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Assessment of Tire Technologies and Practices for Potential Waste and Energy Use Reductions

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Table of Contents

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Executive Summary

Tire purchasing and disposal impose considerable cost and waste burdens on private vehicle owners and fleet managers. This research investigates tire maintenance management practices and tire-related vehicle technologies that have the potential to relieve some of these burdens. We investigate behavior, attitudes, and practices of fleet personnel and individual drivers as they relate to tire attributes and technologies. Based on this research, we analyze and recommend critical practices that could improve tire purchasing, tire management, average tire life within existing vehicles in vehicle fleets. We evaluate the tire wear and energy use of various tire technologies and improved fleet tire management and find several fleet practices that offer substantial potential improvements in tire-related energy and waste consequences. Advancements in three particular areas – tire pressure monitoring, nitrogen as a tire inflation medium, and the selection of tires with lower rolling resistance – are commercially available and promising in terms of their potential benefits. Additionally, to demonstrate and empirically test the potential impact of nitrogen as an inflation medium for tires, we deploy several technologies on fleet vehicles, including data acquisition systems for retrieval of information from fleet vehicles and nitrogen inflation equipment at the California Department of General Services vehicle fleet facility. We develop the accompanying experimental design for testing the impact of nitrogen inflation on these fleet vehicles. This experiment is created in such a way that the fleet personnel can undertake the experimental testing and statistically evaluate the impact of nitrogen inflation on their vehicle fleet. From our findings, we develop best practices recommendations, which are meant to serve as a guide for improving tire practices in vehicle fleets.

Chapter 1. Introduction

Background

Although tire technologies have advanced considerably in the last several decades in terms of durability, safety, and fuel economy, the use of tires still results in considerable cost, environmental, and waste management consequences. The manufacturing of tires results in the use of energy and natural resources. The rolling resistance of tires is an important component of vehicle efficiency, thus impacting the fuel consumption and emissions of vehicles. Due to the durability of tires, the disposal of tires poses a substantial waste management issue.

The federal government has several programs designed to minimize the adverse impacts of tire use. Tires are a key consideration in the safety and fuel economy regulation of vehicles, as set by the U.S. Department of Transportation's National Highway Traffic and Safety Administration (NHTSA). For example, automakers tend to place relatively low rolling resistance tires on new passenger cars and light trucks to aid compliance with Corporate Average Fuel Economy (CAFE) regulations. A recent NHTSA regulation mandates devices on vehicles to aid in the monitoring of tire pressure to ensure driver awareness of tire under-inflation; the measure is aimed at improving vehicle safety but is also expected to yield fuel economy benefits (NHTSA, 2005). Also, by request of Congress, a National Academy of Sciences National Research Council (NRC) study recently assessed potential improvements in replacement tires, considering factors of rolling resistance, tread wear, and traction, and investigated potential testing procedures and consumer information campaigns for tires (NRC, 2006).

The State of California is actively engaged in reducing the negative consequences of tires used on public and private vehicles through numerous state agency programs. A 2003 California law tasks the California Energy Commission with developing a tire efficiency program to promote fuel-efficient tire purchasing and improved tire maintenance practices (CEC, 2006). The CEC and the California Air Resources Board (CARB) assessed lower rolling resistance tires to be a cost-effective method of reducing petroleum usage (CEC and CARB, 2003). CARB regulates pollutants involved in tire manufacturing and disposal practices. Additionally, CARB has identified low rolling resistance tires as one method to reduce greenhouse gases in its proposed new regulation of vehicle greenhouse gas emissions (CARB, 2004). Beyond the "in use" issues addressed by CEC and CARB, numerous programs and projects undertaken by the California Integrated Waste Management Board (CIWMB) are aimed at reducing the waste, landfilling, and related consequences at the end of tires' useful life (CIWMB, 2005).

Various tire management practices and tire technologies have the potential to defray the costs, environmental burdens, and waste issues that result from tire use. More durable tires last longer; purchasing such tires means less frequent tire purchases and fewer tires disposed. Improved tire inspection and maintenance practices (e.g., tire rotation, tire inflation) improve tire longevity, tire safety, and vehicle fuel economy. Tire technologies, such as tire pressure monitoring systems (TPMSs) increase driver awareness of tire maintenance needs. More efficient, lower rolling resistance tires reduce vehicle fuel use and emissions. Increasingly tire waste is being diverted from landfills to other uses, including tire-based aggregate for road building, use as fuel for electricity or cement production, and other end-of-life management practices.

This research focuses on ways to improve vehicle tire procurement and maintenance to increase tire longevity and decrease tire-related energy use. Researchers collected original data for this project by coordinating with fleet personnel and customers (i.e. drivers) and tracking vehicles of a large government fleet. The large quantity of tires purchased, managed, and discarded by government fleets represents a substantial expenditure. Government fleets also offer an opportunity to test and implement improved tire practices and new technologies. Although this research specifically investigates vehicle fleets, it addresses maintenance practices and technologies that are applicable to both fleets and private vehicles.

Research Overview and Objectives

The project is primarily concerned with the practices that tire purchasers, vehicle maintenance personnel, and vehicle users can undertake to reduce tire waste and lessen the environmental consequences of tire use. Table 1 provides an overview of the key aspects of this investigation of tire-related technologies and practices. The first part, "Literature Review," discusses the relevant background on tire-related practices and technologies for this assessment in Chapter 2. The two following sections – assessments of fleet personnel and individual driver practices – are presented in Chapter 3, "Data Collection." Chapter 4 details installation and demonstration of tire technology on fleet vehicles. The synthesis and analysis of these parts comprises the final sections: Tire practice analysis (Chapter 5), Life cycle assessment (Chapter 6), and the development of a "Best Practices" guide for vehicle fleets (Chapter 7).

TABLE 1. Research Overview

Research Parts	Task Description, Key Aspects
Introduction (Chapter 1)	• Introduce key elements of research project • Describe motivation for research on tire waste, tire longevity, and tire-related energy use
Literature review (Chapter 2)	• Review available knowledge on tire practices (inspection, maintenance, etc.) and guidelines for proper tire usage and practices • Assess current knowledge on various tire technologies, including "smart tire" devices, such as self-inflating tires and low-pressure alert systems, nitrogen inflation, and low rolling resistance tires
Data Collection (Chapter 3)	Fleet personnel practices • Explore general fleet personnel practices with respect to tire purchase, use, behavior, and maintenance • Assess fleet personnel perceptions and willingness to implement different tire inflation practices or purchase novel tire technologies Private vehicle user practices • Explore general vehicle user practices with respect to tire purchase, use, behavior, and maintenance • Assess vehicle user perceptions and willingness to implement different tire inflation practices or purchase novel tire technologies
Technology Demonstration (Chapter 4)	• Install and demonstrate novel tire technologies to conventional tires • Examine how actions designed to increase tire longevity may impact vehicle fuel use, emissions, and safety
Analysis of Tire Practices (Chapter 5)	• Analyze tire service life impact of various modifications in tire maintenance and management
Life Cycle Assessment (Chapter 6)	• Analyze the life-cycle energy associated with various tire-related processes and practices
"Best Practices" Guide (Chapter 7)	• Recommend practices and technologies for vehicle fleets • Develop guide for vehicle fleets

A large number of potential technological innovations and best practices can be identified across the life cycle of a tire (i.e., material extraction, manufacturing, transport, use and disposal). The present study focuses on the use phase of a tire. A detailed assessment of tire design options, manufacturing methods, material recycling and other end-of-life practices is outside the scope of this study. However, a life cycle framework is used to place into context the potential improvements offered by the innovative tire technologies and practices addressed in this study. These innovations and practices include the following: tire pressure monitoring systems, nitrogen inflation systems, low rolling resistance tires, improved vehicle user tire maintenance, and improved fleet tire management practices.

, The results of this research focus generally on tire maintenance and monitoring technologies and tire practices; however, there is one primary limitation. The original data collection for this study is based primarily on the tire-related practices and technologies deployed by a single government fleet. As such, the research, analysis, and conclusions of this study are in some cases more pertinent to fleet tire practices (purchasing, maintenance, management, and disposal) than to private vehicle user practices. However, the use of fleets as units of analysis is nonetheless justified for several key advantages, including economies of scale for technology implementation, centralized hub of many vehicles, access to many vehicle users for surveying, and consistency in vehicle inspection and maintenance practices on vehicles being analyzed.

The objectives of the demonstration portion of this study are to bridge existing gaps in the research knowledge on tire practices to demonstrate and evaluate the current state of nitrogen tire inflation technology. With the current dearth of general information on fleet tire management practices, this work is geared toward collecting such information and targeting areas for improvement. Our findings on operating and maintenance practices are most likely to affect fleets. As such, one of the key results of this work is the creation of a "Best Practices" manual that offers guidance on proper tire purchasing, inspection, and maintenance practices. Assessing nitrogen technology with real-world, on-road data is likely to have implications first and foremost for vehicle fleet operators who purchase, use, and maintain a large number of tires, and are therefore significantly affected by tire-related costs and waste. Beyond aiding in fleet operations, the formulation of guidelines regarding proper tire practices is also expected to offer direction for government information programs for private vehicle users to support public waste, fuel use, and emission reduction objectives.

Chapter 2. Literature Review

Tire attributes are subject to myriad government regulations and customer demands. NHTSA regulations mandate tire tread testing and specification labeling on tire sidewalls. Fuel economy regulations ensure low rolling resistance on new vehicle tires. The 2000 federal Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act and the subsequent NHTSA rulemaking updated and instituted new tests for tires and mandated tire pressure monitoring systems on new light-duty vehicles. Beyond government requirements, consumer-demanded attributes for tires include cost, ride comfort, noise, fuel efficiency, longevity, traction, air retention, and speed rating – and some of these characteristics have complex and competing trade-offs associated with each other (Lamb and Pyanowski, 2002).

This chapter summarizes available information on tire maintenance practices technologies and discusses the relevant trends in tire characteristics. Technologies investigated and summarized include tire pressure monitoring devices, low rolling resistance tires, and nitrogen inflation. It is important to emphasize that tire characteristics like tread wear, rolling resistance, and traction are by no means mutually exclusive; as a result, the trade-offs of characteristics and their mutual dependencies are discussed in the final section of this chapter.

Background on Tire Service Life

This section introduces the key aspects of tire life from tire purchase to replacement. Data are presented on tire life and tire replacement to provide context for the upcoming sections that assess new tire technologies that could impact these factors. In addition, this section introduces the key aspects and variables for this report's life cycle analysis of alternative tire technologies.

There are two primary markets, original equipment (OE) manufacturer and replacement equipment tires. OE tires are purchased in high-volume, long-term contracts for new passenger vehicle models. Replacement tires are purchased by individual consumers and fleet owners as needed. In both markets, many tire manufacturers offer many models with differing attributes (performance, wear, cost, etc.). OE tire sales represent about one-quarter of the passenger tire market. This market demands more lower rolling resistance tires to enable new vehicles to comply with fuel economy and emissions certification requirements. The replacement tire market, which comprises about three-quarters of passenger tire sales, generally demands tires with longer life more so than lower rolling resistance (Ecos, 2002). In both markets, the trade-offs in tire attributes are complex and subject to competition between tire suppliers to innovate with new tire composition and design to balance consumer demands for tire safety, durability, handling, comfort, and fuel economy.

Tire life has showed marked improvements over the past two decades due primarily to technology shifts. As shown in Figure 1, average tire life has improved from less than 30,000 miles per tire in 1981 to more than 40,000 miles today (RMA, 2002). The dominant tire technology factors attributable to the increase in tire life are composition and design shifts over the last two decades. The principal early factor increasing tire life was the shift from bias-ply to radial-ply tires. Since then, tire longevity has increased largely due to innovations in tire composition, such as improvements via the time- and equipment-intensive method of mixing silica and silicone butadiene rubber compounds to give the best material properties of each (Joshi et al, 2003).

While there has been substantial research in tire chemistry, the choice of monomers for elastomer synthesis has been economically limited to butadiene, styrene, and isoprene. As a result, the emphasis has been on improving the chemistry of the butadiene by adding neodymium (Nd) or bromine (Br) to improve the polymerization of the tire compounds. Additional work has been done in improving the process and removing the costly mixing steps (Quirk, 2003).

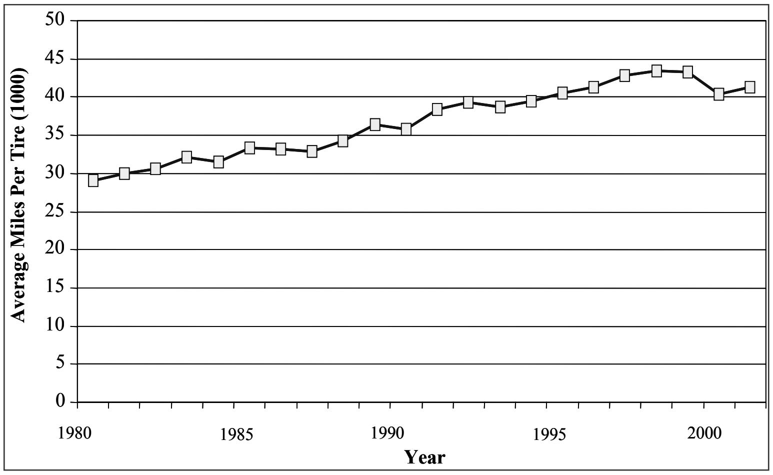


FIGURE 1. Average Tire Life, 1980-2001 (from RMA, 2002)

Although tire longevity has improved over the past decades, data on tires, average tire mileage, and tire disposal are not well characterized in comprehensive, publicly available data. Different subsets of tires in the vehicle fleet (e.g., OE versus replacement, different vehicle types, different driving styles) could have average lifetime mileage values that are different from the reported (i.e., from RMA, 2002 data) average in ways that are not well characterized by existing public data. For example, a CEC (2003) report found that OE low rolling resistance (LRR) tires average only 77% of the lifetime mileage of replacement tires. Additionally, the wide variety of proprietary tire designs and compounds makes these figures difficult to apply to any particular model of tire. Other prominent factors beyond tire technology that influence average tire life include consumer choice in tire purchasing and vehicle user tire maintenance practices, although the extent to which these factors have changed over the past two decades is not well known.

A key part in understanding tire life – and differentiating between the tire practices and tire technologies that impact tire life – is determining why tires are ultimately replaced and discarded on vehicles. A survey of available tires on the market reveals limited tire warranties that range from 30,000 to 80,000 miles. Many of the most popular tire brands have warranties 50,000 to 60,000 miles. This warranty is generally contingent upon the customer documenting that they have properly maintained the tires, including periodic rotation of the tires.

As indicated by Figure 1 above, actual average tire mileage is substantially below the ideal tire life warranty mileage. The primary reason for this is that the majority of tires are not replaced due to “normal wear.” New tires generally start with approximately 9/32 inches of tread (actual tread depths generally range from 8/32 to 12/32 inches), and, for safety reasons, end when at the minimum tire tread depth of 2/32 inch. (In many states this is a legal minimum.) Due to varying driving conditions and the differing inflation and maintenance practices of vehicle users, most tires do not last until a “normal wear” replacement. Michelin data on tire replacement indicate that 10% to 30% of tires could be retired from the vehicle fleet due to sustained long-term wear, while 40% to 60% tires are replaced for “abnormal wear” reasons, 5% to 10% are replaced with “nothing observed,” and the remaining 20% are replaced for other reasons (including road hazard puncture, oxidation, and separation) (Weissman et al, 2003). Factors related to, and potential improvements to, tire maintenance practices are examined in the following section.

Tire Maintenance Practices

Key to assessing potential improvements in tire maintenance practices is quantifying current inspection, inflation, and maintenance practices by vehicle owners and operators. Although data on the subject is sparse, there currently does appear to be room to significantly improve vehicle users’ tire maintenance practices. This section summarizes what is known about current tire-related vehicle practices, with emphasis on potential areas of improvement for tire longevity.

Vehicle users’ knowledge and practice of proper tire pressure monitoring and maintenance is thought to be generally poor. Proper tire inflation is prescribed by the vehicle manufacturer and is displayed on the vehicle “placard,” or sticker in the vehicle driver-side doorframe. This placard pressure varies by vehicle, but generally values range from 25 to 40 pounds per square inch (psi). NHTSA (2005) found that placard values average 30 psi for passenger cars and 35 psi for light trucks. These placard pressure values are the pressures that tires should be set at, as measured “cold,” or after the vehicle has been at rest for some time.

However, several studies have indicated that tires are consistently at pressures quite different from the recommended placard pressure. One study suggests that vehicle users could use the maximum tire pressure cited on the tire sidewall, which is generally about 40 psi, to set their tire pressure, instead of the lower and correct placard value (CSUS, 2003). More likely, however, is persistent under-inflation of vehicle tires. A survey by NHTSA (Thiriez and Bondy, 2001) found that approximately 25% to 30% of light-duty vehicles have at least one tire that was under-inflated by at least 25% below placard. This study found the average under-inflation for passenger cars to be 6.8 psi (or 23% of 30 psi) and for light trucks to be 8.7 psi (25% of 35 psi).

Moreover, these percentages have the potential to understate the magnitude of the under-inflation problem. Because the pressure testing of many of the vehicles is likely to have been when vehicles had just been driving, the reading will be tainted by the tires not being “cold.” Even if a vehicle operator attempts to set the inflation of the tires to the placard pressure, they could ultimately be several psi too high. For example, based on Tooke (2003), if the internal tire temperature is 20°F above the “cold” placard temperature of 65°F, the tire pressure would be set 2 to 3 psi too low. Additional potential inflation-setting errors could result from the ambient air temperature not being 65°F. Further inaccuracy is introduced by instrumentation errors. Gas station tire pressure gauges are prone to over-reporting, with about one-third of station gauges reporting at 4 psi or more greater than reference pressure (NHTSA, 2001), and handheld “pen-type” are prone to inaccuracy.

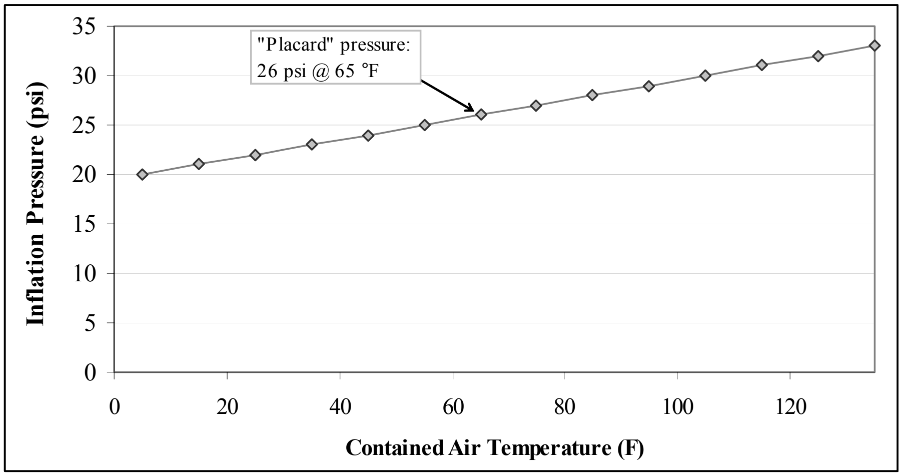


FIGURE 2. Deviation from Set Pressure with Temperature (from Tooke, 2003)

Two other tire maintenance practices of importance are tire rotation and wheel alignment. Although there are not extensive data regarding vehicle operators' general practices, the substantial percentages of tires replaced due to "abnormal" or uneven wear attest to a general deficiency in following regimented rotation schedules and alignment checks. Rotation is necessary due to the uneven wear characteristics of each wheel position on the vehicle. For example, front-wheel drive vehicles which place braking, steering, and driving forces on the front axle tires, result in a much faster wear rate for the front axle tires. While large tire misalignments are likely to be noticed by drivers and corrected, smaller misalignments can go undetected and cause significant accelerated and uneven wear.

Tire practices have a significant and quantifiable impact on tread life and, ultimately, tire replacement. One degree of misalignment is estimated to double the rate of tire wear (Trimbach and Engehausen, 2003). Trimbach and Engehausen (2003) also reveal a considerable increase in the tire tread wear rate as inflation decreases below the placard pressure, as shown in Figure 3. In turn this tire wear increase results in a reduction in tire life. Tire manufacturer Goodyear reported a linear relationship, where, for every one psi below vehicle placard pressure a loss of 1.78% reduction of tire tread life would result (NHTSA, 2002). Estimating from this relationship and average under-inflation levels (6.8 psi for cars and 8.7 psi for light trucks), average tire life for U.S. tires is reduced approximately 12% to 15%. This under-inflation-related reduction in tire service life is examined more thoroughly in Chapter 5.

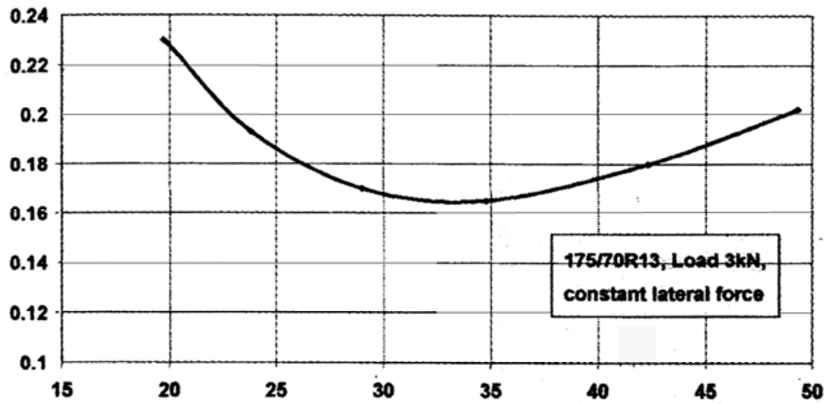


FIGURE 3. Influence of Inflation Pressure on Rate of Wear (from Trimbach and Engehausen, 2003)

Table 2 shows the reasons tires are replaced and the estimated percentages represented by those replacements (from Weissman et al, 2003). The most common replacement reason – for about half of tires – is "abnormal wear," which includes tire unevenness due to improper tire inflation, rotation, and alignment practices, but could also include a braking incident causing tire flat spots. For example, under-inflated tires will wear more on the outsides of each tire rather than in the middle, and over-inflated tires will wear more quickly in the middle. More infrequently, about 10% to 20% of tires are replacements for tires that have no visible defect or failure. Most likely these tires are retired because one or more tire in its set is discarded for abnormal wear or other reasons, and the tires are discarded as a set to maintain vehicle balance (regardless of the remaining tread on remaining "good" tires). As many as 10% of tires are replaced due to road hazards, punctures, and traffic accidents. Poor driving conditions and aggressive driving behavior contribute to this category of discarded tires; to some extent the susceptibility to any puncture incident increases with improper tire inflation levels. Oxidation and separation, accounting for 10% of tires discarded, are the result of chemical degradation processes involved with the aging and overheating of tires.

TABLE 2. Tire Replacement Reasons

Tire Replacement Reason	Estimated Percentage of Tires[a]	Description / Comments	Practices for Improved Tire Service Life
Normal wear	10-30%	Tire tread depth wears down over normal driving conditions from original depth of approximately 9/32 inch to the minimum depth of 2/32 inch	Proper inspection and inflation
Nothing observed	5-10%	Tire with tread remaining that is removed in a set of tires because one (or more) tires are worn, punctured or otherwise need replacing	Proper inspection and inflation
Abnormal wear	40-60%	Unevenness in individual tire's wear due to wear asymmetry, relative flat spot (e.g. from braking incident)….	Proper inspection and inflation; rotating tires; balancing tires; aligning wheels; non-aggressive driving
Road hazard	10%	Tire leak or puncture due to driving conditions or traffic accidents	Proper inspection and inflation; non-aggressive driving
Oxidation and separation	10%	Tire materials degrade through chemical oxidation, aging, and overheating	Proper inspection and inflation; reduced moisture and oxygen in tires

[a] *based on Weissmann et al, 2003, based on Michelin data from 1992 to 1999*

This section is used as a starting point in understanding the background and key factors affecting maintenance practices. We assess the extent to which improvements in tire practices could result in increased tire service life in Chapter 5 and reduced tire life cycle energy use in Chapter 6.

Tire Pressure Monitoring Technologies

In 2000, Congress passed the Transportation Recall Enhancement, Accountability, and Documentation Act (TREAD) in response to tire safety problems on light trucks. As part of the implementation of that act, NHTSA issued a ruling in December 2001 that after November 2003, all light-duty vehicles must have a Tire Pressure Monitoring Systems (TPMS) with a dashboard indicator light to warn drivers if their tire pressure was low. Multiple legal actions by industry and consumers challenging the ruling and how it would be implemented delayed its implementation until the 2008 model year.

The two TPMS types are direct and indirect. Direct TPMS uses a sensor within the wheel to directly measure pressure and other parameters and relay them to a receiver. Indirect TPMS uses wheel speed sensors and infers inflation levels from the difference in their rotational speed. Indirect TPMS requires a large degree of integration with a particular vehicle and its braking system. Because of this degree of integration, it is an approach that is generally used by OEMs rather than being an aftermarket solution.

Most of the 2008 models will detect the presence of low pressure tires by an indirect method integrated with the anti-lock braking system (ABS) of the vehicle. Low pressure of a tire will be inferred from significant differences in the rotation speeds of one or more tires resulting from decreases in the effective radius of under-inflated tires. This indirect approach meets the requirements of the NHTSA rule requiring the ability to detect a pressure that is 25% (approximately 8 psi) or greater below the proper inflation pressure of the tire, but it does not give a direct, quantitative measurement of inflation pressure. This approach relies on training the TPMS to tire conditions that are assumed to be uniform. Unfortunately, the accuracy of this sort of a system can be compromised by road conditions or uneven wear and has a poor ability to detect discrepancies in tires on different axles. In general, ABS-based systems have trouble detecting more than one tire with pressure loss, under inflation warning thresholds vary by axle and the detectable pressure threshold varies between 10% to 40% of the cold inflation pressure level. In the present study, only direct measurement of tire pressure is considered as this approach can detect much smaller degrees of under-inflation with a much higher degree of reliability

Direct TPMS come in a variety of configurations and features. The main differences are the circuitry and the type of measurements that are taken. All of the direct TPMSs measure pressure via a sensor that is mounted within the rim of each tire. The sensors then relay their measurements wirelessly to a receiver in the passenger compartment. Some of these receivers evaluated were standalone units, and some were incorporated to the vehicle's computer system.

The circuitry for measurement comes in two forms: Printed Circuit Board (PCB) and Application Specific Integrated Circuit (ASIC). The PCB form uses a sensor on a printed circuit board in conjunction with a microprocessor and other components to form its circuitry. The ASIC form incorporates the sensor and other electronics into one sealed package. The ASIC form is much more rugged than the PCB, protecting circuitry and connections from the harsh conditions found in the tire.

All of the TPMSs that were evaluated for this study measured pressure and temperature, and some measured wheel speed as well. Both Yokohama and Nokian have TPMSs that are in prototype phase and have speed sensing capability (Hattori, 2004; Hakanen, 2003). The TPMSs with speed sensing capability are being developed for integration with a vehicle's anti-lock braking system, rather than as an aftermarket system. Only TPMS without speed sensing were available for the purposes of this study.

An additional form of direct TPMS that is under development is Passive Transponder TPMS. This system utilizes transponders that are built into or attached to a tire's interior. To date, there have been no systems for passenger tires that have been able to endure the manufacturing process and provide reliable performance. An advantage to this sort of a system would be savings on installation costs. A possible disadvantage to this sort of system is the need to replace a tire if the sensor malfunctions.

