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Economic Analysis of Continuous Monitoring of Commercial Truck Tire Pressure Using Tire Pressure Monitoring Systems (TPMS) and RFID Technologies.

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Economic Analysis of Continuous Monitoring of Commercial Truck Tire Pressure Using Tire Pressure Monitoring Systems (TPMS) and RFID Technologies.

By

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Economic Analysis of Continuous Monitoring of Commercial Truck Tire Pressure Using Tire Pressure Monitoring Systems (TPMS) and RFID Technologies.

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The trucking industry is a major contributor to the US economy. By providing the essential services of transportation and distribution needed in today's dynamic industry, the transportation industry has evolved into an integral player in various supply chains. The trucking industry is the largest transportation provider for other industries and employs 10.1 million workers in the United States (ATA, 2003).

This research is an analysis of the economic impact of maintaining proper air pressure in the tires of commercial trucks. Various studies have been carried out on understanding the relationship between tire pressure and fuel consumption (National Research Council, 2006). For the trucking industry, monitoring and regulating tire pressure offers significant opportunity to drive down fuel costs and improve on overall efficiency as well as on business turnover. A properly inflated tire reduces rolling resistance which in turn reduces fuel consumption and thus saves fuel costs. Some technologies have been developed to help drivers continuously monitor tire pressure and optimize fuel consumption.

The objective of this study is to determine the economic value in dollar savings, of the available technologies for continuous tire pressure monitoring devices to a standard trucking fleet company while exploring additional capabilities that can be incorporated

into such technologies in order to increase their value and economic return to the trucking industry in general.

Data regarding the operating costs and other relevant factors for a trucking company were obtained from earlier related research studies. It was discovered that using tire pressure monitoring technologies on a single commercial truck can result in an annual savings of $2,400 from fuel consumption alone. Additional benefits achievable from savings from repair and maintenance costs were estimated to be between $213,500 and $3.5 million depending on the severity of the damage caused by tire blowouts. The breakeven price for the technology was determined to be $8,100 for 5 service years and sensitivity analysis was carried out on the fuel savings.

Dedication

To Him Who sits on the Throne, The Immortal, The Invincible, The Only Wise God.

To You be Glory, Honor and Majesty forever.

AMEN.

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Firstly, I want to deeply thank the Almighty God for giving me the strength and carrying me through this stage in my life. I give Him all the praise.

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And to 'My Treasure and Perfection of Beauty', my lovely wife, Abimbola, every moment with you and every thought about you makes life more desirable than paradise. I wonder if angels could build a home that could match the radiant beauty and virtue you exude.

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Chapter One

1.1 Introduction

The trucking industry is regarded as the backbone of transportation and distribution of commercial and industrial goods in the United States. By providing the essential need of freight movement over land and connecting different geographical locations connected by road networks, the industry has proven itself overtime as a backbone in the manufacturing, transportation and warehousing industries. From the manufacturer to the final consumer, and from raw materials to finished goods, the trucking industry has helped to connect various industries and communities in ways that have enabled businesses to grow and break geographical boundaries.

Commercial trucking is viewed to be very important to the entire U.S. industrial sector with over 80% of communities depending solely on trucks for the delivery of fuel and other consumer goods. It is estimated that the industry contributes about 5% to the United States Gross Domestic Product (GDP) every year. For every dollar acquired in the freight transportation industry in the United States, the commercial trucking industry accounts for 87 cents of it, hence, it has been acclaimed to be the largest freight mover even ahead of the rail (ATA, 2003). Participation in the industry is growing and is expected to continue as the demand increases. As at November 2006, the U.S. Department of Transportation released the following statistics for carriers registered with the Federal Motor Carrier Safety Administration:

For-hire Carriers - 290,629;

Private Carriers – 504,166; and

Interstate Motor Carriers – 234,892.

The American Trucking Association estimated that from 1988 to 2008, the number of registered large trucks increased by 47% while the miles traveled by large trucks have increased by 67%. Despite the positive trend and business turnover within the industry, the effects of the current economic downturn is very evident. Higher fuel prices and rising insurance premiums have pushed many operators to cut down on their operating costs which most times are very hard to achieve. Fuel cost and driver wages have been identified as the two highest operating costs in the industry. The advent of highly effective engines that deliver excellent mileage has helped drive down fuel costs over the years. Industry experts recommended that by employing safer practices and ensuring driver compliance to standards, fuel costs and other associated costs can be driven down significantly.

Various studies have been carried out on understanding the relationship between tire pressure and fuel consumption (National Research Council, 2006). For the trucking industry, monitoring and regulating tire pressure offers significant opportunity to drive down fuel costs, improve on overall efficiency as well as on business turnover. Although heavy-duty trucks usually utilized by commercial fleet operators are exempt from the TREAD act (NASS, 2001; TPMS, Wikipedia 2010) which mandates all new vehicles to be equipped with Tire Pressure Monitoring Systems, it is necessary to investigate and justify the need for operators to voluntarily adopt the technology in order to achieve their bottom line.

A properly inflated tire reduces rolling resistance which in turn reduces fuel consumption and equivalently amounts to savings in fuel costs. Some technologies have been developed to help drivers continuously monitor tire pressure and optimize fuel consumption. An example of such technologies is the Tire Pressure Monitoring System (TPMS) which warns drivers when the pressure drops to about 25%. There are different types of TPMS in the market today and they come in different designs at varying costs. Another system for monitoring tire pressure utilizes radio frequency identification (RFID) technology. If operators are able to use these readily available technologies to maintain optimum tire pressure, safety will greatly improve in addition to the savings in fuel and tire maintenance.

Despite the acclaimed benefits associated with the pressure monitoring systems, it is important to understand if such an investment would be worth the return. In addition, it is necessary to quantify in monetary terms the benefits accrued from improved safety in order to account for the actual return on investment.

This study examines the available tire monitoring technologies in the trucking industry while enumerating their different underlying working principles and limitations. Their various capabilities to measure and display fluctuations in tire pressures in real time are also investigated. Although the actual extent of penetration for these technologies within the trucking industry could not be estimated, the actual dollar value for the associated benefits such as the possible savings in fuel costs, repair and maintenance costs, tire replacement costs and improvement in safety was determined. The economic model was analyzed for sensitivity so as to identify the weight of uncertainty in any of the independent variables and its impact on the study's conclusion. Overall, this study attempts to make an objective analysis and justify or otherwise refute the claims for continuous monitoring of tire pressure as applicable to the trucking industry.

1.2 Objective of the Study

The objective of this study is to determine the economic value in dollar savings, of the available technologies for continuous tire pressure monitoring devices to a standard fleet carrying company while exploring additional capabilities that can be incorporated into such technologies in order to increase their value and return to the trucking industry in general.

Chapter Two

Background

2.1 The Fleet/Trucking Industry in the United States

The trucking industry for so many years has been a major contributor to the US economy. By providing the essential services of transportation and distribution needed in today's dynamic industry, the transportation industry has evolved into an integral player in various supply chains. The trucking industry has been acclaimed to be the largest transportation provider for other industries with an estimated 10.1 million jobs in the United States (ATA, 2003). In 2010, over 9 billion tons of freight was hauled by trucks accounting for over 67.2 percent of freight tonnage in the United States. This is expected to have increased to 70 percent of total freight tonnage in 2022 (ATRI, 2011).

From suppliers to manufacturers and onto retailers, the timely delivery of raw materials, work-in-progress, and finished goods makes the trucking industry a mainstay in modern business models such as in just-in-time manufacturing and other "pull" business models. Trucking is currently the dominant mode of freight transportation earning nearly 75% of the transportation industry's revenues while moving only 25% of the ton-miles and this situation is likely to remain unchanged in the future.

A report submitted by the American Trucking Association to the United States Office of Management and Budgets in 2003 stated that "over 81% of all interstate motor carriers operate six or fewer trucks and 93% of motor carriers (nearly 539,000 in number) have 20 or fewer trucks" (ATA, 2003). The American Transportation Research Institute (ATRI) in a recent report stated that 96% of motor carriers in the United States operate fewer than twenty trucks while most freight operations in the US (based on drivers employed, tonnage of freight moved, and truck registration) is carried out by medium to large carriers (i.e. carriers with over twenty trucks) (ATRI, 2011).

A survey by the American Transportation Research Institute (ATRI, 2011) revealed that the most common vehicle configuration in the trucking industry is the 5-axle semi-truck followed by straight trucks with a significantly wide margin between them (see Table 2.1).

Table 2.1: Truck Type Configurations and Average Monthly Vehicle-Miles-Traveled (VMT) Per Truck (ATRI, 2011).

Truck Type	Percent of Total Trucks	Average Miles Driven Per Month Per Truck
Straight Truck	6.9%	2,213
5-axle Tractor/Semitrailer	86.2%	8,781
6-axle Tractor/Semitrailer	0.2%	5,970
LCVs (Doubles/Triples)	6.7%	9,267

The industry has faced major challenges through the years with some arising from strict government regulations which some experts believe to have increased the burden on operators. Despite these challenges, the industry has kept a strong and active presence with increasing productivity resulting from the development of useful technologies such as satellite communications, computers and the internet.

2.2 Operational Costs in the Trucking Industry

Numerous studies have been conducted on determining the comprehensive cost per mile (CPM) operating cost for the industry but most have fallen short of expectations especially from industry operators regarding its accuracy and practicability.

Barnes and Langworthy (2003) in their study on the operating costs for automobiles and trucks in 2003 concluded that

> in "a 'baseline' case of highway driving on smooth pavement, with a fuel price of $1.50 per gallon, and other costs in 2003 dollars … trucks average 43.4 cents per mile, not counting costs associated with the driver or travel time. City driving conditions, involving frequent stops and starts, increase this cost by… 9.5 cents for trucks. Extremely rough pavement increases the baseline cost 5.5 cents…"

In 2008, the American Transportation Research Institute (ATRI) conducted a study to "document and quantify motor carriers' key marginal costs, stratified by fleet size, sector and region of the country" and to accurately determine operation costs from data acquired directly from motor carriers (ATRI, 2008). Based on numerous requests from fleet operators for updated benchmarking metrics, the study was repeated in 2011 and showed significant reduction in the average marginal cost per mile (CPM) in 2009 as $1.45. The same cost was found to be $1.49 in the first quarter of 2010 (Table 2.2 and 2.3). The revised analysis in 2008 showed higher figures for the average marginal cost per mile as $1.65.

