Tire Remanufacturing and Energy Savings

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1. Introduction and Motivation

The transportation sector is one of the major energy consuming sectors in the U.S. and worldwide. In the U.S. alone nearly 28% of the national energy expenditure takes place within the transportation sector. Amongst all transportation modes, the use of on-road vehicles has grown enormously in the past few decades. The figure below illustrates increase in energy consumption of on-road transportation sector by mode.

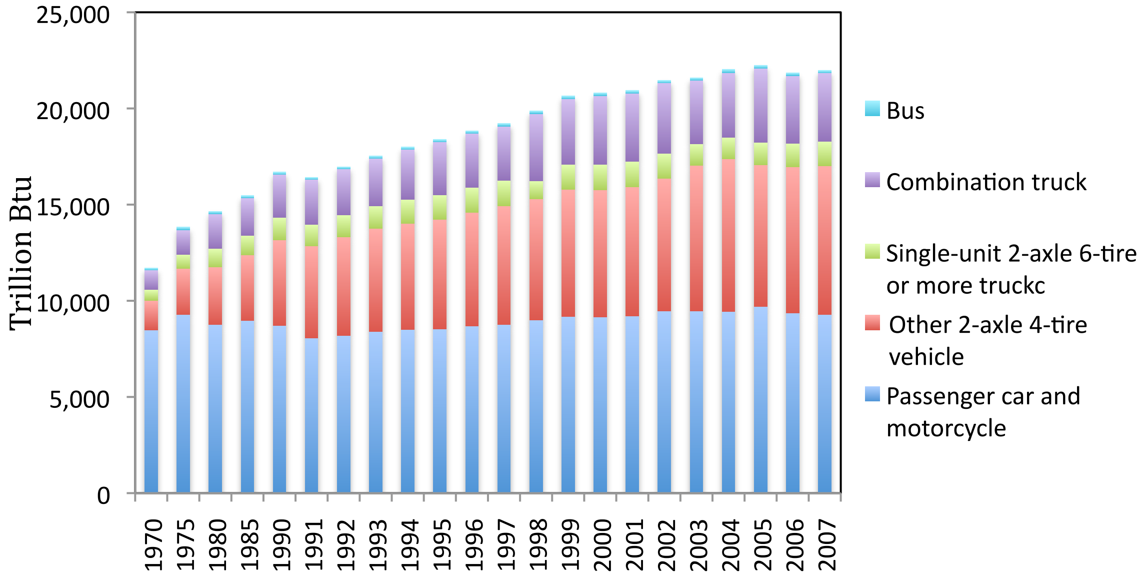

Figure 1 U.S. Energy Consumption in the U.S. by on Road Transportation Mode (1970-2007) [1].

The rise in energy consumption and fossil fuel demand of on-road transportation modes is coupled with substantial rise in demand for raw materials and production of waste. In addition, rising concern about global change, volatility in fuel prices, and continued growth in transportation demand has caused policy advocates and industry officials to take critical steps towards saving energy, minimizing emissions, and reducing depletion and production of waste. Ever since the introduction of Corporate Average Fuel Economy in the U.S., passenger car vehicles have become more fuel-efficient. Since a considerable amount of energy during a life cycle of a vehicle is expended in operation, it is important to evaluate the energy savings improvements for each of the components in the vehicle that contribute to losses.

Tires are of the major components that contribute to energy losses in a vehicle. The tread of a tire encompasses only 10 to 20 per cent of the construction weight of the tire, hence, scrap tires retain high material and energy value that can be effectively recaptured. This has led to diversified applications of scrap tires beyond the conventional disposal path of being sent to land fills. For example, the sectors that utilize scrap tires extensively are using it for tire-derived fuel applications (cement industry, pulp and paper industry, industrial boilers), electricity co-generation (electric utilities), civil engineering purposes, etc. Another promising market for scrap tires is tire retreading. Tire remanufacturing (commonly known as tire retreading) is the process of remanufacturing a used tire to like-new by applying a new tread to the tire. A retread is a previously-worn tire that has gone through a remanufacturing process designed to extend its service life. Retreads are significantly cheaper than new tires. As such, retreads are widely used in large-scale operations such as bussing, trucking, and commercial aviation.

The tire retreading industry is reportedly the largest sector of remanufacturing industry in the United States in terms of the number of remanufacturing (retreading) plants as shown in figure below [2].