The need to monitor tire pressure can be eliminated by utilizing a self-inflating tire system. While there are systems available for high pressure tires and large trucks, only one was found for passenger vehicles. The "Auto-Pump" system manufactured by Cycloid has been used on some of the Jeep Grand Cherokee vehicles. This system utilizes a centrifugal pump mounted in the rim of each wheel to maintain tire pressure. Attempts to find information on this system yielded nothing more recent than 2002. It is unknown if this company is still in existence. This technology is not being considered for the demonstration portion of this study.

Lower Rolling Resistance Tires

When tires interact with road pavement the results are traction, which moves the vehicle, and rolling resistance, which is an energy loss consequence. Tire rolling resistance energy loss accounts for a substantial road load force that a vehicle must overcome to move at a given speed and acceleration. As a result, tire manufacturers have consistently sought to minimize tire rolling resistance, subject to the other demanded tire attributes. Over the past several decades, tire manufacturers have made innovations in tire design and composition to steadily improve the average rolling resistance of light-duty vehicle tires without compromising other tire qualities such as traction, safety, and drivability. This section briefly discusses trends in lower rolling resistance in tires and the prospects for further improvements.

Driven primarily by vehicle manufacturers' concerns for achieving federal fuel economy and emissions standard targets, tires' rolling resistance has improved significantly. . Original equipment (OE) tires on new vehicles experienced an average rolling resistance coefficient decrease of approximately 50% in the last 20 years (Cook, 2003). Figure 7, based on data from LaClair (2002) and CEC (2003), approximates this improvement in new tire rolling resistance coefficient over time. These data were consistent with new data on late model tires from NRC (2006), which also found that the rolling resistance coefficients of individual tire brands and models varies quite significantly, generally from 0.0065 to 0.013.

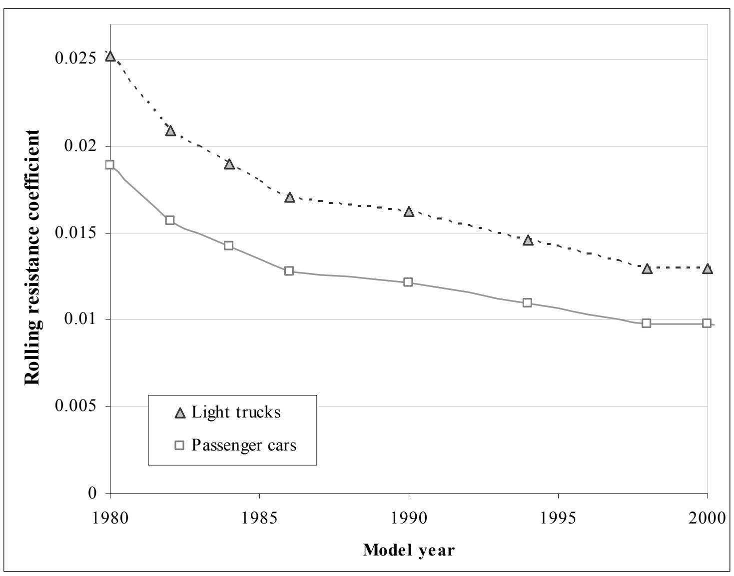


FIGURE 4. Tire Rolling Resistance, 1980-2000 (Based on LaClair, 2002 and CEC, 2003)

Rolling resistance improvements have resulted from both tire construction changes and introduction of novel tire compounds. The major early (i.e. through the 1970s and 1980s) rolling resistance changes were due to the switch from bias-ply to radial-ply tires, which reduced the hysteresis[1] losses (Schuring, 1980). Changes in tread design and material compounds have more

[1] The mechanical energy loss in the form of heat loss associated with the deformation and recovery of a material (in this case, of a pneumatic rubber tire) going through a cycle.

substantially influenced rolling resistance since then. Currently, tread compounds utilize different polymers, reinforcing fillers, and anti-degradants to simultaneously improve rolling resistance, tire wear, and other properties; however specific details on these compounds are complex and generally proprietary. Carbon has become the dominant filler, but recent advances have been made in silica filler with a silane coupling agent, and various oils and polymers (NAS, 2006).

We use the analyses from two recent prominent reports on LRR improvements for this report's assessment. First is a report prepared for the CEC by TIAX Corp. in response to California 2001 Senate Bill 1170 that authorized the CEC to investigate opportunities to increase the purchase and use of low rolling resistance tires on vehicles in California as a means of reducing fuel consumption. The major conclusion of the report is that the use of low rolling resistance tires in California could increase average fuel economy and reduce fuel consumption by 3%, with the fuel savings benefits outweighing the additional tire cost increase of the technology. This would require a reduction of 20% in the rolling resistance of replacement tires. The limited tire test data available for this study indicated that the rolling resistance coefficient of most of the tires was in the range 0.01 to 0.011. Hence a 20% reduction in rolling resistance would put the low rolling resistance tires in the range .0083 to .0092.

A recent, comprehensive text that explores tire rolling resistance is the National Research Council's *Tires and Passenger Fuel Economy* report (NRC, 2006), which estimates potential rolling resistance reductions and their impact on fuel consumption. This study more cautiously discusses the potential for 10% rolling resistance improvements. The study finds the relationship between the tire rolling resistance coefficient and fuel economy is well understood and quantified. Based on multiple data sources and methods, a 10 % reduction in average rolling resistance of passenger vehicles will lead to a 1 to 2 % reduction in fuel consumption; more specifically the lower boundary improvements (or 0.70 to 1.28 %) result from urban driving cycles, while higher gains (1.60 to 1.96 %) result from highway driving conditions (NRC, 2006). Independent analysis conducted by ITS-Davis using ADVISOR vehicle simulation software confirms these estimated % improvements. Additionally these data are consistent with the work of the CEC (2003). Based on the boundaries from the two studies (CEC, 2003; NRC, 2006) we assess, in later portions of this work, impacts of up to 20% improvements in rolling resistance coefficients. Because of the higher energy inputs in manufacturing, it is crucial to account for upstream cycle energy inputs, and we do so in Chapter 6. Additionally, rolling resistance, as it relates to other tire attributes, is discussed further in the "Trade-Offs" section of this chapter.

Nitrogen Inflation Systems

Inflating tires with nitrogen has long been the standard practice in racing and aerospace industries and is now receiving considerable attention and limited use in trucks and passenger vehicles. Costco Wholesale Corp. has installed nitrogen inflation systems at its 400-plus U.S. and Canadian vehicle service locations to enhance tire sales and improve member benefits (Manges, 2004). Many smaller outfits have already adopted the technology and some of the largest tire service providers, including Pep Boys and Big O Tires, are currently test marketing nitrogen inflation (Manges, 2005; Miller, 2004). One article states that, by 2004, thousands of nitrogen inflation units had been installed, and dealers generally charge between $2.50 and $12 per tire (Tire Review, 2004). Many tire service providers are unsure and many consumers remain unaware and suspicious of the technology (Manges, 2004). To note, Costco offers nitrogen inflation at no additional charge to members who purchase their tires at its retail centers.

The use of nitrogen in lieu of air, which is approximately 78% nitrogen and 21% oxygen, as an inflation medium for automobile tires has several purported benefits. Most potential benefits are based on several factors: increased pressure retention by tires due to nitrogen's lower permeability through tire layers than air, reduced oxidation in the tire's rubber compounds, and nitrogen's lower water retention resulting in more consistent air pressure with changing temperature (Baldwin, et al, 2004). Numerous media reports and anecdotal accounts refer to these fundamental benefits in discussing and offering rough estimations about improved tire life, improved fuel economy, and improved overall maintenance costs.

Table 3 shows selected chemical property difference between, air, oxygen, and nitrogen gases. These properties were taken from *Lange's Handbook of Chemistry* (Dean, 1992), and these are the most pertinent properties to the present discussion of tire inflation. Note that except for the permeability in rubbers, the properties of the three gases are not very different. This is not unexpected, as air is comprised of 78% nitrogen by volume. The major difference in properties is in permeability through rubber for nitrogen versus oxygen. The permeability of air is less straightforward to determine, largely because it is highly dependent upon the amount of water vapor (even in small amounts) that is present within air. From these known properties it is plausible that a switch from air to nitrogen could reduce tire pressure leakage due to nitrogen's improved permeability and to the reduction in water vapor in the medium. Furthermore, the presence of any water vapor in tire increases the occurrence of oxidation. The failure of tires due to oxidation-related effects account for approximately 10% of tire failures, as previously stated in Table 2.

TABLE 3. Selected Properties of Air, Nitrogen, and Oxygen

Property	Air	Nitrogen	Oxygen
Molecular weight	29	28	32
Composition	78% N_2 , 21% O_2	100% N_2	100% O_2
Molecular diameter (nm)	---	.315	.292
Specific heat (kJ/kg ^{0}K)	1.007	1.039	.919
Heat conductivity (mW/m ^{0}K)	26.2	26.0	26.3
Gas permeability thru rubbers	*---	9.43	23.3

** permeability coefficient of water vapor is 2290*

There is, at present, a lack of comprehensive data to verify or validate the potential benefits of nitrogen as an inflation medium for passenger vehicle tires. The only available experimental study on nitrogen inflation did show reduced tire rubber oxidation under increased stress and high temperature oven-aged conditions (65 psi tire inflation, at 60 C for up to twelve weeks). However, the same study did question the true real-world "reduced leakage" benefit of nitrogen inflation for passenger tires because in these tires much of the leakage is associated with losses around the rim flange and at the valve itself rather than permeating through the tire rubber (Baldwin et al, 2004).

With this information and limited data, we estimate the extent to which nitrogen inflation systems for vehicles could prolong tire service life for average vehicles. The primary mechanism explored is the improved (i.e., lower) oxidation effects of nitrogen as an inflation medium, and how this could reduce the number of some premature tire replacements. We also assess the potential benefits of improved retention of air pressure, for its potential impacts on tire longevity. We emphasize that it is difficult to estimate quantitatively the improvement in fuel economy, tire wear, and mileage life that could result from the use of nitrogen inflation. If the use of nitrogen would result in significantly less variability in tire pressure, then improvements could be significant – possibly as large as the 25% claimed in some of the articles on the subject. This would only be the case if the tires using air were under-inflated by 10-15 psi, which is quite large. The magnitudes of the improvements strongly depend on the attention given to tire maintenance using air. As a result we employ ranges for potential effects.

Trade-Offs in Tire Attributes

Although tire technologies and attributes were discussed independently above, there are known critical dependencies and trade-offs associated with many of the attributes of tires.
Figure 5 illustrates with the “magic triangle,” how three critical tire factors – durability, traction, and rolling resistance – all have to be simultaneously balanced in the development and manufacturing of tires technologies. It is commonly held that many LRR tires of the past have delivered sub-optimal performance on at least one leg of the “magic triangle.” However, the development of newer silica-filled, lower rolling resistance tires continues offer promising improvements simultaneously in fuel consumption, traction, and tire wear life as compared to conventional carbon black-filled tires.

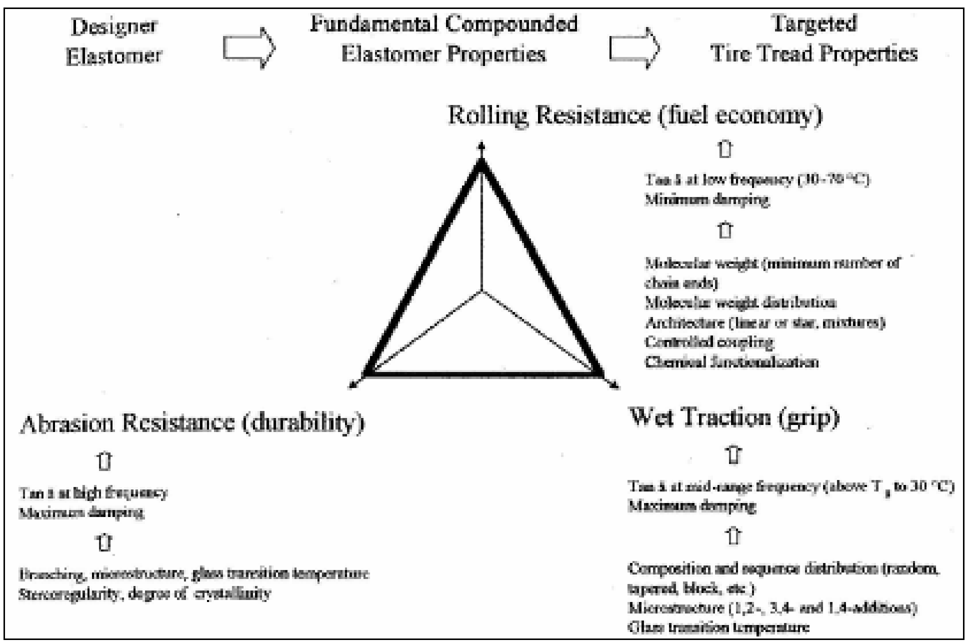


FIGURE 5. The “Magic Triangle” of Tire Design

The design and construction of the tire and the selection of materials used strongly affect the rolling resistance simultaneously with other attributes of tires. The switch from bias-ply to steel belt construction in the 1970s resulted in a reduction of at least 25% in rolling resistance at the same time as a large increase in tire mileage life. More recently, the NRC (2006) study attempts to correlate the rolling resistance of the tires with tire geometric, traction performance, and tread wear ratings, and some general conclusions can be drawn from the correlations. It was found that in general the rolling resistance of tires for large rim diameter (16”) were lower than those for small rims (13-14”) and that tires designated as performance tires (better traction and higher speeds) had relatively higher rolling resistance than the average. It was uncommon to find a tire with a rolling resistance coefficient less than 0.009 that also had high performance ratings. The wear grades of tires vary over a wide range from Uniform Tire Quality Grading (UTQC) ratings from 200 to greater than 600. The correlation of these UTQG ratings and the rolling resistance coefficient (RRC) were found to be uncertain in general, but the tires with the lowest rolling resistance (<0.008) have low-to-middle wear ratings (UTQG 300-500) in nearly all instances, as shown in Figure 6.

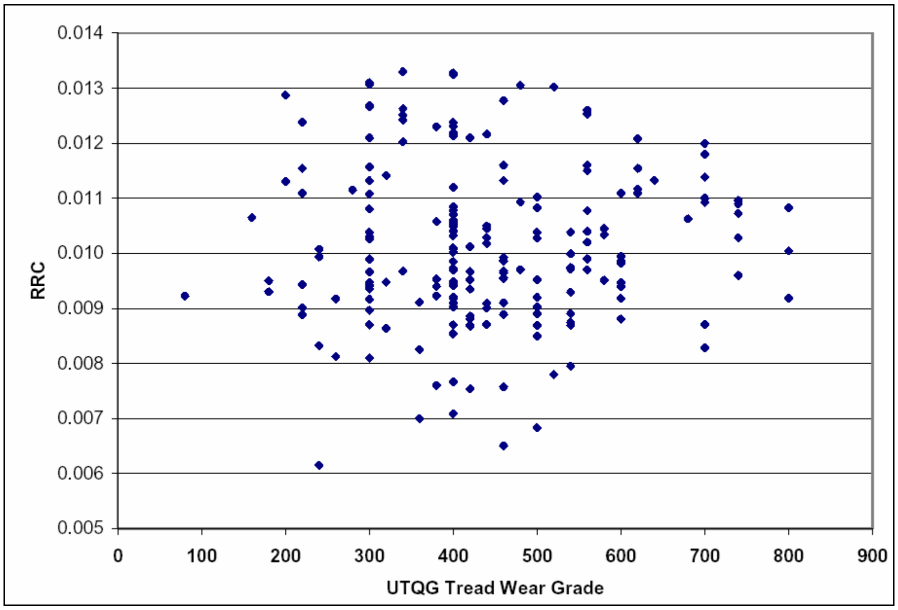


FIGURE 6. Tire Data on RRC and Tread Wear (NRC, 2006)

Tires of all sizes are available with a wide range of characteristics and prices. Information on tire load, speed, traction, wear, and temperature characteristics can be inferred from the tire ratings required by the U.S. Department of Transportation (US DOT). In addition, for many tires, the manufacturer lists a mileage warranty. Unfortunately, no information is presently available to the tire purchaser concerning the RRC of the tires. Hence it is not possible for the consumer to determine the trade-offs between rolling resistance and the other tire characteristics. This deficiency in the information available to the consumer is now recognized. Some rolling resistance data are now available in the technical as well as the popular automotive literature, but most consumers are not aware of it. Some of that information is reviewed in this section and what it means relative to purchase decisions is discussed.

Information on tire characteristics including price is readily available on the web for most of the tire manufacturers. Many of the large tire dealers have websites that list the tires available by size, characteristics, and price using the USDOT rating designations. If rolling resistance was included in the ratings, it would be rather straightforward to make the traction, wear, rolling resistance, and price trade-offs that would be appropriate. Researching the tire lists on the web, it soon becomes apparent that any trade-offs must be done for a fixed tire size and manufacturer as each manufacturer seems to have a "price niche". In general, the tire price increases as the size (rim diameter and tread width) increases (NRC, 2006). In addition, tires with higher speed and traction ratings are more expensive. Except for tires with very low wear rating (UTQG rating less than 300) and high wear rating (UTQG greater than 600), there does not seem to be a strong correlation between wear rating and price. Other rating and marketing factors seem to be more important in the mid-range of wear rating. The manufacturer's mileage warranty for these tires is 40,000 to 60,000 miles. In most cases, tires in the low range of wear rating have no mileage warranty indicated and tires in the high wear range are warranted for 70,000 to 90,000 miles. These high mileage tires are usually significantly more expensive than the other tires.

The key issue for this report is the trade-off between rolling resistance, wear, and prices. This question has been considered in some detail in the recent report of the NRC Tire Committee (NRC, 2006), which concluded that there was no clear correlation between rolling resistance and price when size and speed ratings were fixed. Table 6 does not address the question of the influence of tire wear on the trade-off between rolling resistance and price. The same report also discusses the trade-off between rolling resistance, tread wear and price, but does not reach any firm conclusion.

There are approaches to lowering rolling resistance and price without compromising tire wear. For example, some data indicate that some tires on the market exhibit low rolling resistance with good tire life and traction properties (Green Seal, 2003). This is especially true for 16" rim tires for which low aspect ratio (55) tires are available. Such designs seem to favor low rolling resistance. Since the wear rating of most tires sold are in the UTQG range of 400 to 600 and those tires have mileage warranties generally between 40,000 and 60,000 miles, it seems likely that a reduction of at least 10% in RRC can be achieved without reducing tire life. This would reduce RRC from about 0.01 to 0.009 in replacement tires. Future developments on tread compounding could lead to further reductions to 0.008 or 0.007 without compromises in mileage life and significant increases in price. If tire labeling would include a rolling resistance designation, then there would be competition between tire manufacturers in that area and improvements in rolling resistance would likely follow. Rolling resistance labeling would also promote the development of a standard test procedure and a large increase in the availability of rolling resistance data.

In addition to the manufacturing trade-offs qualitatively addressed above, there are several important real-world trade-offs between maintenance practices, rolling resistance, and tread wear. It is well known that under-inflation of the tires and wheel miss-alignment result in higher rolling resistance. It is generally accepted (Kelly, 2002) that RRC varies as the inverse of the square root of the tire pressure ($RRC = RRC_o (P/P_o)^{-.5}$). The increase in rolling resistance with under-inflation for a typical tire is shown in Table 4. The pressure shown is gage pressure, not absolute pressure. As can be seen in Table 4, the rolling resistance increases by about 1.8 % for each psi of under inflation. And, applying the above finding that a 10% reduction in RRC will result in a 1.5% increase in fuel economy for a 10% reduction in rolling resistance, we estimate the extent to which under-inflation impacts fuel economy. An average 7 psi under-inflation (20% below a 35 psi placard level) would result in a 11% increase in rolling resistance, and a 1.6% decrease in average fuel economy. The mis-alignment of the tires can also increase the rolling resistance. According to Duleep, 2005, the effect of toe-in alignment is a 1% increase in rolling resistance per 0.15 degrees; the effect of the slip angle is larger, at 5% increase for 0.5 degrees and 16% for 1.0 deg slip of the tires.

TABLE 4. Variation of Rolling Resistance Coefficient with Tire Pressure

Tire pressure (psi)	Standardized Pressure (P/P_o)	Rolling Resistance Coefficient	Standardized Rolling Resistance Coefficient (RRC/RRC_0)
35	1.0	.010	1.0
32	.914	.0105	1.05
28	.8	.0112	1.12
25	.714	.0118	1.18
21	.6	.0129	1.29

Chapter 3. Data Collection

This project's data collection concerns multiple facets of tire maintenance and tire technology. Original data was collected through interviews with vehicle personnel about tire-related procurement, inspection, and maintenance practices and surveys of vehicle users. This chapter details the methods and results from these sessions.

Fleet Personnel Interviews

This section summarizes the information gathered from a series of interviews of vehicle fleet managers and maintenance personnel. Information was gathered from two different fleets, dubbed "A" and "B," with facilities in northern California. This summary is intended as a general narrative of key features of fleet management, tire maintenance and monitoring procedure, tire replacement practices, and fleet receptiveness to new technologies as they relate to our overall project. Information gleaned from these interviews informs the later project steps of deploying, monitoring, and assessing new tire technologies in vehicles, and aids in the development of the "best practices" guidelines for fleets. In most cases, Fleets A and B shared similar practices. Where noteworthy differences between the two fleets' policies and practices exist, these distinctions are highlighted. Note that quotations may not be verbatim from the interviews but rather are meant to emphasize a general point made by interviewees. Also note that all numbers given here are estimates from the interviewees, and do not involve any data gathering from log sheets or databases.

Method of Information Collection

A total of three interviews were administered – all in similar settings. The Fleet A interview was conducted as an open discussion between three researchers and four managers (in positions or areas of maintenance, management, purchasing, and technician) in an office on the fleet's work site. For Fleet B, two separate interview sessions were conducted – one with seven maintenance or shop personnel and the other with four managers. Both of the Fleet B interviews took place in the break room at the vehicle fleet garage.

The survey questions asked in the interview are reproduced in Appendix A. Although the entire survey was conducted verbally for all sessions, blank question sheets were given to the respondents to guide them through the topics and give them a chance to jot down additional notes throughout. Both the Fleet A and Fleet B manager interviews lasted about one hour. The Fleet B maintenance personnel interview, with more participants and more input, lasted an hour and a half. Researchers took notes throughout the interviews; audio recordings of the sessions facilitated clarifications of the notes. The below sections summarize and reorganize the information from the discussion-style interviews.

General Fleet Information

Fleet A is a smaller fleet, with approximately 700 to 800 vehicles affiliated with a university campus. Of this fleet, about a tenth of the fleet are heavy-duty (i.e., one-ton or larger) trucks, including the campus buses and larger utility trucks. There are also nine police cruisers, seven 40-passenger buses, and about 120 mid-size and small sedans. The rest, approximately 500 vehicles, are half-ton and three-quarter-ton pickup trucks and vans.

Fleet B is a larger fleet of several thousand vehicles, although only a fraction of these are seen with any regularity. (For example, some this fleet's vehicles are sent off to college campuses for extended periods of time.) Approximately 1,000 of the vehicles see the maintenance garage in any given month. Of these vehicles, about three-quarters are shorter-term daily- or weekly-use vehicles, similar to a commercial rental vehicle fleet. These short-term vehicles, being seen more often by the shop, are generally checked and maintained more routinely. Most of the other vehicles that are routinely seen are longer-term, generally monthly, leases. These vehicles are seen less often at the fleet garage, and generally are brought into the shop after the driver has either accumulated a list of "to-do" problem items. In some cases these long-term vehicles had repair work done by outside vendors.

General Tire Maintenance Practices

There is no official guidance manual or formalized set of procedures for tire maintenance and monitoring. Vehicle and tire manufacturer specifications offer the bare minimum requirements for tire inflation and maintenance, and, in addition, fleets implement their own routines for monitoring and maintaining tires. Fleets include tire upkeep in their preventative maintenance program that includes tire monitoring, tire rotation, oil change, etc., on each vehicle for every six months or 6,000 miles of vehicle use (whichever comes first). At that time, tires are inspected for inflation pressure, tread wear, and any other defects. In addition to these scheduled maintenance procedures, tires are visually inspected each time they come into the shop for obvious problems or defects. Special attention is given to the vehicle tires if the operator, when dropping off the vehicle, notes any particular problems with driving, handling, or road noise that may be associated with tires. The "long-term" vehicles that are checked out for many months at a time are not monitored by the fleet personnel; these vehicles may or may not be monitored by vehicle operators or other mechanics elsewhere.

Tire Monitoring and Inflation

During vehicle servicing, tire pressure is generally checked with handheld, pen-sized (non-digital) tire pressure gauges. Several respondents questioned the accuracy of the devices and mentioned they are not calibrated or checked for accuracy. Several stated that the inflation was always checked cold (generally in morning, before the vehicles are driven). One technician noted that checking cold makes a large difference – about 10 pounds (per square inch). This procedure is not uniform, however; one manager said that often, immediately after vehicles were in service, the tire pressure is checked. Although managers and mechanics alike acknowledged potential inaccuracy of the handheld devices and had seen digital tire pressure monitoring devices, purchasing these devices was described as low priority. Despite the higher cost of the digital gauges, the managers made it clear that operating budget was not an issue. One manager noted the study to be an opportune time to invest in digital tire pressure readers.

Fleet maintenance personnel offered numerous tire pressure inflation guidelines or "rules of thumb" that they follow. Setting "to the manufacturer specs," or "at least at the manufacturer specs" (from specifications in the vehicle owner manual and/or as dictated by the plate inside the vehicle door) were stated several times. The recommended pressure varies by vehicle and specifically the wheel size and type on the vehicle (e.g. Chevrolet Impala wheels, steel vs. aluminum have different specs; the steel wheels—and naturally the tires fitting them—are narrower than the aluminum ones, therefore calling for a higher inflation pressure).

However, when prompted to state the advisable value or range of values at which tire pressure should set, many mechanics offered different responses based on varied reasoning. For example, one mechanic noted that many clients will complain about a rough ride if the tire pressure is set too high. In contrast, another mechanic's recommendation was to set pressure 5 pounds (all respondents referred to the unit of "pounds" more often than "psi" or "pounds per square inch") over the manufacturer specifications, claiming a result of increased fuel economy and reduced wear. Other individuals offered their own ideal numbers of 32, 35, and 36. The "36" response was followed with the explanation that you never know when the shop will see some of the vehicles again (it could sometimes be many months without routine maintenance or monitoring for the longer-term leased vehicles), so it was best to err on the high side. It was mentioned that, according to a manufacturer, tire pressure can be inflated to 40+ psi for improved economy and wear (with a negative trade-off of perceived road harshness and uncomfortable driving). One mechanic mentioned that gas-electric hybrid tires are supposed to be inflated much higher – up to 55 psi.

Data Tracking

There is no set mechanism to track or log the life cycle of tires while also noting replacement, wear and tread depth, maintenance/repair work, and discarding. There are data taken on each vehicle's history that would contain information on some of these factors. Information related to tire history, such as tire purchase, tire repair work, and discarding of tires are kept in work orders, but are not specifically logged or thought to be readily available in a database. The tire recycling company could keep more reliable data on discarding. Even the data that is available in work orders for tire maintenance could be somewhat suspect; work orders could convey whether tire work was done, but with a lack of description of the nature of the work (e.g. tire repair, patch, inflation, alignment), or the comments could be inaccurate (e.g., order could refer to "left front, but it's really right rear" tire). A manager suggested that a new log could be made and kept in the vehicles to keep better track of tire history. (This could be similar to the "Automobile Maintenance" record-keeping book already kept in the glove box.)

Tire Replacement Practices

Fleet workers were asked numerous questions about tire replacement practices in order to increase researchers' understanding of what dictates the life cycle for a tire in the fleet. General reasons for disposing tires (or retiring them from the fleet) included low normal tread wear, irregular tread wear (e.g. flat spot), irreparable puncture or defect, and replacing tires with a set of two or four to maintain overall vehicle balance (despite some tires having useful tread life remaining). Several fleet mechanics commented on the importance of vehicle balance and on tires' link to the computers of the anti-lock braking systems (ABS), emphasizing that it was necessary to keep tires that are very similar in sets.

