickering” indicator light, and a faulty valve. The faulty valve was a true system failure, but the other instances were due to either improper maintenance techniques or a misunderstanding of the capabilities of the system. The hoses leading from the wheel hub to the tire valve would become loose at the tire valve. The mechanics identified the failure to be the result of improperly tightening the hose after removing it to record the tire pressure for the field test. Although the tire pressure measurements are not required for normal installations, the field test required the collection of tire pressures on a monthly basis. The problem was resolved when the mechanics modified their maintenance procedures to ensure proper tightening of the hoses. The second issue, the flickering of the fault indicator light, demonstrates the proper operation of the equipment. The light will illuminate whenever air is being added to the tires. Therefore, the light will “flicker” at the start of a shift if the vehicle has been sitting for an extended period. The system is adding “make-up” air to the tires to bring them back to the proper pressure. No actions by the driver or the technician are required. The final issue relates to a faulty valve. The technicians noted on the data sheets that a valve had to be replaced due to leaking. This was the only component that was replaced due to a true failure.

The survey responses indicate that the drivers were receptive to the TPMS and ATIS technologies, although they expressed frustration at the frequent sensor failures on the in-cab system. The drivers stated that when the equipment was working, the pressure readings in the cab allowed them to monitor the tire pressure during daily operations. Similarly, the drivers stated that the tanker inflation system permitted them to maintain tire pressures when a foreign object was in the tires. The drivers stated that an in-cab monitor for the inflation system would be beneficial to provide actual air pressures. In this instance, further information on the inflation system would have allowed the drivers to understand that the tanker tire pressures remained constant.

4.2 GFS

The GFS field test began in June 2009 and continued through November 2010. The GFS tractors operate a single delivery shift per day and average 350 miles per day per tractor. The tractor fleet operated a total of 3,406,570 miles during the field test (as shown in Table 19). The GFS trailers operate independently from the tractors and are not assigned a daily route. The tractors operated a total of 5,461,159 miles during the field test, averaging 140 miles per day. The trailers experienced higher mileage because the reefer pups were operating as dual units.

Table 19. Total field test mileage (GFS).

GFS	Tractor	Trailer
Test Fleet	1,463,193	2,861,016
Control Fleet	1,943,377	2,600,143
Total Mileage	**3,406,570**	**5,461,159**

4.2.1 Fuel

The GFS field test only tracked the fuel economy of tractors pulling 50-foot trailers equipped with the tire monitoring system. Due to GFS's operational model for reefer pups, the team could not guarantee that tractors equipped with TPMS equipment would always pull trailers equipped with inflation systems. Therefore, the reefer pups were monitored for wheel wear, tire replacements, tire failures, and system reliability. The fuel economy improvement findings do not apply to the trailers equipped with inflation systems.

The study team downloaded GFS's daily fuel logs from its maintenance database. The fuel logs recorded fueling date, vehicle identification, vehicle odometer, and fuel quantity. The fleet consumed a total of 520,546.6 gallons of fuel during the 18-month field test (as shown in Table 20).

Table 20. Fleet fuel consumption (GFS).

GFS	Mileage Under Test	Fuel Consumed	Average mi/gal
Test Tractors	1,463,193	220,036.8	6.59
Control Tractors	1,943,377	300,509.8	6.50
Total	**3,406,570**	**520,546.6**	**6.54 (Average)**

The team tracked the average monthly fuel economy of the test tractors and control tractors. As shown in Figure 36, the fleet fuel economy followed the cyclic expectations of seasonal operation. The fuel economy of each fleet reached the lowest in December and the highest in July. The test fleet consistently exceeded the control fleet's average monthly fuel economy. The test fleet averaged a 1.38-percent improvement over the control fleet during the field test.

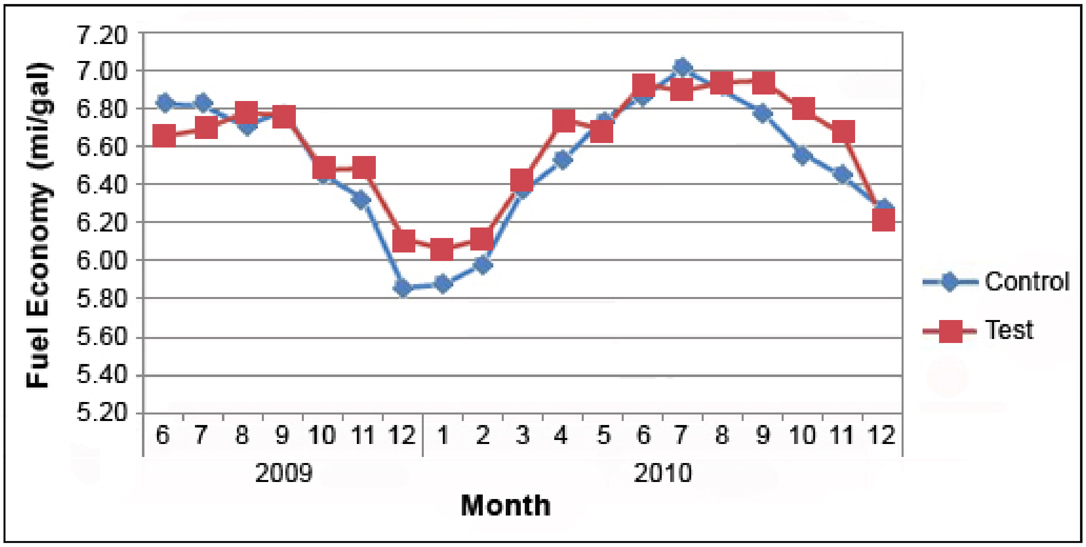


Figure 36. Graph. Monthly average fuel economy (GFS) for control and test fleets.

4.2.2 Tires

An independent tire company performs all tire maintenance for GFS. GFS removes a failed or worn tire from the axle and installs a tire from stock. The tire company representative services the GFS maintenance facility on a daily basis. During the service trip, the representative addresses all tires accumulated since the last visit. The tire company repairs punctures, replaces worn tires, and in general, replenishes the GFS tire supply with functional tires. For the field test, the tire company installed, replaced, and tracked tire sensors on the wheel rims. The tire company stocks the GFS maintenance facility with new and retreaded tires. Retreaded tires are used only on drive and trailer axles. New tires may be used at all axle locations.

4.2.2.1 Tire Maintenance Actions

GFS technicians inspected tires for current pressure, wear condition, and foreign object presence during periodic inspections. Technicians documented the findings according to their current maintenance procedures. All tire replacements, repairs, failures, and rotations were recorded in the maintenance database. The authors tracked the remaining tire incidents using GFS's internal maintenance database. The database tracked tire replacements, repairs, failures, and rotations.

GFS conducted 355 tire maintenance actions during the 18-month field test, as shown in Table 21. The authors downloaded all tire maintenance actions from the maintenance database. Tire wear, at 78 percent, represented the largest contributor to tire maintenance. GFS replaced 278 tires due to wear, 44 due to failure, and 19 due to road calls. GFS performed 14 tire repairs during the field test.

Table 21. Tire maintenance actions (GFS).

GFS	Tire Wear	Tire Failure	Repair Only	Road Call	Total Tire Actions
Test Tractor	28	6	0	1	35
Test Trailer—Pup	42	11	1	2	56
Test Trailer—50-Foot	40	12	6	5	63
Control Tractor	100	8	0	2	110
Control Trailer—Pup	24	1	2	6	33
Control Trailer—50-Foot	44	6	5	3	58
Total Tire Actions	**278**	**44**	**14**	**19**	**355**
Percent	**78.3%**	**12.4%**	**4.0%**	**5.3%**	**N/A**

Tire wear contributed to 78 percent of the tire maintenance actions. Significantly fewer tires were replaced for wear on the test tractors compared to the control tractors, which will be discussed in the following section. The rate of tire maintenance actions, as shown in Table 22, shows that the steer and drive axles of the test fleet outperformed those of the control fleet. The test tractors experienced fewer tire failures, repairs, and road calls. In comparison, the test trailers performed marginally better than the control trailers. The control trailers experienced fewer tire failures, but more tire repairs and road calls.

Table 22. Maintenance actions per million miles, by axle (GFS).