Table 2.2: Average Marginal Costs per Mile, 2008, 2009, Q1 2010 (ATRI, 2011)

Motor Carrier Marginal Expenses	**2008**	**2009**	**Q1 2010**
Vehicle-based			
Fuel & Oil Costs	$0.633	$0.405	$0.465
Truck/Trailer Lease or Purchase Payments	$0.213	$0.257	$0.235
Repair & Maintenance	$0.103	$0.123	$0.120
Truck Insurance Premiums	$0.055	$0.054	$0.052
Permits and Licenses	$0.016	$0.029	$0.023
Tires	$0.030	$0.029	$0.026
Tolls	$0.024	$0.024	$0.024
Driver-based			
Driver Wages	$0.435	$0.403	$0.404
Driver Benefits	$0.144	$0.128	$0.142
TOTAL	**$1.653**	**$1.451**	**$1.491**

Table 2.3: Average Marginal Costs per Hour, 2008, 2009, Q1 2010 (Source: ATRI, 2011)

Motor Carrier Marginal Expenses	**2008**	**2009**	**Q1 2010**
Vehicle-based			
Fuel & Oil Costs	$25.30	$16.17	$18.59
Truck/Trailer Lease or Purchase Payments	$8.52	$10.28	$9.39
Repair & Maintenance	$4.11	$4.90	$4.81
Truck Insurance Premiums	$2.22	$2.15	$2.06
Permits and Licenses	$0.62	$1.15	$0.92
Tires	$1.20	$1.14	$1.06
Tolls	$0.95	$0.98	$0.95
Driver-based			
Driver Wages	$17.38	$16.12	$16.17
Driver Benefits	$5.77	$5.11	$5.67
TOTAL	**$66.07**	**$58.00**	**$59.61**

The recurring trend of increasing fuel prices coupled with the failing economy has necessitated the need for many fleet operators to find ways of determining and reducing their costs. By consistently and accurately monitoring their operating costs, it becomes easy to strategize and increase investment with good understanding of trends in the industry backed with dependable forecasts.

Levinson *et al*. (2004) wrote that “fuel, repair and maintenance, tire, depreciation, and labor cost are the most important costs that are considered in the estimation of operating cost per kilometer.” Though labor costs used to be the highest operating costs as of 2008, many operators today identify fuel consumption as the most fluctuating as well as the highest operating cost. ATRI (2011) revealed that as at the first quarter of 2010, fuel cost and driver wages (excluding benefits) constituted 58% of the average operating cost within the trucking industry (Table 2.3). According to the report, the trucking industry’s expense on diesel fuel in 2011 will amount to almost $136 billion exceeding the previous year by an amazing $34.5 billion and resulting in the second highest amount spent on diesel by the industry (the record high was recorded in 2008 as $142.9 billion).

Table 2.4: Share of Total Marginal Cost, 2008, 2009, Q1 2010 (ATRI, 2011).

Motor Carrier Marginal Expenses	**2008**	**2009**	**Q1 2010**
Vehicle-based			
Fuel & Oil Costs	38%	28%	31%
Truck/Trailer Lease or Purchase Payments	13%	18%	16%
Repair & Maintenance	6%	8%	8%
Truck Insurance Premiums	3%	4%	3%
Permits and Licenses	1%	2%	2%
Tires	2%	2%	2%
Tolls	1%	2%	2%
Driver-based			
Driver Wages	26%	28%	27%
Driver Benefits	9%	9%	10%
TOTAL[1]	100%	100%	100%

[1] The total does not add up to 100% due to rounding up of entries to the nearest whole number.

Due to macroeconomic forces and the rising demand for diesel, the rising trend in fuel price is expected to continue through 2012 and beyond. This will inevitably result in overwhelming increase in operational costs for truckers in the near future. It is pertinent then for the trucking industry to embrace any technology that will in the long run help reduce the marginal costs especially in those areas with high costs.

Although the resulting operational cost for tires is quite small when compared to others, its impact on fuel costs and repair and maintenance cannot be undermined. It is important to note that tire related issues can impact both the fueling and the repair costs at unprecedented levels which could negatively affect business turnover.

Most accidents relating to trucks are as a result of driver-related causes than by component failures. For example, investigations have revealed that most drivers are more likely to neglect tires that are further away from them down the rear making them much more vulnerable to the risks and dangers of under-inflation and poor maintenance. In fact, it is estimated that 45% of drivers with tire pressure monitoring technologies still drive with underinflated tires despite their awareness about the technology being installed on their vehicles (NHTSA, 2009).

A tire that is not well-maintained and not operated at the required specifications can significantly increase fuel consumption and in cases of accidents caused by tire blowouts, result in huge repair and other related costs. Blowouts on front tires result in deviation to other lanes or completely from the road which could result into a head-on collision; while blowouts on the rear tires results in loss of control and spinning. The annual estimate for crashes involving light vehicles caused by flat tire or blowout has been found to be 414 for the number fatalities and 10,275 for the number non-fatal injuries (NHTSA, 2005).

It becomes imperative, therefore, for this study to understand and estimate as accurately as possible, the impact of using improperly inflated tires on the overall economy of the trucking operation as a justification for tire pressure monitoring technologies available today.

2.3 Tire Pressure Monitoring Systems (TPMS)

After the incidence of failures and fatalities involving Firestone/Bridgestone tires used on Ford Explorers in 2000 which resulted in one of the greatest and most sensitive recalls in tire manufacturing, Congress under the influence of consumer safety activists as well as automobile and tire manufacturers, enacted the Transportation Recall Enhancement, Accountability and Documentations Act (TREAD Act) (Orna, 2003). The components of the TREAD Act, among other things, mandated that new vehicles sold in the United States be equipped with Tire Pressure Monitoring Systems (TPMS) and Early Warning Reporting Systems in order to increase safety and awareness while driving (TREAD Act, Wikipedia 2010). It is an established fact that visual checks are not dependable in detecting under-inflated tires, and this, apart from causing safety hazards also is responsible for increasing braking distance, poor handling, and reduction in both fuel economy and overall tire life (Wingert, 2000). Some causes of under-inflation include hazardous road conditions, changes in temperature and natural leakages over time (Normann, 2000).

Generally, a Tire Pressure Monitoring System (TPMS) is a short range wireless electronic safety device installed inside pneumatic tires in order to measure air pressure and report same to the driver of the vehicle. The TREAD Act mandated that all passenger vehicles and light trucks in the United States weighing less than 10,000 pounds be equipped with TMPSs beginning from 2006 which must be able to warn drivers when tire pressures are abnormally below or above prescribed limits (NHTSA, 2005). The exemption of heavy duty trucks from the act does not undermine the achievable benefits of the technology, and neither does it exonerate the commercial trucking industry from adopting the technology as a cost saving option.

A typical Tire Pressure Monitoring System consists of the following components: battery based wireless sensor/transmitter device, high frequency (HF) antenna module, and a central receiver. The sensors are directly mounted inside the four tires of the vehicle and they are responsible for measuring the tire pressure and sometimes temperature which is then wirelessly transmitted to the central receiver in the vehicle (See Figure 2.1a and b). The receiver analyses every piece of data sent from the sensor and issues warning signals whenever there are abnormalities in pressure and temperature levels. Pressure and temperature are simultaneously measured via micro-mechanical sensors while a wake-up circuit which triggers the sensing circuit is activated by a 125 kHz LF signal (Qingxia *et al*., 2006; Ho *et al*., 2009).

There are basically two types of TMPS based on their method of measuring the tire pressure and temperature. These are the direct TMPS and the indirect TPMS.

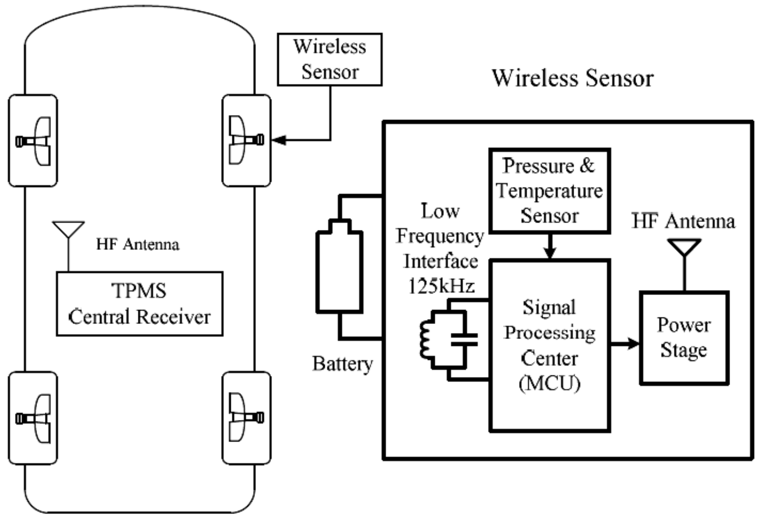


Figure 2.1: (a) A Typical TPMS architecture (b) Wireless Tire Sensor Architecture.

2.3.1 Direct Tire Pressure Monitoring System

In the direct TPMS, the internal air pressure of a tire is measured directly using specialized sensors installed internally on wheel rims or externally on tire/tube valves of the vehicle. These sensors are capable of detecting pressure changes as low as ±0.1bars (i.e. ±1.45 psi). Each tire's pressure can be independently measured and wirelessly transmitted by its corresponding sensor to the receiver for decoding and processing. Although there are variations in the system design, some setups are equipped with real time capabilities while others take measurements at predetermined time intervals or working conditions. An important universal design requirement is for the sensor to be small both in size and weight in order to eliminate unwanted imbalance associated with any generated centrifugal forces (Velupillai, 2007). According to NHTSA (2010), heavy trucks currently use the direct TPMS. Examples of available direct TPMS presently in the market are shown in the Figures 2.2 – 2.6.

Figure 2.2: Components Kit for SmartWave 10-Tire system (NHTSA, 2010)

Figure 2.3: SmartWave Sensor Mounted on Lowest Section of Rim with Steel Band (NHTSA, 2010).

Figure 2.4: SmartWave Receiver/Gateway Mounted on Transmission Lower Crossmember (NHTSA, 2010)

Figure 2.5: Components Kit for Tire-SafeGaurd 10-Tire Rim-Mount TPMS (NHTSA, 2010)

Figure 2.6: Side View of Two PressurePro Sensors mounted on Dual Steel Wheels (NHTSA, 2010).

2.3.2 Indirect Tire Pressure Monitoring System

In this case, pressure changes are predicted indirectly by monitoring changes in both the tire's diameter and rotational speed. The idea stems from the fact that a decrease in pressure will result in a corresponding decrease in diameter (resulting from compression under the vehicles weight) and a decrease in the tire's rate of rotation (or particularly an increase in angular velocity ω) as compared to at optimum pressure. Other parameters can be used or included in the calculations as determined by the system design. For example, using changes in tire stiffness (a non-linear factor) in determining the pressure is a feasible practice.