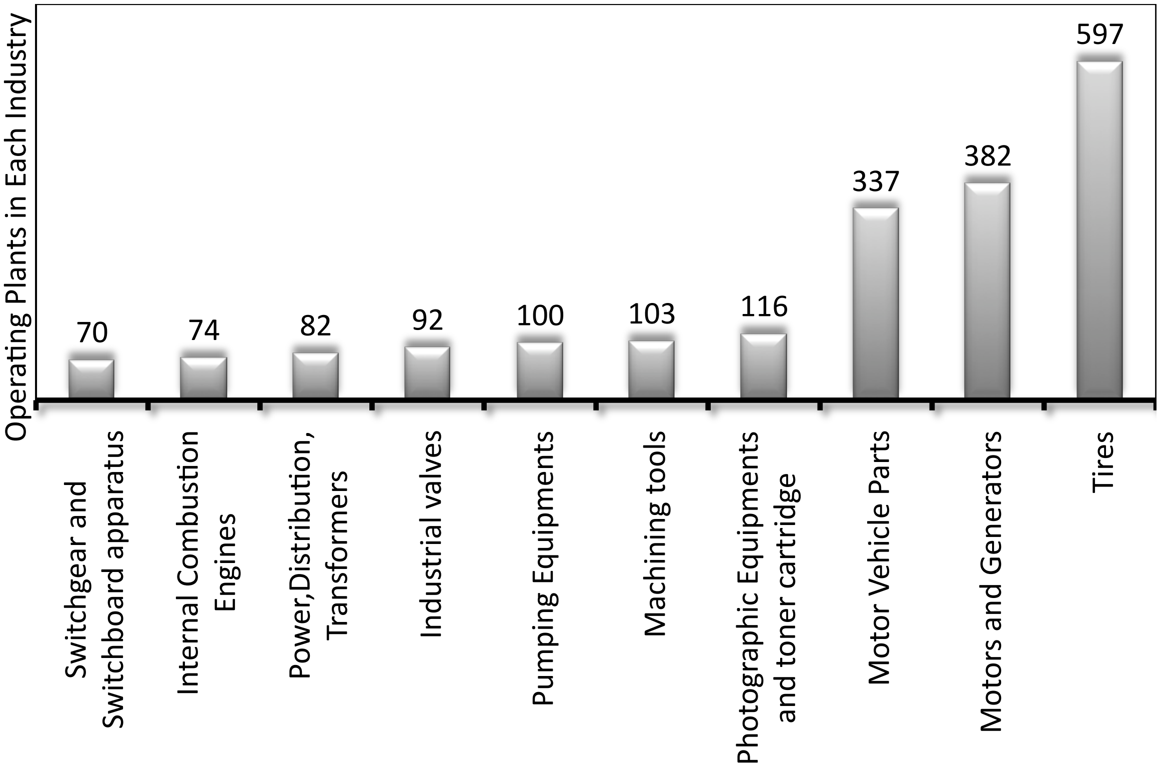

Figure 2 Remanufacturing Establishments in the U.S. [2].

It is apparent that tire retreading leads to energy and materials savings in the production process due to minimization of raw materials requirement and reduction in capacity of manufacturing energy consumption. However, the ultimate energy savings strategy depends on whether it could save energy in all life cycle stages of the product including use-phase. In this paper we analyze the energy savings potential of tire retreading from a total lifecycle perspective.

2. Tire Industry Overview

Tire industry is reportedly the largest consumer of rubber in the world. [3]states that tire manufacturing is a mature industry with annual industrial revenue of $17.6 billion in 2008 [3]. In

2004, 323 million new tires were manufactured in the U.S.; 255 million (79%) of the tires shipped were for passenger cars, and 58 million (21%) for trucks, aircrafts, buses, and off-the-road vehicles. Furthermore, 68 million (21%) of sales were to original equipment manufacturers (OEM), and 254 million (79%) were replacement tires for used tires [3].

In the U.S. tire industry there are 16 main Original Equipment Manufacturers that dominate the production output in tire industry. They operate 48 tire manufacturing plants in 17 states across the U.S. Figure 3 below provides information about the annual production of tires for these manufacturing plants [4], [5].