GFS	Tire Wear	Tire Failure	Repair Only	Road Call	Total Tire Actions
Test Fleet Steer Axle	6.2	0.0	0.0	0.0	6.2
Test Fleet Drive Axle	13.0	4.1	0.0	0.7	17.8
Test Fleet Trailer Axle—Pup	25.8	6.8	0.6	1.2	45.4
Test Fleet Trailer Axle—50-foot	32.4	9.7	4.9	4.1	51.1
Test Fleet Total	**25.4**	**6.7**	**1.6**	**1.9**	**35.6**
Control Fleet Steer Axle	11.3	1.0	0.0	0.0	16.4
Control Fleet Drive Axle	40.1	3.1	0.0	1.0	58.8
Control Fleet Trailer Axle—Pup	15.3	0.6	1.3	3.8	34.2
Control Fleet Trailer Axle—50-foot	45.5	6.2	5.2	3.1	60.0
Control Fleet Total	**37.0**	**3.3**	**1.5**	**2.4**	**44.2**
Average Maintenance Actions between Fleets	**31.3**	**5.0**	**1.6**	**2.1**	**40.0**

Table 23 and Table 24 break down the tire failures for the test and control fleets. The study team downloaded all tire failure reports from the maintenance database and identified the failure type, the failure cause, and any road calls through the database's comments section. The database did not provide feedback on the ability of the equipped fleet to warn the driver or the mechanic of the failure.

The analysis identified 44 tire failures for the test fleet and 33 tire failures for the control fleet. Similar to CLI, the GFS test fleet had more tire failures during the test period. Although the test fleet had a higher overall number of tire failures, it had fewer road calls. Foreign objects in the tractor tires contributed to the largest difference between the two fleets. The test trailers had 20 tire failures due to foreign objects—compared to the control fleet that had 5 tire failures due to foreign objects. The team could not establish a link between the test fleet and the higher number of tire failures due to foreign objects.

Table 23 breaks down the test fleet tire failures. As the information was downloaded from the maintenance database, minimal information was available to document the ability of the test equipment to reduce or prevent tire failures. The database identified a single occurrence of the inflation system warning the driver of a potential tire failure. Upon inspection, the maintenance technicians identified a foreign object. The technicians repaired the tire, preventing a road call.

Prior to the start of the test period, a reefer pup equipped with the MTIS experienced a catastrophic failure. A wheel end overheated due to a dragging brake. The MTIS attempted to maintain the tire pressure, but when the trailer's air system dropped below the required pressure for minimum brake operation, the safety valve isolated the system from the trailer's air supply.

Table 23. Test fleet tire failures (GFS).

Incident	No. of Events	Road Call	Comment
Tractor Event Flat	1	No	–
Tractor Event Foreign Object Detected	4	No	All tires replaced. None repaired.
Tractor Event Air Leak	1	No	–
Tractor Event Tire Failure	1	Yes	Night service call in yard.
Total Tractor Events	**7**	**No (Average)**	**–**
Trailer Events—Pup Flat	3	No	Drivers identified screws, nails, and bolts. Illuminated light reported for one event.
Trailer Events—Pup Foreign Object Detected	7	No	Tires repaired—1. Tires replaced—6.
Trailer Events—Pup Tire Damage	1	No	Cut in sidewall identified.
Trailer Events—Pup Air Leak	1	No	–
Trailer Events—Pup Tire Failure	2	Yes	–
Trailer Events—50-Foot Flat	5	No	Drivers identified screws, nails, and bolts.
Trailer Events—50-Foot Foreign Object Detected	13	No	Tires repaired—6. Tires replaced—7.
Trailer Events—50-Foot Tire Failure	5	Yes	–
Total Trailer Events	**37**	**No (Average)**	**–**
Grand Total	**44**	**No (Average)**	**–**

Table 24 breaks down the control fleet tire failures. Due to GFS's reporting methods, an analysis of the tire failures on the control fleet was difficult. The team conducted an analysis of all failures for the control fleet and the test fleet using the descriptions written in the maintenance database.

As stated earlier, the test fleet had fewer road calls due to tire failures. In addition, if TPMS or ATIS equipment had been installed on the control fleet, the total number of road calls for the fleet might have been reduced. For example, the team identified a road call due to a flat tire from a foreign object. The road call was reported for a 50-foot trailer due to a flat inner tire. The tire servicing company conducted an inspection and determined that the tire could be repaired on site. If the trailer had been equipped with a monitoring system, the driver would have received a warning before the tire became flat (while in service). If the trailer had been equipped with an inflation system, the system would have likely maintained the proper tire pressure until the driver returned to the maintenance facility. In either event, the TPMS or ATIS equipment likely would have prevented a road call.

Table 24. Control fleet tire failures (GFS).

Incident	No. of Events	Road Call	Comment
Tractor Events Flat	1	No	–
Tractor Events Foreign Object Detected	5	No	All tires replaced. None repaired.
Tractor Events Air Leak	2	No	–
Tractor Events Tire Failure	2	Yes	One steer tire failure caused progressive damage to surrounding equipment.
Total Tractor Events	**10**	**No (Average)**	**–**
Trailer Events—Pup Flat	1	No	–
Trailer Events—Pup Foreign Object Detected	2	No	All tires repaired.
Trailer Events—Pup Tire Failure	6	Yes	One tire failure involved the catastrophic failure of two inner tires.
Trailer Events—50-Foot Flat	8	No	–
Trailer Events—50-Foot Foreign Object Detected	3	No	All tires repaired.
Trailer Events—50-Foot Tire Failure	3	Yes	–
Total Trailer Events	**23**	**No (Average)**	**–**
Grand Total	**33**	**No (Average)**	**–**

In summary, the test tractors outperformed the control tractors in the number of tire failures accumulated (7 tire failures on the test fleet versus 11 failures on the control fleet). The single road call for the test tractors occurred in a maintenance yard, but occurred after hours. As a result, the driver required the tire servicing company to perform a road call to return the unit to service. The control trailers outperformed the test trailers in the number of tire failures accumulated (23 tire failures on the control fleet versus 37 tire failures on the test fleet). Most importantly, the test fleet experienced fewer road calls during the field test, which reflects significant cost savings to the owner.

4.2.2.2 Tire Wear Data

The authors originally intended to complete a thorough analysis of tire wear on the GFS fleet, similar to the analysis for the CLI fleet. The CLI analysis calculated the tire wear rate at each of the axle positions for the fleet. However, due to the technicians' limited interaction with the tires, tire wear depth data were insufficient for a thorough analysis. As an alternative, the team attempted to use the data to identify the average mileage between tire wear replacements. This type of analysis proved difficult for two reasons:

- GFS does not necessarily replace worn tires with new tires. GFS's replacement policy permits the installation of used tires. If a used tire was installed, the accumulated mileage for the tire would be significantly less. The analysis could not track total mileage accumulated when a used tire was installed.
- GFS replaced a significant number of tires for failure, not wear. When a tire was replaced for failure, the tire had not reached its end of life. To perform a sound assessment of average mileage between tire wear replacements, the team must calculate the mileage accumulated over the entire life of the tire. A failed tire is removed prior to reaching the minimum tread depth allowed for the wheel position.

For these reasons, the team only conducted an analysis on the number of tires replaced on each fleet. The team identified 278 tire wear replacements (as shown in Table 25) during the test period. Comparing the tire wear during the test period, the control fleet replaced more tires than the test fleet.

Table 25. Tire maintenance actions (GFS).

GFS	Tire Wear (Test Period)	Tire Wear (2008–10)
Test Tractor	28	87
Test Trailer—Pup	42	61
Test Trailer—50-Foot	40	61
Control Tractor	100	116
Control Trailer—Pup	24	48
Control Trailer—50-Foot	44	51
Total Tire Actions	**278**	**424**

The analysis identified a significant difference between the test tractors and the control tractors. According to the maintenance database, the test tractors experienced a significant improvement in tire wear, replacing less than one-third of the number of tires that the control fleet replaced. The team expanded the analysis of the tire replacement to identify any cyclic patterns in the tire replacement schedules for both fleets.

Figure 37 tracks the tire replacements for the test and control fleets between January 2008 and November 2010. The replacement of the test tractor tires spiked in early 2009. The team attributed the spike in the test fleet to the installation of the TPMS equipment. The installation of the TPMS sensors required the tire technician to remove the tire carcass from the rim. The tire technician may have installed the first three sets of sensors on new tires. Then, as the maintenance technicians removed tires from the tractors to install the equipment, there was no downtime to mount the sensors to the rims. Sensors were mounted on the removed tires during the tire technician's next service call. This method of installation provided minimal downtime for both the maintenance and the tire technicians.