Indirect TPMS requires a dedicated software algorithm which in some cases is combined with the Anti-Lock Braking System (ABS) or Electronic Stability Control Systems.

However, ABS systems cannot independently identify pressure changes in individual tires and it can only detect pressure drops greater than 25% (Yang *et al*., 2007). Other limitations of indirect TPMS include its inability to keep tract of any pressure changes while the vehicle is not in motion, inability to distinguish when two tires are equally under-inflated, and its proneness to give false alarms on curvy or slippery roads (Velupillai, 2007; TPMS, Wikipedia 2010).

2.3.3 Hybrid TPMS

The hybrid system tries to combine the benefit of both direct and indirect TPMS. The design utilizes fewer sensor modules but overcomes the deficiencies of an indirect TPMS.

2.4 TPMS Challenges

Manufacturers of TPMS often face a tremendous challenge in their attempt to balance both regulatory requirements and design considerations with consumer satisfaction and market competitiveness.

For example, the TREAD Acts outlines several requirements which TPMS devices must satisfy, some of which includes: (i) 7 to 10 years battery life; (ii) working automotive temperature range of -40^{o}C to 125^{o}C; and (iii) low weight and small volume. In addition, US laws mandate the use of direct TPMS which relies on sensors and are powered by batteries. Hence, manufacturers are challenged with ensuring very limited weight and volume for TPMS devices embedded with the additional weights of sensors and long lasting batteries (VisiTyre, 2009). An obvious and major challenge is the conflict of interest between having a ‘long-lasting battery’ while ensuring ‘limited weight and volume’.

At the moment, some manufacturers are working on direct TPMS that do not rely on battery power. For example, IQ-mobil Electronics GmbH claimed that it has successfully designed a small 1” by 1” “battery-less transponder” chip that would be ready for production soon. Another form of battery-less powering utilizes the kinetic energy of the rotating wheel to power the system (NHTSA, 2005).

Another challenge in the design of TPMS device is the working condition as there will be constant exposure to harsh weather and rough terrains which will greatly affect the device performance and reliability. TPMS devices embedded inside the wheel rim also must be able to handle great amount of temperature and pressure. In any circumstance, there is the high risk of battery temperature rising above 150^{o}C at which the possibility of the high energy density batteries exploding is very likely.

Furthermore, manufacturers need to ensure that TPMS devices are relatively affordable despite all regulatory requirements and design considerations.

2.5 Introduction to RFID

Radio Frequency Identification (RFID) is a technology that utilizes radio frequency signals to transmit encrypted and specific information about an items unique identification. It is a fast developing Automatic Identification and Data Capture (AIDC) technology highly ranked in modern industries as the most efficient and most viable replacement for the barcode. In a typical RFID system, data encoded as a unique identifier is wired into a tag which consists of a chip and an antenna. This encoded information is then transmitted to an interrogator in response to a radio pulse intended to serve as a request order. The potentials for this simple technology are limitless as it offers unmatched opportunities and flexibility to collect, authenticate, analyze, identify, and control information even to an item specific level. The non-requirement of a line of sight for successful reads has made it the most preferable choice for organizations to improve on operational efficiencies (White *et al*., 2007). Furthermore, the ability to provide real time, precise and accurate data and its suitability for different fields in industry makes RFID a top-ranked option for improving efficiency and providing savings both for businesses and consumers alike.

RFID as a technology was first used by the military during World War II in the Identification Friend or Foe (IFF) System and ever since, it has gained widespread attention in research and development for successful application in industry, military, medicine and other applicable fields. Today, RFID is being used by companies as a cost saving alternative to error-prone human-dependent data capture and data analysis systems in warehouses, distribution centers, retail outlets, toll gates and other sections of the supply chains. Many organizations today invest huge funds and time in order to explore immediate and tangible benefits associated with RFID especially throughout the supply chain. It is widely recognized that understanding the capabilities of this technology within the supply chain will profoundly increase inventory visibility while streamlining operations. Supply chains with a well implemented RFID model will be able to boast of competitive leverage resulting from benefits such as real-time inventory control, product identification and authentication, plus efficient and responsive operation.

In recent years, Wal-Mart, a major retailer, and the Department of Defense (DoD) have rolled out mandates which require their suppliers (and the suppliers' supplier) to integrate a comprehensive RFID system into pallets and cases meant to be shipped to their distribution centers and stores. Other manufacturers and retailers are following likewise so as not to be left behind in the pending change in business trend. While businesses are looking forward to using the technology in many applications across various industries, researchers agree that the retailer mandates especially by major players such as Wal-Mart and the DoD are the main driving force behind the current interest and widespread demand for the technology.

The need for a dependable and efficient automatic identification technology has particularly resulted in an increase in demand for RFID implementation in various areas such as in automatic access control, automotive sensing and vehicle security, electronic toll collection and most importantly, and in item-level tracking of goods within a supply chain (Yang *et al*., 2007).

For so many years now, RFID has been the focus of various industrial and academic research efforts aimed at overcoming the numerous challenges inhibiting the wide scale adoption of RFID technologies as identified by industries and researchers alike. At the forefront of these challenges is the design and realization of low cost RFID tags without trading key performance requirements. Efforts are being made to ensure that the cost requirement for individual tags fall below five cents in order to achieve cost effective mass production of tags for item-level identification and tracking. However, the cost of a tag is dependent on various factors such as its type (active or passive), antenna size and design, and additional required functionalities. Another challenge as noted by Yang *et al*. (2007) is the "the design of small-size tag antennas with very high efficiency and effective impedance matching for IC chips with typically high capacitive reactance". He further explained that the performance requirement for the tag antennas is a very important factor to "optimize the power performance for RFID system, especially for passive or semi-active configurations, where the only energy source is the incoming reader energy".

Like other wireless technologies, there are numerous security and privacy issues affecting the implementation of RFID technology. The fact that the technology requires no contact and line of sight for successful tag reading and data base access creates a disturbing vulnerability that requires immense effort and resources in curbing. In addition, the 'promiscuity' of RFID tags, though not unique to the technology also contributes to privacy concerns and the impending danger of unauthorized access. Sarma *et al*. (2002) emphasized that a successfully implemented RFID project must have clearly defined security goals which must include the "ability of tags not to compromise the privacy of their holders, sealing of channels and data encryption to avoid leakages to unauthorized readers, and the possibility of building long term tracking associations between tags and holders".

2.6 History of RFID in Automobiles

RFID is currently enjoying widespread adoption in various industries which evidently have contributed to the advancement of the technology in meeting various enterprise needs. Developers and prospective users hope to utilize the technology in resolving a wide range of challenges including better inventory management and goods availability, efficient management of distribution networks for dispatch and receipt of goods, and increased visibility in product tracking, product authentication and anti-counterfeiting. The automotive industry on its own part has not been out of the RFID hype since it has been exploring opportunities to implement and harness the benefits offered by the technology for a long time. However, Schmitt *et al*. (2008) noted that RFID adoption in the automotive industry lagged behind when compared to the level of adoption witnessed in other industries such as the retail sector. Though the usage of RFID technology has been evident in the industry for a while (e.g. vehicle immobilizer), wide spread integration within the automotive supply chain partners was yet to be witnessed. A notable reason for this was the absence of a uniform single RFID standard specifically for use with the automotive industry similar to the Electronic Product Code (EPC) for data standards and unique identifiers. Another stated reason was the lack of a RFID mandate like that of Wal-Mart and DoD (Schmitt *et al*., 2008).

The Automotive Industry Action Group (AIAG) was founded in 1982 by giant automotive manufacturers such as Ford Motor Company, General Motors, and Chrysler with the initial objective of developing recommendations and a framework for the improvement of quality in the North American Automotive Industry (AIAG, Wikipedia 2011). After its inception, the organization has grown to incorporate a global mission with over 1600 members across the globe. Part of AIAG's accomplishment was the institution of the AIAG Automatic Identification Standards and Guidelines which serves as a standard requirement for the usage of Auto ID technology within the industry. In 2006, AIG published the revised 'B-11: Tire and Wheel Label and RFID Standard' which was original enacted in 2001 as a response to the Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act passed by the US Congress. The B-11 Tire identification Standard was the first item-level RFID tracking and traceability standard in the world and its purpose was "to provide an electronic means of transferring data from the tire to anywhere it needs to go" (AIAG, 2006, Bi & Lin, 2009). The following summarizes the standard.

B-11: RFID Specifications

Configuration

- Passive
- Read /Write; at a minimum of 24 inches from the tire

Memory

- Minimum 128 bytes (1024 bits) of total memory
- Minimum 110 bytes (880 bits) of user-addressable memory

Frequencies

- UHF
- Not specifically defined, but understood to mean 860 MHz to 950 MHz

Protocols

- MH10.8.4: 2001, Section 3: air-interface
- ISO 15434: data syntax (industrial)
- UCC/EAN: EPC (Data ONLY, retail)

The B-11 standard and requirements was universally acceptable as it conformed to EPC numbering conventions and were based on ISO 18000-6C/EPC Gen2 (Daily & McCann, 2007). The standard supports both retail and industrial based data on the same tag with the requirement that the appropriate data-syntax is followed. Since the enactment of the B-11 by AIAG, the technology has undergone various refinements and extensive testing which have led to numerous landmark achievements. Some notable achievements are the development of attachable and implantable tire RFID tags which are exceeding the basic requirements of 24 inches read/write distances.

Other specific applications for RFID technology in commercial trucks include fuel authorization, real-time locating systems and automotive manufacturing (Daily and McCann, 2007).

2.7 RFID in TMPS

There have been plenty of projects aimed at increasing the efficiency and effectiveness of Tire Pressure Monitoring Systems by incorporating into it basic RFID technological principles in order to deliver safety as a requirement with additional benefits.

As mentioned in the earlier section on direct TPMS, sensors installed on tires transmit pressure readings wirelessly to the receiver for decoding and processing using RF signals. According to Velupillai (2007), “the radio frequency transmission stage expends five times more energy than the sensing stage”. The tire pressure module was also identified as a major consumer of available power. Hence, power management which involves regulating power consumption to the minimum has become the most vital operational issue in TPMS design.