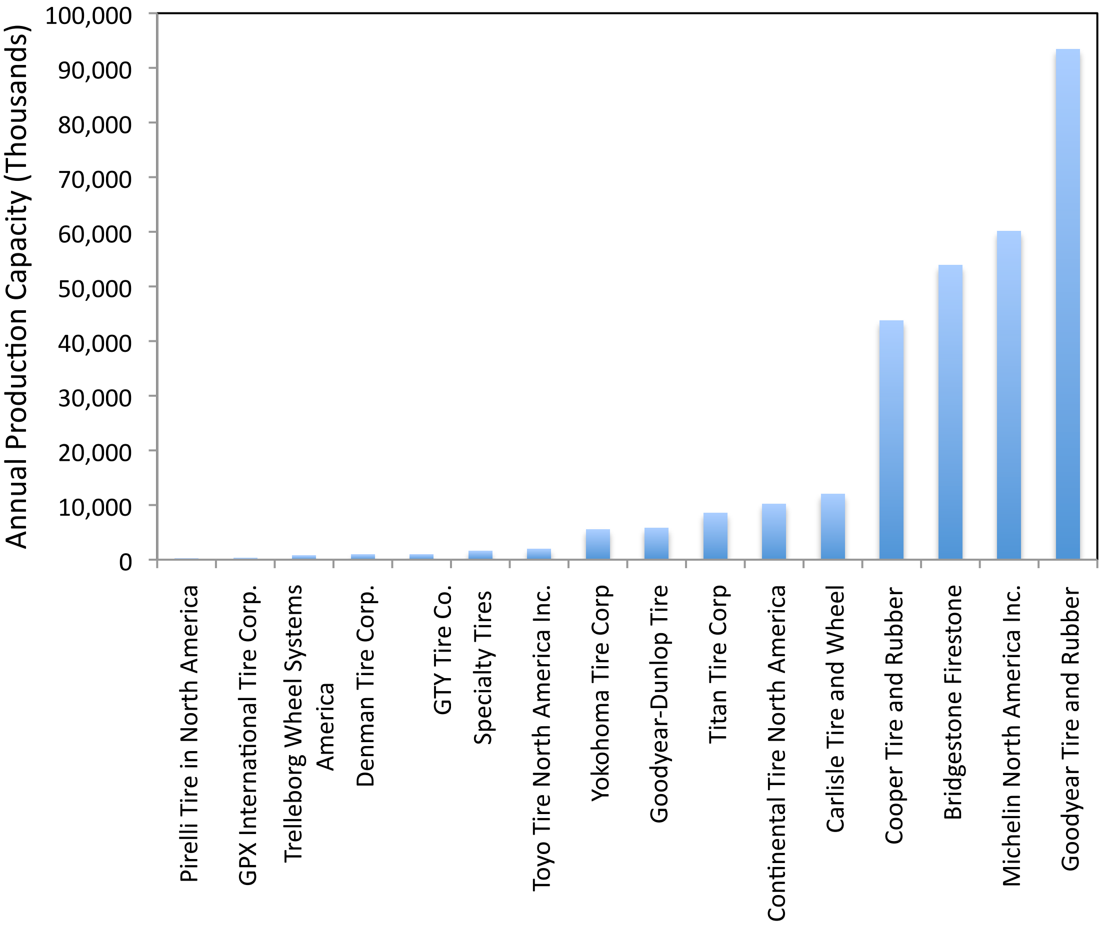

Figure 3. Annual Tire Production Units in 2005 [4], [5].

The tire manufacturing industry consists of large firms some of which either primarily service the Original Equipment Manufacturing (OEM) market, the replacement aftermarket, or both. The Rubber Manufacturers Association (RMA), the national trade association for the rubber products, supports the tire manufacturing industry. Its members include more than 100 companies that manufacture various rubber products, including tires, hoses, belts, seals, molded goods, and other finished rubber products.

The majority of establishments are small organizations within the tire industry that provide services such as tire repair and retreading. Tire retreading accounts for an estimated 79.1% of industry establishments, but only an estimated 3.9% of industry revenue [3].

Table 1. Employment size for tire OEM and retreading plants in the U.S. [6].

Employment Size Class	OEM Establishments	Percent	Retreading Establishments	Percent
1 to 4	43	27.2%	219	36.7%
5 to 9	18	11.4%	110	18.4%
10 to 19	11	7.0%	140	23.5%
20 to 49	10	6.3%	110	18.4%
50 to 99	12	7.6%	13	2.2%
100 to 249	17	10.8%	5	0.8%
250 to 499	12	7.6%	0	0.0%
500 to 999	5	3.2%	0	0.0%
1,000 to 2,499	26	16.5%	0	0.0%
> 2,500	4	2.5%	0	0.0%
Total	158	100.0%	597	100.0%

Tire retreading and rebuilding share 3.9% of industrial revenue, which is equivalent to $686.4 million [IBISWorld]. The production statistics for retreaded tires are provided by [7], which ranks the top 100 retreading plants in the U.S. [4], [5]. The ranking is performed based on the average usage of tread rubber in producing retreaded tires. Table 2 below reveals the production capacity of the top 10 retreaders in year 2005 [7]:

Table 2. Top ten retreaders in the U.S. : (1) Number of plants (2) Types of tires retreaded (3) Retread process franchiser [7].

Rank	Name	# Plants	Light-Truck Retreads*	Medium/Heavy-Truck Retreads*	Off-the-Road Retreads*	Retread Process Franchiser
1	Wingfoot Commercial Tire Systems LLC	54	390	5290	40	Goodyear
2	Bridgestone Bandag Tire Solutions	37	20	3094	6	Bridgestone Bandag
3	Purcell Tire and Rubber Co.	5	150	1,300	120	Goodyear

4	Southern Tire Mart	17	0	2930	0	Bridgestone Bandag
5	Tire Centers LLC	15	0	2928	0	Michelin
6	Best-One Group	17	0	2100	0	Bridgestone Bandag
7	Northwest Retreaders Inc.	1	25	210	105	NA
8	McCarthy Tire Service	5	132	900	38	Bridgestone Bandag
9	Les Schwab Tire Centers	4	0	1220	15	NA
10	Snider Tire Inc.	8	75	1350	0	Michelin

*The values are expressed in terms of daily unit production capacity

According to Table 2 the top 10 retreaders are for the most part wholly-owned subsidiaries of the large tire OEMs such as Goodyear, Bridgestone, and Michelin. According to the above observations, major tire companies have well invested into the retread sector and have expanded their infrastructure extensively. For example, Wingfoot Commercial Tire System LLC, the top ranked retreader, has 150 retail locations spanning across U.S. as shown in Figure 4 below [8]:

Figure 4. Wingfoot Commercial Tire System LLC distribution of 150 retreader retails locations in the U.S.

With the cost of retreaded tires being 30% to 50% less than the cost of a new tire, it makes them appealing to consumers such as truck fleet operators that travel extensively and demand higher rates of tire replacement. More specifically, the demand for retreaded tires from fleet operators is the largest in the tire retreading industry for a variety of reasons:

1. Tire maintenance and replacement is the third highest cost for fleet operators after labor and fuel

2. With the advancement in tire retreading for heavy-duty tires, some OEMs offer warranties for retreaded tires that are originally applied to the purchase of new tires
3. One of the key success factors for effective retreading is retrieving cores that have been properly maintained during use phase. Given that fleet operators consistently monitor the inflation pressure, and other operations characteristics of their tires in use phase, the used tire is in ideal conditions upon reaching end-of-life.
4. The turn-over rate for tire replacement is much higher for heavy truck fleets. As such, tire retreading is desirable from an economic and material savings standpoint