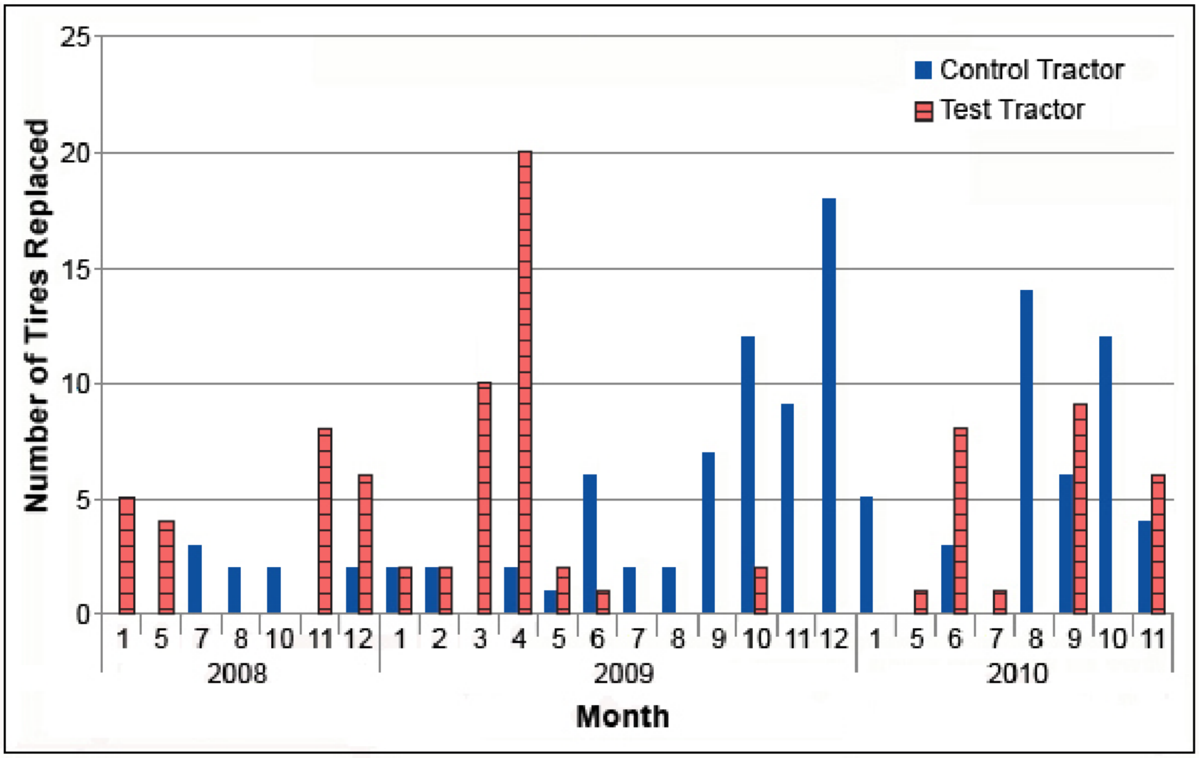


Figure 37. Graph. Analysis of tractor tire wear for control and test tractors (GFS).

Upon reviewing all the available data, the authors determined that an analysis of the tire wear patterns between the test fleet and the control fleet could not be completed. The team identified too many variables (e.g., tire replacement policies, premature tire replacement on test fleet) during the study that did not allow a clear distinction on tire wear between the fleets.

4.2.3 System Reliability

The authors tracked system reliability through staff interviews, database queries, and component returns. The team identified two recurring complaints for the equipment:

- Inflation systems inflated tires beyond preset pressure.
- Monitoring systems lost communication with wheel sensors.

In addition, two catastrophic failures occurred during the field test:

- An overheated wheel end.
- A failed wire harness.

4.2.3.1 Overinflated Tires

Early in the field test, the GFS technicians identified increased tire pressures on several of the ATIS-equipped reefer pups. Tire pressures measured up to 15 psi higher than the fleet's recommended tire inflation pressure. The team identified two conditions that could contribute to the increased pressures: an improperly set regulator valve, or an extended layover period during cold temperatures. The authors contacted PSI to conduct an analysis of the failure. PSI inspected various systems at the facility but could not identify any discrepancies. PSI also tested the pressure setting of the regulators and confirmed the pressure setting of 95 psi.

Figure 38. Photo. GFS reefer pups in yard.

In addition, the authors reviewed the operation of the GFS fleet and determined that the reefer pups experienced extended layovers between trips. During these layovers, the trailers likely experienced a cold-soak event. A cold-soak event exposes the tires to an extended period of below-average temperatures. As a result, the tire pressure decreases due to the temperature drop. Therefore, during the cold winters and cool evenings in Grand Rapids, the tire pressure dropped during the reefer pup's layover. When the GFS driver hooked up the reefer pup, power was restored to the inflation system, and it re-inflated the tires to the proper pressure. The operation of the trailer throughout its route raised the temperature in the tire, and thus the tire pressure. Depending on the ambient temperature during the technician's maintenance, the tire pressure readings would exceed the pressure set by the inflation system during the startup procedure. If this is the cause for the raised pressures, the tire industry advises not to remove air pressure from tires during a cold pressure reading (after the tire was properly inflated).

4.2.3.2 Communication Loss with Sensors

During the field test, technicians expressed concern over the intermittent communication between the wheel sensors and the cab display. Reported concerns included communication loss between trailer and display, communication loss at specific tire locations, and lack of sensor tracking ability.

Drivers reported the absence of all trailer tire information on the in-cab display when dispatched from the distribution facility (as shown in Figure 39). The cab display recognized the trailer tire information after driving a short distance down the road (less than 2 miles). As stated earlier, Tire-SafeGuard provided a system capable of monitoring unmarried tractor-trailer pairs. To accommodate unmarried pairs, the system conducts a handshake sequence at startup to validate and link the correct tractor-trailer pair. Two scenarios generate the handshake startup: a key-up/key-down sequence, or a verification of a single trailer in the area. For the GFS test, the drivers were not informed of the key-up/key-down procedure. Therefore, the system delayed linking to the trailer until the system verified the sensors on the trailer. The verification process could take up to 5 minutes due to other sensors communicating in the surroundings. After a trailer linked to a tractor, the DDU stored the trailer's identification in the control unit. Future communication links would occur within seconds. In summary, the latency in the display of the trailer tire pressures results from the design of the system programming. A discussion with the manufacturer identified potential areas for improvement, including an automatic startup sequence to eliminate the key-up/key-down requirement for tractor-trailer linkage.

Figure 39. Photo. Tire-SafeGuard reliability, displaying tractor tire data only (GFS).

Technicians commented on the difficulty of monitoring trailer tire pressures in the maintenance yard. Due to the size of GFS's trailer fleet, trailers frequently remained in the maintenance yard for several days without use. The technicians could not monitor the trailer tires without a linked tractor. In addition, due to the standby mode of the sensors, the trailer sensors had to sense movement prior to decreasing the time between system messages. As a result, the connection of a tractor to the trailer would not resolve the issue unless the tractor moved the trailer and a link was established between the two units. The fleet managers recommended a standalone unit that could query a tire's pressure by passing a handheld reader over the tire. The manufacturer stated that a new standalone trailer system includes an external display for the trailer. The unit monitors the trailer's tires, allowing technicians to view tire pressures without the tractor display unit. The trailer-only system will transmit the trailer's tire pressures to the in-cab display unit when a link is established.

Drivers and technicians reported missing tire pressure measurements at varying tire locations on the in-cab display unit. The display would provide tire measurements for some tire locations, but would not display a tire measurement at other tire locations on the same tractor (as shown in Figure 40, the left inside tire on the front axle is not displaying tire information). While conducting interviews with the technicians and the tire representative, the authors identified inconsistent maintenance practices that may have contributed to this phenomenon. When conducting tire rotations or replacements, the technicians must ensure that a wheel sensor is installed at each location and the cab display is updated to reflect the changes. Interviews with the technicians and tire representative uncovered a lack of diligence in conducting these maintenance tasks. As a result, many “blank” tire pressures on the display may have been due to not updating the sensor locations or not installing sensors on new tires. These issues would be less apparent if an entire fleet were outfitted with the wheel modules. The tire technicians would only have tires with wheel sensors installed. When replacing a wheel, the technician would install the tire and immediately reprogram the cab display to recognize new tires and new tire locations. After establishing a maintenance procedure, the number of “missing” wheel modules should decrease. As a result, no additional downtime would be required to install wheel sensors on new rims.

Figure 40. Photo. Tire-SafeGuard reliability; display missing left inside tire data (GFS).

4.2.3.3 Equipment Failures

GFS management reported a single equipment failure for the inflation system and one for the monitoring system. The inflation system failed when a wheel end overheated due to a dragging brake. The monitoring system failed due to an overheated wiring harness for the trailer monitoring system. The fleet technicians identified this.