The tires that are disposed of for the reason of normal tread wear achieve their full useful life cycle. Whether this full useful life is 20,000 miles, 40,000 miles, or more, is highly variable based on vehicle type, tire type, and driving behavior. Interviewees were reluctant to offer any usual, average, or expected tire life mileage. Personnel also did not offer any rules or guidelines on tread depth to indicate the time for discarding the tires.

Tires did not last their full useful life for several reasons. Uneven or irregular wear could cause a "secondary vibration," where a relative flat spot in one or more tires could have resulted from an abrupt braking incident. Such an incident would make for uneven driving and would prompt the driver to take the vehicle in to the shop to fix the unevenness with replacement tires. Tire defects, tire separation, or tire oxidation are rarely the cause of replacing tires. In the case of vehicles that are likely to be checked out for monthly leases, where there is a low likelihood of seeing the vehicle soon, mechanics could opt to replace tires a little earlier than normal, to be on the safe side, assuming that many drivers would not be monitoring their tires.

Fleet workers were reluctant to estimate when and why tires were replaced; they offered very rough estimates when pressed. Fleet B estimated about half (answers "about 50%," "35% to 45%") of their tires made it to the end of useful tire-wear life – where low tire tread depth is the primary reason for disposal. Fleet A estimated approximately 80% to 90% of their tires lasted until the end of useful tire-wear life. More irregular reasons like tire unevenness (e.g. flat spot) or tire defect could be responsible for about 10% to 20% of replacements, Fleet B estimated. The majority of these irregular reasons were thought to be due to driving-related problems like where and how the vehicles are driven (as opposed to inherent tire manufacturing defects).

Based on the above numbers, the remaining tire replacements, perhaps lower than 10% (Fleet A) or as high as 30% to 40% (Fleet B), are discarded when useful life remains but a member of that tire's set (two or four) is being discarded. Note that these numbers are rough estimates, on which no data has been collected. When one tire is discarded due to uneven wear, the decision on what to do with the other "still good" tires in the set differs to some extent depending on the mechanic. In Fleet A, most of these "still good" tires would be put aside, and would remain stored until another similar tire (same size/type and with very near the same tread-depth) was in need of a similar tire to make a pair. In Fleet B, guidelines for the "still good" tires were offered: if the tires still had less than 20,000 or 25,000 miles on them or at least half of the tread remaining, they kept them; however, if the remaining tires had more than 20,000 or 25,000 miles on them (or less than half of the tread) the tires would go to the disposal tire pile. For example, if a car with 25,000 miles on each tire came in with an irreparable flat, the whole set of four would likely be replaced. These guidelines for miles and tread depth appear to be based on appearance of the tires rather than on actual measurements. Also, if tires were in storage too long, they would be discarded (because of concerns about drying/cracking).

On the issue of reuse tires within the fleet's vehicles, a worker from Fleet B thought that perhaps 5% (but probably less) of tires taken off of one vehicle would ever be placed onto another vehicle in the fleet. Related to this lack of reuse of tires, a worker showed one of the interviewers the rack of about twenty "still good" tires that were ready to be reused for combining to a similar tire size and type with approximately the same tread-wear. The tires were unlabeled and unsorted (by size, type), and the fleet worker commented on how this inconvenience and lack of organization limited the likelihood that workers would opt to reuse these tires; it was simply much easier to grab a new tire (or set of tires).

Overall cost trade-offs factor into the mechanics' decisions on tire replacement and tire/vehicle repairs. Fleet mechanics said that they tried to look at the "bigger picture." Related to the question of replacing tires, fleet personnel sometimes reacted differently to a driver claim of unevenness on the road. Even if a minor alignment problem could be the cause of uneven wear in the tires, sometimes a decision could be made to replace the tires (a set of two at about $60 for the set or all four for $130) *instead of* a more labor-intensive alignment repair (at about $150); however, sometimes the tires could be replaced *with* the alignment correction if the problem was more substantial. As with the alignment issue, the "bigger picture" cost perspective was cited in the case of replacing two versus four tires. When only two tires were ready to be replaced (but the other two tires still had some life remaining) all four could be replaced. Considering that any job is a minimum of one hour labor, it would be best to replace all four (instead of later, perhaps in a couple months, having another job to replace the other two).

In response to a separate question about whether tires were replaced individually, in twos, or as a full set of four, Fleet A and B responses were roughly consistent with one another (although, again, the percentages are only crude estimations). Mostly, tires are replaced in pairs or as a full set of four. Again, percentage estimates were offered only when prompted by interviewers. Perhaps 10% of replaced tires are replaced individually. Approximately 45% to 75% of tires are replaced as a set of two. The remaining 15% to 45% of tires are replaced as a full set of four at a time.

Mechanics pointed out that law enforcement officers demanded new tires more frequently than any other drivers. Law enforcement vehicles had special driving needs (more aggressive driving, handling, safety in pursuit driving situations) that were likely to cause more instances of uneven wear; as a result, law enforcement drivers would dictate when their tires get replaced. When law enforcement drivers requested new tires, the tires would be replaced. If there was a nail in a tire, instead of patching the tires, the tire (or set of tires) would be replaced. In part, this relative lack of desire to repair could be due to the different (softer) rubber of these higher traction tires for police squad cars. Fleet personnel suggested that sometimes these drivers "just wanted new tires."

Tire Purchasing

For both Fleets A and B, the key determining factors for tire purchasing were government-discounted pricing contracts and maintaining the status quo. State government discount contracts with several tire companies (e.g. Goodyear, and Bridgestone/Firestone) offer substantial discounts from retail prices, and one of the fleets may receive additional discounting (beyond government pricing) from a local retailer. One worker stated that their discounts could get the fleet $200 retail-priced tires for just $50 per tire. When asked about which qualities of tires they focus on in purchasing new tires, they responded with common themes: "stick with the same," "are they the same as the old ones?" and "never go cheaper or worse in quality than the previous." For fleet managers to consider new or different brands of tires, the new brands would have to be as good as or better than the OEM tires and the tires they had chosen in the past. Exceptions to these tire choice criteria were rare, but would be made, for example, for tires on hybrid vehicles, or for a new trend in vehicle tires. In the latter case, such as a trend from 16" wheels to 17" wheels, exceptions would be made when a standard brand is somewhat slower in deploying these tires to the market than other companies.

After being pushed to speak more generally about tire qualities (i.e. outside of contract/status quo related reasons for choosing particular tires), Fleet B workers listed some criteria. They mentioned that the life of tires (e.g., rated at 60,000 miles or more is better) was important. A worker involved with purchasing commented that they would want to avoid switching to any other brands and models to reduce chances of mismatch problems (tire type, rating, wear qualities), which could result in drivability problems. Also, there was a comment on tread design regarding new RSA (a Goodyear model) tires were better than some weather tires. However, Fleet B personnel did not bring up topics of safety or fuel economy.

Fleet A offered up some commentary about the criteria that weighed into their purchasing decisions. Safety comes first, and tire longevity is also very important. This fleet's reduced tire pricing has been so good that they can just look to get the best tires in terms of safety and longevity, without being all that concerned about the potential trade-offs that these tires could have with respect to per-tire costs. The rolling resistance of the tires was not mentioned until we brought it up. The fleet's only experience with LRR tires was with electric vehicles. The fleet managers mentioned that the suppliers/sales agents from whom they bought tires were very helpful and knowledgeable with respect to Goodyear tires.

Independent of the tire contracts, workers offered additional commentary on tire brands. Several were partial toward the Goodyear Regatta II tire, citing that it was a high quality tire at a great price ($33/tire, after discount). On the General brand, one worker commented, "we hate them" and others agreed, citing issues with balancing, uneven wear, and separation. About Bridgestone/Firestone, there was mention of a separation issue, but generally fleet personnel thought the tire was a quality value tire.

Fleet Personnel Commentary on Vehicle Drivers

Fleet workers expressed general, mild resentment toward drivers of fleet vehicles due to their lack of care for the vehicle they are operating. Mechanics of Fleet B said that the vehicle users, especially the long-term leasers, should check oil and tire pressure, but they do not. Another commented that he just wished that the drivers would, "Keep tire pressures up … there's no way to train these people."

Some problems pertaining to the vehicles and their tires are reported to the fleet personnel upon vehicle return. In a 3-month period, one pool attendant gets five or so tire complaints (generally concerned about safety) out of dozens of vehicles. Drivers can be either indifferent or negligent in reporting obvious issues when bringing in cars. Sometimes flat tires are not discovered until the attendant retrieves the vehicle from the parking garage, when such a problem presumably would have been noticed by the last driver. Many drivers will run vehicles on flat or extremely under-inflated tires for many miles, which ruins the tires and risks tires shredding or blowing out.

Despite the generally negative outlook on the drivers, there was one small silver lining: The late model Chevrolet Impalas are equipped with tire inflation warning indicators, and operators are quite quick to bring them in for maintenance when indicators directed them to do so. A technician commented that noticing under-inflation visually could occur only in very serious cases of under-inflation (i.e., of 50% too low, or 15 psi to 20 psi too low), but with the indicators, people were more likely to bring problem vehicles in, if and when the light came on.

Purchasing Budget and Impact on Tires

There is not an itemized tire-specific budget. Tires are incorporated in the general maintenance budget. Fleet B managers estimated that tires could be about one-third of the maintenance budget, excluding the costs from work that is contracted out to outside vendors (see next section).

Fleet A managers, when prompted, estimated that the tire procurement and maintenance work was about 25% to 35% of their total expenditures.

When asked if budget constraints affect their decisions at all, the purchasing agent for Fleet B said that the fleet got what it needed and there was no perceived restriction or limit on getting high-quality (safe and long-life) tires. The managers echoed this comment. Manufacturer discounts provide large cost reductions that allow more flexibility in purchasing higher quality tires. Likewise, Fleet A managers said they were not constrained by budget. They focused on the great value they get with tires (e.g., $200 high-speed v-rate tires for police cruisers for about $50). Additionally, they said they experience very low failure rates, get great tire performance, and have safe, long-lasting tires.

Throughout the interview, several commented that time can be a much more significant cost to the agency than money. This sentiment was present in a statement, noted earlier, that it was cheaper to replace tires than to fix an alignment. It can be cheaper to change a tire than to do other maintenance work in some circumstances. For example, if a car with more than 100,000 miles on the odometer will be retired at 120,000 miles, they may simply change tires instead of realigning because it is less expensive.

Work Contracted Out

Both of the fleets contracted out tire work on the heavier trucks in their fleet (generally 1-ton and greater trucks, those with tires 20 inches or larger), primarily due to equipment limitations at the fleet garages and personnel safety reasons. They lack the racks, floor jacks, tire machine, wheel balancer, and tire retreading ("recaps") equipment needed for heavy-duty trucks tires. The key safety concern: "Why do the harder stuff?" Also, the ceiling height, space, and time limit the fleet personnel from working on larger trucks. They commented that they "Use our vendors as a safety net" or "We bring in what our guys can handle in a day's work. The rest we send out to our vendors."

Disposal of tires is also contracted out. Fleet A pays $0.90 per tire for disposal for a state-registered waste hauler (TriC Tire in Sacramento) to pick up the tires. The tires are shredded and used in road asphalt. They previously paid $3 per tire for disposal. Fleet B, on the other hand, receives $0.75 per tire for removal of their tires. A private contractor, who also removes old batteries, picks up a load of tires every two weeks and probably resells some of the tires with significant tread remaining.

Tire-Related Technologies

Fleet managers offered generally optimistic outlooks on tire technology, past and present. One technician commented that the that tire technology has made "huge leaps" in the past decades – that they have had virtually no trouble with the Goodyear tires they have been using and that they now have a very low probability of rollover when tires blow out (because the tires stay on rim after blow out now). Managers were very optimistic toward research like this UC Davis study, feeling that it was a "real world" type project that can be used for wider benefits. The following section highlights response from fleet personnel and managers on specific technologies related to tires.

The technology of note for this UC Davis tire project with which the fleets have experience is tire pressure monitoring systems (TPMSs). These inflation monitoring systems have indicators built into the vehicle dashboard of the late model Chevrolet sedans, including Impala models. They are not on the police package vehicles. The dashboards feature an indicator light that illuminates in instances of significantly under-inflated tires or slow-leaking punctures. Describing the indicators as "large," "hard to ignore," and "conspicuous," personnel thought that these systems were "useful" and "helpful" in that they probably "scare the driver into bringing in the vehicle" to get the light to go off when tire pressure is low. This in turn was probably good for safety because it could help avoid a blowout. Personnel noted that the shop visually checks tires anyway when they come in, so the TPMSs are not thought to greatly impact vehicles that come into the garage regularly, but the systems would help more with longer-term leased vehicles that are not checked as frequently.

Mechanics commented that the TPMSs had to be reset after a driver had taken the systems in to be checked out in response to an indicator light. When asked if the systems were always accurate, mechanics could not recall any incidents otherwise. One mechanic mentioned a circumstance of a customer learning how to reset the indicator with the radio panel to make the light go away without taking the vehicle in.

Fleet A also had some experience with a valve stem cap technology for truck and bus tires. The valve stem caps had lighted indicators on the tip that had certain colors to indicate tire pressure under- or over-inflation. Personnel found the caps especially useful on the back inside dual wheels, where the inside wheel is hard to get at and hard to gauge. These devices were quite expensive when the fleet first got them (approximately $12 apiece). Even though the cost may be down to $20 per set of four now, they said they could not justify the price to continue purchasing.

Fleet A was familiar with nitrogen inflation; they had read about it and had salespersons pitch the idea. They are generally in favor of implementing it if the department is willing to invest the funds. Cited reasons for using nitrogen included that it is cleaner, nitrogen sustains air pressure in tires longer, there is no fluctuation of pressure with temperature with nitrogen in the tires, and there is a reduction in the oxidation of the tires. If offered the opportunity to switch over to nitrogen inflation, the head mechanic responded, "Why not?"

Fleet B was similarly in favor of nitrogen inflation for their tires. They mentioned that the system does not lose pressure with temperature, and nitrogen allows no moisture inside the tires. Personnel cited that they "do it at Costco." They recognized that it must have some benefits if they are using nitrogen inflation in NASCAR and in aircraft tires. On the other hand, one fleet worker suggested that they change and monitor tires so much that maybe such a technology at their garage may have less impact: "The benefit's not gonna be that great for us. We replace tires too often."

There is minimal experience with low rolling resistance tires. Hybrid-electric vehicles in the fleet come with low rolling resistance tires. The replacement tires for these vehicles are specially ordered, and the tires are inflated to higher pressures than the normal tires.

Another technology idea was offered by a Fleet B employee. A pool attendant who oversees vehicles coming into the garage raised the idea of a vehicle scanner. The vehicles, previously embedded with a bar-code, could be scanned when entering the garage. The scanner computer could flag or indicate whether the tires on the vehicle were old and need changing with a “tire repair/check recommended” prompt. This could supplement the ongoing visual checks.

Impact on Personal Tire/Vehicle Decisions

The fleet manager and personnel were asked about whether their on-the-job exposure to many vehicles and tires impacted their personal tire practices in any way. Several interviewees commented that it impacted what tire brands to purchase (pro-Goodyear, anti-General). One mechanic mentioned that he checks tires monthly for tire pressure for better mileage and wear. Another checks and adjusts every 6 months, citing seasonal changes. Another said that he checks tire pressure more often due to his experiences at fleet services.

When asked about the impact of managing Fleet A’s tires on their own personal lives, one garage head thought mostly about under-inflation. When his daughter is setting out on a long (8+ hour) trip, he tells her to be sure to check the tire pressure due to his concern about safety. He, however, does not check his own tires that often. He is worried about under-inflation more than anything else, because of their susceptibility to blow-out, especially if the tires get hot on a long trip. Another commented that since manufacturers went from bias-ply to radials years ago, there is much less burden on vehicle users, and there may be some rationale for less concern about tires now. The porosity has gotten so much better, and the tires retain their air much better than before; as a result, he used to check tire pressure all the time, but now not so much.

Driver Survey

The driver survey portion of this study concerns a collection of data on driver behavior, preferences, and attitudes on topics of vehicle maintenance, tire attributes, tire purchasing, and new tire technologies. Of interest for this study were the following areas:

- Existing air pressure knowledge and practices
- Prior incidents of low tire inflation in personal vehicles
- Prior incidents of low tire inflation in fleet vehicles
- Method for recognizing low tire inflation
- Operator action in the case of low tire inflation
- Practices in personal vehicles
- Willingness to implement technological measures in fleet/personal vehicles

Survey Method

The survey population is the users of fleet vehicles at a northern California fleet vehicle garage. The sampling frame is the vehicle users who passed through the vehicle dispatch office at the garage to check out vehicles between March 30, 2006 and April 18, 2006. These drivers, government employees who obtain rental vehicles for their work duties, were solicited to participate in the survey by a graduate student and/or the fleet’s operating dispatch employee. The drivers were given informational letters on the purpose of the survey and were given a chance to ask any questions about the research. The drivers were then asked to fill out the brief

10- to 15-minute surveys before checking out their vehicles. The driver surveys were self-administered. The informational cover letter and survey are reproduced in Appendix B.

About 40 to 70 clients passed through the dispatch office per day during the surveying period. By the third week of surveying, there were many repeat clients who had already taken the survey and were ineligible to take it again. A total of 165 surveys were returned. The response rate, based on the number of unique vehicle users passing through the office who turned in surveys, is estimated to be approximately 50%.

As suggested by the above survey topics, the surveys were designed to capture a wide array of variables to better understand vehicle operators' working knowledge of tires and potential barriers and opportunities for new tire-related technologies. Most questions related to their own vehicles, and several questions on the survey were asked specifically about the drivers' use of the state fleet vehicles. The survey results are summarized below, with emphasis on capturing information relevant to developing a "best practices" manual for managing fleet and gauging drivers' interest in new tire-related technologies that are assessed in this research project.

Because of the narrow scope of this study, and its aim of aiding fleet tire-related practices, there are several limitations in generalizing the results of this study to the wider population of vehicle users. The survey's population (client of one vehicle fleet) is not necessarily representative of the population at large; to the extent that the government employees who are checking out vehicles are not representative of general vehicle users. Additionally, to some extent, the survey-taking fleet clients during the March-April timing of the study could differ from those clients who check out vehicles at other times of the year, and therefore not be representative of the yearly population of drivers. The context of the study involving research on waste and energy saving tire technologies could induce some social desirability bias, if survey respondents were compelled to give the "right answers." For example, vehicle operators could feel compelled to overstate how well they take care of their vehicles.

Survey Results

The survey respondents were overwhelmingly personally responsible for maintaining their own vehicle's tire pressure inflation and tread wear. Most survey respondents, 77%, reported that they do check their own tire pressure on their personal vehicles, while 13% rely on someone else to do so, and the remaining 10% did not have their tire inflation monitored. When drivers discovered improper tire pressure, whether from an actual tire pressure measurement or visual observation, 87% personally restored their tire pressure to the correct level while 11% took the vehicle to an auto garage to have someone else refill the tires. Likewise, 90% of vehicle operators reported to check the tread wear of vehicles they own.

The frequency with which tire inflation was monitored by vehicle users varied greatly. A small percentage, 10%, checked their pressure weekly or within a month. Most common frequencies were approximately monthly monitoring with 36% of respondents (including responses between 6 and 12 times per year), and seasonal monitoring with 33% of respondents (including responses from 2 to 5 times per year). Significantly, 11% of respondents reported that they relied on appearance of the tires to dictate the frequency of tire pressure monitoring and inflation. The remaining 11% used other various timing indicators (e.g. when vehicle is serviced) to dictate how often they had their tires checked. One driver reported reliance on the dashboard indicator (presumably from a new late model TPMS) to inform on whether any low pressure tires.

Those surveyed generally rely on simple devices or visual inspection for monitoring of tire inflation and tread wear. Of the persons who monitored their own inflation pressure, the vast majority, 72% of vehicle operators, rely on "pen-type" tire pressure gauges. Other tire pressure measuring devices were less common: Digital gauges (11%) and dial-type gauges (11%). And 5% of respondents relied on "visual inspection" to gauge their air pressure. To monitor tread wear, 81% of respondents relied on "visual inspection," while another 10% used a coin (e.g. penny, dime, quarter) to approximately gauge remaining tread life. Much smaller percentages (1% and 7% for digital and ruler-type gauges, respectively) utilized actual measurement devices.

A sizeable number, 27% of respondents did not offer an answer for the correct tire pressure for their vehicle. Respondents' reported values for their vehicles' correct tire inflation pressure were consistent with average vehicle placard levels in the NHTSA (2005) nationwide survey. Reported correct tire pressures for respondents' personal vehicles are shown in Figure 6. The mean reported tire pressure was 33 psi (median 32 psi). The responses for drivers who monitored their own vehicles tires had the following distribution for their vehicle's correct tire pressure: 15% less than 32 psi, 43% from 32.0 to 33.9 psi, 28% from 34.0 to 35.9 psi, and 13% at 36 psi and above.

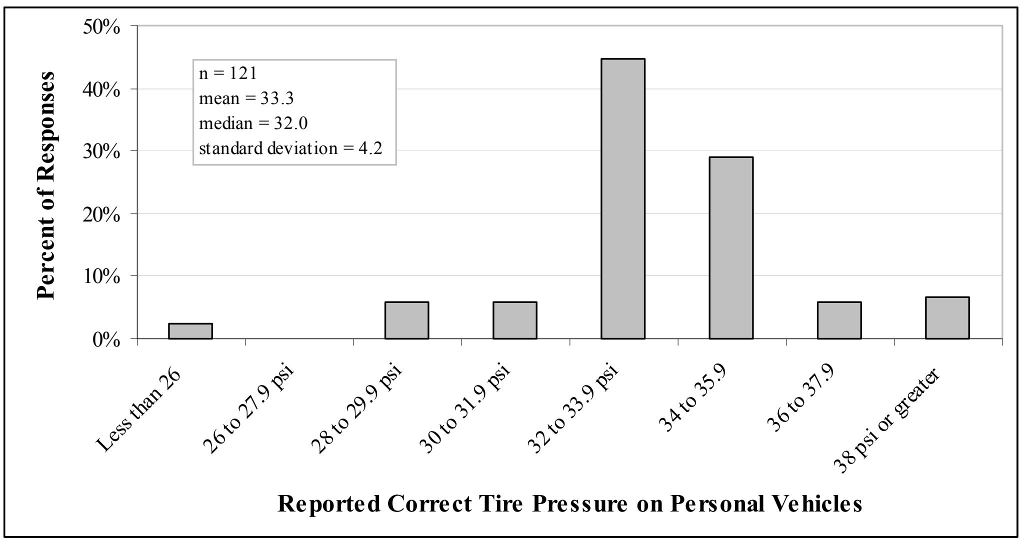


FIGURE 7. Responses for Correct Vehicle Tire Inflation Pressure

Several survey questions inquired about tire procurement decisions and the relative importance of various tire attributes. Using a five-point Likert-type scale, tire attributes were rated from 1 = "Not Important" to 5 = "Very Important." The results from this question are ordered and reported in Figure 8. Safety was the highest-rated tire attribute, with an average score of 4.6 on a 5.0-point scale, and with 92% of respondents reporting it as a 4.0 or 5.0. "Expected tread life" registered the second highest score, followed by wet-whether performance. Each of these three factors scored higher, on average, than the factor for tires' purchase price in importance in the tire purchasing decision.

Tire Attribute	Mean Score	Standard Deviation
Safety	4.60	0.74
Expected tread life	4.28	0.94
Wet-weather performance	4.17	0.96
Price	4.11	0.91
Handling	3.98	1.06
Fuel economy	3.80	1.12
Comfort/Ride	3.74	1.14
Noise	3.57	1.18
High-speed performance	2.91	1.30
Style/Appearance	2.50	1.27

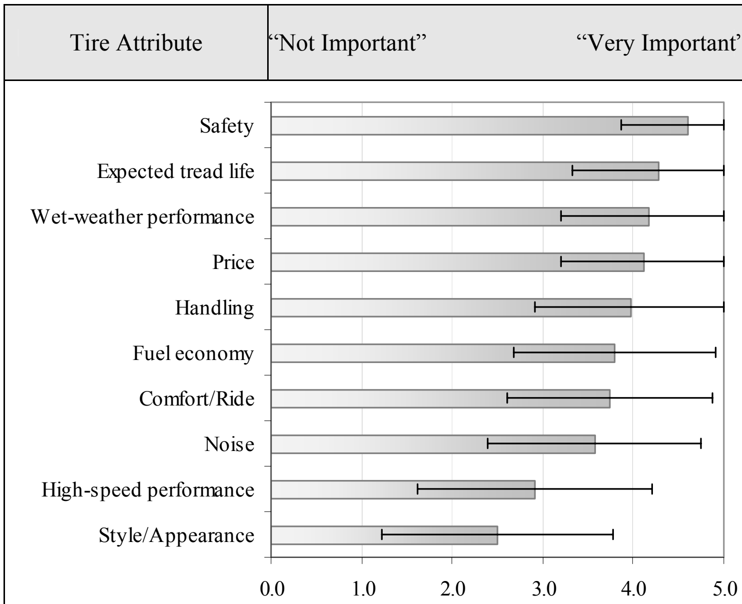


FIGURE 8. Driver Tire Attribute Importance on Five-Point Scale

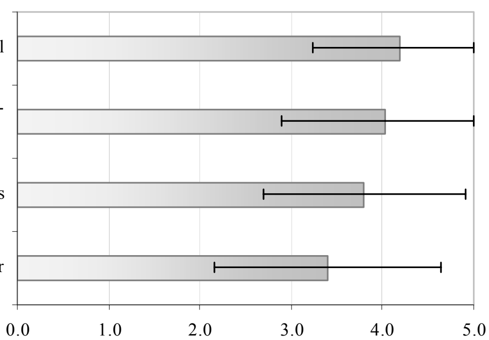
When asked more generally and qualitatively to define "How do you decide which brand and type of tires to buy?" a wide range of answers were offered. Many respondents were brand loyal (e.g. always buy Michelin), while others were loyal to specific retailers (e.g. always go to Pep Boys). Also, many drivers' first response was regarding the pricing or whether certain tires were on sale. In purchasing tires for vehicles, drivers reportedly spent on average $100 per tire (mean: $108, median: $100, as shown in Table 5). A large number of respondents deferred to the advice of shop mechanics or used consumer guides or customer reviews to guide their purchasing decisions. A smaller but still substantial number of operators referenced tire ratings. Few responses offered particular tire attributes or factors, like safety, handling, tread life (as discussed above), as the key factor on deciding on tire purchases.

TABLE 5. Average Price Paid for Last Tire Replacement

Average Price per Tire	Number of Responses	Percent of Total
$50 or less	6	5.8%
$51 to $75	18	17.5%
$76 to $100	29	28.2%
$101 to $125	24	23.3%
$126 to $150	16	15.5%
$151 to $175	5	4.9%
$176 or greater	5	4.9%
	103	100%

Drivers were asked about their interest in several emerging tire technologies: lower rolling resistance, TPMS, self-inflating or "run flat" tires, and nitrogen inflation. In some cases, technologies were defined in simpler terms for the general survey audience (e.g. "more efficient" instead of "lower rolling resistance"), and their benefits were identified. For example, in regard to nitrogen inflation, the phrase “to hold pressure longer” was added. Additionally, respondents were not offered “I don’t know” as an option to force them to speculate on the concept of the technology and its potential benefit.