On one part, design modifications to the TPMS module allows for intermittent readings and data transfer with intervals between readings primarily determined by prevailing safety conditions as sensed by the device. Hence, extended battery life can be achieved when TPMS wheel modules are activated and deactivated to conserve both the usage of the device and the available ‘power budget’. A good example is the wake-up circuit which activates the sensing circuit by using a 125 kHz LF signal (Ho *et al*., 2009). With the aid of the wake-up circuit, the battery life is prolonged considerable even if the module is fitted with other circuits requiring large power resource such as an RF amplifier. Another example of a triggering device is the usage of motion sensors to trigger sensors and receivers into active modes whenever the tire is in motion. This activation can increase the recurrence rate for subsequent readings and transmission rates by as much as 100 times that of the sleep mode. Alternatively, some system designs tend to shut down the sensors completely when the tire is not in motion for a predetermined length of time in order to preserve battery power.

On the other hand, a more promising option would be to entirely eliminate the use of batteries in powering the device while seeking an equally reliable and cost effective option. One of such options is the integration of RFID technology into the system. It is interesting to note that passive tag RFID have been identified to be the most widespread contactless power transmission technology.

Ho *et al*. (2009) conducted research on utilizing the contactless RFID principle to power tire pressure monitoring systems and also to enhance data transmission. The system design involved using a transponder equipped with a sensing circuit to read pressure and temperature, an RF power rectifier, a modulation circuit and a RFID reader. The transponders are powered by the RFID readers and the inductive power generated is fed into the TPMS sensing circuitry thereby eliminating the need for a battery and a wake-up trigger circuit. Evidently, the system design offered excellent results as it was possible to measure and transmit data in real time without fear of battery depletion. The elimination of the need for a battery made the strict requirement for small size and light weight TPMS achievable. Despite the successful trial, noticeable set-backs for the system includes a low optimal moving speed of 45 km/hr and the additional cost of installing RFID readers in the vehicle (Figure 2.7).

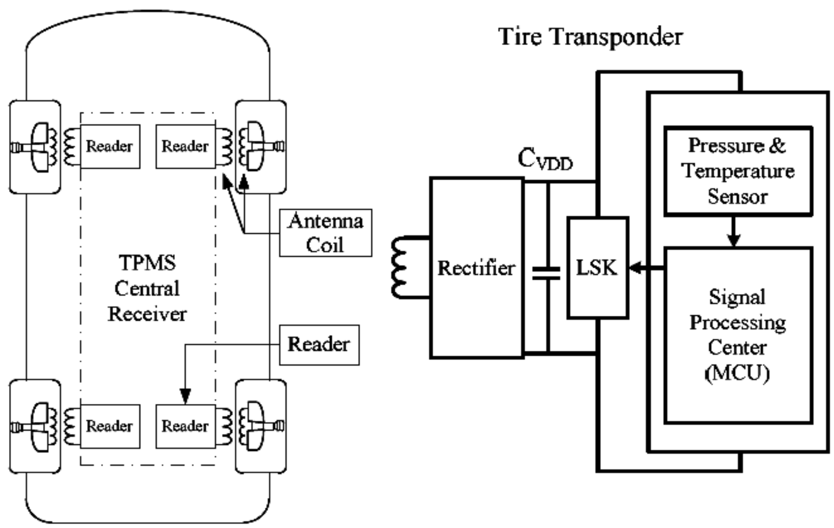


Figure 2.7: (a) Proposed Battery-Less TPMS Architecture (b) Sensing Architecture

An important factor in the system structure is the position of the transponder antenna. Leng *et al*. (2007) carried out a comparative performance analysis on wheel antennas as against dynamic antennas for RFID technology based tire pressure monitoring systems. The research was conducted using a dynamic antenna type TPMS from a manufacturer against a wheel antenna type TPMS made by the authors. The wheel antennas, held in place while the transponder and sensor rotates with the tire, showed better performance particularly in the area wireless data transmission and power transmission. The authors summarized their findings that “it means the wheel antenna is a better radiator of electromagnetic power, and the TPMS system with wheel antenna has the better wireless transmission performance: better power transmission efficiency, better frame error ratio”. This research emphasizes the importance of antenna positioning to the overall efficiency of the TPMS. Another factor that will affect performance is the antenna design.

2.8 RFID in Tires

The application of RFID technology has had limited application so far in the tire enterprise. On its own part, barcode technology has been able to proffer solutions to some logistical problems in tire manufacturing but not without certain limitations and difficulties in its execution. For example, a comprehensive tire manufacturing line is comprised of numerous types of materials, semi-products and products each of which must be recorded or scanned individually as it passes through different stages of the production line. Consequently, there is an overwhelming need and diversion of labor and time towards scanning operations alone which usually is error prone due to inevitable human mistakes.

The idea of independently integrating RFID technology into tire manufacturing and the entire supply chain has been an important subject of focus among researchers and industry alike. Intelligent tires have been acclaimed to be a key component in achieving and ultimately advancing the very much proposed concept of intelligent transportation systems. The complex networks of road systems and the desire to advance transportation into tomorrow's world necessitates the need for tires to become an active element in future vehicle and transportation design. A program in Finland tagged the 'Apollo Project' which started in 2002 with the aim of developing innovative vehicles for an accident free traffic concluded in 2005 that "tire intelligence is necessity for vehicle active safety systems of the future". Hence, the quest to make tires intelligent and active has resulted in the development of numerous technologies, which today are visible as standard requirements in any automotive design. Some of these technologies include the development of Tire Pressure Monitoring Systems (TPMS) which have been discussed in earlier sections. In addition to this, the Side Wall Torsion (SWT) sensor was developed in 1999 to make up for the TPMS in order to further optimize the electronic vehicle stability control systems (Taheri, 2011). The SWT provides information on the estimated forces acting on the tire at the point of contact while measuring the extent of deformation of the tire sidewall (Jim, 1999). Other proposed functions for intelligent tires include the implementation of advanced active safety systems, including traction control systems, early detection of tire separation systems, vehicle stability assists and tire burst prevention systems (Gavine, 2001; Parwardhan *et al*., 1997).

The successful implementation of RFID systems into the collection of intelligent tire technologies will greatly impact future prospects with outstanding opportunities to explore unforeseen possibilities. Some of the major challenges with the idea included maintaining the read range for the tag which is definitely affected by rubber; determining the right position on the tire to place the tag for optimal reading from the interrogator; and developing a tag that can withstand the various external tire forces and conditions. Another important factor for consideration is how the integration of RFID systems into tires would affect the cost i.e. both the cost of the tag and the cost of implanting or attaching the tag as the case may be. As at 2004, the cost of a RFID tag for tires was estimated at $1 which was regarded as too costly for implementation. However, as expected with many technologies, the price is expected to fall with an increase in demand (Murphy, 2004).

Evidently, embedding an RFID tag into the tire layer frame would be the best option but this also is affected by numerous factors such as the highly intricate processes involved in tire manufacturing and the embedded wire mesh in tires which would evidently affect RFID tag performance.

However, a major landmark was achieved by Michelin in 2003 when the company announced that it had successfully embedded a RFID transponder into its tires to enable electronic tracking. According to the company, the tags can be successfully read from distances of 24 inches in accordance with the requirements of the Automotive Industry Group's B-11 standard for North America. In order to achieve this, Michelin designed its own unique antenna using microchips from Fairchild Semiconductor® and Philips Semiconductor®, developed a proprietary coating for the transponders before embedding them into rubber. The result was a RFID transponder that loses only 10 percent of its read range after being embedded into rubber. A remarkable achievement about this is that the Michelin tag is rewriteable and cured-in which the life span equal to that of a vehicle. Michelin stated in a press release that the "RFID transponders are mainly for fleet use and will be used for data collection and quality purposes". The product will later be extended to other commercial-use vehicles. Other details about the how this landmark was achieved are inevitably being kept as a company secret.

In addition to this, Michelin developed an attachable shirt-button-sized RFID tag and sensor module (eTire II) for tire pressure and temperature monitoring for fleet management industries. This was an improvement to the earlier module introduced in 2002 which was bulkier and required lower speed of 50 mph for optimum functionality among other limitations. The new design incorporated Surface Acoustic Waves (SAW) technology with UHF RFID inlay compliant with ISO 18000-6b standard to create a more efficient and accurate pressure and temperature monitoring system. Another advantage is the fact that these tags are attached to the tire sidewall by means of strong adhesives rather than the rim-mounted ones which are liable to errors arising from higher rim temperature resulting from braking.

Goodyear followed suit in the integration of RFID into their tires since it was a major supplier both to Wal-Mart and US Department of Defense and is subjected to their RFID mandates. According to the company, tagging tires with RFID labels was a very challenging endeavor since their product is composed of reinforced carbon which ultimately absorbs RF energy. The initial plan was to use low-cost, disposable RFID tags on light tires and after several attempts and numerous testing, Goodyear finally rolled out several RFID enabled tires with the tags imbedded. In 2006, being the exclusive supplier for all NASCAR racing events, Goodyear successfully implemented a RFID-structured tire leasing program in line with a request from NASCAR to enable to a leveled playing field for all participants. According to Goodyear's website, the goal for the tire leasing program was "to control the tire inventory available to teams in order to limit team testing to just six NASCAR-approved tests a year - thus making it fair for all teams, regardless of their size or resources. By Goodyear leasing its tires instead of selling them, and requiring their return before teams can depart a race or a test, NASCAR's goal of advanced inventory control is attained". As stated, Goodyear was able to successfully track individual tires used for the races from the manufacturing facility to the track, all the way to participating teams and upon their subsequent return after the race. This program provided Goodyear with an outstanding opportunity for the field testing of their RFID enabled tires under extreme conditions which in turn will be useful in making necessary adjustments to suit commercial applications.

Evidently, the successful implantation of RFID tags into tires by these two manufacturers created an opening to endless possibilities as far as harnessing the benefits of RFID technology. It is apparent that unlike initial attempts where RFID played a subordinate role in TPMS devices, the technology has become a mainstay in adhering to the TREAD ACT while other technologies are being incorporated as additives. A simple RFID tag can store vast information ranging from a tire brand, to the size, load, speed ratings and other performance features. In addition to these and with the standardization of the technology, tags embedded in tires can also “interact with other vehicle systems to enhance performance of ABS brakes, traction control and vehicle stability control”. Furthermore, shipping errors can be eliminated with the better inventory visibility afforded by the technology. The added benefit of a foolproof solution against counterfeiting must not be overlooked since RFID technology has been applied in various industries as a viable product authentication and anti-counterfeiting solution (Lehtonen *et al*., 2008; Filimon, 2008).