Prior to the start of the test period, a reefer pup equipped with the inflation system experienced a catastrophic failure. The driver reported a smoking wheel end while conducting the daily service route. The valve stem on the inner tire failed, causing a blown tire. The failure required a roadside service call to replace the tire and failed equipment. An investigation into the failure identified a dragging brake as the cause of the overheated wheel end. An analysis of the event attributed the failure to a faulty brake valve. One of the MTIS safety features related to the inflation system was effective during this event. While attempting to maintain the trailer’s tire pressure, the trailer’s air system dropped below the required pressure for minimum brake operation. As a result, the inflation system’s safety valve cut off the air supply to the tires.

GFS identified a failed TPMS wiring harness on a tractor in November 2010. The wire harness routed the tractor's power to the in-cab display unit. The harness consisted of three wrapped wires connected to the in-cab display, as follows:

- A red wire connected to the tractor's primary power.
- A yellow wire connected to the tractor's auxiliary power.
- A black wire connected to the tractor's ground source.

Two fuses were installed on the cables carrying power to the cab display. A preliminary inspection of the wire harness concluded that it experienced an extreme heat event. The casing on the yellow wire, leading from the tractor's ignition, completely melted off the wire. Surrounding wires in the harness were charred. The state of the harness did not lend itself to a complete failure analysis. The technicians did not supply the system's in-cab tractor display as part of the failed equipment. The harness was returned to the manufacturer for a failure analysis, but no conclusive results were received.

Figure 41. Photo Tire-SafeGuard reliability; failed wire harness.

4.2.4 Technician Feedback

At the completion of the field test, the authors administered a survey to the GFS maintenance technicians. The survey questioned the technicians in three areas—mechanical knowledge, display interaction, and overall equipment interaction. Due to the limited responses from the written surveys, the authors also conducted interviews with technicians in the facility to gather feedback on their overall experiences during the field test.

The survey documented the mechanics' knowledge of TPMS and ATIS prior to and following the field test. The survey requested pretest opinions on the systems to document the technicians' preconceptions of them. A followup question at the end of the test documented whether there were any changes in the technicians' views of the products. The survey found that the GFS technicians had no previous experience with TPMS or ATIS. Despite the lack of experience with the systems, the technicians expressed varying opinions on the perceived usefulness of the equipment. Technician responses ranged from the equipment providing a moderate aid to their daily tasks to the equipment increasing maintenance requirements with little return in terms of safety, maintenance, and troubleshooting.

At the conclusion of the field test, the majority of the technicians stated that the equipment increased the maintenance requirements with minimal advantages. The technicians identified reliability issues that increased the maintenance requirements for not only the installed system but also GFS equipment. For example, a technician stated that the ATIS routinely overinflated the trailer tires, requiring the technicians to bleed air from the tires during periodic inspections. As discussed previously, GFS's practice of adding or removing air to meet the fleet tire-pressure requirement increased the additional maintenance requirements. Industry procedures strongly discourage the removal of air from the fleet's tires in all circumstances. A change in the maintenance practice to discourage bleeding air pressure from the tires could reduce the increased maintenance interaction. In addition to overinflated reefer pup tires, a technician commented on the inability of the TPMS to provide tire pressures at all locations on the tractor or trailer. He stated that the cab display frequently lost communication with various tire positions. To resolve the issue, GFS mounted new tires to the faulty location and reprogrammed the in-cab display. After removing the non-functioning tires, the technicians did not always inspect the wheel rims to confirm installation of a wheel sensor. As a result, the team could not conduct a failure analysis. From prior experience with the equipment, the team identified three scenarios that could have contributed to the failure: loss of communication between the sensor and the in-cab display, missing wheel sensor, and replacement of the tire without resetting the in-cab display. In the future, the technicians must monitor and record the location of wheel sensors. If a sensor fails, it must be returned to the manufacturer for analysis. In addition, the technicians must ensure that all tires installed on equipped tractors or trailers contain wheel sensors. After installing a new tire or rotating tires, technicians must reprogram the in-cab display to recognize the new sensors or the new sensor locations.

For display interaction, the survey documented the display's ability to accurately reflect the current pressures of the unit's tires. For the TPMS, the display had to accurately display the tire pressures at each location and represent all locations outfitted with wheel sensors. For the ATIS, the indicator light had to illuminate when the system was providing supplemental air to the wheel ends. The truck technicians stated that the TPMS in-cab display provided intermittent feedback on tire pressures. For example, a technician stated that the display would not provide tire pressures for all tire locations. At the beginning of the test, he stated that the system worked accurately, providing tire pressures for all locations. As the test progressed, the display began to omit tire pressures at various locations. As stated above, the cause for this failure could not be documented, because failed sensors were not returned for analysis. In addition, due to the lack of failure reports, the team cannot validate that wheel sensors were installed at these locations when the failure occurred. Again, the fleet must make sure to document tires with wheel sensors installed. In addition, all equipped units must have wheel sensors at all tire locations, and the in-cab display must be reprogrammed during tire installations or rotations. The trailer technicians stated that the trailer systems rarely provided accurate fault status. In one example, the technician stated that he did not experience the tractor and trailer units married to validate the ability of the systems to communicate. In addition, the technicians expressed concern throughout the test about the in-cab display's delay in communicating the trailer tire pressures. For the ATIS, the technicians rarely experienced the illumination of the indicator light. Therefore, the trailer system was not adding pressure to the tires. In these cases, the system accurately provided fault status.

In general, the installation of TPMS and ATIS increased the daily maintenance tasks for the technicians, from adjusting tire pressures on the reefer pups to replacing wheels due to failed wheel sensors. Although the technicians understood the benefits of a functioning TPMS or ATIS, they felt that the systems under test hindered their daily tasks. The technicians stated that the systems provided little assistance in the maintenance of tires. Comments gathered during personal interviews identified system improvements that would allow for easy incorporation of the systems into GFS maintenance procedures. Technicians requested a method to read the tire pressures of trailer monitoring systems without requiring the tractor to be connected. GFS's operation model is not conducive to requiring the tractor to read tire pressures in the yard. The technicians would prefer to be able to monitor the trailer tires prior to releasing a trailer to service. In addition, technicians requested an ATIS capable of inflating and deflating tires. Throughout the test, technicians released air from trailer tires equipped with the ATIS. As stated earlier, deflating tires after properly setting the pressure is not recommended. Instead, the authors recommend that the manufacturer advise the technicians to allow the ATIS to maintain the tire pressures. The technicians would not release air from the tires, accepting that the pressure was set to the recommended cold pressure setting.

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5. CONCLUSIONS

This section reviews the findings from the entire field test. The team conducted a hypothesis analysis to determine the success of the field test, based on the hypotheses established as part of the field test plan. In addition, the team conducted a cost-benefit analysis to identify the ROI for the purchase of the TPMS and ATIS for a single unit (tractor and trailer/tanker).

5.1 HYPOTHESIS ANALYSIS

The authors analyzed the hypotheses established as part of the test plan for the field test. The analysis determined that each of the hypotheses met one of three criteria: valid, inconclusive, or invalid. Due to the variations between the test fleets, the team independently evaluated the findings from each fleet against the hypotheses. Table 26 summarizes these evaluations, including the analysis technique used to evaluate each hypothesis. The evaluation concluded that 60 percent of the hypotheses were valid using the field test data. The following subsections detail the basis for these findings. The authors conducted a statistical evaluation of the appropriate hypothesis to determine the significance of the conclusion. The detailed analysis of each hypothesis provides the results. **Note:** The statistical evaluations assumed that the control fleet and test fleet were homoscedastic (i.e., having equal variance). The statistical evaluation assumed a two-tailed test, with $\alpha = 0.05$ to test for 95-percent confidence.