Figure 7 shows results from this inquiry about vehicle users’ interest in new tire technologies. As above for the tire attribute question, allowable responses were in a check box five-point Likert-type scale. To note, all of the technologies drew, on average, positive responses, with scores ranging from 3.4 to 4.2 on a five-point scale. Of the technologies, higher efficiency tires for fuel savings drew the most interest, with a score of 4.19. Dashboard tire pressure indicators, akin to TPMSs, for vehicle safety rated second, and self-inflating or “run-flat” tires to aid drivers in emergencies rated third. Respondents showed the least interest in “nitrogen inflation” with a score of 3.4 out of 5.0; however this technology’s highest standard deviation suggests that it is the technology with the most disagreement or perceived uncertainty about its purported benefits.



Tire Technology	“Not Important” … “Very Important”	Mean Score	Standard Deviation
Tires that are more efficient and save you fuel		4.19	0.95
A gauge in your dashboard that tells when tires are under-inflated for safety reasons		4.03	1.14
Self-inflating or “run flat” tires for emergencies		3.80	1.11
Nitrogen inflation to hold pressure longer		3.40	1.24

FIGURE 9. Interest in Emerging Tire Technologies on Five-Point Scale

Chapter 4. Technology Implementation

This section describes the implementation of new tire technology at the Department of General Services vehicle fleet in Sacramento and the preparation and development of an experimental design by which to test the new technologies. A main conclusion of this study's literature review, fleet interviews, and driver surveys is the critical nature of maintaining proper tire pressure in vehicle's tires toward improving tire mileage life, reducing tire rolling resistance, and thus improving fuel economy. Tire pressure technologies, such as tire pressure monitoring systems (TPMSs) and nitrogen inflation systems, appear to offer significant potential in this area of maintaining proper tire pressure. TPMSs offer the potential to track real-time records of tire pressure and temperature, and the systems have the ability to introduce an interaction between the vehicle and driver to alert the driver of the status of the tires. One variant of these technologies is already installed on a limited number of the fleet vehicles; we, however, install higher-precision, "direct type" TPMS technology to monitor and quantify changes in tire pressure for the fleet vehicles. Nitrogen as a tire-filling medium offers the potential to reduce leakage, and therefore less maintenance and longer tire life. With these benefits not yet substantiated in the literature, our experimental set-up intends to bridge this data gap.

This section summarizes the key installation features of the technologies and the methods that are to be employed to carry out testing on the vehicle fleet. A brief overview of the nitrogen inflation equipment is given. To facilitate diagnosing and testing of the tire pressure impacts of nitrogen inflation technologies, data acquisition systems from which time-stamped tire pressure changes can be monitored are installed on the vehicles. After a brief summary of this installation process, a statistical testing methodology by which to experimentally determine the inflation retention potential of nitrogen as an inflation medium for the fleet vehicles is presented. Further details and system specifications can be found in Appendix C.

Nitrogen Inflation System

The nitrogen inflation system is comprised of several interconnected elements. The source of the nitrogen used is the compressed air system of the facility. As illustrated in Figure 10, nitrogen is isolated from compressed air by a semi-permeable membrane in the nitrogen generator. The semi-permeable membrane allows nitrogen to pass to the storage tank and shunts all other components of the compressed air to the permeate port. The nitrogen is then held at an elevated pressure in the storage tank and dispensed with the inflator as needed for test vehicle pressure fill-ups. The storage tank allows for nitrogen to be stored for periods of high demand. The inflator allows for uniform and automatic setting of tire pressure. The inflation pressure can be adjusted by the user to ensure that the correct placard pressure is always used.

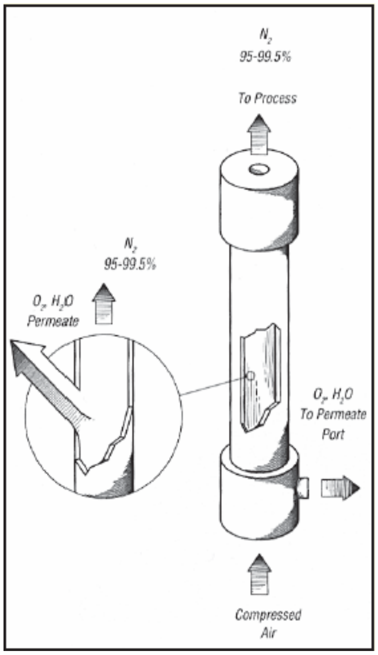


FIGURE 10. Semi-Permeable Membrane of Nitrogen Generation Equipment (Parker-Hannifin, 2006)

There are several large manufacturers of nitrogen inflation systems, including Branick, Parker-Hannifin, and Ingersoll-Rand, as well as several smaller manufacturers. Parker-Hannifin was chosen as our supplier of nitrogen inflation equipment based on their large market share, proven record of performance, and suitability to the conditions of the application. Further details about this procurement decision are laid out in Appendix C.

FIGURE 11. Nitrogen Inflation Equipment (Parker-Hannifin, 2006)

Once a vehicle has had its tires inflated with nitrogen, green valve stem caps are applied to conspicuously notify fleet personnel that the tires are nitrogen-filled. In addition to the green valve stem caps, the test vehicles have prominent stickers reading "nitrogen inflation installed" on the back (non-reflective) side of the rear view mirror assembly.

Tire Pressure Data Acquisition Systems

The main components of the tire pressure (and temperature) data acquisition systems for each vehicle are the four strap-mounted, in-tire sensors, the receiver, and the data acquisition module (DaQ). The sensors used in this study are of the direct type, sending gauge pressure and temperature data to the receiver over a wireless signal (as opposed to the indirect type, using the relative wheel speeds across axles to infer differences in pressure via effective radii). With a motion switch, the sensors only send data on timed intervals when the study vehicle is being driven, thereby saving battery power and eliminating unnecessary data transfer. The receiver passes data packets onto the DaQ, which stores them in memory.

The four sensors to be installed in each test vehicle were designated with their wheel positions and respective colors (pre-assigned by SmarTire – P1 green, P2 red, P3 blue, and P4 yellow – with vehicle positions as shown below in Figure 12) and entered into a spreadsheet-based lookup table, which kept track of all vehicles with their respective equipment. A test set-up consisting of a DC power supply and IBM compatible computer was then prepared for each vehicle's equipment to ensure proper functionality and programming of the sensor identification numbers (IDs). As the receivers relay wireless signals indiscriminately, it is necessary to input each vehicle's sensor IDs into the DaQ to prevent it from taking data from other cars in the area. The sensor ID is printed on a barcode on each sensor. Programming the sensor IDs into the equipment, via the barcodes, was done before installation of sensors into the wheels

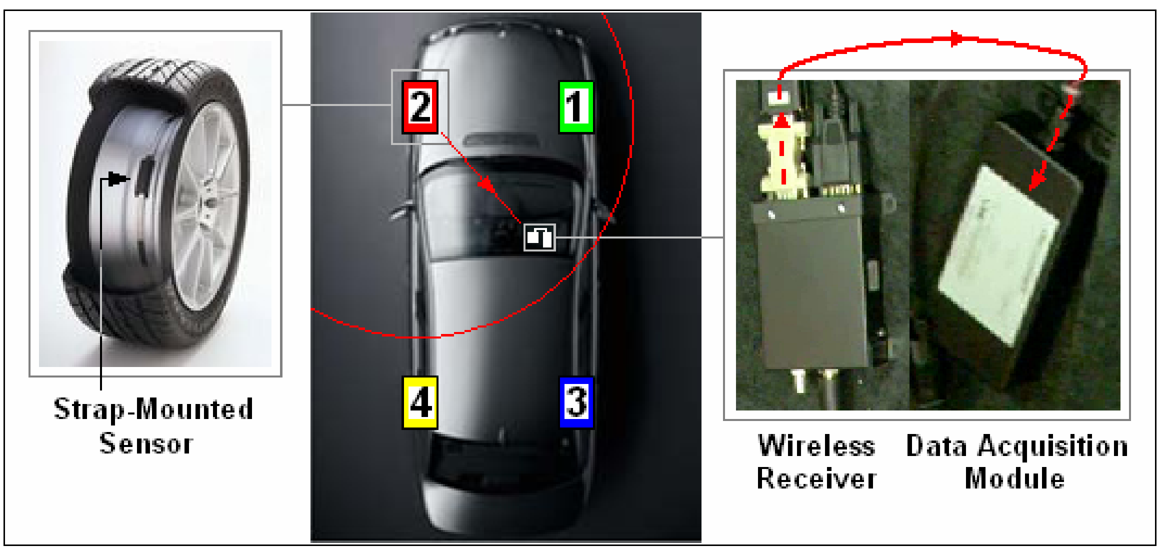


FIGURE 12. Key Components of Tire Pressure Monitoring and Data Acquisition Systems (SmarTire, 2005)

Once each bundle of equipment – comprised of four strap-mounted sensors, installation hardware, a receiver, and a DaQ programmed with the IDs of the four sensors – has been tested, it is ready for installation on a study vehicle. The sensors are installed in the vehicle rims, and the instrument cluster is installed inconspicuously under the passenger seat. Power for the sensors is provided by an internal battery, while power for the receiver and DaQ is provided by the vehicle electrical system. The components that are connected to the vehicle electrical sensor utilize a fused, switched positive lead. This allows the vehicle electrical system to be protected from excessive current draws that would result in electrical damage or a discharged battery.

With the equipment installed, the DaQ accumulates time-stamped tire pressure and temperature data. When the data is collected from a vehicle, the same procedure as the test setup is used. Unlike the test setup, however, the equipment is now bundled under the passenger seat of the vehicle, making a laptop computer imperative. A sample of offloaded data is illustrated in Table 6; the raw data, exported by the DaQ in simple tab-delimited, plain text format, is now ready for statistical analysis.

TABLE 6. Sample Data Output

Packet Line #	Pressure	Temp	Sensor Voltage	Life	Units	Sensor ID	Timestamp	Converts to	Units
1	273.68				kPa	01129558	Wed Apr 12 12:48:42 2006	39.695	psig
2		36			°C	01129558	Wed Apr 12 12:48:42 2006	96.8	°F
3			2.85		Volts	01129558	Wed Apr 12 12:48:42 2006	—	—
4				0	—	01129558	Wed Apr 12 12:48:42 2006	—	—

Statistical Methodology for Comparing Pressure Loss

This subsection covers the statistical methodology for comparing the pressure loss characteristics of nitrogen-inflated tires against air-inflated tires. The test fleet is a set of Chevrolet Cavaliers from the fleet's daily trip vehicle fleet. The vehicles have between 60,000 and 100,000 miles on their odometers. Discussed in this section are the development of two hypothesis tests of interest: (1) a comparison of pressure loss per car per time and (2) a comparison of tire position pressure loss with regards to the type of inflation. As will be described, the tests are constructed in this way to account for the sensitivity that pressure loss might have to either the car itself, or the tire position.

Table 7 shows an example of the data format after downloading initial data points from the test vehicles. Each row is uniquely identified by the combination of observation date, a vehicle identification number, and tire sensor identification (ID). As discussed above, the position variable represents the location of the wheel on the car. The gas column contains a string representing the inflation gas used in the tire to denote whether the tire is filled with air or nitrogen (presented as N2). The pressure column is the average psi for that tire on that day. Note this averaging distinction from the above Table 6 (for initial individual data points): the measurements are averaged because, even though they are temperature standardized, multiple factors cause small variances over the day. The standard deviation column provides information on the measurement variance for the particular tire, and the final column provides the number of measurements that were used to calculate the average.

TABLE 7. Sample Tire Pressure Data

Date	Vehicle	TireID	Tire position	Gas	Average pressure (psi)	Pressure standard deviation	Data points
4/12/2006	243132	607069	1	air	38.5478	0.1435	6
4/12/2006	243132	616162	2	air	40.2946	0.1024	3
4/12/2006	243132	1774362	3	air	40.4228	0.528	9
4/12/2006	243132	1774370	4	air	39.1973	0.5266	7
4/12/2006	81238	60364	1	N2	40.3690	0.5261	10
4/12/2006	81238	60366	2	N2	40.2946	0.1024	3
4/12/2006	81238	60368	3	N2	39.1449	0.5096	8
4/12/2006	81238	60370	4	N2	38.5478	0.1435	6

The cars in this experiment are part of a rental fleet. Because the cars will be driven by different people on different roads in different climates we must consider that the pressure changes across the tires in a car might be correlated. In order to compare car dependent pressure losses we develop a scoring system. The following scoring system is one which looks at the sum total of air pressure loss per car over the test period. The measure, the "S score," quantifies the accumulated gas flowing out of the tire, without regard to the origin of the gas.

Figure 13 graphically illustrates with example data the reduction of tire pressure and refilling of air over a given time period. The dots represent pressure readings over 100 successive days for a single tire. On day 51, the tire was inflated back to 32 psi. It can be seen that the dots do not decrease uniformly over the time period; there is a general downward trend, but sometimes the pressure reading increases between days. This is explained by the fact that the standard deviation of the pressure readings for a given day, 0.5 psi, substantially exceeds the typical psi pressure loss per day by an order of magnitude (e.g. a tire that loses 4 psi over 6 months has a pressure loss rate of ~ 0.02 psi/day).

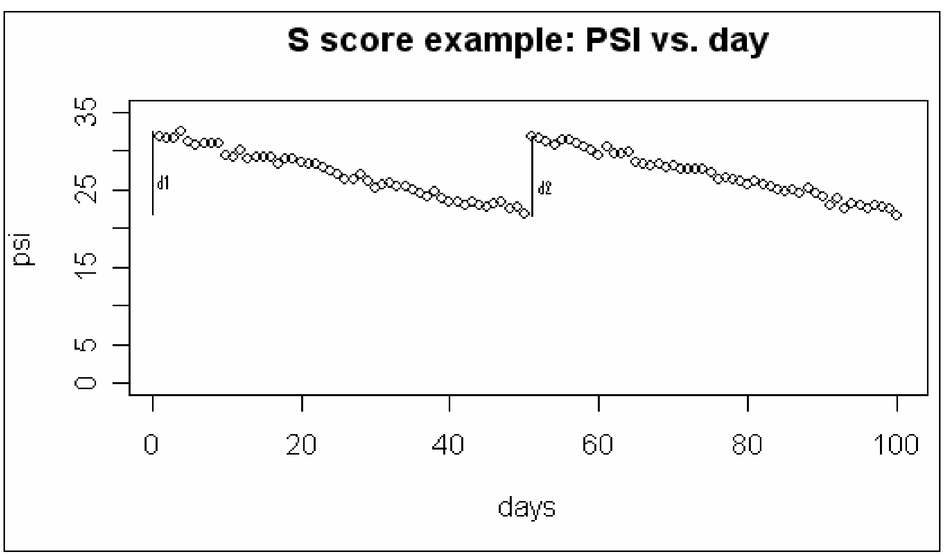


FIGURE 13. Illustration of the Tire Pressure Data

We are interested in measuring only the total loss of pressure over the time period. The loss for the first 50 days is equal to the sum of the losses over that time period. This distance is represented by the line marked ‘d1’ on the chart. Likewise, for the second 50 days the accumulated loss is represented by the line marked ‘d2.’ By adding the lengths of those two lines we get the total pressure loss for the tire over the 100-day period.

The “S score” is the measure of the accumulated pressure loss for all of the tires on a car over the observation period. The equation for the *S score* is:

$$S_n = \sum_i \sum_{j=1}^{4} (p_{i,j} - p_{i+1,j}) \times I_{(p_{i,j} > p_{i+1,j})}$$

where:

n = the car identification number (1 – 49)
i = test day number
j = tire number (1-4)
Let p_{ij} = the *average pressure* of tire *j,* on day *i*

This score represents the total loss of air pressure in psi for car *n* over the test period. The ***I*** operator is the indicator function; in this application we only include the difference value if it is less than the prior value. This allows for us to account for the refilling or replacement of the tire.

With this definition of the S score, we state the first hypothesis:

Hypothesis 1: The accumulated pressure losses per car, the S scores, for nitrogen- and air-filled tires are the same.

We will pair hypothesis 1 with the alternative hypothesis that the accumulated pressure loss for nitrogen inflated tires is less than that of air inflated tires. In statistical terms, this is called a *one-sided test;* we are not concerned that nitrogen will perform worse than air. The S score will be additionally useful for detecting outliers. Vehicles with extraordinarily high S scores should be examined for abnormal usage.

The second dependency we must account for is that of tire position. Tire position may be a factor in pressure. For example, a front tire on a front-wheel drive car could be more stressed than a rear tire, or tires on one side of the vehicle may be more stressed than the other side. Here, we state our second hypothesis:

Hypothesis 2: The accumulated pressure loss, by tire position, for air-filled tires is equal to the accumulated pressure loss for nitrogen-filled tires.

As with hypothesis 1, we will pair hypothesis 2 with the alternative that the accumulated pressure loss by tire position is less for nitrogen than for air. Again, this is a one-sided test, for we are assuming that nitrogen will perform at least as well as air as an inflation gas. In actuality, hypothesis 2 involves four separate tests, i.e. nitrogen in tire 1 vs. air in tire 1, nitrogen in tire 2 vs. air in tire 2 and so on.

The tests will be processed and analyzed by a computer program. Because of the processing and analysis requirements, the statistical tests are made to be simple, robust and conservative. The two-sample "t-test" meets all of these requirements and is a sufficient tool to statistically examine the two stated hypotheses. A rigorous explanation of the t-test method is beyond the scope of the paper, but we provide a brief explanation here.

Two samples of data are compared in a two-sample t-test. The samples are randomly selected subsets of numeric observations (e.g., height, weight, cost, etc.) from a larger population. Each sample has three important properties: a size, a mean, and a standard deviation. The sample size is the number of observations contained in the sample. The mean is the sum of all the observations divided by the sample size. The standard deviation is a numeric description of the variability of the sample around the mean.

Using these three properties along with a statistical tool called the *t distribution* we can develop a confidence interval at a given percentage level for the true mean of a population. For example, we consider a sample of 20 tires that lose pressure at an average rate of 1.0 psi/month with a standard deviation of 0.2 psi. A 95% confidence interval for the true pressure loss per month is equal to,

sample mean ± (t value) x *(standard deviation / square root of sample size)*

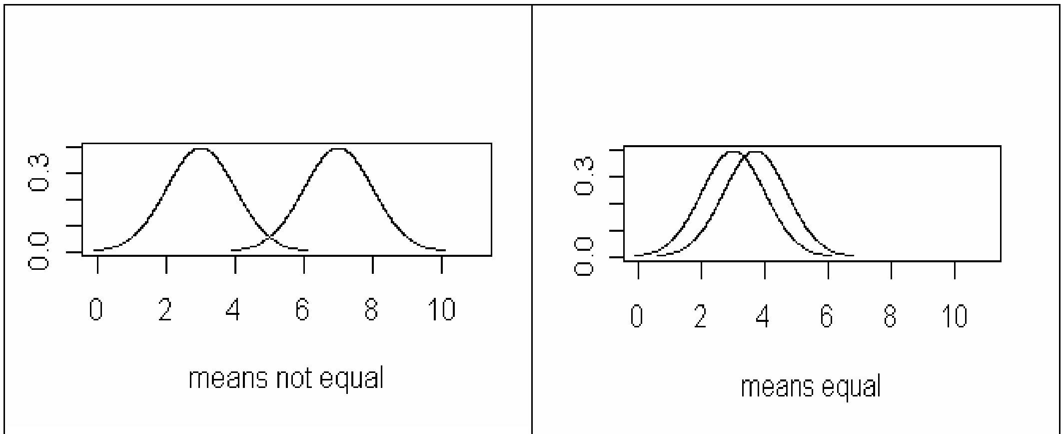
For the given example, the results is –

$$1.0 \pm 2.08 * (0.2 / 4.47) = [.91, 1.09]$$

Thus we would expect that, 95% of the time, the true population of values for tire pressure loss mean would fall between the values 0.91 and 1.09, given our sample.

For a two-sample t-test, we have two samples and thus two intervals. If the intervals overlap, such as [.91, 1.09] and [1.05, 1.15], we say that they are not significantly different. If they do not overlap, such as [.91, 1.09] and [.74, .86], we say they are significantly different.

This point on determining statistically significant difference from a two-sample t-test is depicted in Figure 14. In the hypothetical illustration, to "means not equal." The horizontal axes in the plots represent the numeric values of the mean. The vertical axes provide a measure of the probability of a mean being a given value for the distributions. In the "means not equal" plot, the true means likely falls in the range from 2 to 4 for the lower value and from 6 to 8 for the higher value. Since these two ranges do not overlap, the test determines that the means are significantly different. For the "means equal," the lower mean most likely falls in the range from 2 to 4 and the higher mean in the range from 3 to 5. The distribution curves substantially overlap, as well as the confidence intervals for the mean value. Thus we would conclude that the sample means were not significantly different.



"Statistically significant difference"	"Not statistically significant difference"

FIGURE 14. Illustration of Significant Difference Between Two Samples

A key assumption of the statistical t-test is that the samples be normally distributed. Determining that a sample is normally distributed, however, is difficult when dealing with small sample sizes, as we are here for this experimental design. However, the t-test is robust with regards to this assumption (Neter et al, 1996). The test works properly with sample sizes of 10 or less provided the distributions are not skewed. Our samples contain either 24 or 25 observations. Given that the data will be the summations of small values over a long period of time it seems reasonable to expect the data will not be skewed. Skewed data is likely when observing phenomena in which the forces that shape low values differ from those that shape high values. For example, income distributions are often skewed because there is an absolute lower bound of zero (no income) with no similar cap on high incomes. Based on our initial acquisition of sample test data, we have no reason to expect the data will not be appropriate for a t-test.

The data will be processed and analyzed using the open source statistical package called "R" (see Leisch, 2006 for further details). All pressures will be temperature standardized to 25° C and recorded in gauge PSI. The operator will not need to know how to use R; all that will be required is that he set the working data directory and then run a script.

Processed output files providing the full temperature standardized data set and the daily averaged temperature standardized data set will be made available in a character delimited file that can be examined with a statistical software package or Excel, should that be desired.

The hypothesis test results will be printed to an output file. Sample means and the confidence intervals will be printed for each test along with a statement declaring whether the hypothesis was accepted or rejected. This computation will be invisible to the operator, who will receive the test data and an indication of whether the populations are statistically different or the same. It is suggested for any automated statistical analysis, including this one, that it be reviewed by a qualified analyst prior to accepting it as a valid decision-making tool.

Chapter 5. Analysis of Tire Practices

This section seeks to integrate information gleaned from the literature review, the driver surveys, and the fleet interviews on tire-related maintenance practices. We analyze the cycle of tires in a fleet of vehicles from the perspective of private vehicle users, and then specifically apply the same tire flow model to fleet management, with an emphasis on formulating recommendations on how fleets can better manage their vehicles' tires. The primary aim here is to assess potential improvement to current practices for use in the life cycle research of Chapter 6 and for the development of a "Best Practices" manual for fleets regarding tire practices.

Private Vehicle Users

Based on information collected from our literature review, interviews, and surveying, it became clear that the known data on tire management is sparse, and, therefore, we developed a set of assumptions and simple tire flow model to assess changes to tire practices. A generalized illustration of tire flow – from new installed tires to the discarding of tires – is shown in Figure .15. The paths' categories are based on those given in Weissman et al (2003) for replacement reasons, using a dataset from Michelin tires introduced above in Table 2.

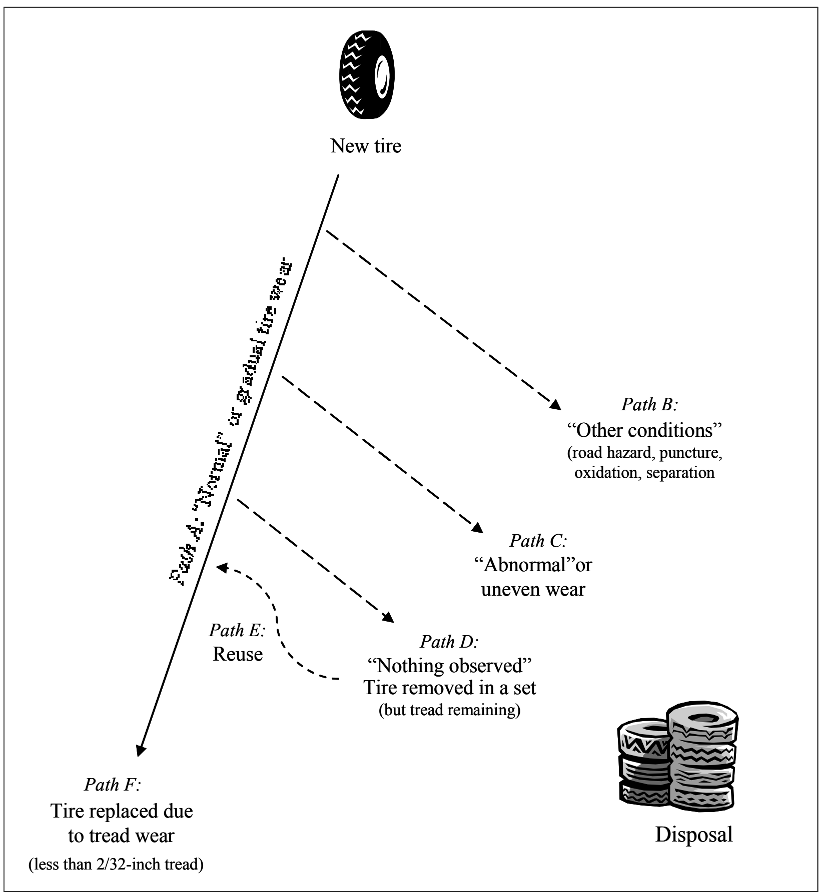


FIGURE 15. General Schematic of Fleet Tire Management Paths

Path A in Figure 15, "normal" or gradual tire wear, is the ideal scenario, where tires make it to their expected, rated service life (e.g., 50,000, 60,000, 75,000 miles) which differs by tire brand and model. Keeping tires in the fleet on Path A requires following proper tire maintenance practices: tire pressure inflation, tire rotation, and wheel alignment. Categories for premature tire failure, Paths B, C, and D, include tires with "Abnormal wear," "Nothing observed," and "Other conditions." The aim of this section is to determine and prioritize practices to minimize the number of tires that prematurely leave the tire fleet on paths B, C, and D. Additionally there is some ability for improvement in the overall tire chain by increasing the reuse ("Path E") of tires that would otherwise be retired with nothing observed.

As reported in Chapter 2, based on RMA (2002), average tire life is about 40,000 miles. However, there is no further publicly available data to better understand whether these data are representative of the fleet at large, of OE versus replacement market tires, or whether these are based on a limited data set of particular brands. Significantly, considering that more than half of tires are replaced before their designed tread wear lifetime, these are important questions. As a result, a quantitative estimation of current tire cycle is developed here.

The first step in developing the tire flow model is setting a baseline assumption for the designed, or expected, tire life based on NHTSA's tread wear testing and publicly available tire warranty information for tire makes and models. NHTSA provides information from its tire tread wear testing at SaferCar.gov (2006). The tread wear grade, a component of the Uniform Tire Quality Grading (UTQG) testing, is a comparative rating generated from the results of an outdoor highway test in which the tire is run in a convoy with several standardized "monitoring" tires. After 7,200 miles, the test tire's wear is compared with that of the monitoring tires. A high rating indicates low tread wear on the standardized test.

The percentages of tire models within given tire grade ranges are shown in Table 8. The wear ratings are meant to give relative tire tread wear, however the grades generally also are proportional to the associated warranties of those tires. The corresponding estimated design tire life, based on warranties of tires of the same tire tread UTQG range, are shown side-by-side in Table 8. Using the percent of available tire models in each category to weigh the design tire mileages, the average expected tire life is estimated to 53,900 miles. Note that these are the number of *models* and not the percentages of *sales-weighted tires,* and therefore this is a non-rigorous result that is to be used only because there is no available data on tire sales volumes in each UTQG range.