J.B Hunt® is a transportation logistics company that has been a key contributor in funding research efforts on the adoption of RFID technology especially within the industry. Their large inventory of tires amounting to an annual cost of around $26 million coupled with their numerous trailers and truck cabs (tractors) necessitated their need for an efficient wireless technology in asset management and inventory control. In 2004, the company explored the possibility of using RFID technology to determine and prolong tire wear while improving fuel consumption. The procedure for achieving follows the underlying proposition that the rate of failure of a tire can be accurately determined by determining the number of revolutions a tire has made under usage and the number of times the cords have flexed. Two separate RF sensor applications were being tested with the hope that there will be full scale implementation in the real world for a better cost-effective management of their tire assets (Sullivan, 2005).

A tire is not limited to a single supply chain since it is very possible for it to move from one supply chain to another. Sometimes, a tagged item can remain within a closed-loop system and other times, the item leaves its originating circle never to return to it again. Standards and requirements established by regulatory authorities like ISO, EPCGlobal and AIAG (B-11) provide the necessary framework and platform to allow for a smooth integration of RFID tag protocols across board. For example, an RFID tag imbedded in a tire, after leaving the manufacturers network, can still be programmed and used in an entirely different network. Hence, various questions arise on adapting an embedded RFID tag to satisfy numerous objectives in varying environments.

With the continuous evolvement of the RFID technology and the increasing component functionalities, such as the integration of 'sensory' tags with external measuring devices, the tire industry market seems to be full of opportunities for suppliers to increase revenues and market share; and the inherent efficiencies of the RFID technology seem like an excellent opportunity for reducing truck fleet operating and tire management costs, and allowing truck fleets to more efficiently utilize their assets.

2.9 Tire Pressure and Fuel Efficiency

The importance of a well inflated tire cannot be overemphasized especially in relation to safety. For so many years now, transportation agencies and safety advocates have been emphasizing the need for motorist to regularly monitor their tire pressures and ensure that they are not driving with over-inflated or underinflated tires. According to experts, tires are supposed to loose between 1 to 2 psi per month if they are maintained and operated under normal driving conditions. However, the pressure loss can be greatly increased by factors such as driving habits, road conditions (potholes), punctures, the tire design and material used. Furthermore, under-inflation increases the risks of increased stopping distance, skidding, hydroplaning and tire blowouts (USGAO, 2007).

Safety concerns are usually related to accidents arising from the risks of tire blowouts, increased rate of tread wear and increased stopping distances. A key element of the TREAD Act enacted by the US congress in 2000 was the regulation that every new motor vehicle from 2004 onwards should have a system that "warns the operator when a tire is significantly underinflated (25% or below)." Apart from the safety concerns for drivers and road users associated with improperly inflated tires, other benefits associated with a well inflated tire includes lower cost of vehicle maintenance, increased traction for vehicle mobility, better fuel efficiency, and the cost savings in road maintenance and reconstruction stemming from road damage (Bradley, 1993). Furthermore, accurate tire pressures ensure safer handling while maintaining excellent gas mileage. According to the US Environmental Protection Agency and the US Department of Energy, Office of Energy Efficiency and Renewable Energy, “keeping tires inflated to the recommended pressure and using the recommended grade of motor oil can improve fuel economy by up to 5%.”

The trucking industry has been affected by losses related to incidents arising from underinflated tires particularly in relation to fuel economy. A major problem with underinflated tires is the increased rolling resistance resulting from a wider contact surface area with the road. This increase in rolling resistance tends to require a higher work from the engine to overcome the additional load and to gain necessary traction which culminates to higher fuel consumption. Fueling cost has been identified as one of the leading operating costs in the trucking industry (Kenworth Truck Company, 2008). In relation to that, the American Trucking Associations (ATA) stated that the number one maintenance issue in the trucking industry has to do with tire pressure management (ATA, 2008).

A research study conducted by the Federal Motor Carrier Safety Administration (FMCSA, 2006) revealed the following facts about tire related issues in the trucking industry.

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

Despite these stated facts and several warnings as well as enlightenment programs on its benefits, studies reveal that there have been very low market penetrations for tire pressure management devices especially in the trucking business. Interestingly, the market today is inundated with numerous types and various designs of tire pressure monitoring systems with stiff competition among vendors lowering costs over the last decade. The range varies from simple tire pressure monitoring to complete monitoring and automated inflation. A notable reason for the lack of interest might be the unawareness of trucking business owners to the cost savings associated with having a dependable tire pressure management system installed in their fleets. With the rising trend in fuel price (especially diesel), there is pressing need to explicitly show that investing in a dependable tire management system is justifiable at the very least, by the accrued savings generated from better fuel economy resulting from proper tire management.

The American Trucking Association (ATA) gave the following estimation on the costs associated with underinflated tires:

> "A set of tires at 60 PSI versus the specification inflation of 100 PSI can reduce fuel economy by up to 6%, as well as destroy the tire. A tire 20% under inflated equates to 25% less tread wear life and …, a tire that is 10% under inflated equates to a 0.5% increase in fuel use. At 30% under inflation, fuel economy drops almost 4%. A tenth here or there in miles/gallon may not appear to be a very large number, until you consider that a line haul truck spends $65,000 per year on fuel (100,000 miles/year divide by 6.5 miles/gallon times $4.25/gal) multiply 4% of $65,000 = $2600 per year in added fuel for just one truck."

The National Renewable Energy Laboratory (NREL) developed a sophisticated mathematical model for computing the energy consumption in various vehicles tested on different cycles and on different tires. The program known as ADVISOR “works from J2452 rolling resistance data and a library of known vehicles and test cycles to quickly model a range of scenarios that would be very costly to test physically” (California Energy Commission, 2003). ADVISOR can also evaluate the impact on fuel efficiency resulting from changes in tire pressure and the tire rolling resistance with likelihood of accurate estimations in fuel cost or savings. A study by Kelly (2002) using ADVISOR model and industry- supplied tire resistance rolling data showed that “fuel economy between 2% and 6.5% lower for a light duty passenger car equipped with low rolling resistance tires; and between 1.0% and 3.4% for a sport utility vehicle over the three different drive cycles.”

Kelly (2002) also used a modeling tool known as VISION developed by the Department of Energy to project fuel consumption through the year 2050. The study revealed that “an energy savings of 3.8 billion gallons per year can be achieved with a 2.5% improvement in fleet fuel economy, and proposes that this improvement can be made by lower rolling resistance tires and improved tire pressure maintenance”.

In a breakdown of how energy is consumed and utilized in a vehicle, the National Research Council stated that the rolling resistance takes one-third of the mechanical energy usually transmitted through the driveline of a passenger vehicle in order to turn the wheels which amounts to about 7% of the total energy depleted by the vehicle. The figure is presumably higher for a truck. Furthermore, increasing the rolling resistance of a vehicle by 10 percent (while keeping other factors constant) can amount to a 2 percent decrease in fuel economy, which is proportional to an equivalent reduction in fuel consumption (National Research Council, 2006).

It suffices to conclude that there is no doubt about how the rolling resistance, which is directly affected by the tire pressure, impacts the overall economic efficiency of the truck and thus must be thoroughly considered in order to maximize efficiency. Also noteworthy is the huge energy savings of almost 4 billion gallons of diesels which amounts to a tremendous reduction in greenhouse gas emission and improved air quality, thereby improving the reputation of the industry in terms of environmental friendliness.

Another issue resulting from improper tire pressure is accidents resulting from skidding (due to increased braking distance) or from tire blowouts. Despite the fact that it is not a leading cause of accidents, most incidents of tire blowouts usually result in fatal accidents involving damages to properties and other road users. A study conducted by the National Highway Traffic Safety Administration (NHTSA, 2005) for the TREAD Act revealed the following:

- 1 percent of passenger vehicle occupant fatalities and injuries occurring in 1999 resulted from loss of control and skidding due to underinflated tires.
- An estimate of 41 deaths and 1,028 injuries occur annually resulting from blowouts from underinflated tires.

Even when a tire blowout does not immediately result in an accident, there is the associated danger from the debris left behind on the road due to the tire peeling and crumbling during the process. Other road users can get involved in fatal accidents either from direct contact or from attempts to avoid tire debris on the highway (Barekat *et al*., 2000).

2.10 Previous Studies by National Highway Traffic Safety Administration (NHTSA)

This section examines the various studies specifically carried out by the National Highway Traffic Safety Administration on different issues related to Tire Pressure Monitoring Systems (TPMS). NHTSA was established in 1970 by the US government as an agency of the US Department of Transportation (DoT) with the aim of drafting and enforcing safety requirements for all vehicles types.

After the enactment of the TREAD act, NHTSA conducted an intensive study on ten different light vehicle Tire Pressure Monitoring systems (TPMS). The study involved testing 6 direct TPMS and 4 indirect TPMS with the objective of determining and understanding their various operational principles, accuracy and repeatability, warning systems, threshold conditions, human factors and comprehension testing. The study revealed the following:

- The indirect TPMS failed to give any warning when there were two underinflated tires on the same side or on the same axle, and when all four tires are equally underinflated. This can be explained by the under-inflation equation below: $\left|\frac{(LF+RR)-(RF+LR)}{Average\ Speed}\right| \leq Threshold \rightarrow No\ Warning, > Threshold \rightarrow TPMS\ Warning$
- The Indirect TPMS is largely dependent on the vehicle loading in order to sense low tire pressure.

- Systems with temperature compensation offers more benefits by avoiding the nuisance associated with false and inaccurate warnings due to temperature changes.
- Both direct and indirect TPMS should be reset or restrained on the average of 7.2 months due to tire rotation or replacement. This could amount to 23 resets/restraints for the lifespan of a light truck.

In 2005, NHTSA and the Office of Regulatory Analysis and Evaluation National Center for Statistics and Analysis conducted another study on TPMS. The study was a Final Regulatory Impact Analysis which focused on the ‘final rule’. The final rule in accordance with the TREAD act required that any TPMS must alert the driver whenever the system detects under-inflation of 25% or more as well as a TPMS malfunction indicator. Three different compliance options were estimated and analyzed for manufacturers to select in order to comply with the final rule. After conducting various performance evaluation and financial analysis, it was determined that the best compliance option most likely to be selected by automobile manufactures was option II which “assumes that manufacturers will supply a direct system with a warning lamp.” Other results from the study included the following.

- Battery-less TPMS were significantly more cost-effective than TPMS with batteries
- Continuous readout or individual tire pressure displays were more cost-effective than just a warning lamp
- A combination lamp malfunction indicator was cost-effective

- A separate telltale lamp for a malfunction indicator was not cost-effective.