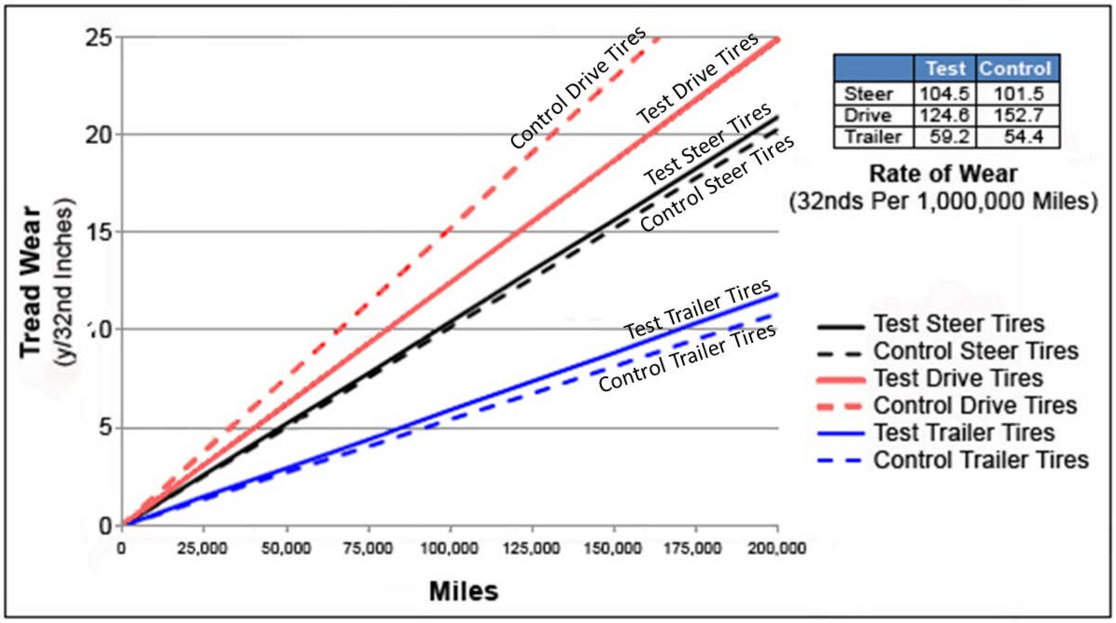
Table 26. Analysis of field test hypotheses.

No.	Hypothesis	Analysis	CLI	GFS
1	The use of TPMS and ATIS will increase the life of TPMS/ATIS-equipped tires.	Analyze tread wear per mile. Analyze based on tire location (steer, drive, trailer).	Valid	Inconclusive
2	The use of TPMS and ATIS will reduce the fuel consumption of equipped tractors.	Analyze average mi/gal.	Valid	Valid
3	The use of TPMS and ATIS will reduce road calls for damaged/flat tires for equipped tractor-trailers.	Analyze overall road calls. Analyze tire failures.	Inconclusive	Valid
4	TPMS and ATIS will accurately display the tire pressure of equipped tractor-trailers at the driver interface.	Analyze accuracy of equipment.	Inconclusive	Valid
5	TPMS and ATIS will not introduce unscheduled maintenance that will affect the day-to-day fleet operations.	Analyze unscheduled maintenance actions.	Valid	Valid

Hypothesis #1—The use of TPMS and ATIS equipment will increase the life of TPMS and ATIS-equipped tires.

The team analyzed tread-depth measurements and tire replacement reports to calculate the tire wear incurred and the miles traveled for each tire replaced during the field test. The team plotted the data on a scatter plot to generate trend lines showing the rate of tire wear at each axle location.

Conclusion: At CLI, the use of TPMS equipment increased the life of the drive tires of TPMS-equipped units. The steer and tanker tires experienced nearly identical wear rates. The trend lines for the tire wear rate (as shown in Figure 42) validated that the test fleet's drive tires experienced a slower rate of wear than the control fleet's drive tires. In addition, the wear rate calculations provided in Figure 42 further clarify the rate of wear at each axle location. The statistical evaluation confirmed the wear rate of the drive tires to be significant at the 95-percent confidence level (t = 38.4 [Mileage] and 5.8 [Variable A]). The wear rates of the steer and trailer tires were nearly identical.



	Test	Control
Steer	104.5	101.5
Drive	124.6	152.7
Trailer	59.2	54.4

Figure 42. Graph. Hypothesis #1—comparison of tire wear per mile (CLI).

At GFS, the ability of TPMS or ATIS to increase the life of TPMS and ATIS-equipped tires was inconclusive. The tread-depth measurements provided during the field test did not provide a large enough sample size to determine statistical significance. The installation of the monitoring systems unintentionally skewed the tire replacement schedule. Complete sets of tractor and trailer tires were replaced earlier than they normally would have been on the test fleet in order to install the wheel modules during the initial phase of the field test. As a result, the control tires experienced a significantly higher tire replacement rate during the field test. By extending the analysis period (Figure 43), the team determined that a significant number of the test fleet's tires were replaced just prior to the official start of the field test. The advantages of TPMS and ATIS with respect to increased tire life could not be proven on the GFS fleet.

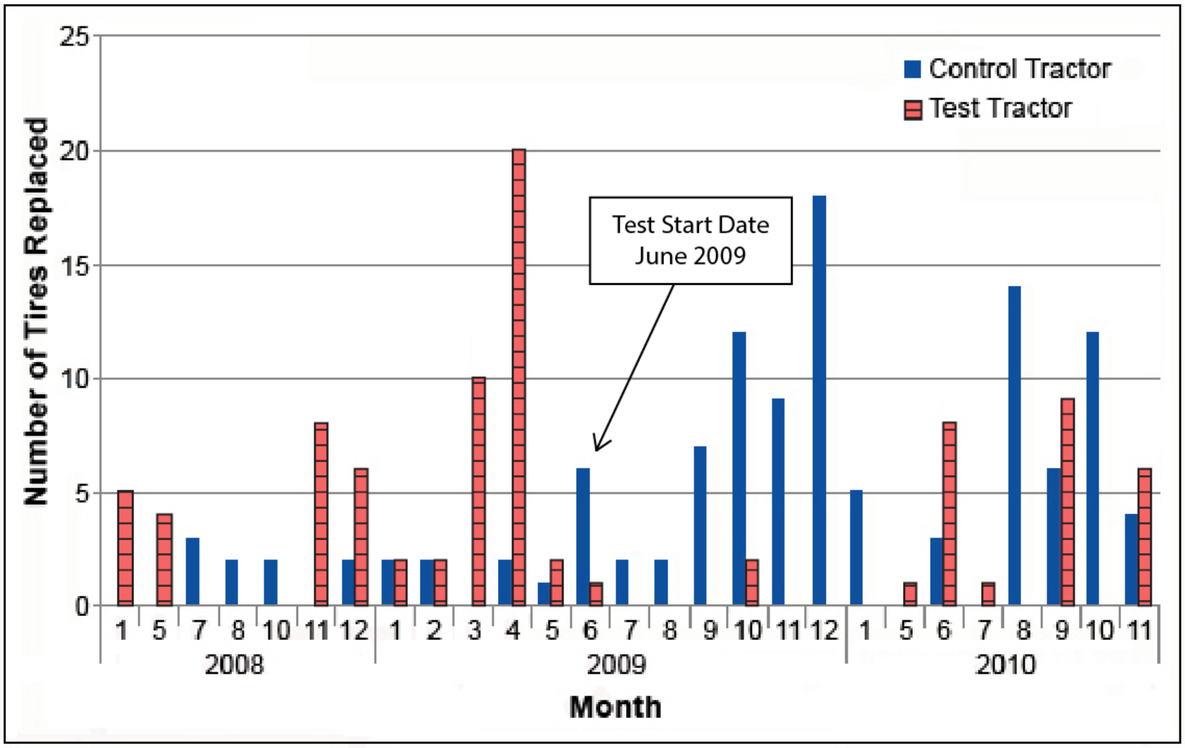


Figure 43. Graph. Hypothesis #1—comparison of tire wear (GFS).

Hypothesis #2—The use of TPMS and ATIS will reduce the fuel consumption of equipped tractor-trailers.

The team analyzed fleet fuel reports to calculate the average monthly fuel economy of the control fleet and the test fleet. At CLI, the fleet supervisor provided a fuel report at the end of each month of the field test. The fuel report summarized the total fuel used and mileage accumulated during the month for each tractor in the fleet. At GFS, the team downloaded the fuel logs for each tractor. The fuel logs recorded the current odometer reading and the gallons of fuel added for each fueling operation.

Conclusion: The use of TPMS and ATIS equipment reduced the fuel consumption of equipped tractors for both fleets. CLI collected fuel data between May 2008 and May 2009 (as shown in Figure 44). The test fleet improved its average fuel economy by 0.085 mi/gal as compared to the control fleet, an average improvement of 1.4 percent. The statistical evaluation confirmed the value to be significant at the 95-percent confidence level. Specifically, the fuel economy improvement was achieved with 97.7-percent confidence (t = 2.29, 95-percent confidence = 1.97).