TABLE 8. Estimated Designed Tire Life

Uniform Tire Quality Grading (UTQG)	Percent of Tire Models Available [a]	Approximated Design Life [b] (miles)
200 or less	15	40,000
201-300	25	50,000
301-400	32	55,000
401-500	20	60,000
501-600	6	70,000
600 or greater	2	80,000
Weighted-average		53,900

[a] *from NHTSA data (Safercar.gov, 2006);* [b] *estimated from warrantees of available tires (Tire Rack, 2006)*

The next step developing the tire flow model is to incorporate the known data on pervasive practice of tire pressure under-inflation and its impact on tire tread life. The impact of this factor shown schematically is to shorten the length of "Path A" in Figure 9. Information about the average under-inflation of tires in the U.S. vehicle fleet is taken from Thiriez and Bondy (2001). As discussed in the "Tire Maintenance Practices" section in Chapter 2, tire manufacturer Goodyear reported a linear relationship between a 1.0-psi under-inflation (below vehicle placard pressure) and a 1.78% reduction of tire tread life (NHTSA, 2002). Estimating from this relationship and average under-inflation levels (6.8 psi for cars and 8.7 psi for light trucks), average tire life for U.S. tires is reduced approximately 12% to 15%. U.S. vehicle stock-weighted numbers of cars and light trucks to these averages results in an average decrease in tire life from the expected design mileage of 53,900 miles to 46,640 for all passenger vehicles.

TABLE 9. Estimation of Reduction in Gradual Wear Tire Life Due to Under-Inflation

	Passenger Vehicles [a]	Cars	Light Trucks
Vehicle stock (millions of vehicles)	218	130	88
Average placard pressure [b]	32.0	30	35
Average tire pressure under-inflation [b]	7.6	6.8	8.7
Percent under-inflation (compared to placard)	23.6%	22.7%	24.9%
Resulting decrease in average tire life [c] (mi)	7,260	6,524	8,347
Resulting decrease in average tire life (%)	13.5%	12.1%	15.4%
Average tire life	46,640	47,376	45,553

[a] vehicle stock-weighted averages (US EIA, 2005); [b] from Thiriez and Bondy (2001); [c] based on NHTSA (2002) linear relationship of each 1.0 psi below placard equivalent to 1.78% tread wear mileage reduction

Estimation assumptions are made here to account for the number of tires that are retired from the vehicle fleet before their design tread wear lifetime, and these assumptions are used to estimate the impact on average tire life mileage. Again, categories and percentages for tire replacement reasons are taken from Weissman et al (2003). "Abnormal wear," accounting for approximately 50% of tire replacements, is defined here as those tires that wear unevenly, for example from an abrupt braking incident causing a relative bald spot or from uneven wear on the outside of under-maintained (e.g., under-inflated or un-rotated) tires. Tires that are discarded with "Nothing observed" are generally thought to be discarded because they are in a set, with one of the tires having failed due to unevenness, puncture or some other reason. From the survey of private vehicle users, this "Nothing observed" category accounts for about 10% of tires discarded. The "Other" tire disposals, about 20%, are for reasons such as road hazards and tire defect-related problems (e.g., oxidation, separation).

With assumptions about when tires are replaced for each of these reasons, average tire life for many tires is estimated from the tire replacement percentages. To emphasize, these assumptions are used for illustration purposes in lieu of data. Using the result from Table 9 for average tire life of 46,640 as a starting point, we estimate the estimated mileage at which the other tire replacement incidents (Patch B, C, and D) could occur to be at three-quarters of the otherwise gradual tire life mileage, or at 34,980 miles. The logic for this estimation is that if the incidents were entirely random (i.e. *not* age- or mileage-dependent) , they would occur at the midpoint of the tire life (i.e. about 19,000 miles); however, because all of the reasons for early disposal have an increased chance of occurring for older and higher mileage tires, we assume they occur at halfway between the mid-life point and the assumed full lifetime.

The result, presented in Table 10, for the given assumptions for percents and mileage estimates is to have a fleet average tire mileage of 37,312 miles for private vehicle users.

TABLE 10. Impact of Early Tire Replacement on Average Tire Life for Private Vehicles

Replacement reason	Tire Flow Path [a]	Percentage [b]	Assumed mileage of replacement incident	Comments
"Other conditions" (road hazard, puncture, oxidation, separation)	B	20%	34,980	Assumed to occur at 75% of tread wear design life
"Abnormal" or uneven wear	C	50%	34,980	Assumed to occur at 75% of tread wear design life
"Nothing observed" tire removed in a set (with tread remaining)	D	10%	34,980	Assumed to occur at 75% of tread wear design life
Tires re-used within fleet	E	0%	0	Assumption
Gradual tire tread wear	F	20%	46,640	From Table 6
Estimated average tire life [c]			37,312	

[a] see Figure 9 above; [b] approximated from Weissman et al (2003); [c] weighted average of tire flow paths

Using the above assumptions as a baseline, changes in tire management practices are evaluated to estimate the extent to which the average life of their tires can be extended from two available options. We apply to the above baseline two different scenarios: (1) improved tire pressure inflation practices and (2) nitrogen inflation.

We elected to characterize the practice of "improved tire pressure inflation" generically – without specifying exactly the means of technology and/or public awareness programs by which to achieve the level of improvement in reducing the gap between average under-inflation and the proper "placard" level. The logic of this is based on the assumption that average private users' improvements could require a combination of both technology and education to bridge the under-inflation gap. For example, we reiterate from the above survey that about a quarter of drivers do not monitor their own tire pressure, another one-tenth did not have anyone (mechanic or anyone else) monitor their tires. A sizeable number, 27% of respondents did not offer an answer for the correct tire pressure for their vehicle. Even those who did give pressure values, offered a large range of pressures, suggesting that some could be either incorrect or simply guessing for the survey. With this prevailing uncertainty about the extent to which inflation practices could change with TPMS plus an education campaign, we estimate tire longevity impact for an outer boundary improvement of a 90% improvement in under-inflation (we analyze the full range of impacts in the life cycle section, Chapter 6).

For estimating the potential impact of deploying nitrogen inflation system technology, we make several assumption based on the findings from this report's literature review. Specifically, nitrogen inflation systems for vehicles could prolong tire service life for average vehicles from (1) improved (i.e., lower) oxidation effects of nitrogen as an inflation medium eliminating some of the premature tire replacements and (2) improved (i.e. increased) retention of air pressure resulting in elongating the long-term gradual tire wear. For the first part, we reduce the oxidation-related tire replacements. To estimate this effect, we reduce the percentage of tire replacement from the "Other conditions" category, (Path B from Table 10, above) from 20% to 10%. For the second part on longer pressure retention, we estimate an improved under-inflation from the current value (7.6 psi below vehicle placard) by one-half (to 3.8 psi below placard). Note that this improvement in under-inflation is lesser in magnitude than the above "tire pressure inflation" practice improvement; this is because nitrogen systems are passive and require no operator changes in maintenance practices. With a lack of data to validate these estimations, we emphasize that they are crude, and only serve to offer a starting point from which this research project's "technology implementation" portion is meant to test.

Table 11 shows the resulting impact of the two scenarios on average lifetime mileage. As applied above we estimate inflation improvement practices using data from the tire manufacturer. Goodyear reported a linear relationship of 1.0 psi under-inflation equating to a 1.78% reduction of tire tread life (as reported in NHTSA, 2002). Under the improved vehicle user tire inflation practices scenario, a 14% improvement (from 37,312 to 42,539 miles per tire) results. With the use of nitrogen inflation, the estimated average tire life increases by 11% (from 37,312 to 41,472 miles per tire).

TABLE 11. Estimations for Two Improved Tire Practice Scenarios for Private Vehicle Users

Scenario	Tire inflation (psi)		Average Tire Life (miles)		Comments, Description
	Baseline	New	Baseline	New	
Improved tire pressure inflation	24.4	31.2	37,312	42,539	Improved tire pressure inflation from tire pressure inflation education and outreach campaign and TPMSs; improve under-inflation by 90% (from approximately 8 psi to 0.8 psi)
Nitrogen inflation	24.4	28.2	37,312	41,472	Eliminate oxidation-related (10% of tires) early tire replacement; improve under-inflation by a half (8 psi to 4 psi under-inflation)

Fleet Tire Management

Based on the above tire flow model and the interviews with vehicle fleet personnel, we took a methodical look at the cycle and flow of tires through vehicle fleets in an effort to determine critical procedural steps that could have a substantial positive impact on tire longevity and waste. We develop assumptions for two fleets, based on Fleets A and B from the Chapter 3 fleet personnel interviews. The differences between how, why, and in what proportions tires were maintained and discarded between fleets A and B offer key insights in formulating "Best Practices" principles later in this report.

Recall that there is not a set procedure for the fleet personnel interviewed to specifically log data on tire use, tread wear, and tire disposal over the tire life cycle. Information is kept at the vehicle level, and general information about tire maintenance is kept, but not in any systematic way that lends itself to development of a model that comprehensively quantifies the flow of tires through the fleets' vehicles. However, the different information from fleet personnel, with estimations about how and why tires are discarded, is sufficient to develop a generalized, illustrative understanding of fleet tires' life cycles through the vehicles to aid in developing recommendations for "best practices" of tire-related procedures in fleet garages.

There are several reasons that vehicle fleets with many vehicles can substantially reduce tire failures and thus increase the average tire life per vehicle, especially when compared with tires in private vehicles. These reasons are highlighted here because they relate to the formulation of recommendations for "best practices" for vehicle fleets. In the most obvious sense, private vehicle owners generally seek the utility of driving (while minimizing the maintenance costs and time), whereas fleet personnel are paid specifically to operate and maintain vehicles. Due to this obvious occupational and motivation difference, fleet personnel have the advantage of tire maintenance expertise and experience. In addition, fleets have economies of scale advantages; simply having many vehicles and many mechanics to work on them provides valuable data on which vehicles, tires, and practices are most important in reducing future maintenance needs. Fleets also benefit from bulk purchasing rates for parts and contracted-out service work.

Most importantly for tire-specific management, fleets have a large enough number of tires to efficiently reuse them within their own fleet. Unlike private users who commonly discard "nothing observed" tires that have significant remaining tread life, fleets have the opportunity to match up these tires (with other similar tires from other vehicles) for re-use on other vehicles. Because matching tires by tire characteristics (size, brand) and tread life is crucial to even wear, economies of scale is a precursor to being able to effectively re-use tires within a fleet's own vehicles. Finally, the frequency of vehicle shop visits is critical in offering fleets a substantial advantage over private vehicle users' automobiles. Whereas private vehicles typically only visit a maintenance garage every 3,000 to 5,000 or more miles for routine visits, many fleet vehicles return daily, weekly, and monthly. And this frequency, in turn, allows additional monitoring, inspection, and maintenance of tires, as needed.

With the information collected from the fleet interviews about how fleets manage and maintain tires, we add an additional tire longevity improvement measure to the two examined for private vehicles. Therefore, for fleets we assess three modifications to fleet tire practices: (1) increased re-use of tires within the fleet of tires with remaining even tread life, (2) more regimented tire inflation practices, and (3) installation of a nitrogen inflation system.

As done previously for private vehicle users, we make assumptions about average tire under-inflation and fleet management of tires (and the resulting tire replacement reasons). With the same starting point as for private vehicles of average designed tire service life of 53,900 miles per tire, we estimate the reduction from this baseline due to under-inflation. For fleet vehicles, due to fleet's improved under-inflation and tire management practices as compared to private vehicle users, we use different baseline assumptions. As above for private users, we start with under-inflation correction, which reduces design life from 53,900 miles to 50,270 miles (assumption here is that under-inflation by fleets is half the magnitude of private vehicle users).

TABLE 12. Estimation of Reduction in Tire Life Due to Under-Inflation for Two Fleets

	Fleet A	Fleet B
Average placard pressure	32.0	32.0
Average tire pressure under-inflation	3.8	3.8
Percent under-inflation[a] (compared to placard)	11.8%	11.8%
Resulting decrease in average tire life[b] (mi)	3,630	3,630
Resulting decrease in average tire life (%)	6.7%	6.7%
Average tire service life (after under-inflation correction)	50,270	50,270

[a] Estimated as half of the value from Thiriez and Bondy (2001); [b] based on NHTSA (2002) linear relationship of each 1.0 psi below placard equivalent to 1.78% tread wear mileage reduction

Based on discussions with personnel at Fleet A and Fleet B, we approximate tire replacement percentages for the tire flow "paths" (comparable to Figure 15 and Table 10, above). The key differences for these fleet tire flows as compared to the private vehicle tire flows are as follows. There are less "other (oxidation, separation, etc.)" tire replacements (fleet 10% vs. private 20%), likely due to better tire inspection and inflation practices by the fleets. The fleets also are estimated to have less "abnormal or uneven tire" replacements (10% vs. 50%), presumably due to the fleets' improved tire rotation and wheel alignment maintenance. The only difference between the two fleets that is examined here is regarding what each fleet does with the "nothing observed" or "still good" tires that are removed from a vehicle due to a problem with some other tire in that vehicle's set of tires. Whereas Fleet A reuses most of the tires (35% out of 40%) that still have remaining and even tread, Fleet B does not as commonly reuse tires (5% out of 40%, or about 13%). These factors contribute to a larger percentage of fleet tires being retired due to gradual tire wear.

Figure 16 schematically demonstrates two fleet management practices with differing percentages for the tire replacement. Note that these are only loosely based on the actual percentage breakdown of all tires that are deployed in Fleet A and Fleet B as described above (considering they are based on interview conversations in lieu of actual data), and it is therefore more apt to refer to these as hypothetical fleets. Nonetheless, examining the breakdown of tire disposal reasons and paths in these two fleets provides insights on how fleets can better manage their fleet tires.

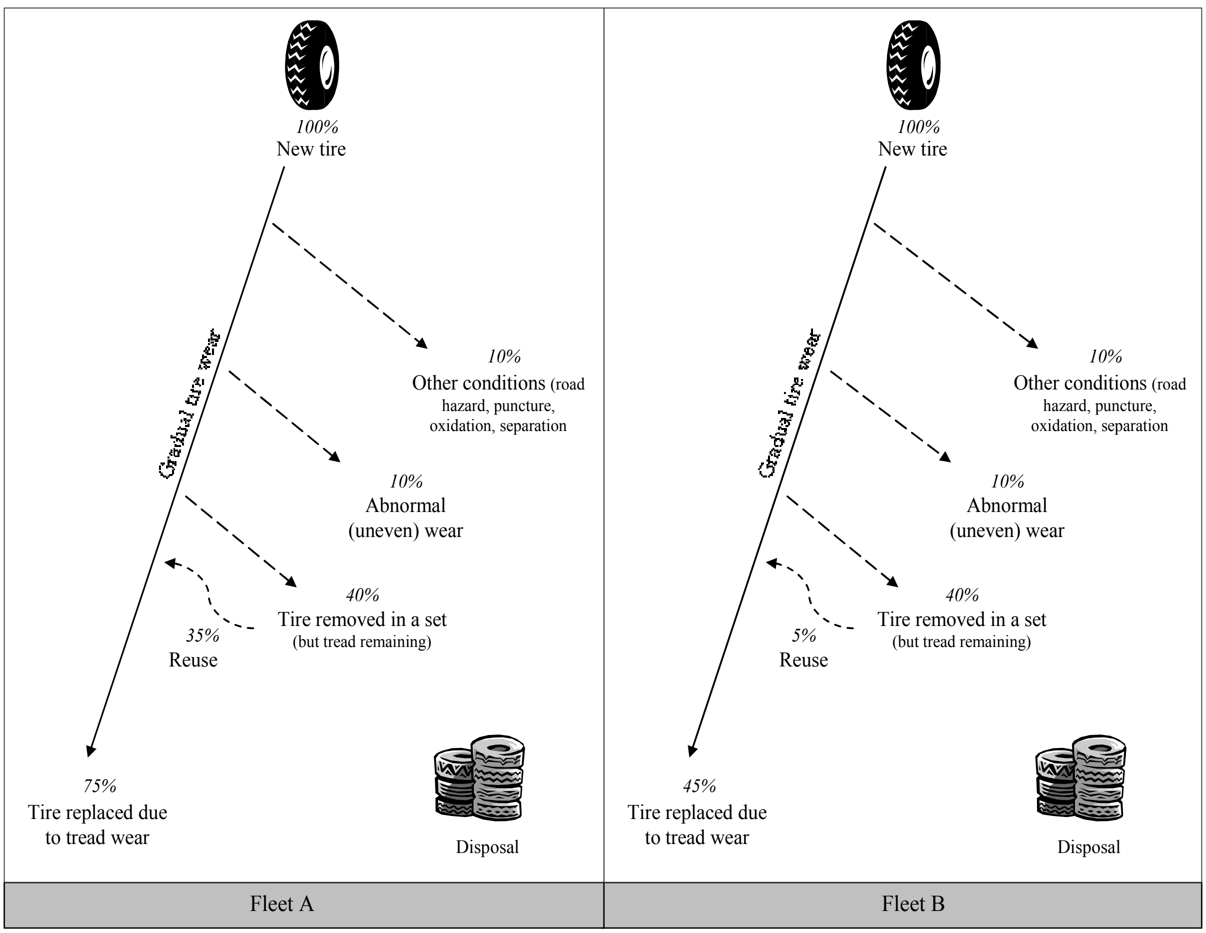


FIGURE 16. Percentage Tire Management Breakdown for Two Hypothetical Fleets

Applying Fleet A and Fleet B's percentage likelihood of tire removal for the various reasons, the average lifetime mileage of tires in each hypothetical fleet is calculated in Table 13. Because

Fleet A re-uses a larger percentage of its replaced tires than Fleet B (namely, those tires that were "removed in a set" with "nothing observed"), Fleet A's average tire life is 47,128 miles, an 8.7% increase over Fleet B at 43,358 miles per tire.

TABLE 13. Impact of Early Tire Replacement on Average Tire Life for Two Fleets

Replacement reason	Percentage [a]		Assumed mileage of replacement incident	Comments
	Fleet A	Fleet B		
"Other conditions" (road hazard, puncture, oxidation, separation)	10%	10%	37,703	Assumed to occur at 75% of tread wear design life
"Abnormal" or uneven wear	10%	10%	37,703	Assumed to occur at 75% of tread wear design life
"Nothing observed" tire removed in a set (with tread remaining)	5%	35%	37,703	Assumed to occur at 75% of tread wear design life
Tires re-used within fleet	35%	5%	NA	
Gradual tire tread wear	75%	45%	50,270	From Table 6
Estimated average tire life	47,128	43,358		

Along with the improvement in tire re-use within the fleet, other modifications in fleet tire practices and their impact on average tire service life are also shown below in Table 14.
As above for private vehicles, we explore improved tire inflation practices and the extent to which nitrogen inflation systems for vehicles could prolong tire service life for average vehicles. To reiterate, the key differences for fleet vehicles are that they have improved baselines characteristics for under-inflation, tire management, and therefore average tire lifetime as compared to private vehicles. As a result, we estimate that the same measures have lesser impacts on tire longevity for fleets than for private vehicles. For example, where we estimate nitrogen inflation for private users to improve average lifetime mileage by 11%, the corresponding impact on the fleets is just 5%. Similarly, improving tire inspection and inflation practices (such that under-inflation is reduced by 90%) results in an increase in private user lifetime tire mileage of 14%, compared to just 6.5% for the fleets. Improved tire re-use within Fleet A affects average tire mileage more prominently, by 8.7%, than either nitrogen inflation systems or more diligent tire inflation inspection and inflation. Utilizing all three fleet practice modifications, nitrogen inflation, reduced under-inflation, and increased in-fleet re-use, resulted in a 15.8% average tire mileage increase for Fleet A.

TABLE 14. Estimations for Improved Tire Practice Scenarios for Vehicle Fleets

Fleet Practice (Base Fleet)	Tire inflation (psi)		Average tire service life (miles)		Percent improvement in average tire service life	Comments, Description
	Baseline	New	Baseline	New		
Nitrogen inflation (Fleet A)	28.2	30.1	47,128	49,481	5.0%	Eliminate oxidation-related (5% of tires) early tire replacement; improve under-inflation by a half (3.8 psi to 1.9 psi)
Nitrogen inflation (Fleet B)	28.2	30.1	43,358	45,574	5.1%	Eliminate oxidation-related (5% of tires) early tire replacement; improve under-inflation by a half (3.8 psi to 1.9 psi)
Improved tire pressure inflation maintenance (Fleet A)	28.2	31.6	47,128	50,191	6.5%	Improved tire pressure inflation from increased maintenance and TPMSs; improve under-inflation by 90% (from 3.8 psi to 0.38 psi)
Improved tire pressure inflation maintenance (Fleet B)	28.2	31.6	43,358	46,176	6.5%	Improved tire pressure inflation from increased maintenance and TPMSs; improve under-inflation by 90% (from 3.8 psi to 0.38 psi)
Improved tire re-use within fleet (Fleet B)	28.2	28.2	43,358	47,128	8.7%	Improved re-use of tires that were removed in a set with "nothing observed"; re-use goes from 5% of tires replaced to 35%
All (inflation practices, tire re-use, and nitrogen system) modifications (Fleet A)	28.2	30.1	43,358	50,191	15.8%	Increased re-use of tires within fleet; eliminate oxidation-related (5% of tires) early tire replacement; improve under-inflation by a 90% (3.8 psi to 0.38 psi)

Chapter 6. Life Cycle Energy Analysis for Tires

Overview of Tire Life Cycle

Life cycle assessment (LCA) methods provide a consistent framework to account for the environmental burdens across each of the life cycle phases of a product or service, including the raw material acquisition, processing, manufacturing, distribution, use and disposal phases (ISO, 1997). Studies that employ LCA methods are typically time and data intensive, and the reliability of the results is dependent upon the availability of adequate data on processes specific to the product or service. While several studies employing the LCA framework or methodology have focused on passenger vehicle tires (Guelorget et al., 1993; Amari et al., 1999; Krömer et al., 1999; Freire et al., 2000; Corti and Lombardi, 2004), few reports provide detailed descriptions of the underlying analysis and data. The present analysis relies upon the LCA framework to discuss the life cycle energy of a passenger vehicle tire, but it is a streamlined analysis, relies upon secondary sources, and does not approach the standards that apply to full life cycle assessment studies (ISO, 1997). The goal of the present analysis is to provide perspective on various tire design and management issues in reference to the life cycle energy of a typical passenger vehicle tire.

Figure 17 depicts the major life cycle phases of a vehicle tire, including raw material acquisition, material processing, tire manufacture, tire use and tire end-of-life (EOL). Variations in material use are represented as a material substitution option, and various tire EOL options are indicated. Three of the EOL options, regrooving, retreading and recycling, involve the reintroduction of tire materials or parts into upstream phases of the tire life cycle. Three more general categories that complete the life cycle include final disposal or placement, material recovery and energy recovery. The present analysis focuses on energy requirements during the first four phases of the life cycle, which tend to dominate the total life cycle energy balance. The energy requirements or credits associated with EOL options are approximated using a more cursory approach and are based upon disposal practices typical for California; energy requirements for these processes are more difficult to quantify on a consistent basis.

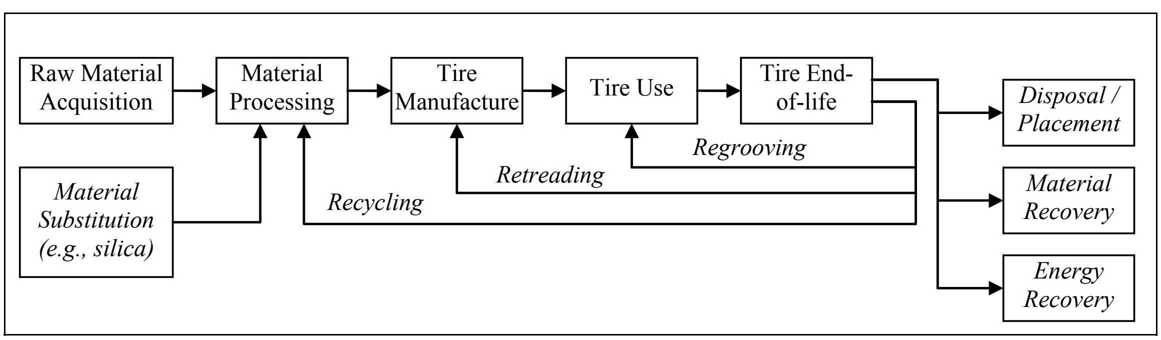


FIGURE 17. Life Cycle Phases of a Tire, Including Material Substitution and End-of-Life Options

The functional unit used as the basis of the present analysis is a single 20-pound (9.1 kg) light-duty vehicle tire with a service life of 37,312 miles on a vehicle with an average fuel economy of 20.4 mpg (see Table 15). It is assumed that the tire is maintained properly, subjected to typical driving conditions and experiences no change in rolling resistance.[2] The results of the life cycle energy analysis are shown graphically in Figure 18 (and in tabular form in Table 16), where the first two phases indicated in Figure 18 have been combined into a single phase, material acquisition and processing. The energy balance for the EOL phase is shown as a net energy gain due to the fraction of waste tires used as fuel for cement kilns or in electricity generation facilities, thereby displacing primary fuels such as coal or natural gas. As indicated, energy consumption during the use phase dominates the life cycle energy balance, contributing to 97.9% of the total life cycle energy and 96.6% of the non-EOL input energy. Material acquisition and processing contributes approximately 2.9% of the total energy requirement and tire manufacturing contributes less than 1%. The original data sources and calculations underlying these life cycle energy results, and the California-specific calculations for the end-of-life phase, are discussed later in the chapter. The effects of varying certain key variables (vehicle mass, coefficient of rolling resistance, average powertrain efficiency, tire pressure, tire service life and tire production energy) on the total life cycle energy of a tire are also discussed later.

TABLE 15. Functional Unit Attributes

Attribute	Quantity
Tire mass (lbs)	20
Tire mass (kg)	9.1
Service life (miles)	37,312
Average vehicle fuel economy (mpg)	20.4

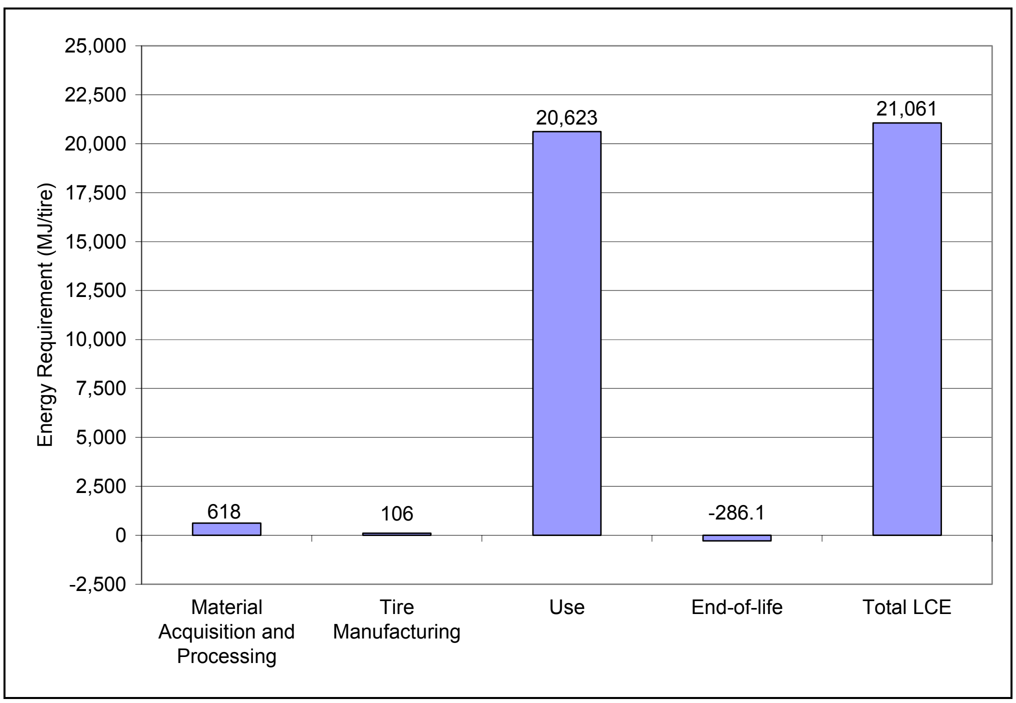


FIGURE 18. Life Cycle Energy of a Typical Passenger Vehicle Tire

[2] In actuality, rolling resistance can be reduced by up to 20% as tread depth decreases over the life of a tire (NRC 2006).