According to Michelin Factbook 2001, retread tires encompass 44% of the total tire replacement market for heavy-duty truck tires [9]. The success of tire retreading in truck tires, has not been observed in the light duty vehicle sector. According to Rubber Manufacturers Association, only 0.6% of replacement tires for light duty passenger car vehicles were retreads in 2001 [10]. Moreover, only 1.67% of replacement tires for light trucks were retreads in 2001 [10]. These numbers signify that tire retreading is insignificant in the light duty tire replacement market. There are several reasons for this that may explain why light duty retreading has not been effective:

1. Tire retreading similar to any remanufactured product suffers from negative consumer perceptions about safety of a remanufactured product. As such, passenger car owners are hesitant to purchase retreaded tires because of association of retreads to tire rubber on the highway road.
2. A passenger vehicle operates on two axles as opposed to 3 to 5 axles. Therefore, from a security purpose, utilizing re-treaded tires may be causing greater concerns in regards to stability, traction, and safety of vehicle.
3. Contrary to fleet tires, passenger car tires are not properly maintained, run below optimal inflation pressure on average, and are not properly repaired. As a result, the quality of cores for retreading purposes becomes an issue. In relation to this, the Tire Retread Industry Bureau (TRIB) conveys that in 2000, 85% of light duty vehicle tires that were inspected for retreading were rejected in the inspection and testing processes [11], [12].

3. End of Life Options of Scrap Tires in the United States

The annual estimate for scrap tire generation in the U.S. is reported to be around 299.2 million [13]. The utilization of scrap tires has substantially increased between 1990 and 2008. More specifically, the markets for scrap tires have increased dramatically, with over 87 percent handled through the marketplace in 2005, compared to 11 percent in 1990 [13]. In 2007, 89.3% of scrap tires generated in the U.S. were consumed in end-used markets. The tires in the scrap tire market can be utilized for various purposes [13]. Table 3 below shows the quantity breakdown for utilization of scrap tires for different applications.

Table 3. Application of scrap tires in end-use markets (2005) [13]

Application	**Quantity (million tires)**
Tire-derived fuel applications	155.1
Civil Engineering	49.2

Ground Rubber	37.5
Electric co-generation	1.3
Exported	6.9
Punch/Stamp	6.1
Agricultural	3.1
Total Tires Applied in end-used markets	259.2
Land Disposed	42.4
Annual Generation of Scrap Tire (% applied to end-used markets)	**299.2 (87%)**

According to table above, tire-derived fuel usage is the single largest concentration of scrap tires utilizing 155 million tires in 2005. Note that Scrap tires in table above refers to any tire where the casing cannot be used as a tire. As such, retreading statistics is not included in the scrap tire analysis conducted by Rubber Manufacturers Association above. Used casings that are in good conditions are retrieved for tire remanufacturing (retreading); tire retreading extends the service lifetime of the old tire.

4. Case Study Objectives

4.1 Introduction

Retreading has the potential to save substantial fraction of energy required for processing the raw materials and manufacturing of tires. This is because more than 80% of embedded energy is retained in the casing of the tire, which is saved after the tires reach end of life. In other words, a tire is scrapped due to tread wear; the tread only takes 10 to 20% of the entire material and energy retained in a tire. Tire remanufacturing is an environmentally friendly strategy since is recovers the high energy and material values in scrap tires that would otherwise end up in landfills. Moreover, tire remanufacturing reduces the energy demands and materials requirements in production of tires. According to [14] and [15], tire retreading can reduce the production energy demands for tires by as high as 66%.

A fraction of vehicle fuel input is consumed to overcome rolling resistance of tires. As the vehicle set in motion, tires undergo cycling visco-elastic deformations leading to dissipative energy losses in the form of heat in use phase. According to [16] the largest share in the cumulative energy input of a tire (more than 95%) in made in the use phase, due to the vehicle fuel requirements for overcoming rolling resistance of tires.

The rolling resistance energy losses of tires depend on various product factors such as tire design, architecture, construction, materials used, etc. Since tire remanufacturing involves re-use of an old casing, the type of casing utilized for remanufacturing and the quality of remanufacturing process constitute energy performance in use phase. Furthermore, if new tires are becoming more energy efficient compared to older remanufactured tires, then this may cause higher expenditures in use-phase that could potentially negate remanufacturing savings in production phase. Therefore, we evaluate the energy savings potential of tire remanufacturing by studying it from a lifecycle perspective.

4.2 Scope of Study

We consider three life cycle phases for evaluating environmental impacts of tires, namely, raw materials processing, manufacturing, and use phase. Analyzing the chosen phases combined will convey relative energy savings in production process as well as relative changes in energy demands between using new tires and re-using old retreaded tires.

In order to holistically evaluate retreading energy savings, we perform the energy analysis based on four distinct scopes:

1. Tire retreading energy savings in the scope of transformational technological changes in tires
2. Tire retreading energy savings in the scope of transitional technological changes in tires
3. Tire retreading energy savings in the scope of degradation in efficiency of retreaded tires compared to equivalent new tires
4. Tire retreading energy savings in the scope of product variations

Tire Remanufacturing Energy Savings in the Scope of Transformational Technological Changes in Tires

In the past few decades, technologists, OEMs, and research centers have progressively enhanced the performance of tires in use-phase. Technological milestones have been achieved through innovative changes to tire architecture, construction, design, etc. (labeled as transformational technological changes in this report). These changes have effectively improved the performance of tires in use phase (e.g. increased durability, traction, efficiency, etc.). For example, the two considerable transformational technological changes in tires are transitioning from tubed to tubeless tires and progressing from bias-ply to radial-ply tire construction (refer to 5.4.5 for more information).