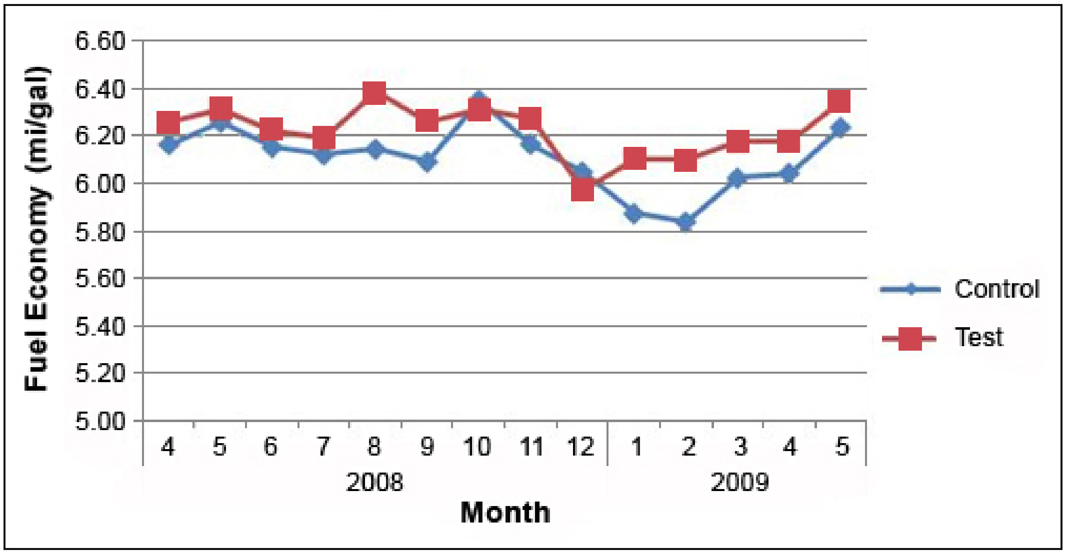


Figure 44. Hypothesis #2—fuel economy analysis (CLI).

GFS collected fuel data between June 2009 and November 2010 (as shown in Figure 45). The test fleet improved its average fuel economy by 0.09 mi/gal as compared to the control fleet, an average improvement of 1.4 percent. The statistical evaluation confirmed the value to be significant at the 95-percent confidence level. Specifically, the fuel economy improvement was achieved with 99.996-percent confidence (t = 4.13, 95-percent confidence = 1.96).

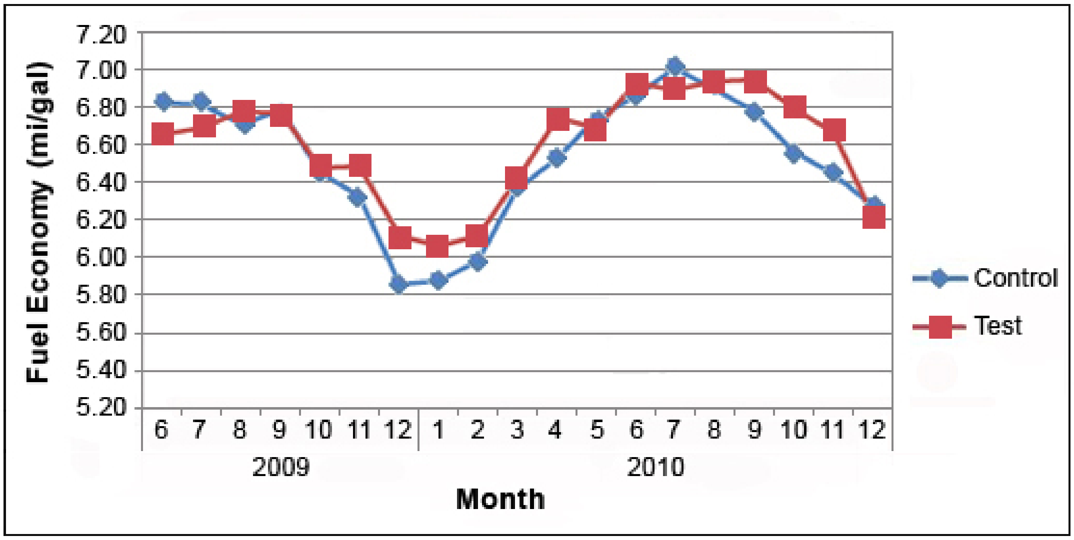


Figure 45. Graph. Hypothesis #2—fuel economy analysis (GFS).

Hypothesis #3—The use of TPMS and ATIS will reduce road calls for damaged/flat tires for equipped tractor-trailers.

The team reviewed failure reports and maintenance records to identify instances of road calls during the field test. The team analyzed the findings based on the number of road calls per million miles per axle.

Conclusion: The use of TPMS and ATIS reduced the overall number of road calls on GFS's test fleet. GFS reported fewer road calls on the test fleet's drive axles and reefer pup axles (as shown in Table 27). The steer axles of both the test and control fleets did not require a road call during the field test. The 50-foot trailer axles experienced more failures on the test fleet. Although findings were not statistically significant at the 95-percent confidence level, this value was achieved with 80-percent significance (t = 1.27, 95-percent confidence = 1.99), which is too low to draw a solid, statistically significant conclusion, but indicates a trend that the test vehicles had fewer road calls than the control fleet.

Table 27. Hypothesis #3—road calls per million miles, by axle.

Axle Type	GFS	CLI
Test Fleet Steer Axle	0.0	0.0
Test Fleet Drive Axle	0.7	1.5
Test Fleet Trailer Axle—Pup	1.2	N/A
Test Fleet Trailer Axle—50-foot	4.1	–
Test Fleet Trailer Axle—Tanker	–	0.5
Test Fleet Total	**6.0**	**2.0**
Control Fleet Steer Axle	0.0	1.1
Control Fleet Drive Axle	1.0	0.0
Control Fleet Trailer Axle—Pup	3.8	–
Control Fleet Trailer Axle—50-foot	3.1	–
Control Fleet Trailer Axle—Tanker	–	0.0
Control Fleet Total	**7.9**	**1.1**

The use of TPMS and ATIS did not reduce the overall number of road calls on CLI's test fleet. Only the steer tires of the test fleet experienced a lower number of road calls. The drive and tanker axles experienced more road calls on the test fleet.

Hypothesis #4—TPMS and ATIS will accurately display the tire pressure of equipped tractor-trailers at the driver interface.

The team evaluated the periodic inspection reports submitted by the fleet supervisors. The technicians recorded tire pressures at each tire location using a calibrated tire pressure gauge. For the monitoring systems, the technicians also recorded the pressures displayed on the in-cab display. The inflation systems were supposed to maintain a preset tire pressure.

Conclusion: Overall, the field test did not conclusively prove that the TPMS and ATIS accurately displayed the tire pressure of equipped tractors, trailers, and tankers. Each fleet experienced minor issues with the equipment, which are explained below.

At CLI, the ATIS accurately inflated the tanker tires to the system's preset pressure. Of the 788 tire pressure measurements, the inflation system properly inflated the tires for 98 percent of the measurements. The technicians recorded 18 manual tire pressure measurements that did not meet the factory-set threshold for the ATIS. The inaccurate tire pressure measurements were found during five periodic inspections. In three of the inspections, the manual tire measurements were within 2 psi of the expected tire pressure. For the remaining two periodic inspections, the technicians measured 105 psi at all tire locations on one tanker and 100 psi at all tire locations on a second tanker. These measurements were assumed to be one-off occurrences, not affecting the overall accuracy of the inflation system.

At CLI, the team could not conclusively prove that the TPMS accurately displayed the tire pressures on the in-cab display. The technicians' feedback during interviews provided subjective evidence on the accuracy of the in-cab display. The technicians stated that the system accurately represented the tire pressures after faulty wheel sensors were identified and replaced. Unfortunately, the objective measurements obtained from the periodic inspection reports did not reflect the technicians' opinions. The reports frequently recorded system tire pressures that were higher than the measured tire pressures. The suspected cause of the discrepancy is the methodology for collecting tire pressure data. The team suspects that the technicians recorded the pressures represented at the in-cab display after adjusting the tire pressures due to low readings identified during the manual tire pressure measurements. In these cases, the TPMS would be correctly representing the current tire pressure of 110 psi, but analysis of tire pressure data cannot prove this. In addition, faulty wheel sensors also influenced the accuracy of the recorded tire pressure data. As the sensors failed, the in-cab display reported excessively high (i.e., 120 psi) or excessively low (i.e., 40 psi) tire pressures. The technicians verified these inaccurate tire pressure readings by conducting manual pressure measurements. The manual measurements validated that the tire pressures were inflated to the recommended tire pressure. In summary, the findings could not prove the accuracy of the monitoring system.

At GFS, the team could not conclusively prove that the ATIS accurately inflated the trailer tires to the system's preset pressure. Throughout the field test, the technicians reported that the equipped trailers had tire pressures exceeding the fleet's recommended inflation pressure. An investigation could not determine why the ATIS overinflated the tires. The manufacturer inspected the regulator valves and verified that they were properly set to 95 psi, the recommended inflation pressure. The increased tire pressures may be attributed to the extended layovers during Michigan's cold evenings. Tire pressures drop during colder temperatures. When the trailer power is restored, the ATIS registers a low tire pressure condition and inflates the tire pressures to the preset pressure. As the temperature in the tire rises, the tires become overinflated. The tire industry does not recommend adjusting tire pressures due to overinflation, as the tires return to the proper pressure as they cool. In summary, the equipped trailers experienced overinflated tires, which could not be attributed to a fault in the system.