TABLE 16. Summary of Energy Requirements and Credits for Each Life Cycle Phase

Life Cycle Phase	Energy Requirement or Credit (MJ/tire)	Percent of Total LCE	Percent of Non-EOL LCE
Material Acquisition and Processing	618	2.9%	2.9%
Tire Manufacturing	106	0.5%	0.5%
Use	20,623	97.9%	96.6%
End-of-life	-286.1	-1.4%	-
Total LCE	21,061	100%	-
Non-EOL LCE	21,347	-	100%

Tire Life Cycle Phases

Material and Energy Inputs

The material composition and associated energy requirements of a typical light-duty vehicle tire are indicated in Table 17. The material composition is primarily based on recent data provided from Modern Tire Dealer (2006).[3] The actual material composition of light-duty vehicle tires will vary by tire type and has varied over time in response to improvements in tire design and changes in raw material costs. The values indicated here are considered representative of a typical light-duty vehicle tire. Some of the materials not accounted for in this study include specialized plasticizers and stabilizers (e.g., zinc oxide), certain filler types (e.g., silane) and some fabric types (e.g., rayon, aramid). Though important for design and performance reasons, these materials are typically used in small enough quantities that their exclusion will not significantly influence the analysis results.

The first column in Table 17 indicates the material content per kg of tire and the second column indicates the amount of primary energy[4] required to produce one kg of each material. This specific energy value does not include the feedstock energy of each material, define here as the amount of chemical energy that would be released if the material were combusted. The total production energy per tire is expressed in absolute units in the third column and as a percentage of the total production energy of a tire in the fourth column. The data sources and assumptions behind each of these energy values are described in detail below.

[3] This breakdown varies from that presented in the recent report from the National Research Council (NRC 2006). Most significantly, the NRC study reports 2.3 lbs of carbon black for a 26.6 lb tire as being typical. This is 8.6 percent of the tire weight.

[4] Primary energy is the total energy extracted from the natural environment (e.g., coal, natural gas, etc.) and used as an input during the life cycle of the product or service. Primary energy does not, in this case, include the energy required to produce conversion or processing equipment, such as delivery trucks, machinery, etc.

TABLE 17. Material Composition and Energy Requirements for a Typical Tire

Tire Material	Material Composition (kg/kg tire)	Specific Energy (MJ/kg material)	Total Production Energy (MJ/kg tire)	Percent of Total Energy (%)
Synthetic rubber	0.26	87.2	22.89	33.6%
Natural rubber	0.09	9.3	0.81	1.2%
Carbon black	0.33	99.5	33.08	48.6%
Silica	0.02	0.38	0.01	0.01%
Steel	0.15	33.5	5.03	7.4%
Plasticizers	0.10	42.0	4.20	6.2%
Fabric	0.05	42.0	2.10	3.1%
Total	1.00	*na*	68.12	100%

Material Acquisition and Processing

Synthetic and Natural Rubber. The rubber used in tires can be of two general types, natural and synthetic. Natural rubber is derived from the sap of rubber trees (*Hevea brasiliansis*) and is a polymer of isoprene (2-methyl-1,3-butadiene). Synthetic rubber is produced from petroleum and coal byproducts, as well as additives such as zinc oxide. The main ingredients for synthetic rubber are styrene and butadiene, which are combined in a polymerization process to produce styrene-butadiene rubber (SBR). In this study, the energy requirements for the production of styrene and butadiene are derived from life cycle energy values provided by the European Association of Plastics Manufacturers (EAPM, 2006). The production of 1 kg of SBR is assumed to require 0.4 kg of styrene and 1.2 kg of butadiene (Amari et al., 1999). In addition to the primary energy required to produce styrene and butadiene as intermediary products, the feedstock energy lost from this conversion process (45.2 MJ/kg for styrene and 46.7 MJ/kg for butadiene) is added to the production energy for SBR, as is energy input to the polymerization process, 8.93 MJ/kg (Amari et al., 1999). The resulting specific energy for SBR is 87.2 MJ/kg. This value is consistent with other LCA studies of rubber use in vehicle tires, such as Stodolsky et al. (1995), who report 88 MJ/kg for rubber material in vehicle tires.

The primary energy resources extracted for the production of styrene and butadiene include crude oil (80.2% of primary energy resources on an energy basis for butadiene, 53.3% for styrene) and natural gas (19% of primary energy resources on an energy basis for butadiene, 43.7% for styrene). Electricity production is assumed to occur onsite at the chemical plant through the conversion of waste byproducts (EAPM, 2006), and therefore draws upon an industry-specific fuel mix and conversion efficiency.

Life cycle energy data specific to natural rubber was not found in the literature. As a proxy, it is assumed that the process energy for the polymerization of styrene and butadiene is equivalent to that needed to process the isoprene (C5H8) collected from rubber trees. It is assumed that transport overseas dominates the transportation energy needed to deliver natural rubber, and it is assumed that natural rubber is shipped via ocean tanker 4,000 miles with an efficiency of 1.9 gallons of diesel per 1,000 ton-miles of transport (US EPA, 2004). The resulting energy requirements are 8.93 MJ/kg for the process energy and 0.33 MJ/kg for transportation, resulting in a total specific energy of 9.3 MJ/kg for natural rubber.

Carbon black. The energy required to produce carbon black from an oil furnace is reported by Kirk-Othmer (1996) as ranging from 93-160 MJ/kg. The value used by Amari (1999) is the average of this range, 126.5 MJ/kg. It is not clear if this energy intensity represents the total upstream energy required to produce carbon black, or if it also includes the feedstock energy. The approximate feedstock energy of carbon black (assumed to be equivalent to that of anthracite coal, 27 MJ/kg) is subtracted from the production energy assumed by Amari, resulting in a net primary energy requirement of 99.5 MJ/kg.

Silica. The raw material inputs for the production of silica are sand and quartz, which are mined at relatively low energy cost and require little processing energy. After mining and transport, the sand or quartz is classified, scrubbed, conditioned, floated and deslimed The total energy required to deliver these materials is strongly dependent on delivery distance, which can vary depending upon the location of the manufacturing facility in relation to the mining location. In a life cycle study of amorphous silicon PV technology, Phylipsen and Alsema (1995) report that 2.85 kg of silica (SiO_2) would be required to produce 1 kg of silicon, and that 0.3 kWh_{th} of primary energy is required to deliver sufficient silica for 1 kg of silicon. This corresponds to 0.38 MJ of primary energy per kg of silica. Silane is used to improve the bonding characteristics of silica, with about 5 pounds of silane needed for each 100 pounds of silica (NRC, 2006). However, the additional energy required to produce silane (SiH4) is not taken into account in the present study.

Steel. The life cycle energy of the steel used for tire production is assumed to be equivalent to that used by Keoleian et al. (1999), 33.5 MJ/kg, where the system being modeled was an air intake manifold for a vehicle. The value from Keoleian et al. includes all upstream primary energy requirements for steel, which does not appear to be the case for the specific energy reported for steel by Amari (27.8 MJ/kg) in his analysis of passenger vehicle tires.

Plasticizers. Mineral oil products are typically included in the elastomer components of tires to increase plasticity and as a material extender. The energy required for these materials is modeled as being equivalent to that needed to produce residual oil product, as reported in the Argonne National Laboratory GREET model (ANL, 2006). The energy content of residual oil is 39.5 MJ per kg, and the upstream energy required for the extraction and refining of crude oil is 2.6 MJ per kg of residual oil. The value indicated in Table 18 does not account for the feedstock energy of the plasticizer material.

Polyester. A life cycle analysis of polyester material for clothing has determined that 97.4 MJ of primary energy is required to produce 1 kg of material. Subtracting the amount of feedstock energy feedstock in this material (33 MJ/kg) results in a net primary energy requirement of 42 MJ/kg.

Material substitution options. Two major material substitution options include: 1) the use of natural rubber rather than SBR, and 2) the use of silica instead of carbon black. Given that the energy intensity of both of these materials is lower than the materials they would displace, the energy inputs for material extraction and feedstock preparation would be reduced to the extent that either of these materials is substituted for those indicated in Table 17. The effects of these material replacement options on the total life cycle energy are examined below.

Tire Manufacturing Phase

The energy required for the manufacturing of a tire, 11.7 MJ per kg of tire, is taken from Brown (1996, cited in Amari 1999). This value is lower than that reported in the 1999 Continental LCA study, 16 MJ/kg (Krömer et al., 1999). It is likely that the manufacturing energy reported by Krömer et al. is based upon industry or plant-specific data, and is therefore more accurate than that reported by Amari. However, this discrepancy has only a small effect on the total life cycle energy. Another discrepancy between the two studies is that the Continental LCA probably accounted for scrap or waste material produced during the manufacturing phase, which has not been taken into account in the present study.

Tire Use Phase on the Vehicles

The use phase of a tire requires the major fraction of the energy across the entire life cycle. This is primarily due to the vehicle propulsion energy required to overcome rolling resistance, which is the conversion of mechanical energy into thermal losses through hysteresis interactions between the tire tread and the road surface. Other energy requirements during the use phase are associated with the linear and rotational inertia of the tire, maintaining tire pressure (compression energy) and loss of material through tire abrasion. These losses are relatively small compared to the energy required to overcome rolling resistance.

The fraction of fuel energy consumed by a vehicle that can be associated with rolling resistance depends upon a variety of factors (Ross, 1997; Sovran and Blaser, 2003; NRC, 2006). In the present analysis, a force function is used to estimate the energy dissipated through rolling resistance:

$$F_{RR} = M_v \cdot g \cdot C_R$$

where the rolling resistance force (F_{RR}) is a function of the vehicle mass (M_v), the acceleration of gravity ($g = 9.8\text{m/s}^2$) and the coefficient of rolling resistance (C_R). The total energy dissipated through this force can then be estimated as a function of vehicle driving distance (d) and the average efficiency of the vehicle engine (η_{eng}) and transmission (η_{trans}):

$$E_{RR} = \frac{M_v \cdot g \cdot C_R \cdot d}{4 \cdot (\eta_{eng} \cdot \eta_{trns})}$$

where the total energy is divided by four to represent the energy required for a single tire. The accuracy of this equation for driving cycles can be verified using vehicle simulation results. Table 18 shows simulation results obtained from Advisor. As indicated in the table, the above equation is accurate for a range of rolling resistances for both the federal urban and highway driving cycles, typically deviating by less than 1%. The equation values are determined for a 1,650 kg vehicle with a combined drivetrain efficiency ($\eta_{eng} \cdot \eta_{trans}$) of approximately 17% (around 16% for the FUDS and around 19% for the FHDS). The average engine and transmission efficiencies vary only slightly for the different rolling resistance values assumed for each driving cycle. The driving distance for the FUDS is 7.45 miles and the distance for the FWDS is 10.26 miles. The fuel economies shown in Table 18 are somewhat larger than the average fuel economy of passenger cars and light-duty trucks in 2002, 20.4 mpg (Davis and Diegel, 2004, Tables 4.1 and 4.2).

TABLE 18. Simulation and Analytic Results for the Fuel Energy Required for Various Rolling Resistance Coefficient Values

Driving Cycle	C_R	Vehicle Fuel Economy (mpg)	Powertrain efficiency (%)	Rolling Resistance Energy (kJ)			Percent of Total Fuel Energy (%)
				Simulation	Equation	% diff.	
FUDS	0.012	21.9	15.8%	14,715	14,702	0.09%	35.3%
FUDS	0.009	22.6	15.6%	11,038	11,159	-1.09%	27.5%
FUDS	0.006	23.3	14.7%	7,897	7,904	-0.09%	20.2%
FWDS	0.01	33.7	19.3%	13,815	13,820	-0.03%	37.1%
FWDS	0.006	36.4	18.4%	8,702	8,707	-0.05%	25.2%

The fraction of energy allocated to rolling resistance is shown as a percentage of the total fuel energy for each vehicle in the last column of Table 18. These results are similar to the general results for rolling resistance energy reported in other studies of vehicle fuel economy dynamics (Ross, 1997; Sovran et al., 2003; NRC, 2006). They are higher, however, than the 16% reported in the 1999 Continental life cycle analysis study (Krömer et al., 1999).

Fuel energy is also required to overcome the linear and rotational inertia of the tire mass. The amount of energy required can be expressed as a fraction of the total fuel energy. For the present analysis, the value of 0.4% from the Continental LCA study (Krömer et al., 1999) is used to determine the fraction of total fuel use required to overcome the linear and rotational inertia of a single tire.

The total fuel use energy allocated to the tires is therefore sum of the rolling resistance energy and the energy needed to overcome the linear and rotational inertia of the tire:[5]

$$E_{fuel} = E_{RR} + E_{LRI} = \frac{M_V \cdot g \cdot C_R}{4 \cdot (\eta_{eng} \cdot \eta_{trns})} + \frac{VMT \cdot EC_{gas}}{FE_{ave}} \cdot 0.04$$

Where EC_{gas} is the energy content of gasoline, and FE_{ave} is the average vehicle fuel economy. To attain the total primary energy associated with this fuel use, upstream energy inputs must be taken into account. According to the well-to-tank energy for gasoline reported in the Argonne National Laboratory GREET model,[6] approximately 149.4 MJ of primary energy are required for each gallon of gasoline, which is 18% greater than the energy content of gasoline (122.5 MJ/gallon, LHV).

Some of the feedstock energy contained in tire tread is lost due to abrasion during the use phase. Material lost through abrasion varies due to a variety of factors, including tire type, driving patterns and climate. Continental (Krömer et al., 1999) reports 20 mg of tire lost per tire-kilometer traveled. With the plasticizer material having a feedstock energy of 30.4 MJ/kg (this study), and a lifetime of 37,312 miles (60,045 km), 1.2 kg of rubber and 36.5 MJ of feedstock energy are lost through abrasion.

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[5] Some fraction of fuel energy is also consumed to overcome air resistance created by the tires, but this quantity is not included in the present analysis (c.f., Krömer et al., 1999).

[6] Default GREET values for gasoline in 2005 were used, including a blend of 35% reformulated gasoline and 65% conventional gasoline, with 2.3% ethanol by weight for reformulated gasoline and electricity produced through the average U.S. grid.

An additional energy requirement during the use phase is the inflation energy used to maintain proper tire pressure during the 37,312 miles of travel. This energy requirement has been estimated theoretically, and appears to be very small compared to other life cycle energy requirements. Assuming ideal gas behavior, the ideal work needed to inflate a tire is:

$$W_{ideal} = \int P \cdot dv = \int P \cdot \frac{dm}{\rho_{air}}$$

Where the change in volume (dv) is assumed to be equal to the change in mass (dm) divided by the density of air in a tire (ρ_{air}). If this change in air mass is assumed to be some constant value (ΔM_{air}), the pressure of inflation is assumed constant (P_{infltn}), and the efficiency of converting primary energy into compressed air is estimated (η_{comp}), then the compression work can be represented as:

$$W_{comp} = \frac{P_{infltn} \cdot \Delta M_{air}}{\rho_{air} \cdot \eta_{comp}}$$

For this calculation, the pressure of inflation is assumed to be 15 psi greater than the typical 35 psi of a properly inflated tire, or 50 psi total (3.4 atm). The density of air in a typical tire is calculated using the ideal gas law:

$$PV = nRT$$

where density can be represented as mass over volume (m/V) and n is the mass divide by the molecular weight of air ($m/MWair$):

$$\rho_{tire} = \frac{P \cdot MW_{air}}{R \cdot T}$$

with R = 0.08206 atm-L/gm-mole°K, MW_{air} = 28.9 grams per mole, T = 300 K and P = 3.4 atm, the density of air in a tire would be approximately 4 grams per liter.

The air leakage rate is assumed to be proportional to a tire pressure drop of 2 psi per month. With typical driving of 1,000 miles per month, this would be 2 psi per 1,000 miles. The ratio of air mass lost to total tire air mass (M_{lost}/M_{total}) is therefore 2/35, or 5.7% of the air mass per 1000 miles of driving. The total air mass in a tire can be determined from the air density (4 gm/l) and the tire volume, which can be estimated by the following equation:

$$V_{tire} = \pi(r_2^2 - r_1^2)w$$

Where a typical internal radius of a tire (r_1) is 20.3 cm, a typical external radius (r_2) is 31.58 cm, and a typical width (w) is 20.5 cm, resulting in a tire volume of approximately 37.7 liters.

The total air mass that would be lost through leakage over the service life of a tire would therefore be:

$$\Delta M_{air} = \frac{\rho_{tire} \cdot V_{tire} \cdot M_{lost} / M_{total}}{1000\, mi} \cdot 40{,}000\, mi / tire = 344 \cdot grams / tire$$

Using these values for the compression pressure, air density and leakage rate, the total work required to maintain proper tire pressure over the service life of a tire would be:

$$W_{comp} = \frac{3.4 \cdot 10^5\, Pa \cdot 344\ g / tire}{4\ g / l \cdot \eta_{comp}} = \frac{2.96 \cdot 10^4\, J}{\eta_{comp}}$$

The total conversion efficiency of primary energy to compression work (η_{comp}) is estimated to be 20%, based upon the following approximate efficiencies: primary resource conversion to electricity (33%), electricity transmission and distribution (90%), compressor efficiency (75%) and air losses during the pumping process (10% lost). The resulting energy required over the service life of a single tire is approximately 0.15 MJ. The energy required for compression is therefore negligible compared to the total life cycle energy of a typical tire.

The total energy allocated to the tire during the use phase is therefore the sum of the energy allocated to rolling resistance (E_{RR}), the linear and rotational inertia of the tire (E_{LRI}), the feedstock energy losses due to abrasion (E_{abrsn}), and the energy required to maintain proper tire inflation (E_{infltn}):

$$E_{use} = E_{RR} + E_{LRI} + E_{abrsn} + E_{infltn}$$

These contributions to the total primary energy required during the use phase are summarized in Table 19.

TABLE 19. Summary of Parameters and Energy Requirements for the Use Phase

Parameter	Unit	Value	% total
Vehicle mass	lbs	4,242	
Fuel economy	mpg	20.4	
Rolling resistance coefficient (RRC)	unitless	0.01	
Service life	miles	37,312	
Fuel energy for rolling resistance	MJ/tire	16,652	81%
Fuel energy for tire inertia	MJ/tire	224	1.1%
Total fuel energy for tire	MJ/tire	16,877	81.8%
Feedstock energy for abrasion	MJ/tire	37	0.2%
Energy for air compression	MJ/tire	0.15	0.0007%
Well to pump energy for fuel	MJ/tire	3,710	18.0%
Total primary energy for tire	MJ/tire	20,623	100%

End-of-Life Phase

Figure 17, in the overview section of this life cycle chapter, indicates a variety of end-of-life options for tires. Three of these options involve reintroducing tire materials or components into upstream life cycle phases, and each is likely to result in a reduction of total life cycle energy. Regrooving (increasing tread depth) is mostly done for heavy-duty trucks due to their thicker tread, and has become increasingly uncommon for light-duty vehicle tires. However, if done properly, regrooving can result in a mileage increase of up to 30% (World Tire Industry 1997, cited in Beukering and Janssen 2001, page 96). Retreading (adding a new tread layer to a used but otherwise sound tire) can save up to 80% of the raw materials and energy required to produce a new tire (Ferrer 1997, ETRA 1996, cited in van Beukering and Janssen 2001, page 96), and could therefore reduce the total life cycle energy by both displacing raw material use and extending the service life of non-tread components. Recycled material currently accounts for up to 5% of the material content of a tire, but could potentially account for up to 15% without negatively impacting tire performance (CIWMB, 2004).[7] This feasibility is largely dependent upon the types of processing methods employed and the quality of the resulting rubber crumb material (Zelibor et al., 1992; Klingensmith and Baranwal, 1998; Myhre and MacKillop, 2002). The energy savings attained through recycling would depend upon which process is employed (Corti et al., 2004). And more generally, the potential for energy savings through any of these “loop closing” options will depend upon a range of factors, including technology development and public acceptance.

Though each of these “loop-closing” options had the potential to improve the life cycle energy balance of tires, they are not considered in the present analysis due to the dominance of more conventional EOL practices. The energy balance for the EOL phase in the present study is based upon typical tire disposal practices in California (CIWMB, 2003), where 44% of waste tires are currently landfilled or placed in some location for an indefinite period of time (e.g., stockpiled, alternative daily cover), 35% are used in some alternative application (e.g., construction filler, rubberized asphalt concrete, recycled for crumb rubber, etc.), 17% are combusted in cement kilns and 4% are combusted in cogeneration facilities. The energy credit indicated in Figure 18 for the EOL phase is based upon this breakdown of disposal options. The energy requirements or credits for each of these disposal options are discussed in more detail below.

The energy requirements for final placement or landfill disposal are typically dominated by the energy needed to transport the tire. Following Keoleian et al. (1997) it is assumed that 2.05 MJ of diesel energy is required per ton-mile for transport energy, resulting in an energy requirement of 3.7 MJ for an assumed delivery distance of 200 miles and an 18-pound tire (assuming a 10% mass loss has occurred over the service life).

The energy requirement for alternative applications can vary widely, and are assumed here to have a negligible effect on the total life cycle energy, partly due to lack of data allowing for a consistent comparison across different applications. Some alternative applications may result in an energy credit while others would result in an energy requirement. For example, recycling requires some energy input for processes such as shredding or pulverizing (Corti et al., 2004), but would save the primary energy otherwise required to produce the alternate product that has been displaced. Though some breakdown of the fraction of tries used for different alternative applications is provided (CIWMB, 2003), the energy requirements for the displaced products or material inputs are not quantified and would be difficult to estimate on a consistent basis.

[7] The 2004 IWMB report notes that there is some uncertainty concerning the origin of this recycled material, specifically what fraction is from pre-consumer factory excess and what fraction is from used tires.

In contrast, the primary energy displaced through energy recovery options can be roughly estimated. The feedstock energies for each of the components of the tire modeled in the present study are presented in Table 20. The total feedstock energy is 1,494 MJ per tire, approximately 12% of the total energy used in the non-EOL life cycle phases. Energy recovery methods have the potential to convert this energy into a useful form, effectively displacing energy resources that would otherwise be used in processes such as electricity production or cement production. The use of tire materials as a fuel, referred to as TDF (tire-derived fuel), is considered advantageous due to the somewhat higher heating value of tires and their lower moisture and sulfur content. Cement kilns have the advantage of being able to accept whole tires, while normal boilers require a steel separation process that involves shredding or grinding and can be energy intensive (Corti et al., 2004). The degree to which TDF can displace coal usage will vary between kiln types, coal types and the energy content of the tires. For the present analysis, it is assumed that TDF is capable of displacing an amount of coal equivalent on an energy basis, thereby improving the energy balance by an amount equal to the feedstock energy of the tire, minus diesel truck transport energy for an assumed distance of 100 miles (1.8 MJ/tire). In the case of energy generation (or cogeneration), it is assumed that that amount of primary energy that can be displaced is equal to 75% of the feedstock energy of a typical tire. Averaging across the share of each disposal method typically practiced in California results in an energy credit of 286 MJ for each tire. The breakdown of energy requirements by EOL option is indicated in Table 21.

TABLE 20. Feedstock Energy for Tire Materials

Tire Material	Specific Feedstock Energy (MJ/kg)	Feedstock Energy (MJ/tire)
Synthetic rubber	32.6	295.7
Natural rubber	32.6	295.7
Carbon black	27.0	244.9
Silica	0	0
Steel	0	0
Plasticizers	39.5	358.1
Fabric	33.0	299.4
Total	*na*	1,493.9

TABLE 21. Energy Required for End-of Life Options in California

End-of-Life Options	Share in CA	Energy per tire (MJ/tire)
Landfill or placement	44%	3.7
Alternate application	35%	0
Cement kiln	17%	-1,492
Energy generation	4%	-1,044
Total	100%	*na*
Average	-	-286

Variations in the Tire Life Cycle Energy Balance

The life cycle energy balance for a tire will vary depending upon a wide range of variables. The recommendations proposed in the present report can be placed into perspective by examining the effects of the variables shown in Table 22 on the life cycle energy of a tire. The original baseline value for each variable is indicated, and the range examined is indicated in both absolute units and as a percentage. In real-world systems, there are significant interactions and couplings between many of these listed variables. These have only been partially taken into account. In general, the effects of each of the variables indicated on the life cycle energy are considered independently (i.e., *ceteris paribas*). This section details the assumptions employed to arrive at summary figures for the sensitivity of tire life cycle energy use to these variables. The results of this analysis are summarized at the end of this section in Figures 20 and 21, which indicate the same results but with the vertical axis having a smaller scale in the second figure. The first figure portrays all changes resulting from the variations listed in Table 22, while the second focuses on effects due to variations in tire service life and material production energy. These variations have been normalized to the total life cycle energy (21,061 MJ per tire) as indicated in Figure 18 and Table 16. The total life cycle energy is determined using the following general equation:

$$E_{LC} = E_{RR} + E_{LRI} + E_{TP} + E_{Abrsn} + E_{infltn} + E_{EOL}$$

Where the total life cycle energy (E_{LC}) is composed of energy for rolling resistance (E_{RR}), the linear and rotational inertia of the tires (E_{LRI}), tire production energy (E_{TP}), feedstock energy losses through abrasion (E_{Abrsn}), inflation energy (E_{infltn}) and end-of-life energy (E_{EOL}). The assumptions behind each of the variations listed in Table 22 are discussed in more detail below.

TABLE 22. Ranges Examined for Key Variables in the Life Cycle Energy Balance

Variable	Original Value	Units	Range	
			Absolute	Percentage
Vehicle mass	4,242	lbs	2,500 to 5,500	-40% to +30%
Rolling resistance coeff.	0.01	unitless	0.008 to 0.012	-20% to +20%
Powertrain efficiency	17%	%	13.6 to 20.4	-20 to +20%
Tire Pressure	32	psi	25 to 35	-22% to +10%
Tire service life	37,312	miles	22,400 to 56,000	-40% to +50%
Material production energy	724.2	MJ	615 to 802	-15% to +11%

Variations in the life cycle energy due to changes in vehicle mass take into account concurrent changes in vehicle fuel economy and in tire mass, that later influencing the tire production energy. An and Santini (2004) provide the following empirical correlation between vehicle mass and fuel economy for model year 2002 vehicles:

$$FE = 46030 \cdot M_V^{-0.9246}$$

where the vehicle fuel economy (*FE*) has units of miles per gallon and vehicle mass or curb weight (M_V) is in pounds.[8] Tire mass is assumed to change linearly with vehicle mass, resulting in proportional changes in tire production and manufacturing energy. As indicated in Figure 20, the life cycle energy required changes linearly with the percent change in vehicle mass. This variation represents changes in the life cycle energy of tires used on vehicles with more or less mass than the base case vehicle. The range indicated represents masses for vehicle sizes ranging from compact cars (2,500 lbs.) up to large sport utility vehicles (5,500 lbs.).