Moreover, ever since introduction of radial tires (commonly referred to as dual radials), tire rolling resistance have been reduced considerably. For example, consumers today can procure fuel-efficiency enhancing low rolling resistance (LRR) radial tires. These tires are designed for minimizing rolling resistance heat losses, and saving automotive fuel. These technological progresses have been led by transformational changes in the tread composite and tire design.

Most tractor-trailer trucks currently utilize a dual assembly on the drive and the trailer axles, with two sets of wheel on each end of the axle. Truckers and fleet operators are advised to replace dual radial tires with a single wide-base tire to reduce the weight of the vehicle and save on fuel consumption. A single wide-base tire is simply a wider tire providing improved floatation versus conventional size truck tires. A single-wide base tire weighs less than two radial tires resulting in reduced weight of the truck. By using single-wide tires on drive and trailer axles, it can increase load capacity and/or reduce fuel consumption. Single wide-base tires can offer lower rolling resistance, lower aerodynamic drag, and avoid the frictional losses existing between radial tires.

Promotion of single wide-base truck tires is yet another transformational technological progress in tires.

Tire transformational technology progresses from bias to radial, from radial to advanced low rolling resistance radial, and from advanced radial to single-wide, typically makes the use performance of the prior generation of tires inferior. Since tire remanufacturing utilizes old tires that may be potentially a generation older, it may expend more energy than new products in the market. For this matter, in this report, we study the energy savings potential of retreading truck tires in the scope of past, current, and future transformational technological changes in tire industry.

Tire Remanufacturing Energy Savings in The Scope of Transitional Technological Changes

The transformational changes in tires in the past few decades have been accompanied by shorter time-scale (annual) improvements in technology employed in tires. For example, Original Equipment Manufacturer (OEM) tires have become more efficient in the past three decades. One of the primary driving forces behind this is the implementation of Corporate Average Fuel Economy (CAFE) standards for automakers in 1975.
Error! Reference source not found. below illustrates the reduction in rolling resistance coefficient of Original Equipment Manufacturer (OEM) passenger car tires (bias-ply as well as radial-ply) between 1975 and 2004 [17], [18].

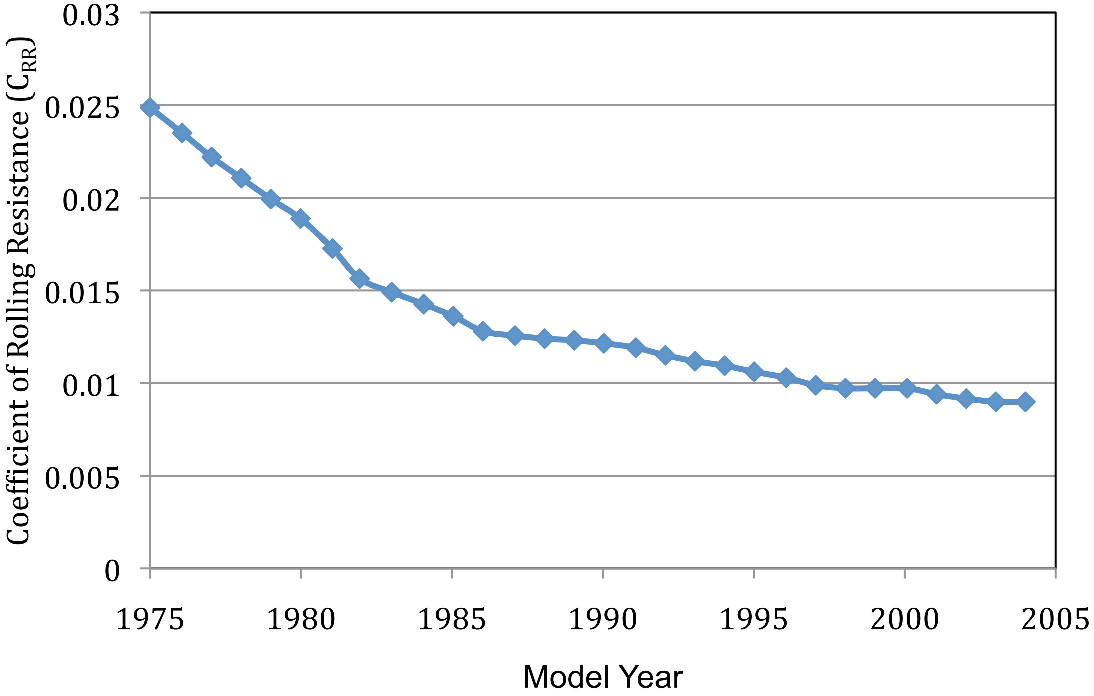

Figure 5. Estimated Original Equipment Manufacturer (OEM) Tire Rolling Resistance, 1975-2004. [17], [18].

Corporate Average Fuel Economy (CAFE) standard:

The trend observed in reduction of coefficient of rolling resistance can be broken into two distinct eras: (1) 1975-1986; (2) 1986-2004. According to the results, average coefficient of rolling resistance was halved between 1975 and 1986. Moreover, between 1986 and 2004, rolling resistance was reduced more moderately.