At GFS, the team qualitatively determined that the TPMS accurately displayed the tire pressures on the in-cab display. During interviews, the technicians raised no concerns with the in-cab display. They stated that the system operated correctly after the tractors and the trailers were linked. Unfortunately, a review of the field test data did not reflect these findings. A pressure differential was frequently recorded between the system tire pressure measurement and the manual tire pressure measurement. The team conducted a thorough review of the discrepancies and identified a repeatable pattern. If a significant difference was recorded between the two measurements, the manual measurement would be recorded as 95 psi, the recommended fleet tire pressure. The team suspects that the technicians would record the in-cab display prior to adjusting the tire pressures. If an adjustment was required, the technicians adjusted the tire pressures and then recorded the new tire pressure setting. As a result, the manual tire pressure did not equate to the original system tire pressure. The team conducted an analysis of the remaining data and determined that the system tire pressures were routinely within 2 psi of the manual tire pressure. The team did not conduct an extensive analysis of these data, as the final number of data points yielded a sample size that was not statistically significant.

Hypothesis #5—TPMS and ATIS technologies will not introduce unscheduled maintenance that will affect day-to-day fleet operations.

The team conducted several informal interviews and asked the maintenance technicians to complete a written assessment after the test was completed. The technicians provided feedback on the maintainability of the equipment and the effect on daily maintenance tasks. In addition, the team monitored unscheduled maintenance tasks related to system failures and equipment maintenance.

Conclusion: The TPMS and ATIS equipment did not introduce unscheduled maintenance that affected day-to-day fleet operations. The team sought to ensure that equipment failures and periodic maintenance requirements did not hinder the fleet's operations. Although the field test identified various system reliability issues, these issues did not require the test fleet to be removed from the operating fleet. For example, the failure of the wheel sensors rendered portions of the IVTM system inoperable, but did not require the tractor to be removed from service.

5.2 COST-BENEFIT ANALYSIS

The findings from this report may encourage the use of TPMS or ATIS technologies due to their potential to reduce CMV operating costs. The authors conducted a cost-benefit analysis of TPMS and ATIS use to determine the length of time required to recover the costs of purchasing TPMS and/or ATIS for a tractor-trailer unit. The authors conducted the ROI analysis for both GFS (a low-mileage, standard-tire fleet) and CLI (a high-mileage, wide-base tire fleet). Table 28 presents the assumptions for conducting the ROI analysis. The fuel costs represent the fuel prices identified in mid-2011, and potential high and low fuel prices in the future. The authors researched tire prices for Michelin standard and wide-base tires. The prices for Michelin tires were used, as both fleets currently use these tires. Finally, the allowable tire wear is based on the tire wear permitted for CLI's drive axles. Because these axles were the only axles to show significant improvement in tire wear, they were the focus of this analysis.

Table 28. Assumptions for ROI calculations.

Characteristic	GFS	CLI
Average Mileage (Daily)	225	450
Average Mileage (Monthly)	6,840	13,680
Average Mileage (Yearly)	81,450	162,900
Estimated Diesel Fuel Cost (Current)	$3.976	$3.976
Estimated Diesel Fuel Cost (High)	$5.000	$5.000
Estimated Diesel Fuel Cost (Low)	$3.000	$3.000
Allowable 32nds of Tire Wear	11	11
Standard Tire Cost	$329.00	$329.00
Wide-base Tire Cost	–	$795.00

Table 29 identifies the commercial cost of each TPMS and ATIS used in the field test. The prices incorporate any discounts offered due to bulk purchases. For the ROI analysis, the team estimated the cost of a complete system to include a TPMS on the tractor and an ATIS on the trailer, for a total system cost of $1,535.

Table 29. Cost of TPMS equipment.

System	Cost
PSI—Tanker/Trailer	$750
IVTM—Tractor	$785
Tire-SafeGuard—Tractor	$709
Tire-SafeGuard—Trailer	$503
Estimated Cost for Tractor-trailer	**$1,535**

The analysis showed that the test fleets experienced a 1.4-percent improvement in fuel economy. Using the average mi/gal calculated previously, the authors identified a 1.4-percent savings in monthly and annual fuel costs (as shown in Table 30, Table 31, and Table 32).

For CLI, a single equipped tractor would save $130 per month or $1,544 per year with the diesel fuel price set at $3.976 per gallon. The savings would drop to $98 per month and $1,165 per year with diesel fuel priced at $3.00 per gallon. With a lower annual mileage accumulation, the equipped GFS tractors experienced lower annual fuel savings. They would save $680 per year with diesel fuel priced at $3.976 per gallon and $513 per year with diesel fuel priced at $3.00 per gallon.

Table 30. ROI calculation for fuel savings (fuel at $3.976 per gallon).

Characteristic	GFS Test	GFS Control	CLI Test	CLI Control
Average Annual mi/gal	6.59	6.50	6.19	6.10
Monthly Fuel Usage	1,037.94	1,052.31	2,210.02	2,242.62
Monthly Fuel Costs	$4,126.83	$4,183.98	$8,787.02	$8,916.67
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$57.14**	–	**$129.64**	–
Annual Fuel Usage	12,359.64	12,530.77	26,316.64	26,704.92
Annual Fuel Costs	$49,141.91	$49,822.34	$104,634.96	$106,178.75
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$680.43**	–	**$1,543.79**	–

Table 31. ROI calculation for fuel savings (fuel at $3.000 per gallon).

Characteristic	GFS Test	GFS Control	CLI Test	CLI Control
Average Annual mi/gal	6.59	6.50	6.19	6.10
Monthly Fuel Usage	1,037.94	1,052.31	2,210.02	2,242.62
Monthly Fuel Costs	$3,113.81	$3,156.92	$6,630.05	$6,727.87
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$43.11**	–	**$97.82**	–
Annual Fuel Usage	12,359.64	12,530.77	26,316.64	26,704.92
Annual Fuel Costs	$37,078.91	$37.592.31	$78,949.92	$80,114.75
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$513.40**	–	**$1,164.83**	–

Table 32. ROI calculation for fuel savings (fuel at $5.000 per gallon).

Characteristic	GFS Test	GFS Control	CLI Test	CLI Control
Average Annual mi/gal	6.59	6.50	6.19	6.10
Monthly Fuel Usage	1,037.94	1,052.31	2,210.02	2,242.62
Monthly Fuel Costs	$5,189.68	$5,261.54	$11,050.08	$11,213.11
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$71.86**	–	**$163.03**	–
Annual Fuel Usage	12,359.64	12,530.77	26,316.64	26,704.92
Annual Fuel Costs	$61,798.18	$62,653.85	$131,583.20	$133,524.59
Percent Improvement	**1.4%**	–	**1.5%**	–
Calculated Savings Over Control	**$855.67**	–	**$1,941.39**	–

Although wheel-wear savings are based on the findings from the drive tires of the CLI tractors, the analysis calculates the savings based on the number of drive tires in each fleet (i.e., four drives at CLI and eight drives at GFS). Table 33 shows the annual savings in tire purchases. The authors conducted the ROI analysis based on a replacement of tires after 11/32nds of an inch of wear, which was the replacement parameter for the drive tires at CLI. In addition, the ROI analysis estimates the overall savings based on the pricing of standard tires for GFS and wide-base single tires for CLI. During the field test, the TPMS-equipped vehicles experienced a 20-percent reduction in tire wear as compared to the control fleet. The equipped CLI tractor-tankers saved $117 per month in tire purchases and $1,389 annually. The equipped GFS tractor-trailers saved $48 per month in tire purchases and $575 annually.

Table 33. ROI calculations for tire replacements due to wear.