A recent study in 2010 was carried out by NHTSA to conduct "preliminary test program in order to explore a series of test protocols that could be used to evaluate the efficacy of heavy truck TPMS." By analyzing different classifications of vehicles based on their Gross Vehicle Weight Rating (GVWR), the study developed and examined different procedures which can be used to check TPMS operations on heavy vehicles. The study examined five different direct TPMS with two rim-mount systems, two in-line systems, and one end-of-valve-stem unit. The system features and basic functions are summarized in Table 2.5.

The result of the study is summarized below.

> "The test results have shown that type or brand of vehicle did not alter the individual TPMS results. The results for a given TPMS on a 10-tire truck were repeated when later installed on a 10-tire tractor, without observing any vehicle influence on the test results even though the vehicles were equipped with different tires, rims, and the TPMS were adjusted to different CIPs. Each system was successful at identifying at least one preset level of low tire pressure, signaling low tire pressure to a driver display, and clearing the low-pressure warning from the display after the tire was re-inflated.

Table 2.5: Component Features of Five Different Direct TPMS Products (NHTSA, 2010).

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

Each system was able to recognize multiple tires with low pressure (10 to 20 percent below Cold Inflation Pressure). Not all the systems recognized when a system malfunction occurred, such as a failed pressure sensor or a disconnected antenna.

Without temperature compensation, tire test pressures set to 3 psi below TPMS “factory” setpoints were satisfactorily detected by each TPMS tested. By adding tire temperature compensation (such as in SmartWave TPMS) the variation between a “hot” over-the-road tire pressure reading and low-pressure alerts for both 10 and 20 percent pressure losses was maintained at tire temperatures elevated to nearly 30°F above initial CIP temperatures. It maintained a fixed ratio of pressure drop from current temperature operating pressures to activate the low-pressure alarm, whereas the systems without temperature compensation allowed much larger pressure drops before activating their alarms.

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

It was noteworthy that some of the systems tested were able to detect and display TPMS malfunctions which could be as a result of damaged receiving antennas, faulty sensors or any related component malfunction.

2.11 Initial Intent of Study

This study was initially focused on evaluating the impact of TPMS and RFID technology on the entire supply chain of the tire industry. It involved examining the challenges associated with embedding RFID tags in tires (optimal position and means of attachment or embedding) and also investigating the reading range efficiency of available RFID systems for tire pressure monitoring and inventory management. Various experiments were to be carried out using different tires and available RFID technology in the market. The objective of the study had to be modified since the resources needed to carry our experiments were no longer available. Hence, it was decided that the study should investigate the economic value of the available tire pressure monitoring technologies to the commercial fleet industry while examining possible capabilities that would improve upon the present value.

The following chapters enumerate the various methodologies and assumptions used in achieving the stated objective.

Chapter Three

Economic Models

In analyzing the relevant cost savings and other associated benefits achievable from well inflated tires (resulting from the usage of RFID technology for continuously monitoring tire pressure), the following assumptions were made in this study.

- All trucks traveled with full truck loads (TL) during their course of operation.
- All tires were regularly monitored and inflated to the specified pressure at all times except when mentioned otherwise.
- All trucks were assumed to be 18-wheeler semi-trailers.

As mentioned in the last chapter, underinflated tires result in higher fuel consumption. This increase in fuel usage coupled with the present failing economy and increasing diesel price can result in a significant impact on a business's bottom line. For example the price for diesel has been rising constantly in recent years and recent forecasts suggest that the rising trend is bound to continue.

3.1 Fuel Savings

By taking into consideration the average pump price for diesel, average mile per gallons for a truck load, and the average distance covered in a given timeframe, the average cost of fueling within the same time frame can be calculated. Consider the following:

Average cost of diesel in 2011	= \$3.86 per gallon,[2]
Average distance travelled by a truck in a year	= 125,000 miles,
Optimal average mileage of a truck	= 6.5 mpg[3],

[2] Source: Energy Information Association.
[3] American Trucking Association (2008). Tire Pressure Monitoring and Inflation.

Average mileage of a truck operating with underinflated tires = 6.3 mpg,

(using 20% under-inflation and 3% reduction in fuel economy)[4].

Using simple mathematical computations reveals that on the average, underinflated tires can increase fuel costs by $2400 (or increase fuel consumption by as much as 620 gallons) for a single truck in a year. This amount is definitely affected by the prevailing cost for diesel with forecasted price rising to as much as $4.50 per gallon by 2015. A savings of $2400 from fuel can be further broken down as 1610 additional miles of work, and 42 additional work hours from a single truck.

The cost savings in fuel alone is sufficient to justify investing in a RFID technology for tire monitoring in an industry where over 93% have less than twenty trucks in operation if the cost of the monitoring system is less than the annual $2400 savings.

3.2 Repair and Maintenance

The actual savings on repair and maintenance costs achievable by the continuous monitoring of tire pressure can vary depending on the extent of damage caused by an underinflated (or overinflated tire) tire. According to ATA (2008), 53% of road breakdowns for trucks and tractors were tire-related, thus making it the topmost factor that results in lost hours and costs from road breakdowns. Road breakdowns for trucks are tire-related 48% of the time and 36% of the time for hours of breakdowns. In summary, under-inflation reduces a tire's lifespan by as much as 20% thereby increasing the frequency and expense on tire replacement on the long run.

A breakdown resulting from the tire might require repair as little as replacing with a spare or might involve towing to shop for an unscheduled maintenance. Unscheduled

[4] Ibid.

maintenance causes delays and unpredictable downtimes which could tremendously affect projected turnover (Christer and Waller, 1984).

In extreme cases, a tire blowout can result in a crash that could involve other road users and cause damage to properties. The fishbone diagram below enumerates the possible effects a tire blowout could have on a typical commercial trucking company.

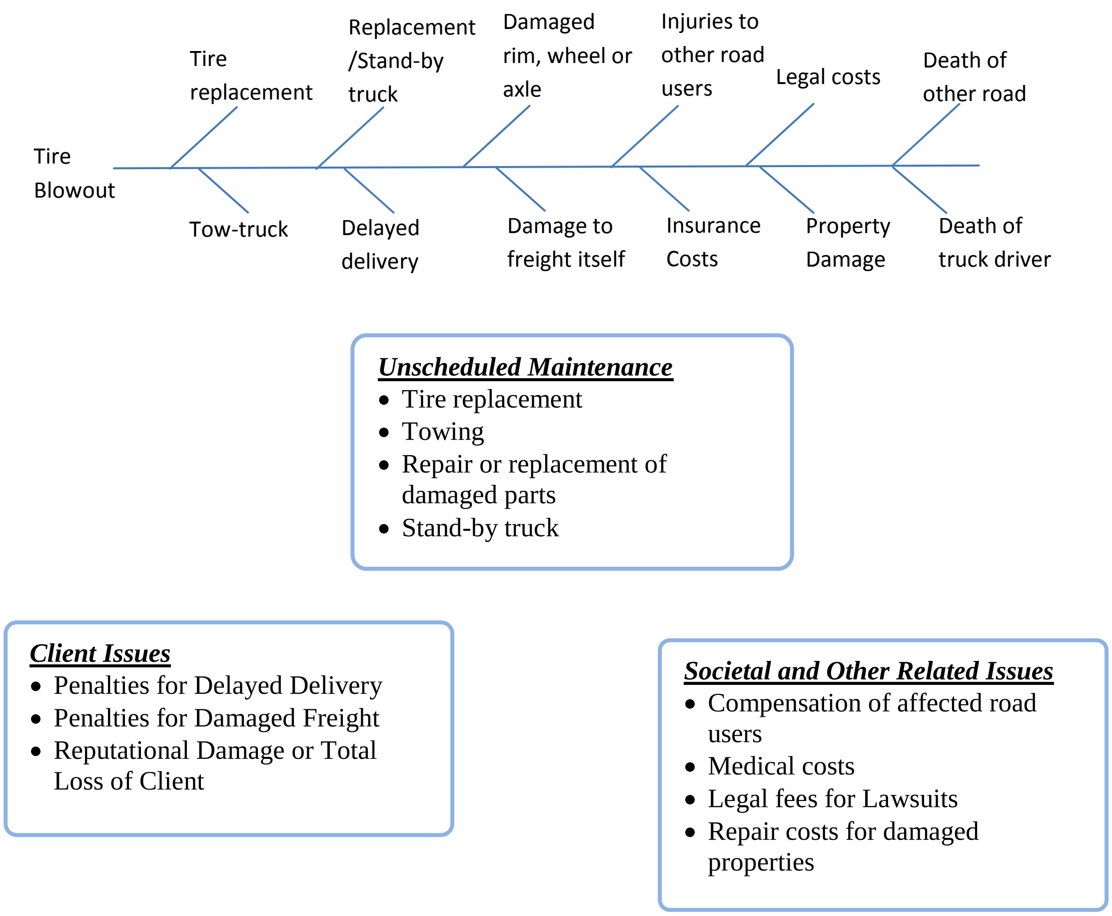


Figure 3.1: Fishbone Diagram on Various Consequences of Tire Blowout

The various costs associated with truck crashes can be classified as direct and indirect costs. Direct costs include immediate or short term costs such as damages, insurance costs, and medical costs while indirect costs include indirect administrative costs and associated costs. According to the Accident Cost Table drafted by the Federal Motor Carrier Safety Administration, it will take an excess of $1 million in revenue for motor carrier to offset $25,000 spent on a crash (that is after accounting for direct and indirect costs). It is estimated that direct and indirect costs for truck crashes resulting in Property Damage Only (PDO) could amount to $15,114 while non-fatal injuries could amount to $195,258. Fatal crashes were estimated to cost over $3.5 million per crash (Zaloshnja and Miller, 2006).

In a simple analysis, a weighted average cost can be calculated by considering different scenarios in the event of a tire blowout and weighing each one based on their probability of occurrence. The table below summarizes the different cases related to a tire blowout with their cost and likelihood of occurrence. These estimates were gathered from discussions with some of the industry experts and truck drivers.

Table 3.1: Weighted Cost Estimate for Repair and Maintenance.

Case	**Estimated Average Cost ($)**	**Weight (Probability)**	**Weighted Cost**
Simple Tire Replacement	350	0.284	99.4
Towing	200	0.244	48.8
Repair of Damaged Properties	125,000	0.084	10,500
Penalties	400,000	0.103	41,200
Cost of losing client	250,000	0.085	21,250
Compensation	1,500,000	0.067	100,500
Legal Fees	300,000	0.133	39,900
Total	**$2,575,550**	**1**	**$213,498.2**

The weighted average or expected cost from the table above gave the estimated average repair and maintenance cost to be $213,500.