The rolling resistance of tires varies significantly between different types of vehicles, but most light-duty vehicle tires have RRCs ranging between 0.008 and 0.012 (NRC 2006). Correlations between average vehicle fuel economy and the RRC for tires are provided in a recent report from the National Research Council (NRC 2006), and a linear fit to these results is indicated in Figure 19. Results from simulations using Advisor on the FUDS and FHDS have been included in this figure. Changes in the RRC result in a reduction or increase in fuel consumption during the use phase, but no changes are assumed for the material production energy or tire manufacturing changes. Changes in the fuel energy requirement resulting from variations in the coefficient of rolling resistance have been determined using the same force function discussed in a previous section. As indicated in Figure 20 and Figure 21, variations in the coefficient of rolling resistance have a nearly identical effect on the total life cycle energy as do variations in vehicle mass.

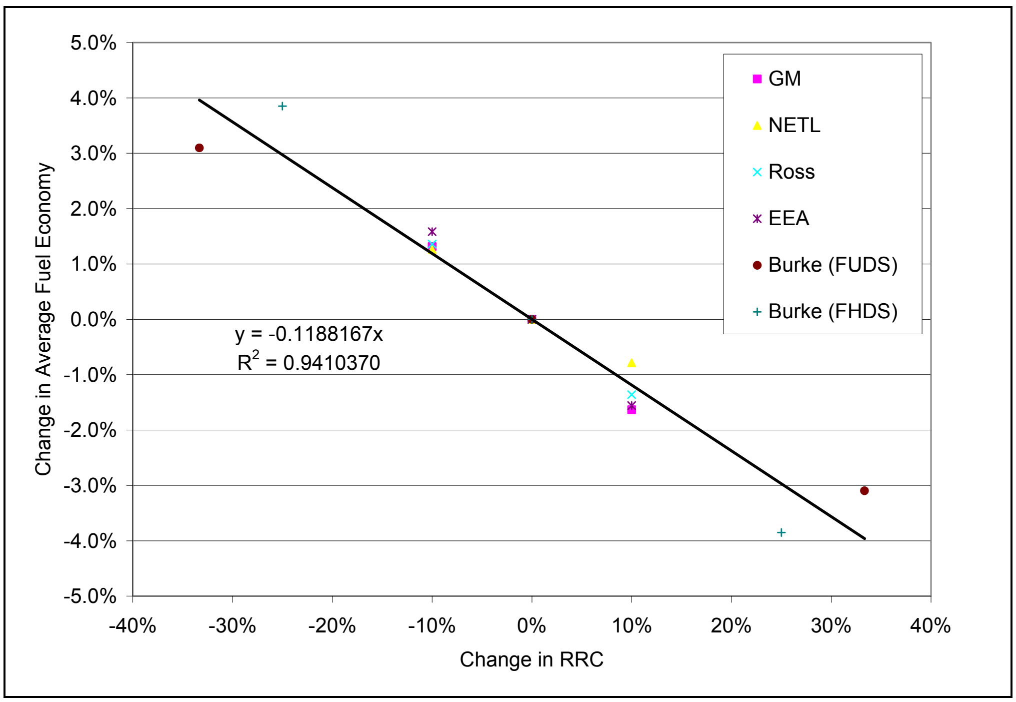

FIGURE 19. Change in Average Vehicle Fuel Economy with Change in Rolling Resistance Coefficient, Results from Four Sources (GM, NETL, Ross and EEA, NRC, 2006) and a Linear Fit to All Results

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[8] This empirical correlation differs from those obtained from the Advisor model. Fuel economies were determined using the Advisor model assuming a constant power to weight ratio of 0.0825 kW/kg across a vehicle curb weight range from 2400 lbs (1091 kg) to 6000 lbs (2727 kg). Results suggest the following correlation for fuel economies on the FUDS, $F.E. = 6059*M^{-0.775}$, and the following correlation applies for fuel economies on the FWDS, $F.E. = 2918*M^{-0.6356}$, where fuel economy (F.E.) is in miles per gallon and curb mass (M) is in kg.

As is the case with vehicle mass or the coefficient of rolling resistance, changes in the efficiency of the vehicle drivetrain also result in changes in the fuel energy needed to overcome rolling resistance. Holding all other variables constant, the powertrain efficiency is varied from -20% to +20%, representing a range of vehicle efficiencies that includes most vehicles within the midsize vehicle class.[9] As indicated in Figure 20, a direct variation in powertrain efficiency, ceteris paribus, results in a non-linear change in required fuel energy, unlike the linear change associated with varying vehicle mass.

Variations in tire pressure can influence the rolling resistance of a tire. In the present analysis the effect of tire pressure on the coefficient of rolling resistance is represented by the following equation:

$$C_R = C_R^{'} \cdot \left(\frac{P_G}{P^{'}} \right)^{-0.48}$$

where the standard tire pressure (*P'*) and gauge pressure (*P*) influence the original coefficient of rolling resistance C_R', as reported by Kelly, 2002. As indicated in Figure 20 and Figure 21, changes in tire pressure can have a significant impact on total life cycle energy.

Changes in the tire service life will influence the amount of energy required in the material acquisition and processing and tire manufacturing phases per VMT. For example, a 50 percent extension in the tire service life from 40,000 VMT to 60,000 VMT would result in two tires being able to provide the 120,000 VMT of service that had previously required three tires. The result is a change in tire production energy proportional to the change in tire service life:

$$E_{TP}(VMT) = E_{TP}^{'} \frac{VMT^{'}}{VMT}$$

Where the original energy for tire production ($E_{TP}^{'}$) is multiplied by the ratio of the original service life (*VMT'*) and the new service life (*VMT*). The average service life of a tire is assumed to be 37,312 miles, though historical trends indicate that the average service life has been increasing since the early 1980s.[10] The result is the non-linear trend indicated in Figure 20 and Figure 21.

Material production energy is examined as a separate variable, but tends to have a smaller effect when compared with variations in tire service life, tire pressure or the RRC. The range of variation indicated in Table 22 is based upon a change in the natural rubber and silica content of the tire, both of which have lower production energy requirements than the materials they are capable of replacing, synthetic rubber and carbon black. With no natural rubber or silica filler, the material production energy increases by 12.6 % to 76.7 MJ per kg of tire. With 50% natural rubber and 20% silica the material production energy decreases by 17.6% to 56.1 MJ per kg of

[9] The extremes within this vehicle class might include a higher performance sports car with a large engine achieving 15 mpg (e.g., BMW M5 or Ferrari 612 Scaglietti) and a more fuel efficient midsize car achieving closer to 30 mpg (e.g., Honda Accord or Ford Fusion). In reality, the masses of vehicles within this class will vary. For fuel economy ratings for comparable vehicles, see the Department of Energy Fuel Economy Website at www.fueleconomy.gov.

[10] Today's steel belted radial passenger tires last approximately 40,400 miles, while properly inflated, rotated and otherwise maintained tires may last 60,000 to 80,000 miles (UK Environment Agency (1998) Tyres in the Environment. UK Government, London.).

tire. Assuming a constant tire mass and manufacturing energy intensity, variations within this range of material compositions result in life cycle energy changes indicated in Figure 20 and Figure 21. This perspective on material production energy is limited. For example, including the reduction in rolling resistance typically associated with increased silica content would significantly change these results. On the other hand, the energy inputs required for such changes during the tire manufacturing process have not be characterized in detail in the present analysis, and it is uncertain to what degree they might influence the total life cycle energy.

The changes in tire life cycle energy indicated in Figure 20 and Figure 21 do not capture the full potential to design or manage tires for increased energy efficiency. Interactions between these parameters would have to be taken into account to provide a full picture of this potential. Table 23 indicates five interdependencies that could have a significant influence on the total life cycle energy of a tire. Dependencies that have not been taken into account are shown as circles (i.e., O's), and dependencies that have been taken into account are shown as checks (i.e., √ 's). In the current analysis, only the dependency of tire mass (and therefore tire production energy) on vehicle weight is taken into account. The effects of these dependencies on tire life cycle energy are uncertain and their quantification would require additional data collection and analysis. For example, powertrain efficiency (η_{pwtrn}) may vary with vehicle mass (V_m). Tire service life ($VMT_{service}$) tends to decrease with low tire pressure (P_{tire}), and the recent NRC report (2006) suggests that there is a slight increase in service life for tires with higher coefficients of rolling resistance, although the influences of different design choices are uncertain. The energy required to produce tires (E_{prdctn}) could either increase or decrease with design choices that influence the coefficient of rolling resistance or tire service life.

A more detailed examination of the influence of tire design and maintenance on tire life cycle energy would take these various interdependencies into account. For example, it is conceivable that a tire with increased silica content would have a lower production energy, higher coefficient of rolling resistance and longer service life. The resulting life cycle energy of this hypothetical tire, however, is not represented by the variations shown in Figure 20 and Figure 21.

TABLE 23. Key Interdependencies between Parameters

Parameters	V_m	C_{RR}	η_{pwtrn}	P_{tire}	$VMT_{service}$	E_{prdctn}
V_m	√					
C_{RR}		√				
η_{pwtrn}	**O**		√			
P_{tire}				√		
$VMT_{service}$		**O**		**O**	√	
E_{prdctn}	√	**O**			**O**	√

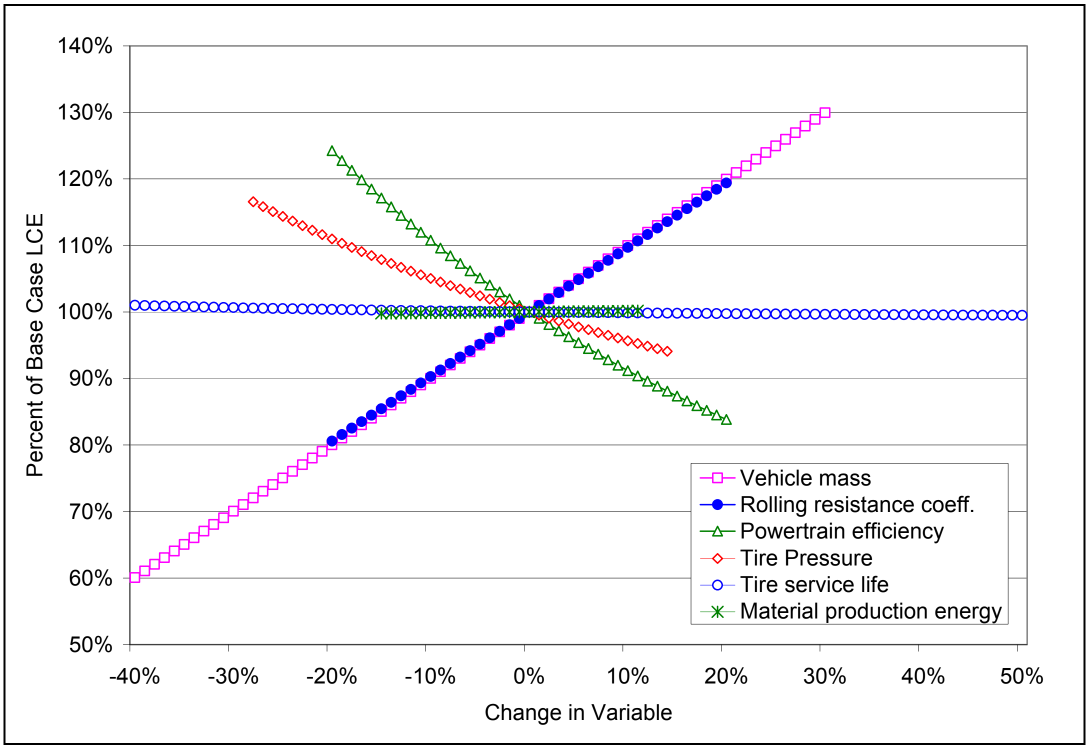

FIGURE 20. Variations in Key Variables Contributing to Tire Life Cycle Energy (LCE)

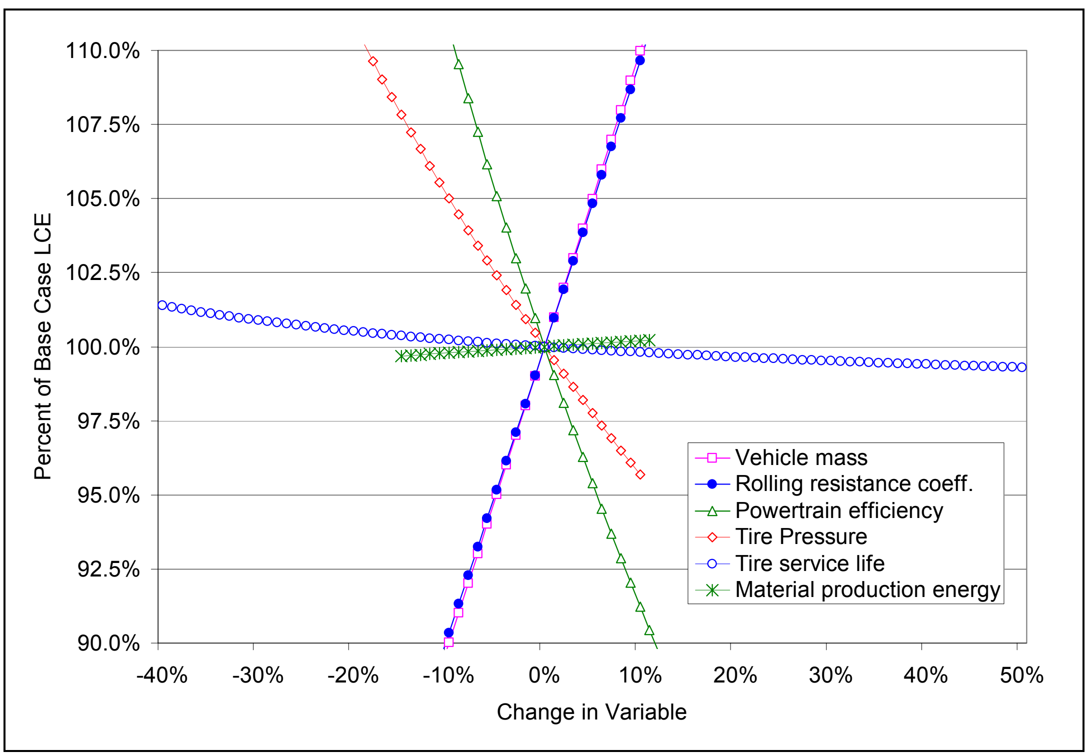

FIGURE 21. Variations in Key Variables Contributing to Tire Life Cycle Energy (LCE), with a Focus on Service Life, Rolling Resistance, Material Production Energy, and Tire Pressure

Chapter 7. Best Practices for Vehicle Fleets

The previous chapters assessed how various tire maintenance, inspection and maintenance practices can impact the longevity and energy use of tires. These observations, taken with information gleaned from the tire research literature review and fleet interview process are combined to develop recommendations of vehicle fleets for tire-related practices. This section summarizes the lessons and principles determined to positively affect tire waste and tire purchasing for management and maintenance of vehicle fleet tires.

There is potential for fuel consumption and waste reduction through a combination of optimization of maintenance procedures and technology implementation. In this best practices section, we outline the suggested fleet practices for achieving these improvements and look at the potential for savings through the fleet procurement and implementation of the following technologies: nitrogen inflation systems, tire monitoring systems, and lower rolling resistance tires.

Maintenance Practices

Simple, tried-and-true maintenance techniques have the potential to significantly increase tire life, reduce waste, and reduce fuel consumption. Cited as the number one cause of premature tire failure, improper inflation is the most important aspect of tire maintenance. Given that the primary tool of the mechanics to assure properly inflated tires is the pressure gauge, the most diligent attention to pressure is wasted when the gauges being used lack accuracy. Pen-type gauges traditionally used by mechanics can deviate several psi from the correct pressure reading. The number of tires needed to be checked exacerbates the relatively large errors in inflation pressure that can arise from the use of these gauges. We therefore recommend the use of calibrated digital gauges. Recalibration of the gauges should be performed at least once per year to assure the quality of their readings. Maintaining a tight tolerance on inflation pressure with the small variance of these gauges (± 0.25 psi) could optimize fleet fuel efficiency and minimize tire turnover.

Tires should be rotated and the tread visually inspected for abnormal wear patterns once every 7,500 miles. The observation of wear patterns will allow the mechanic to diagnose any issues with inflation or alignment. Any abnormality in wear should be noted in the fleet management software and the cause corrected as soon as possible. While these inspections are critical, mechanics' attention to detail will not immediately catch all of the issues that can lead to premature tire failure or loss of performance. For this reason, it is our recommendation that all customers be asked how the vehicle felt to them when they return the vehicle. Concerns should be logged in the fleet management software and addressed at the next available opportunity.

There are factors other than inflation issues that can be addressed with periodic maintenance. During normal vehicle operation, tires pick up abrasive road debris, oils and other vehicle fluids that degrade the tire compound and accelerate the tread wear process. For this reason, it is important to perform the visual inspection on vehicle return and to wash the tires at least once a month.

The fleet interview and accompanying analysis for this study have brought to our attention that fleets can successfully maintain an internal tire reuse program. Tires that are replaced as part of a tire set are not all necessarily at the end of their service life. The fleet with poor reuse rates for tires that still had serviceable life did have a holding area for these "still usable tires;" however, the fleet personnel commented on this rack as being inconvenient and unorganized. Two simple modifications could remedy this situation to make these "still serviceable" tires more convenient: (1) labeling and organizing tires on the rack with tags that detail the pertinent factors (e.g. tire size specifications, tread depth) so tires would not have to be pulled out of the multi-tiered rack to examine these features and (2) record-keeping in a computer database of the available "still serviceable" tires. In addition, offering sufficient space for these reusable tires should be made a priority. The holding area for discarded tires (to be hauled off by the contracted tire disposal company) was much larger than the holding rack for re-usable tires. Coupled with the fact that there were some tires in both piles with comparable, moderate tread depth (4- to 6- 32nds inch) remaining, it is plausible that the space-constraint was in fact restricting tire re-use within the fleet. Our estimations for the two fleets studied showed that just the practice of within-fleet reuse could increase average tire life by approximately 10% and in turn reduce tire waste and purchasing costs.

Any one of these maintenance recommendations has the potential to make a contribution to the economic and tire disposal savings of the fleet, while additionally contributing positively toward public goals of reduced energy and tire waste. Beyond these maintenance practices that fleets can undertake, we also examine several enabling technologies that can offer further waste, energy, and cost benefits in this section's "Procurement Guide."

filled with air. The system should be regularly checked to be outputting greater than 95% pure nitrogen, as less purity will defeat the potential benefits of nitrogen inflation.

The tire pressure data acquisition systems can also play a large role in the optimization of maintaining fleet tires. It is recommended that SmarTire and VMC be utilized as the vendors for supplying TPMS and data acquisition systems, based on their ability to be installed in any passenger vehicle and take reliable data. .A regular offloading schedule should be kept to ensure proper functioning of the system and prevent any significant pressure losses or irregularities in inflation from going unnoticed. Also purchased for the study were sets of full-function displays for the tire pressure monitoring systems. We feel these could be valuable in gauging user response to tire awareness, and recommend their eventual implementation.

Tire maintenance clearly plays a large role in the upkeep of the fleet, but discretion in tire purchases can yield significant benefits as well. As shown in the life cycle energy analysis of tires (in Chapter 6), the vast majority of energy spent during the life of a tire is that consumed in overcoming rolling resistance due to friction (designated in the analysis as "use"). As this is obviously the greatest potential for energy savings, we recommend the use of low rolling resistance tires where applicable tires with adequate traction and wear attributes are available. Although the purchase price of these tires are generally slightly greater than that of conventional tires, the fuel savings in many cases will be substantial enough to offset the difference in purchase price.

We investigated the current common tire purchases for common state fleet vehicles in order to find lower rolling resistance tires that matched the required fit and performance specifications. Table 24 shows common representative vehicles and corresponding tire models.

TABLE 24. Common Vehicle and Tire Combinations in the California State Fleet

Combination Number	Vehicle	Tire Make	Tire Model	Tire Size
1	Dodge Neon	Goodyear	Regatta II	P185/65R14
2	Ford Contour	Goodyear	Regatta II	P195/65R14
3	Chevrolet Cavalier	Goodyear	Regatta II	P195/65R15
4	Ford Crown Victoria	Goodyear	Regatta II	P215/60R16
5	Dodge Neon	Goodyear	Integrity	P185/65R14
6	Ford Contour	Goodyear	Integrity	P195/65R14
7	Chevrolet Cavalier	Goodyear	Integrity	P195/65R15
8	Ford Crown Victoria	Goodyear	Integrity	P215/60R16
9	Chevrolet Malibu	Goodyear	Eagle GT	P215/60R15
10	Ford Crown Victoria (pursuit vehicle)	Goodyear	RSA Plus	P225/60R16

In evaluating the potential for fuel use and waste reductions, tires with equivalent or better UTQG ratings for traction, temperature and tread are were evaluated for their potential to provide fuel and money savings. Results for alternative, lower rolling resistance tires are shown in Table 25, based on a series of assumptions outlined here. The tires that are currently in use were evaluated against potential alternative tires from a data set from the RMA for price, tread life, and rolling resistance. This data set was provided by the RMA to the NRC for the purpose of their report. It includes the rolling resistance, full UTQG ratings, weight, and tread depth of 154 passenger tires, as provided by the tire manufacturers.

The contribution of the tires to the cost of operating a vehicle involves both their performance on the vehicle and their longevity. Tires that last longer have lower installation costs on a per mile basis. The fuel economy of the vehicles and mechanic labor rates of the state fleet were used to evaluate the potential for savings by implementing lower rolling resistance tires. The traction grades are based on a tire's measured coefficient of sliding friction when it is tested on wet asphalt and concrete surfaces. The temperature grade indicates a tire's resistance to the generation of heat during operation at high speeds. Tires are tested under controlled conditions on a high-speed laboratory test wheel. The UTQG tread wear grade is comparative rating generated from the results of an outdoor highway test in which the tire is run in a convoy with several standardized (ASTM E 501) "monitoring" tires. After 7,200 miles, the test tire's wear is compared with that of the monitoring tires. A high rating indicates low tread wear on the standardized test. Although these wear ratings are relative to the standard (and not real-world road conditions) we use these ratings as proxy values for expected life (as above in Chapter 5) here.

The choice of tires to install, with largely differing RRCs, has a large effect on the fuel consumed and waste stream generated. It is assumed that each vehicle travels 15,000 miles per year, the price of gasoline is $3.00 per gallon, and that there is no difference in non-tire maintenance costs. Table 25 details the all of the tire and vehicle combinations that have potential for extended tire life, fuel savings, and financial benefits from utilizing different tires on the vehicle combinations given above. The criteria for their selection is that they must provide no worse tread life, fuel economy, or total cost than the tires currently in use and must have equivalent or better performance in UTQG traction and temperature. In wide application, the operational savings are expected to be slightly larger than those given here, due to the opportunity for volume pricing.

TABLE 25. Tire Selections Offering Fuel, Tire Waste, and Cost Reductions

Combination Number	Replacement Tire	Expected Increase in Tire Life [a] (miles)	Expected Annual Fuel Savings Per Vehicle [b] (gal.)	Expected Annual Operational Savings Per Vehicle [c] ($)	Additional cost of each low rolling resistance tire ($)
3	CONTROL PLUS	2500	16.57	$8.15	$14.93
3	INSIGNIA SE 200	0	14.94	$8.48	$5.93
3	HARMONY	11250	10.50	$7.61	$26.93
3	HYDRO EDGE	15000	10.90	$8.84	$35.93
3	TIGER PAW AWP	1250	14.07	$21.90	$1.43
5	INSIGNIA SE 200	6250	16.80	$45.65	14.64
5	TURANZA LS-T	15000	6.36	$28.53	24.64
5	CONTROL PLUS	8750	10.93	$20.96	24.64
5	HARMONY	17500	12.30	$38.54	35.64
5	HYDRO EDGE	21250	12.69	$38.76	44.64
5	SYMMETRY	8750	19.28	$26.14	36.64
5	TIGER PAW AWP	7500	15.88	$55.53	10.14
6	INTEGRITY	0	20.50	$22.69	$15.99
6	CONTROL PLUS	8750	19.93	$49.57	$23.66
6	AFFINITY LH30	6250	8.28	$21.83	$13.66
6	INSIGNIA SE 200	6250	18.14	$49.64	$14.66
6	TURANZA LS-T	15000	6.87	$30.02	$24.66
6	CONTROL PLUS	8750	11.83	$23.63	$24.66
6	HARMONY	17500	13.26	$41.39	$35.66
6	HYDRO EDGE	21250	13.70	$41.74	$44.66
6	SYMMETRY	8750	20.82	$30.73	$36.66
6	TIGER PAW AWP	7500	17.18	$59.37	$10.16
10	TURANZA LS-H	8750	0.05	$125.80	$37.95
10	RAPTOR H4	8750	5.21	$151.20	$31.95
10	TPAW TOURING HR	8750	7.13	$183.46	$15.95

[a] increased life based on difference UTQG ratings; [b] change in fuel consumption based on 1.5% change in fuel economy for each 10% reduction in RRC; [c] savings based on computing annual cost of tire installation labor, tire costs, and fuel consumption

While Table 25 outlines the replacement options that will meet our goals of reducing energy use and waste, there are several of these options also meet the criteria of paying back the initial incremental cost of their purchase quickly. The three options for each vehicle that have the shortest payback period are detailed below in Table 26.

TABLE 26. Recommended Replacement Tires for State Vehicles

Vehicle	Replacement Tire	Expected Repayment Period (years)
Cavalier	TIGER PAW AWP	0.07
Cavalier	INSIGNIA SE 200	0.70
Cavalier	CONTROL PLUS	1.83
Neon	TIGER PAW AWP	0.18
Neon	INSIGNIA SE 200	0.32
Neon	TURANZA LS-T	0.86
Contour	TIGER PAW AWP	0.17
Contour	INSIGNIA SE 200	0.230
Contour	CONTROL PLUS	0.48
Crown Victoria	TPAW TOURING	0.09
Crown Victoria	RAPTOR H4	0.21
Crown Victoria	TURANZA LS-H	0.30

Chapter 8. Conclusions and Recommendations

Conclusions

The chief purpose of this study was to better understand the tire practices and technologies that offer the most promise in reducing tire tread wear, tire-related energy use, and tire waste generation. This study entailed a synthesis of research data from (1) the literature, (2) the original data collection on behavioral aspects of tire maintenance, the (3) the installation of nitrogen inflation technology and data acquisition systems, and (4) a life cycle analysis of tire-related technologies and practices. Here we summarize the key findings of this research.

Our literature review yielded several key background findings about tire practices and technologies. We determined tire inflation practices by vehicle operators to be a critical issue in reducing tire lifetime mileages. The prevailing practice of under-inflation by private vehicle users increases the rate of tread wear, increases fuel use, and increases the likelihood of premature tire failure. For example, average tire under-inflation, roughly 7 to 9 psi below the appropriate vehicle-specific pressure (generally 28 to 38 psi), reduce average tire lifetime mileage by about 12% to 15%, as well as increases fuel use by 1.5% to 2%. We have identified several promising technologies that could mitigate the practice, and negative impacts, of tire under-inflation. Two technologies – tire pressure monitoring systems, prompting more diligent monitoring by vehicle users, and nitrogen inflation systems – showed particular promise and were assessed for potential tire longevity and energy cycle impacts.

Tire Pressure Monitoring

Surveyed drivers offer a wealth of problematic responses that demonstrate a lack of understanding and/or a willingness to maintain appropriate tire pressure for their vehicles. A NHTSA study revealed that drivers use the vehicle placard only 8% of the time as a reference for proper tire inflation, while responses for inflation references that were erroneous (27% looked to tire labeling, which gives the maximum pressure), imprecise (10% relied on tires' visual appearance), and uninformed (6% do not know) comprised sizable percentages of the responses (Thiriez and Bondy, 2001). When asked to report the right tire pressure for their vehicle, 27% of drivers from our survey did not respond. Of those who did monitor tire pressure, two-thirds said they used the error-prone pen-type gauge. These problematic responses point to two important needs: increased driver awareness and education, and more precise and regular tire monitoring.