Characteristic	GFS Test	GFS Control	CLI Test	CLI Control
Average Drive Axle Tire Wear (32nds of Wear Per Million Miles)	125	154.5	125	154.5
Monthly 32nds of Wear/Tire	0.86	1.06	1.71	2.11
Monthly 32nds of Wear/Tractor	6.84	8.45	6.84	8.45
Monthly Tires Replaced/Tractor	0.62	0.77	0.62	0.77
Monthly Tire Cost/Tractor	$204.58	$252.86	$494.35	$611.01
Percent Improvement	**19%**	–	**19%**	–
Calculated Savings Over Control	**$48.28**	–	**$116.67**	–
Annual 32nds of Wear/Tire	10.18	12.58	20.36	25.17
Annual 32nds of Wear/Tractor	81.45	100.67	81.45	100.67
Annual Tires Replaced/Tractor	7.40	9.15	7.40	9.15
Annual Tire Cost/Tractor	$2,436.10	$3,011.01	$5,886.61	$7,275.85
Percent Improvement	**19%**	–	**19%**	–
Calculated Savings Over Control	**$574.92**	–	**$1,389.24**	–

The analysis showed that the equipped tractor-trailers eliminated an average of 1.1 road calls per million miles traveled. The authors estimated the cost of a single road call and analyzed the overall savings per equipped tractor-trailer, as shown in Table 34. The complete cost incurred by a fleet for a single road call includes the labor billed by the roadside service provider, the labor lost to the driver, and the cost of a replacement tire. As stated earlier, the authors estimated the cost of a standard tire for GFS and a wide-base single tire for CLI. The study estimated the cost of a single road call at $797 for GFS and $1,265 for CLI. Using these estimates, GFS-equipped tractor-trailers saved $72 annually. CLI-equipped tractor-tankers saved $227 annually.

Table 34. ROI calculations for road calls eliminated.

Characteristic	GFS Test	GFS Control	CLI Test	CLI Control
Average Road Call Differential (Per Million Miles)	Baseline	1.1	Baseline	1.1
Road Call Costs: On-call Labor	$265.00	$266.00	$267.00	$268.00
Road Call Costs: Driver Pay Lost	$203.13	$203.13	$203.13	$203.13
Cost of Driver Pay Lost: Driver Pay/Mile	$1.25	$1.25	$1.25	$1.25
Cost of Driver Pay Lost: Average Time Delayed	2.5	2.5	2.5	2.5
Cost of Driver Pay Lost: Average Speed (mi/h)	65	65	65	65
Cost of Driver Pay Lost: Average Miles Lost	162.5	162.5	162.5	162.5
Total Cost of Road Call (Including Tire)	**$797.13**	**$797.13**	**$1,265.13**	**$1,266.13**
Monthly Savings: Monthly Road Calls	0	0.01	0	0.02
Monthly Savings: Monthly Cost of Road Calls/Tractor	$0	$6.01	$0	$19.05
Calculated Savings Over Control	**$6.01**	**–**	**$19.05**	**–**
Annual Savings: Annual Road Calls Savings	0	0.09	0	0.18
Annual Savings: Annual Cost of Road Calls/Tractor Savings	$0	$71.51	$0	$226.88
Calculated Annual Savings Over Control	**$71.51**	**–**	**$226.88**	**–**

In summary, the reduction in fuel costs and tire purchases offered the largest savings for equipped tractor-trailers. The ROI analysis calculated the overall annual savings to be between $3,557.51 (CLI with $5.00 diesel fuel prices) and $1,159.82 (GFS with $3.00 diesel fuel prices). Figure 46 shows the complete results.

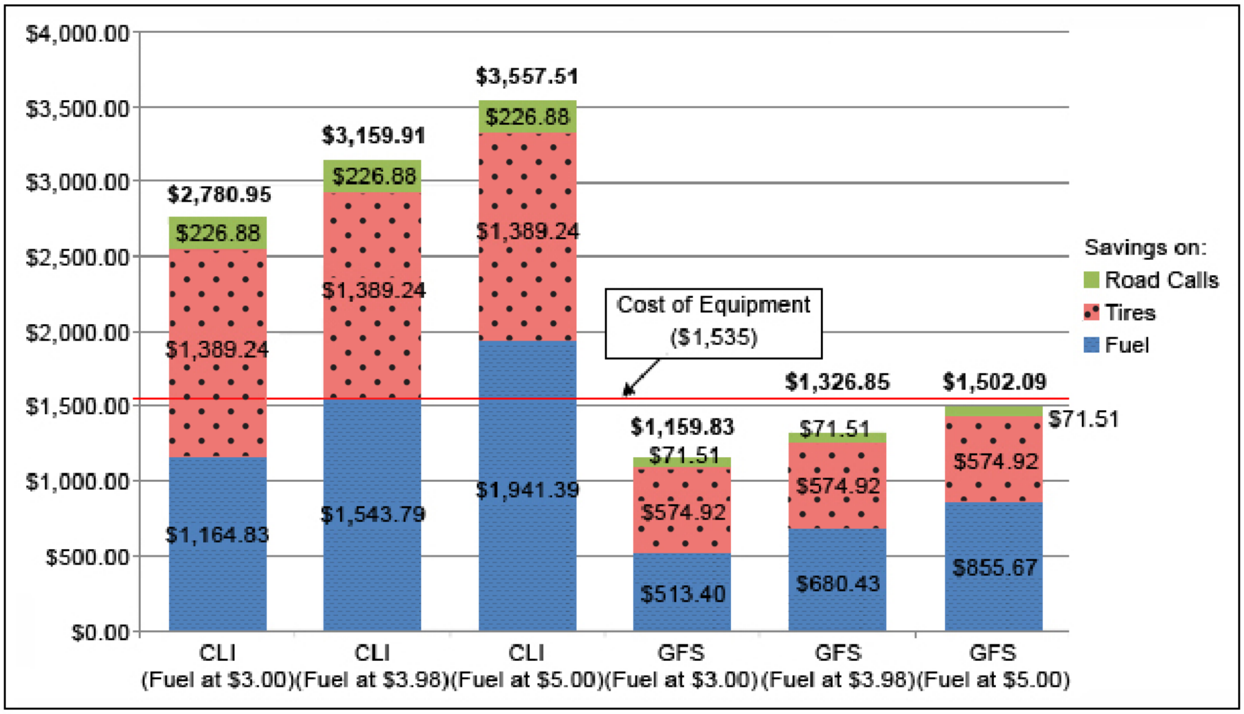


Figure 46. Chart. Annual savings per TPMS/ATIS-equipped tractor-trailer.

CLI could recover the initial cost of the installed equipment in less than 6 months of operation at current fuel costs, as shown in Figure 47. CLI would experience a quick ROI due to the high cost of the wide-base single tires and high daily mileage. In comparison, GFS has a lower daily mileage and uses standard-width tires, which would require less than 14 months to recover the cost of the installed equipment. These findings are based on a single tractor-trailer. The fleet savings would increase with the installation of the TPMS and/or ATIS equipment on additional vehicles.

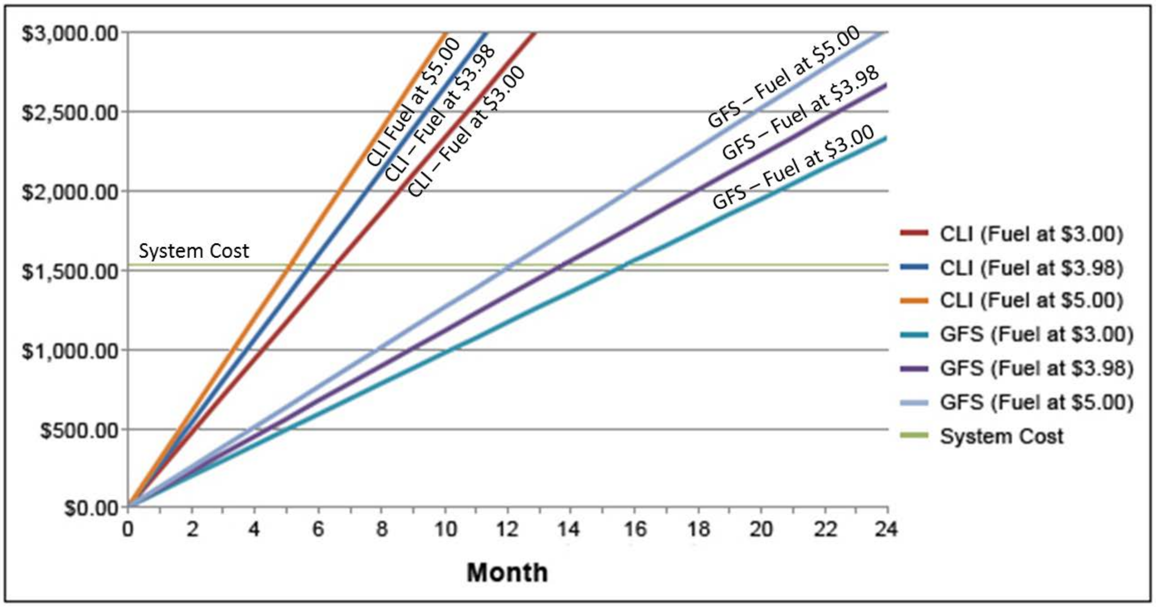


Figure 47. Graph. Accumulated monthly savings per TPMS/ATIS-equipped tractor-trailer.

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