In a study carried out by NHTSA (2005), the impact of a well implemented TPMS on reducing losses associated with skidding/loss of control, increased stopping distance, tire blowouts, property damages and other fatalities resulting from underinflated tires was comprehensively estimated. By using the Maximum Abbreviated Injury Scale (MAIS)[5], the net benefits with respect to the safety from fatalities achievable by implementing three different options of TPMS in vehicles were calculated. The value of $3.5 million per statistical life used in estimating the net reduction in fatalities was in line with the Department of Transportation (DoT) directive on valuing fatalities (DoT, 2002, Blincoe *et al*., 2002). As a sensitivity analysis, a value of $5.5 million per statistical life was used in the evaluation of net reductions in fatalities.

[5] The Abbreviated Injury Scale (AIS) is an anatomically based system that classifies individual injuries by body region on a six point ordinal scale of risk to life. The AIS does not assess the combined effects of multiple injuries. The maximum AIS (MAIS) is the highest single AIS code for an occupant with multiple injuries.

Chapter Four

Investigating Tire Pressure Loss Sequence

It was observed that the various estimated percentage given on the impact of underinflated tires on fuel economy falls short on providing details on the fuel economy is affected by varying numbers of underinflated tires. For example, the 3% reduction in fuel economy at 29% under-inflation fails to mention how many tires would result in such an impact. A fundamental requirement is to first understand the impact a single and sufficiently underinflated tire would have on the overall fuel efficiency of the vehicle. Afterwards, it would be necessary to investigate how fuel economy reduces with each increase in the number of underinflated tires. The relationship could be linear, geometric or exponential. Such an investigation will provide invaluable insight into the behavior of fuel economy in relation to the number of underinflated tires with the possibility of determining a critical point where there is no longer any significant change (or could be an extremely damaging reduction) in fuel economy. In summary, one can be able to determine how many underinflated tires at the minimum, can significantly affect fuel consumption and increase the safety and maintenance risks for a commercial truck.

4.1 Determining the Tire Conditions Using Markov's Chain

A major need in this study was the necessity to develop a model to determine the various states a tire can be found and the possibility of finding each in that state. Also important is determining how many underinflated tires on the average, can be found at any given time on an 18-wheeler fully loaded truck. By assuming that the probabilities do not change over time and it is an independent random process, we can apply the Markov chain theory to solve the problem.

Consider a given tire at any given time; it is over-inflated, well-inflated or underinflated. Overinflated tires will either blowout under the applied load or loose pressure until it reaches the level for a well-inflated tire. Definitely, the age and condition of the tire comes into play in determining which outcome will most likely occur. By assuming a standard scenario for the tire's condition, we can avoid any complexities and keep our model as simple as possible.

In the case of a well inflated tire, we assume that the only reasonable outcome is for it to lose pressure and become underinflated after a specific period of time. Accidental blowouts resulting from potholes, sharp objects on roads or any uncontrollable and unpleasant circumstance are random events and are considered rare.

Finally, an underinflated tire would fail (or blowout) during operation, or most likely be detected and inflated back to or over the appropriate level. Hence an underinflated tire can transit to any of the states mentioned above.

This problem is best represented such that:

States, $S = \{H, W, L, F\}$

Where H – Over-inflated, W – Well inflated, L – Underinflated, F – Tire Failure or Blowout

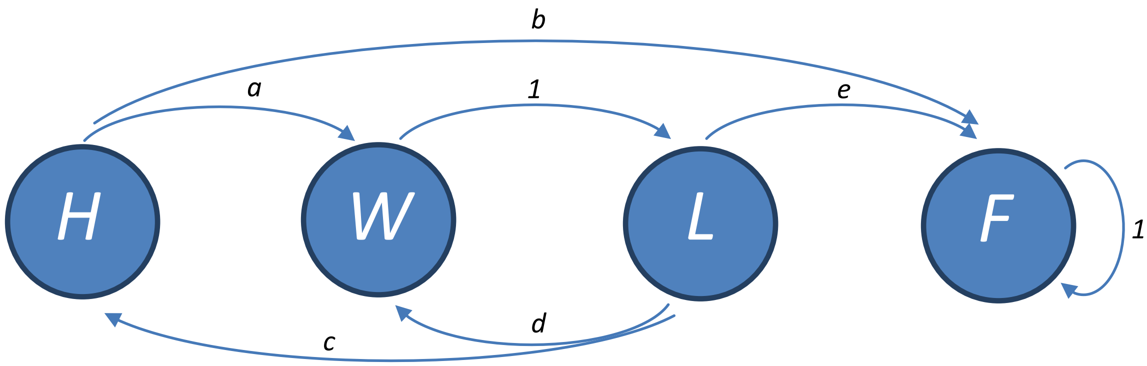


Figure 4.1: Markov's Chain Diagram for Different States of a Tire at Any Given Time.

The transition matrix, X for the problem is given below:

$$X = \begin{array}{c} \\ H \\ W \\ L \\ F \end{array}\begin{array}{c} \begin{array}{cccc} H & W & L & F \end{array} \\ \begin{bmatrix} 0 & a & 0 & b \\ 0 & 0 & 1 & 0 \\ c & d & 0 & e \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

As evident in the probability matrix and in the chain diagram, the probability that a well-inflated tire will become underinflated with time is 1. Also, a tire that fails cannot be restored but must be replaced, resulting in additional expenses which must be put into consideration. Hence, the cost of a failed tire will be the associated cost for replacement, including labor and any lost work hour at the repair shop. The simplified model for the problem have zeroed out a number of values leaving the transition probability values for a, b, c, d and e to be calculated from collected data relating the problem.

For the model, the following are true.

$$a + b = 1$$

$$c + d + e = 1$$

In the same manner, it is possible to use the Markov chain approach to determine the number of tires on an 18-wheeler truck which is or is not operating at the specified optimum inflation pressure. A general module is represented below:

Considering

$$Y_t = number\ of\ underinflated\ tires\ at\ the\ end\ of\ period\ t$$

Where *t* could be weekly, fortnightly or monthly.

$$P\{Y_{t+1} = j | Y_t = i\}\ for\ all\ t = 0, 1, 2, \dots, n.$$

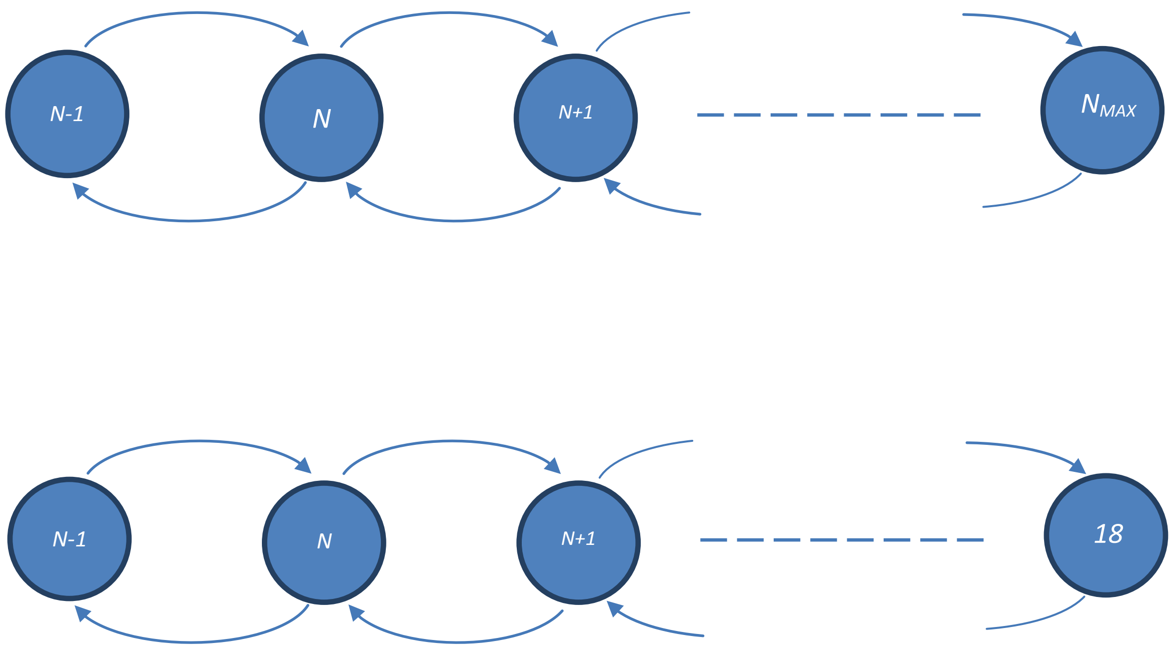


Figure 4.2: Markov's Chain Diagram to Determine the Number of Underinflated Tires at Any Given Time.

The model above explains the sequence by which one tire after another gets underinflated with varying probabilities. It makes sense to assume that the transition probability of a subsequent tire getting underinflated increases with the number of already underinflated tires on a truck. Hence the transition probability that a fifth tire will get underinflated with four already underinflated tires will be much more than the probability of the first underinflated tire assuming all tires were initially at the specified tire pressure.

Table 4.1 below summarizes the findings of NHTSA (2005) on the number of underinflated tires on a number of different passenger cars and light trucks that was surveyed.

Table 4.1: Distribution of the Number of Tires on Vehicles That Have One or More Tires that is 25% or more Below Placard (Source: NHTSA, 2005)

Number of Tires 25% or more Below Placard	Passenger Cars	Percent	Light Trucks	Percent
1	880	55.9%	542	47.2%
2	399	25.3	313	27.3
3	139	8.8	145	12.6
4	157	10.0	148	12.9
Total	1,575	100%	1,148	100%

By determining the average number of underinflated tires on a truck and the likelihood of finding such number at any given time, it becomes possible to estimate with greater precision, the impact a given number of underinflated tires will have on fuel consumption. The study can be further extended to understand the impact the position of an underinflated tire will have on overall vehicle performance.

Chapter Five

Sensitivity Analysis

The sensitivity analysis was an important part of this study in determining the level of variability or uncertainty in the problem at hand. It is imperative to understand how sensitive the various parameters in the problem were affected by inevitable fluctuations in price overtime. An investment might initially seem worthwhile at the moment, but understanding the forecasts of the possible changes in the associated market forces can help predict the actual feasibility of such an investment beyond the present time and into a determined period in the future. Consequently, with proper forecasts and analysis, it can be possible to identify any point in time where a shift in the cost-benefit analysis of an investment will significantly affect the expected return on investment.