This phenomenon can be explained by the policy standards enforcing minimum efficiency performance for vehicles under the Corporate Average Fuel Economy (CAFE) standard. First enacted by the U.S. congress in 1975, the purpose of CAFE standards are to reduce the energy consumption of passenger car vehicles and light trucks. The standards were implemented in year 1978 under the responsibility of National Highway Traffic Safety Administration (NHTSA). As a result, automakers began providing explicit rolling resistance design parameters to their tire suppliers. More specifically, automakers demanded improved technology for OEM tires as a key strategy for achieving CAFE across vehicles they sell. This led to substantial improvements in tire technology between 1975 and 1986 and increased demand for radial tires over bias tires. However the pace in reduction of coefficient of rolling resistance for OEM tires was more moderate there after. This correlates directly with the change in CAFE standards, as shown in Figure 6 below.

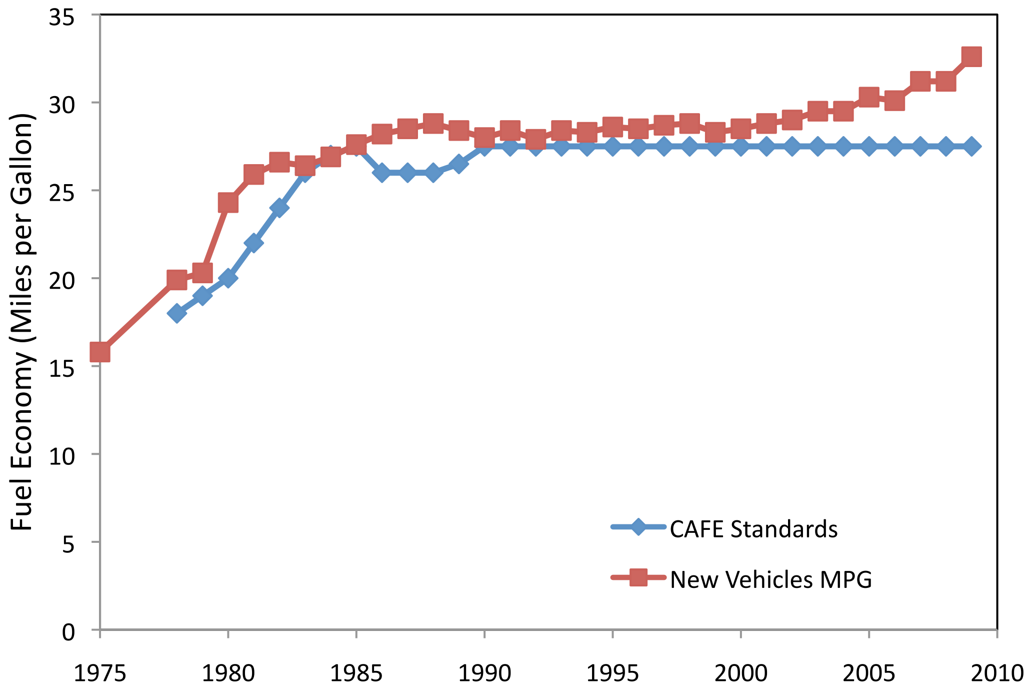

Figure 6 Corporate Average Fuel Economy Standards 1975-2009.

According to Figure 6 above, after 1985, CAFE standards for passenger vehicles have remained steady at around 27.5 miles per gallon. As a result automakers have steadily improved the technology of vehicles between 1986 and 2004, including OEM tires, and without much change in stringency of CAFE standards.

Under President Obama's administration, the CAFE standards will increase by five percent each year, reaching 35.5 mpg by 2016. In other words, in 7 years the national average CAFE has to increase by 8 mpg per vehicle. Therefore, drastic changes in fuel standards can potentially cause OEM tires to become more efficient at a faster rate, perhaps similar to improvements observed during 1975-1985 era.

Assuming a passenger car tire lasts for 3 years, would retreading and re-using the set of old tires result in lifecycle savings when compared to newly produced tires? How would the conclusions of the analysis change if we perform the assessments retrospectively?

In this report, we analyze the performance of retreaded tires for passenger cars in the context of transitional technology changes.

Tire Remanufacturing Energy Savings in the Scope of Degradation in Efficiency

The primary analysis for this study is conducted by assuming that old tires are retreaded to like-new conditions. This means that after retreading old tires, they would perform with similar rolling resistance characteristics and mileage lifetime as when it were first produced. Though retreading technology has been advanced to bring tires to like-new conditions, some retreading processes may not achieve this objective. [16] performs analysis for remanufacturing passenger car tires based on two scenarios: (1) increase of 3% in rolling resistance of retreaded tires (claims to be best in class), (2) increase of 10% in rolling resistance of retreaded tires (claims that this is the average change in rolling resistance). We perform sensitivity analysis to reveal the impacts of increase in rolling resistance of retreaded tires on lifecycle energy savings.

According to TRIB retreaded tires may last 75% to 100% of the lifetime of a new tire, based on the quality of retreading process. An important question to address is how does this affect the energy savings of tire remanufacturing. We also perform sensitivity analysis for assessing degradation in mileage lifetime of retreaded tires for both trucks as well as passenger cars.

Tire Remanufacturing Energy Savings in the Scope of Product Variations

There is a wide range for types of tires sold in the market due to variations in design, performance requirements (e.g. high traction, high durability, low rolling resistance), construction, size, speed rating, etc. Therefore, each set of tire casings has performance attributes that are unique and different from other tire cases on the market. When comparing lifecycle energy demands of a retreaded tire with a new tire, the results may strongly depends on which casings are compared in the wide range of product offerings for tires. For this scope of study, we provide a qualitative discussion about the existence of wide range of rolling resistances for both retreaded as well as new truck tires. As discussed in detail later, data suggest that a strong analysis requires careful identification of the type of products studied in order to achieve strong conclusions about tire retreading and energy savings.