A variety of tire pressure monitoring technologies is available to aid in minimizing this deleterious practice, but one particular type of system offers the ability to promote both driver awareness and inflation monitoring precision. One type of tire pressure monitoring systems (TPMS), the "indirect" type, is already entering the market place and will help to catch the most problematic, highest-magnitude (i.e. greater than 25% individual tire under-inflation) tire safety issues. However, beyond the NHTSA-mandated indirect TPMS regulation that is currently phasing in, there are other TPMS technologies that offer more wide-reaching safety, tire longevity, and fuel economy benefits. . Available "direct" type TPMS technology offers the ability to more precisely monitor individual tires' pressure levels, and could therefore be a keystone technology in promoting the driver awareness that is required to achieve proper inflation levels. For drivers to be able to see a clear and present signal of their tire inflation level via an illuminated dashboard indicator would appear to be a necessary precursor to proper tire inflation maintenance.

We estimate the potential impact of substantial advances in tire inflation monitoring on average tire longevity. The level of improvement in mitigating the practice of under-inflation was set to 90% reduction from the current average tire under-inflation level (7.8 psi below 32.0 psi). This high level of improvement is based on presumption that direct-type TPMS technology provides the necessary sufficient feedback for private vehicle drivers to understand and act upon under-inflation when the TPMS alerts them to do so. For this more steadfast tire monitoring, we set an upper boundary of improving tire under-inflation by 90% and, thus, estimate a potential increase in average lifetime tire mileage of approximately 14% for private vehicle drivers (from our baseline of 37,300 to 41,500).

For the case of commercially operated vehicle fleets, because their baseline practices include more regular tire maintenance, the impact of the increased attention to under-inflation is less substantial. Fleets generally understand and maintain, tire pressure better than private vehicle owners, and as a result are estimated to have longer average tire lifetimes than private vehicles (for the same tires) due to regular inspection and maintenance. For fleets, we estimate increases in tire longevity of about 6.5% for lifetime average miles per tire.

Nitrogen Inflation Systems

Another technology with potential to mitigate the pervasive under-inflation practice, as well as reduce some forms of premature tire retirement, is the use of nitrogen, instead of the standard air, as the inflation medium for tires. Nitrogen inflation can extend pressure retention (on account of nitrogen's lower permeability than air) and can reduce oxidation-related premature tire failure (due to reduced oxygen in tire). Although available data that quantifies the different ways and the magnitude of the impact that nitrogen inflation could have on a fleet of vehicles is lacking, our crude estimations found significant enough benefits to warrant further study and data collection of the real-world impact of nitrogen-inflation technology on a fleet of vehicles.

With a series of assumptions about nitrogen systems – that under-inflation improved by 50% and oxidation-related tire replacements are eliminated – we estimate that nitrogen inflation technology could have a varying impact on average tire longevity for private users and fleet vehicles. Private users are estimated to experience an increase in average tire life of about 11% with the use of nitrogen inflation systems. Based on our estimations for public vehicle fleets, however, the comparable increase in tire longevity was about 5%. This lesser impact of nitrogen inflation for fleets is on account of the better maintenance practices, which result less oxidation-related premature tire replacements and reduced average under-inflation.

Interestingly, contrary to the lesser impacts on increasing average tire lifetime mileage for fleet-operated tires, fleets were more interested in nitrogen inflation than private users. In the interview sessions with both fleets, both the mechanics and managers were aware of the growing use of nitrogen could quickly recite the potential benefits of nitrogen inflation, citing media reports. Many expressed interest in having nitrogen inflation at their fleet if supervisors approved the purchase. Private vehicle users expressed less interest in the nitrogen inflation technology than any of the other technologies mentioned (i.e., more fuel-efficient tires, "run flat" tires, and tire pressure monitoring systems). This circumspect response toward nitrogen is found anecdotally in media articles about nitrogen where numerous vehicle service centers who offer nitrogen for a price are viewed with skepticism.

Important progress on better understanding the true impact of nitrogen inflation will result from our experimental set-up to conduct real-world testing of nitrogen as an inflation medium for fleet vehicle tires. It is important to emphasize that our assessment of the potential benefits of nitrogen inflation are crude approximations of the extent to which nitrogen could improve average tire longevity. The one available experimental study (Baldwin et al 2004) on nitrogen inflation systems documented clear improvements in reducing oxidation-related tire failure under extreme duress. However, the more often discussed positive impact of nitrogen as an inflation medium is the ability of nitrogen to retain tire pressure for longer periods of time than air. The technology our group installed at the fleet and the experimental design set-up is aimed to bridge this data gap and test the touted potential benefits of nitrogen inflation.

A technology implementation and experimental design for nitrogen inflation has been developed and summarized in Chapter 4 (and Appendix C) of this report. The technology set-up includes the installation of 49 mid-size sedans of a fleet with in-tire pressure gauges and a centralized data receiver and data acquisition device. The nitrogen inflation unit, which separates non-nitrogen components of air and holds the nitrogen gas under pressure, has been purchased for use at the fleet. Special labeling stickers and tire valve stem caps have been installed. The next step is to continue to run the nitrogen-inflated vehicles in regular service and monitor the effects. Experimental tests for statistical significance have been developed that will ultimately be used to validate the impact of the testing.

Tire Rolling Resistance

In addition to our finding on tire pressure monitoring, we offer several comments on the potential for lower rolling resistance tires. Foremost, our life cycle analysis revealed that low rolling resistance tire clearly impacted overall tire energy more than any of the other studied factors.

The relationships between rolling resistance and other tire characteristics such as tread wear, traction, and price are somewhat uncertain at the present time. These relationships are highly complex and highly dependent on tire design and materials selection. It seems clear that unless special attention is given to maintaining excellent wear and traction ratings along with reducing the rolling resistance, those characteristics can suffer. Although there are some data results that show a trend to shorter tire life (lower composite tire wear rating) with lower rolling resistance, there are numerous tires in which a reverse trend is evident. These findings would seem to indicate that with proper attention to simultaneously targeting and managing tread wear, traction, and rolling resistance characteristics when designing new tires can deliver fuel efficiency gains while circumventing trade-offs in other attributes.

Due to the difficulty in untangling the trade-offs between rolling resistance and other tire attributes, it is difficult to make any broad conclusions on the potential deployment and impacts from lower rolling resistance tires in the fleet. The proprietary nature of tire composition and design that could bring about simultaneous, balanced improvements in traction, durability and rolling resistance make thorough examination of these trade-offs rather difficult. However, two conclusions can be made regarding tire procurement. First, tires are available with good traction, durability, and rolling resistance properties. Our examination of fleet tire procurement options identified multiple such options for several different vehicle types with varying tire sizes. Tire purchasers should request information on these traction, tread, and rolling resistance factors at the time of tire purchasing to promote tire manufacturers (particularly in the replacement tire market) to place more emphasis on deploying and marketing lower rolling resistance tires.

Second, a more prominent signal should be offered to tire consumers on tire rolling resistance rating (e.g., on tire sidewalls, or like new vehicle fuel economy labeling) to offer the ability for consumers to act on their relative demand for the energy-use aspects of tires. Our surveying of drivers indicates conflicting signs regarding their demand for tires that offer reductions in fuel use. Drivers exhibited a clear demand for more fuel efficient tires; survey respondents reacted more positively to tires that would offer fuel savings than for tire technologies that are already available in the market place (run-flat tires, tire pressure monitoring, and nitrogen inflation) that offer potential improvements in other tire attributes. However, when drivers purchase replacement tires, they consistently purchase tires which offer improved tire longevity and increased rolling resistance than their original tires. This could very easily reflect the fact that vehicle consumers are only offered information about tire tread wear and traction rating, but not any official rolling resistance ratings. Rolling resistance labeling could remedy this information barrier.

Recommendations

Fleet Management Practices

One of the primary objectives of this study was to systematically study fleet practices and formulate a "Best Practices" manual for fleets to manage their fleet of tires. A set of best practices has been outlined in this report, and it is our recommendation that the guide that we have put forth be circulated among the maintenance staff of the garages of the state fleet. The dissemination of this information and adherence to its suggestions have the potential to make a positive impact in the tire-related energy use and waste generation due to improved fleet operations.

The contribution of nitrogen inflation to tire pressure retention and waste reduction has been estimated, but not empirically validated. It is our recommendation that the monitoring of tire inflation and average tire service life be continued in the vehicles presently instrumented until a statistically valid outcome is attained. Should the results warrant it, it is our recommendation that this instrumentation and monitoring of nitrogen-inflation vehicle tires be repeated in other vehicle classes. If nitrogen inflation realizes the potential that we have estimated in our assessment, it should adopted more widely across state vehicles, and measures should be undertaken to aid its widespread use in private vehicles.

Abbreviations

ABS: Anti Lock Braking System
ASIC: Application Specific Integrated Circuit
CAFE: Corporate Average Fuel Economy
CARB: California Air Resources Board
CEC: California Energy Commission
CIWMB: California Integrated Waste Management Board
DaQ: Data acquisition
DGS: Department of General Services
DOT: Department of Transportation (United States)
EPA: Environmental Protection Agency (United States)
EOL: End-of-life
FFD: Full function display
I2C: Inter Integrated Circuit
ITS-Davis: Institute of Transportation Studies, University of California, Davis
LCE: Life cycle energy
LRR: Low rolling resistance
MPG: Miles per gallon
N2: Nitrogen
NHTSA: National Highway Traffic and Safety Administration
NREL: National Renewable Energy Laboratories
OE: Original equipment
PCB: Printed circuit board
PSIL: pounds per square inch
RS-232: Recommended Standard 232
SBR: Styrene butadiene rubber
SUV: Sport utility vehicle
TPMS: Tire pressure monitoring system
TREAD: Transportation Recall, Enhancement, Accountability and Documentation
VMT: Vehicle miles traveled

Lists of Tables and Figures

Tables:

Figures:

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Appendix A. Fleet Interview Questionnaire

UC-Davis Fleet Manager/ Maintenance Personnel Survey

This is a list of questions that we will be discussing in the interview session. Please feel free to write down any notes or comments in these pages as we discuss each topic. Your participation in this study is voluntary, and you will remain anonymous. Thank you for your input in this important study.

1. Do you have a specific procedure for checking tires? Please describe how you monitor and maintain tires in your vehicle fleet.
2. Are any tire data tracked over time, e.g., tread life? If yes, what all is tracked?
3. If "yes," to question 2, do you use these data in your decisions about tire replacement? If yes, how?
4. How do you usually decide it is time to replace tires on the vehicles in your fleet?
5. Are tires replaced in sets of two, four, or individually?
6. Do you have a specific annual budget to spend on tires?
7. How do you choose replacement tires? What are the criteria? How important are they in relation to each other?
8. Does your fleet buy, install, and recycle tires, or is the work sent out to a tire specialist?
9. Do you have experience with tire inflation monitoring technologies in your fleet?
10. If "yes" to #9, how did implementing each of these technologies affect your tire maintenance and replacement procedures?
11. If "yes" to #10, has anything about your experience with these tires technologies in your fleet changed how you buy tires for *your personal vehicles*?
12. If low RR not mentioned in #8 criteria, do you have experience with low rolling resistance tires in your fleet?
13. Summary of main points… Are there any other key factors in how you maintain, operate, purchase and discard tires that we have not yet covered here?

FIGURE A1. Fleet Personnel Interview Questions

Appendix B. Driver Survey

UNIVERSITY OF CALIFORNIA, DAVIS

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

INSTITUTE OF TRANSPORTATION STUDIES
(530) 752-6548 PHONE
(530) 752-6572 FAX

ONE SHIELDS AVENUE
DAVIS, CALIFORNIA 95616

Dear Sacramento State Garage Customer,

Did you know that Californians throw away over 40 million tires each year? Yet there are many ways to extend the life of these tires while saving money. In order to explore ways to reduce this tire waste, the California Integrated Waste Management Board has commissioned a study with the Institute of Transportation Studies at the University of California, Davis.

We are asking you to fill out this short survey in order to help us better understand how vehicles, and in particular, tires, are used, maintained, and cared for. Better understanding these factors allows us to develop new tire technologies that can save money and waste for the State of California and for you as taxpayers and vehicle drivers.

To thank you for your participation in this research, we would like to offer a gift coupon for a **free beverage (brewed coffee, iced tea, or soda) at the nearby La Bou Cafe** (at 1100 O St.). You will receive a coupon after you complete and turn in the survey to the dispatch office staff.

Thank you for your participation in this important study. Please feel free to contact me with any further comments or questions at 530-848-3740 or *nplutsey@ucdavis.edu*.

Sincerely,

Nicholas Lutsey
Survey Coordinator
UC-Davis Innovative Tire Technology Project

FIGURE B1. Informational Cover Letter for Driver Survey

UC-Davis Driver Survey

Thanks for your interest in this important study on vehicles, tires, and tire technology. The survey should take just ten minutes. Please fill out the following survey and hand in to any fleet worker.

1. Do you check the air pressure in the tires of any motor vehicles you own or lease?

- ☐ Yes → If so, how often? _______________
- ☐ Somebody else does it → If so, how often? _______________
- ☐ I don't own or lease a car. Please skip to question 13.
- ☐ No. Please skip to question 3.

2. How do you measure the air pressure in your vehicle?

- ☐ Pen-type gauge ☐ Dial-type gauge ☐ Other: _____________
- ☐ Digital gauge ☐ Visual tire inspection ☐ Don't know

3. What is the right tire pressure for your personal motor vehicle?

_______________ pounds per square inch (psi) (or check here ☐ if you don't know)

4. What do you do, or what would you do, if you discovered one or more tires on one of your vehicles was under- or over-inflated?

- ☐ Nothing
- ☐ Personally refill or deflate air (at a gas station or other place)
- ☐ Take vehicle to auto garage (or other place) to have someone else refill
- ☐ Other: _______________

5. Do you check the tread wear of your tires of any motor vehicles you own?

☐ Yes ☐ No

6. How do you check the tread wear of the tires on your own motor vehicles?

- ☐ Digital tread gauge ☐ Visual inspection
- ☐ Ruler-type gauge ☐ Other: _______________
- ☐ None

7. How do you decide which brand and type of tires to buy?

8. When you buy tires for your vehicles, how important are these factors?

	Not Important		*Somewhat Important*		*Very Important*
Expected tread life………………………...........	☐	☐	☐	☐	☐
Wet-weather performance………………………	☐	☐	☐	☐	☐
Handling………………………………….........	☐	☐	☐	☐	☐
Comfort/Ride…………………………………...	☐	☐	☐	☐	☐
Noise……………………………………………	☐	☐	☐	☐	☐
Safety…………………………………………...	☐	☐	☐	☐	☐
Style/Appearance……………………………….	☐	☐	☐	☐	☐
Price…………………………………………….	☐	☐	☐	☐	☐
High-speed performance………………………..	☐	☐	☐	☐	☐
Fuel economy…………………………………...	☐	☐	☐	☐	☐
Other factor (please specify:______________).	☐	☐	☐	☐	☐

FIGURE B2. Driver Survey, Page 1 of 2

9. Do you remember what you paid the last time you had to replace your vehicle tires?

☐ Yes. How much did you pay, to replace how many tires:
I paid $_________ total to replace ______ tire(s).

☐ No. How much do you think it would cost to put four new tires on the automobile you drive most:
I think it would cost $____________ for four new tires.

10. If the following tire-related technologies were available for a little extra cost over normal tires, how interested would you be in checking them out?

	Not Interested		*Somewhat Interested*		*Very Interested*
Tires that are more efficient and save you fuel........	☐	☐	☐	☐	☐
A gauge in your dashboard that tells when tires are under-inflated for safety reasons……………..	☐	☐	☐	☐	☐
Nitrogen inflation to hold pressure longer....………	☐	☐	☐	☐	☐
Self-inflating or "run flat" tires for emergencies…..	☐	☐	☐	☐	☐
Other (please specify: ___________________)….	☐	☐	☐	☐	☐

11. Have you had to replace a tire prematurely because of poor tire wear?
☐ Yes ☐ No

12. Have you personally had the experience of a flat tire on one of your vehicles?
☐ Yes ☐ No

13. Have you personally experienced any tire problems on *a State fleet vehicle*?
☐ Yes ☐ No

14. What problems did you have, and what did you do on *a State fleet vehicle*?

	Number of times	*What did you do?*
☐ Under-inflation……………………..	____	________________________________
☐ Over-inflation………………………	____	________________________________
☐ Flat tire……………………………..	____	________________________________
☐ Uneven tires………………………..	____	________________________________
☐ Other problem (please specify:_______________).	____	________________________________
☐ None		

15. Do you have any other comments on the tires of your own vehicle(s) or on the State fleet vehicles? If so, please share.

Thank you for your time filling this survey out. Your input is very important!

FIGURE B3. Driver Survey, Page 2 of 2

Appendix C.

ITS-Davis makes no recommendation concerning nitrogen inflation equipment

TABLE C2. Purchasing Issues of Nitrogen Equipment

Feature	Parker TireSaver	Branick	Importance:	Financial impact:
Membrane protection cost	Carbon tower included	Carbon tower not available.	The Branick manual states "NOTICE: the presence of any oil in the Nitrogen Membrane will void the manufacturer's warranty".[14] Instead of a carbon tower to protect the membrane, Branick recomments an air dryer. Air dryers lower the dewpoint of air, they do not remove oil.	The membrane is the single most expensive part of the unit.
Air pretreatment cost	Air dryer not required upstream of Parker unit	Air dryer is recommended upstream of Branick unit, and is extra.[15] Note that if oil gets in the membrane, the Branick warranty is void.[16]	The only requirement for the inlet air to TireSaver is that the inlet air be below 110 degrees F[17]. This is to ensure that the membrane is not overheated and that the moisture content of the compressed air can be handled by the membrane. The membrane removes oxygen AND water vapour. The Branick system requires the air dryer to pre-treat the air. However, air dryers do not remove oil, only carbon towers do.	Cost of an air dryer must be added to the base price of the Branick system.
Nitrogen Receiver tank	Receiver tank included	Receiver tank extra	The Branick manual states that the system is ready for use when the generator is running or the receiver tank is full.	Cost of a receiver tank must be added to the base price of the Branick system.
Experience	With over 6,000 units installed and +20 Years of System Manufacturing experience, Parker Hannifin Corporation is the World Leader in Nitrogen Gas Generation for the Tire Inflation Marketplace.	"We carry the most complete line of tire spreaders for both inspection and repair, tire service equipment for many applications, and undercar tools for suspension and brake work."[18]	This is a piece of process equipment and your supplier should have the expertise to service it. Nitrogen generation is the core of Parker's business.	
Membrane technology	Parker owns the patents, manufactures, sells, and services the membranes in these units. The membrane life is over 10 years of continuous service. Because the TireSaver shuts off automatically, the actual service life is much longer.	Branick buys in the membrane packaged in their system. Branick's membrane life is 16,000 hours, which is only 7-1/2 years, based on 8 hour days and 5 day weeks[19].	Parker has over 6,000 nitrogen generation systems in service world wide. Parker controls and has total responsibility for the technology. Parker's membrane is tougher and will last longer than Branick.	Parker's membrane life is 25% longer than Branick's in continuous use, and much longer in actual service due to the automatic shut off system.

[14] Branick Installation, Operation and Repair Parts Information Manual P/N 81-0072B rev 070704 page 3
[15] Branick Installation, Operation and Repair Parts Information Manual P/N 81-0072B rev 070704 page 3
[16] Branick Manual page 3 and page 6.
[17] TireSaver User Manual TI-TireSaver page 11 Table 4.1
[18] http://www.branick.com/about.asp
[19] http://www.branick.com/n2/faq.html

TABLE C3. Operating Issues of Nitrogen Equipment

Feature	Parker TireSaver	Branick	Importance:	Financial impact:
Energy savings	Automatic shut-off when no Nitrogen demand on the system.	Continuous operation	The Branick system does not have an automatic shut off valve. The unit continually bleeds compressed air through the membrane even if there is no demand on the system. The flow for the Model 1500 is 41.4 scfm.[20] This is bad for two reasons: the membranes are in service continually and this reduces the useful membrane life. Also, this uses compressed air unnecessarily, which is very expensive in terms of electrical cost and compressor wear and tear. The Parker system has a pressure switch which controls a flow control valve. When there is no demand, the pressure switch shuts off the air flow. This saves compressed air costs, and this extends membrane life significantly.	The cost of compressed air, especially if the shop has limited compressed air capacity. Membrane replacement costs.
Operating temperature	Ambient air operating range between 40F and 110F	Minimum ambient air limit of 60F[21]	Minimum ambient air temperature can be a problem in Winnipeg in winter. If the temperature is too low, the N2 spec won't be reached.	Unknown
Floor space	Wall mount unit	Floor mount unit.	Space in a shop is scarce. TireSaver saves space compared to Branick, especially if access is allowed to the back of the unit.	Minimal financial impact unless space constraints

[20] Branick Installation, Operation and Repair Parts Information Manual P/N 81-0072B rev 070704 page 2
[21] The minimum temperature is NOT given in the Branick 500/1000/1500 manual. It is given as 60F in the Model 350 manual page 3.

BALSTON® A Parker Hannifin Industrial Business

Parker Filtration

May 8, 2006

Prepared by Matt Belluomini for:

Mr. Justin Regnier
UCD
Davis, CA 95616

Parker Hannifin Corporation
Filtration and Separation Division
242 Neck Rd.
Haverhill, MA 01835
Telephone: 800-343-4048
Order Fax: 978-858-0668

Parker Hannifin Recommendation

Application

Generate a continuous supply of Nitrogen using house compressed air for tire filling applications

Nitrogen Generator - TS02

Is a reliable source of compressed air available?	Yes
Type Number:	TS02
Prefiltration:	Standard
Storage Tank:	Standard
Nitrogen Dew Point:	-50°F
Tire Inflation Capacity:	30 Tires per hour
Particles > 0.01 µm:	None
Suspended Liquids:	None
Min./Max. Operating Pressure:	100 psig - 145 psig
Flow Rate:	1.75 SCFM
Purity (% Nitrogen):	95%
Recommended Ambient Operating Temp.:	50°F - 104°F
Min./Max. Inlet Air Temp.:	50°F - 104°F
Dimensions:	32"H x 19"W x 5"D
Shipping Weight:	150 lbs
Storage Tank Dimensions:	40"H x 18" Diameter

Ordering Information

Item	Qty	Description	Unit Price	Total Price
1	2	TS02 Tiresaver Nitrogen Generation System and tank.	$3,575.75	$7,151.50
2	1	MK-L9000 Maintenance Kit. optional at this time...	$138.00	$138.00
3	1			
4	1	Plus Tax		
			Total:	$7,289.50

Terms:Net 30 days
Delivery: 1 to 2 Weeks A. R. O.
Place order with: MATT BELL 408-776-2020 OR FAX PO TO 408-776-2033

FOB: Haverhill, Massachusetts
Prices Effective Through: 06/19/2006
Follow-up Date: 05/15/2006

Parker products are offered for sale by Parker Hannifin Corporation, its subsidiaries and its authorized distributors subject to the terms and conditions of Parker's Offer of Sale which is available from your Parker representative or can be found on-line at www.parker.com/saleterms/

Note: This pricing was given to match the offer made by Branick. The retail price for the TS-02 is $4998.00

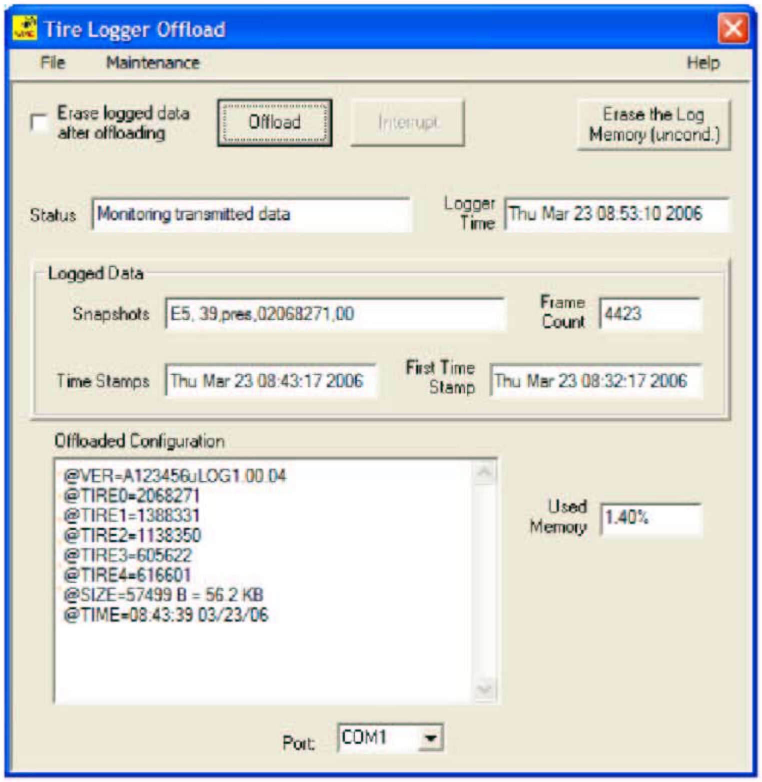
VMC uLogger-209 SmarTire DataLogger

Vehicle Monitor Corporation

- An "Off the Shelf " SmarTire Data Logger solution.
- Vehicle Ready Electronics
- Connects directly to the SmarTire receiver.
- Operates from Vehicle Power.
- Records time and date with every packet of SmarTire data.
- Data offloading software included.
- The collected data is saved in tab-delimited text format, ready for importation into a spreadsheet.
- Small rugged die cast enclosure.
- Other inputs and custom requirements can be accommodated.

Description:
The VMC uLogger-209 is specifically designed to be used with SmarTire tire pressure monitoring system to record tire pressure and temperature data. All data transmitted from the SmarTire receiver is recorded along with the date and time. In most applications the uLogger can store one month's worth of data without offloading. The Windows-based offloading utility is easy to use and stores the data in a simple to use spreadsheet-ready tab-delimited text format.

The screenshot below illustrates the user interface for the Tire Logger Offload application:



When the user clicks on the "Offload" button, logged data is immediately saved in a tab-delimited text file, which can be easily imported into a spreadsheet application such as Excel. The following illustrates sample data from an Excel file:

Pressure (kPa)	Temperature (C.)	Voltage	Life	Sensor ID	Error Byte	Time Stamp
855.67				1910470	0	Wed Mar 29 14:39:58 2006
	18			1910470	0	Wed Mar 29 14:39:58 2006
855.67				1910470	0	Wed Mar 29 14:39:58 2006
		2.69		1910470	0	Wed Mar 29 14:39:58 2006
855.67				1910470	0	Wed Mar 29 14:39:58 2006
			0	1910470	0	Wed Mar 29 14:39:58 2006
866.67				339453	0	Wed Mar 29 14:40:49 2006
866.67				339453	0	Wed Mar 29 14:40:49 2006
866.67				339453	0	Wed Mar 29 14:40:49 2006
	19			339453	0	Wed Mar 29 14:40:50 2006
866.67				339453	0	Wed Mar 29 14:40:50 2006
		2.71		339453	0	Wed Mar 29 14:40:50 2006
866.67				339453	0	Wed Mar 29 14:40:50 2006

Environmental and Operating Conditions:

- Operating Power: 9 to 20VDC
- Operating Current: 25mA
- Size: 5.5" L X 2.4" W X 1.3" D
- Weight: 1.0lbs
- Case Material: Die Cast Aluminum
- Connectors: DSUB 9 pins (port 1 connects to SmarTire receiver, port 2 for offloading.
- Operating Temp: -40C to +80C
- Storage Temp: -40C to +80C