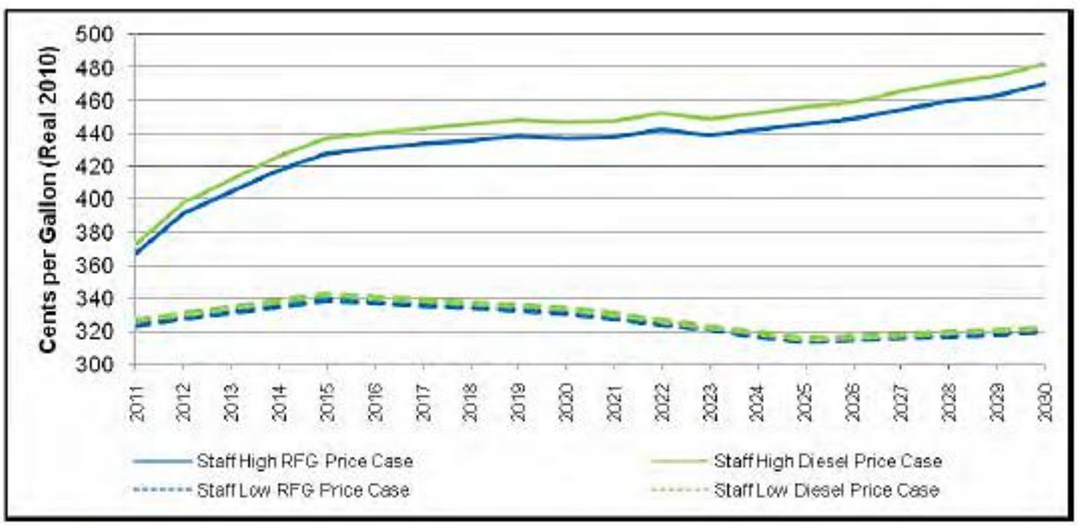
In the case of a trucking company investing in continuous tire pressure monitoring technology, valuing the various associated savings in operation costs was attempted. The question was what components of the related operations costs will greatly affect the expected savings and what would be the nature of such an impact (either positive or negative). Each of the parameters in our associated cost savings are considered.

5.1 Fuel Savings

The fuel savings was calculated using three parameters with the formula:

$$Fuel\ Savings\ (dollars/year)$$
$$= f\left(Mileage\left(\frac{gallons}{mile}\right), Fuel\ Price(\frac{dollars}{gallon}), Distance\ Travelled(\frac{miles}{year})\right)$$

It is very evident from the equation above that overall fuel savings was mostly determined or affected by the prevailing pump price for diesel. It was reasonable to assume that the average miles travelled by a truck in a year and the average truck mileage will remain unaffected (or not significantly changed overtime). Various studies have predicted that the rising trend in diesel pump price will continue uncontrollably for the next couple of years with an estimated price of $4.50 in 2015. This will increase the fuel savings to $2750, an increase of about 15%.



Source: California Energy Commission

Figure 5.1: California Gasoline and Diesel Price Forecasts (2010 cents per gallon)

5.2 Savings in Maintenance Costs

The cost savings achievable from repairs and maintenance by implementing continuous tire pressure monitoring technology depends on various factors one of which is the actual extent of damage in the case for which the technology was not in use. It has been estimated that an underinflated tire's lifespan can be reduced by as much as a year.

Hence, cost savings can be as simple as the additional year of tire usage before replacement. In the case of a blowout, the cost savings could be significantly low such as in the case of simply replacing the damaged tire, or in extreme cases, the total costs associated with a fatal accident. The cost of replacing a tire at the moment is estimated to be $300.

According to Larry Johnson, the president of Nebraska Trucking Association, the average minimum costs as a result of a fatal accident is $1.8 million covering lawsuits, repairs, and compensations etc. Of this, the maximum insurance coverage is $1 million while the remaining $800,000 is borne by the trucking company. Although no data was acquirable on the changing trend in the cost of insurance for a trucking industry, it is assumed that this present estimated value will not change significantly over time.

5.3 Life Span

The life span of any technological undertaking is vital in estimating the return on investment and deciding on its viability. In the case of tire pressure monitoring technologies, it was essential to know how long the technology will last after installment. Such technologies were expected to have very appreciable life spans with minimal operating and recurring costs in order to maximize their viability.

By combining all the factors discussed above, one can develop a comparison between optimistic and pessimistic estimates and afterwards determine the most likely breakeven point for our estimate.

To determine an acceptable cost for an RFID based tire pressure monitoring technology for example, the focus was on an investment justifiable by the fuel savings alone. By determining the present worth (PW) of an annual savings of $2400 for 5 years at a minimum annual rate of return (MARR) at 10%, we can determine the breakeven price for such investment provided the annual operations and maintenance cost is known from the formula

$$2400(P/A, 10\%, 5)$$
$$= Price + Annual\ Operating\ and\ Maintenence\ Cost\ (P/A, 10\%, 5)$$

Note that the net disposal cost*(A/F) was not part of the equation since our calculation is for the monitoring system technology and not the tire itself.

By modifying the estimated maintenance cost for a typical TPMS as calculated by NHTSA (2005), the average maintenance cost for that installed on a truck was estimated to be between $195.27 and $269.62 (increase due to 18 tires for the truck in consideration when compared to 4 tires for a passenger vehicle).

Using this information to solve for the above equation yields a price of approximately $8100 for the technology to breakeven when considering fuel savings alone.

According to NHTSA (2005), the average cost for indirect TPMS could range from $130 per vehicle or for full ABS at a cost of $240 per vehicle. On the other hand, the cost for direct TPMS is dependent on the market price for various necessary components such as tire pressure sensors at $7.50 ($135 for 18 wheels), $3.85 for a selectable display, $19 per vehicle for the control module, $11.50 for additional components and $40 for an added pump (optional component for refilling air while the vehicle is still in motion). This amounts to about $210 for a direct TPMS.

Table 5.1: Estimated Original Equipment and Aftermarket System Costs for Indirect TPMS (NHTSA, 2001).

System	E	F	G	H	I	J
O.E.M. Price per System	$50	No Estimate	No Estimate	$50	No Estimate	60
Aftermarket Price per System:	n/a	n/a	$249	$245 to 295	$200	Basic $150 Full $250

The estimated costs for the TPMS systems as illustrated above falls short of our calculated breakeven price. Hence, this investment is justified by the benefits achievable from reduced fuel consumption alone. By the time other benefits such as reduced repair and maintenance costs, reduced crash incidents and fatalities were added to our estimate, it becomes evident that any trucking industry can invest in implementing tire pressure monitoring technologies within its fleet with the assurance of maximum benefit achievable.

Chapter Six

Conclusion

This study has examined two different types of technologies available for continuous monitoring of tire pressure and attempting to evaluate the economic impact such technologies would have on a trucking company's bottom-line. So far, by using available data and estimates based on professional recommendations, the possible savings achievable from reductions in operations cost (as a result of continuous usage of properly inflated tires) was calculated to either justify, or otherwise refute the need of such technologies in a fleet company.

At the very least, the minimum possible cost savings achievable was found to be $2,400 from reduction in fuel consumption alone in a year. The actual cost of investing in Tire Pressure Monitoring Systems (TPMS) was found to be $270 on the average. However, for RFID technology, the tags alone at the moment cost between $25 and $75 dollars. The industry goal is to achieve tags that are not more than 2% of the actual tire cost (or being closer to $3 to $5 a tag). The cost for the reader, middleware and network set-up is variable depending on the size of the system. The cost of the computer hardware and software is expected to decline and an estimate of $2,500 for purchase to get started is not unreasonable. However, it can be assumed that the annual worth (AW) for the cost of deploying the technology should not exceed at the minimum the achievable fuel savings.

In line with the objective of this study, it has been shown that tire pressure monitoring technologies can add economic value to a trucking company's bottom-line if implemented across its fleet. At the very minimum, a trucking industry can earn $2400 per annum in savings from fuel consumption alone due to proper utilization of specified tire pressure.

A savings of $2,400 per year from fuel consumption might seem small. But considering that the average trucking company has 20 trucks in its fleet, this amounts to $48,000 savings in operations cost in a year. Furthermore, considering the fact that the motor carriers market today is highly competitive with very thin profit margins, any means of reduction in its recurring expenses, including operational cost would be a welcomed idea. According to ATRI (2011), there is an increasing trend in freight demand which is very likely to pressure operators into increasing their fleets. This will definitely impact trucking industry's average fleet and consequently, the marginal operating costs. Furthermore, if savings in other repair and maintenance costs are considered, the value can rise to much as over $800,000 per truck per annum in cases of fatal tire failures and related client issues.

With the available data at hand, this study has been able to show that the savings in fuel consumption alone justifies investing in TPMS for any trucking company considering the option. The study also showed that the breakeven price for a 5 year tire life at 10% MARR would be $8100 which far exceeds the available current market price for TPMS (i.e. $270 per vehicle).

It is imperative to emphasize that this study can be further upgraded by attaining very specific information that would help improve the accuracy of our analysis. For example, by analyzing and determining the impact of varying numbers of underinflated tires on the overall performance of a semi-truck, and by determining the average number of underinflated tires expected to be on an 18-wheeler semi-truck at any given time, we can be able to achieve a more accurate measure of the economic impact as well as related safety concerns. In this study, a Markov chain approach was used to analyze the problem but this can be actually solved if the required data was available.

In the case where fleet operators still question the viability of investing in technologies that enable continuous tire pressure monitoring, it is important to explain that these technologies are being improved to incorporate additional functionalities apart from pressure monitoring alone. Increasing the technology capabilities without significantly affecting the cost of implementation will eventually increase the benefits and of course, the return on investment to the end user. A good recommendation based on suggestions from the Nebraska Trucking Association, would be to incorporate weighing capabilities in the RFID tags for tires. This would prove to be an inexpensive weigh-in-motion concept for truckers and will save both the government and the trucking industry a reasonable amount of labor, time and, of course, money involved in the traditional weighing stations.

Likewise, this study assumed that the every truck driver will immediately respond to warnings of under-inflation from the installed pressure monitoring device. However, this is not what obtains in reality. As mentioned earlier, only one-third of drivers with tire pressure monitoring systems currently installed immediately responds by refilling their tires to the proper pressure level. The low response rate will definitely defeat the purpose of the technology in the first place. Some motor carriers' solution to this problem was to provide incentives for drivers who turn out with lower energy consumption by following proper guidelines and standards in their operation.

Lastly, it is important to question for how long tire pressure monitoring technologies will outlive their benefits before they replaced with newer and more promising technologies. In fact, emerging technologies in tire manufacturing coupled with state-of-the-art research are proving that additional technologies currently used in monitoring tire pressure can become obsolete anytime soon.

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