In summary, we conduct the tire remanufacturing energy savings analysis in the scope of four categories, as discussed above in detail. More specifically, we analyze remanufacturing energy savings for truck tires in the scope of transformational technological changes (1), degradation in efficiency (3), and product variations (4). For passenger car tires, the scope of study consists of retrospective assessment of transitional technological changes (2), and degradation in performance of retreaded tires and its impacts on remanufacturing energy savings potential (3).

5. Methodology: Life Cycle Assessment

5.1 Raw Material Production and Tire Manufacturing Phase

Introduction

The two main components of a tire are the tread and the casing. Prior to manufacturing the tire by vulcanizing the tread and the casing, different materials utilized in the generation of tire must be produced. In order to get a holistic perspective on tire manufacturing it is critical to start by the very initial processes involving extraction and transport of raw materials. A conventional tire is typically made of synthetic rubber, plastic rubber, carbon black, fabric-type materials, plasticizers and other additives.

Synthetic Rubber (Styrene-Butadiene Rubber)

Synthetic rubber (also referred to as styrene-butadiene rubber) is predominantly made from styrene and butadiene amongst other polymeric additives. Styrene is an organic compound with the chemical formula $C_6H_5CH=CH_2$ that is generated mostly from the benzene product from crude oil [19]. Styrene is produced industrially from ethyl benzene, which in turn is produced from alkylation of benzene with ethylene. Benzene is generally produced from a class of organic compounds referred to as aromatic compounds [19]. The most commonly known feedstock for aromatic compound production is petroleum naphtha.

There are mainly two ways to produce styrene. The first process, which is currently the most conventional process, is the dehydrogenation of ethyl benzene [20]. More specifically, ethyl benzene undergoes catalytic dehydrogenation (chemical elimination of hydrogen process), which takes places on an iron oxide or potassium oxide catalyst in presence of steam [19]. This process is typically performed at a temperature of 630 degrees Celsius [20].

A more recent methodology for producing styrene involves oxidizing ethyl benzene and reacting it with propylene to generate methyl benzyl alcohol and propylene oxide [20]. Dehydrating the alcohol at fairly low temperatures completes the process of producing styrene. Table below provides information about primary fuels and associated energy required for producing 1 Kg of Styrene [20].

Table 4. Gross primary fuels required to produce 1 kg of styrene. (Totals may not agree because of rounding) [20]

Fuel type	Fuel Production and Delivery Energy (MJ)	Energy content of Fuel (MJ)	Fuel use in Transport (MJ)	Feedstock Energy (MJ)	Total Energy (MJ)
Coal	0.78	2.60	0.12	<0.01	3.51
Oil	0.88	14.32	0.18	28.67	44.06
Gas	1.46	17.93	0.12	16.57	36.08
Hydro	0.09	0.05	<0.01	-	0.15
Nuclear	1.16	0.45	0.09	-	1.69
Lignite	<0.01	<0.01	<0.01	-	<0.01
Wood	<0.01	<0.01	<0.01	<0.01	<0.01
Sulphur	<0.01	<0.01	<0.01	<0.01	<0.01
Biomass (solid)	0.01	<0.01	<0.01	<0.01	0.02
Hydrogen	<0.01	0.38	<0.01	-	0.38
Recovered	<0.01	-3.35	<0.01	-	-3.35
Unspecified	<0.01	<0.01	<0.01	-	<0.01
Peat	<0.01	<0.01	<0.01	-	<0.01
Geothermal	0.01	<0.01	<0.01	-	0.01
Solar	<0.01	<0.01	<0.01	-	<0.01
Wave/tidal	<0.01	<0.01	<0.01	-	<0.01
Biomass	0.02	<0.01	<0.01	-	0.03
Industrial waste	0.01	<0.01	<0.01	-	0.01
Municipal	0.02	0.01	<0.01	-	0.02
Wind	<0.01	<0.01	<0.01	-	0.01
Totals	4.44	32.39	0.53	45.24	82.60

Butadiene (C_4H_7) is produced as a by-product petro-chemical compound in the steam cracking of hydrocarbons to produce ethylene from ethane [19]. Cracking is an industrial process that is utilized to take the output fractions from an oil refinery (generally complex mixtures of saturated and un-reactive hydrocarbon) and reduce it to smaller number of low molecular weight hydrocarbons. In addition, cracking makes hydrocarbons unsaturated to become more reactive [20]. Cracking is a three-step operation, which begins with raw hydrocarbon feed from the oil refinery in a pre-heated form that is mixed in steam and introduced into the furnace. The temperature of the mixture is raised to 810-880 degrees Celsius in the furnace [20]. The properties of the reaction product that is output from the furnace is directly correlated to the mixture composition, furnace temperature, and the amount of time the mixture is held in the furnace for heating (residence time) [20]. Typically the residence time is around 1 second or less for optimizing the product mixes from a given feedstock. After the gaseous mixture leaves the furnace it is suddenly quench cooled to mitigate further chemical reactions in preparation for the separation chamber. This section is where hydrocarbons are distinctly separated from one another. More specifically, separation and purification of Butadiene is carried out by extractive distillation [19]. Figure 7 below provides a graphical schematic of the cracking process and the types of conventional hydrocarbons outputted:

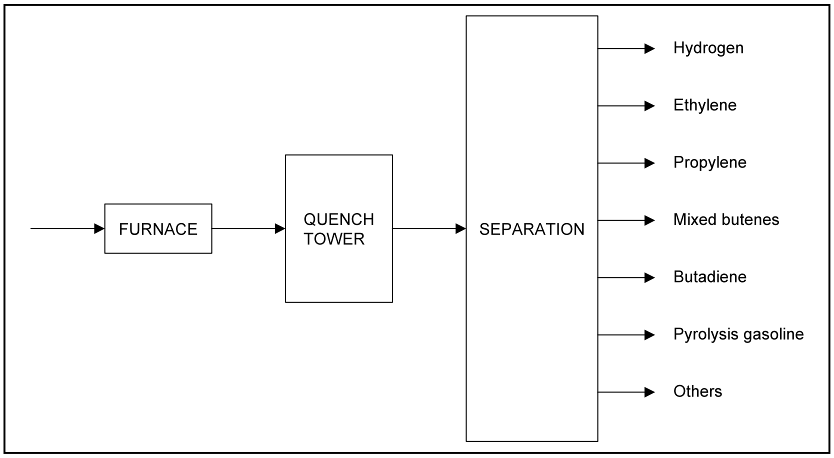

Figure 7. Schematic diagram of a cracker [20].

Table 5 below provides the energy and resource requirements for producing 1 Kg of Butadiene [20]:

Table 5. Gross primary fuels required to produce 1 kg of butadiene. (Totals may not agree because of rounding) [20].

Fuel type	Fuel Production and Delivery (MJ)	Energy Content of Delivered Fuel (MJ)	Fuel Use in Transport (MJ)	Feedstock Energy (MJ)	Total Energy Consumption (MJ)
Coal	0.38	0.21	0.14	<0.01	0.73
Oil	0.74	12.18	0.13	38.97	52.02
Gas	0.54	3.02	0.13	8.65	12.34
Hydro	0.05	0.03	<0.01	-	0.08
Nuclear	0.53	0.16	0.10	-	0.79
Lignite	<0.01	<0.01	<0.01	-	<0.01
Wood	<0.01	<0.01	<0.01	<0.01	<0.01
Sulphur	<0.01	<0.01	<0.01	<0.01	<0.01
Biomass (solid)	0.01	<0.01	<0.01	<0.01	0.02
Hydrogen	<0.01	<0.01	<0.01	-	<0.01
Recovered energy	<0.01	-1.14	<0.01	-	-1.14
Unspecified	<0.01	<0.01	<0.01	-	<0.01
Peat	<0.01	<0.01	<0.01	-	<0.01
Geothermal	<0.01	<0.01	<0.01	-	<0.01
Solar	<0.01	<0.01	<0.01	-	<0.01
Wave/tidal	<0.01	<0.01	<0.01	-	<0.01
Biomass (liquid/gas)	0.01	<0.01	0.01	-	0.02
Industrial waste	<0.01	<0.01	<0.01	-	<0.01

Municipal Waste	0.01	<0.01	<0.01	-	0.01
Wind	<0.01	<0.01	<0.01	-	<0.01
Totals	2.27	14.47	0.51	47.62	64.87

Styrene and Butadiene are polymerized in order to produce styrene-butadiene rubber (synthetic rubber). Amari et al. conveys that the energy to polymerize 1 Kg of synthetic rubber is 8.93 MJ [19]. This is based on [21] detailed assessment of polymerization process of styrene and butadiene to produce styrene-butadiene rubber (synthetic rubber) [21].

Moreover, in order to produce 1 Kg of styrene-butadiene rubber (synthetic rubber) it requires 0.4 Kg of styrene and 1.2 Kg of butadiene [19]. As such, in order to produce 1 Kg of synthetic rubber requires 33 MJ for producing the required amount of Styrene, 77.8 MJ for producing required amount of Butadiene, and 8.93 MJ for the polymerization process. This results in energy cost of 119.8 MJ energy required to extract raw materials and produce 1 Kg of synthetic rubber.

Natural Rubber

Natural rubber requires much less energy than synthetic rubber since the raw ingredients of natural rubber is isoprene (C_5H_8), which is directly extracted from sap of the para rubber tree [22]. The energy consumption for production of natural rubber is not extensively cited in literature. As such, the value from [22] is utilized in this study, which claims that 9.3 MJ of energy is expended to produce 1 Kg of natural rubber [22].

Carbon Black

Carbon black is utilized in automobile tires as a pigment and reinforcing agent. In addition, carbon black assists the thermal extraction from the tread and the belt, hence, reducing thermal damage and increasing tire lifetime. Carbon black is a form of amorphous carbon that has high surface area to volume ratio, which is generated from incomplete combustion of heavy petroleum products from catalytic cracking. Catalytic cracking is the chemical process where by utilizing catalysts complex organic molecules such as those found in heavy petroleum are broken into smaller and simpler molecular structures. The Encyclopedia of Chemical Technology derives the energy consumption required for producing 1 Kg of carbon black, which ranges between 93 MJ and 160 MJ [23]. For this analysis the average value of this range, 126.5 MJ, is associated to the energy required for producing 1 Kg of carbon black.

Steel

Steel is used in producing beads in tire manufacturing. Beads are high-tensile-strength bands of steel wire encased in a rubber compound. The steel beads provide mechanical strength between the tire and the wheel. Steelmaking is one of the most conventional industrial processes in ferrous metallurgy, which primarily designed to utilize carbon-rich pig iron into steel. Pig iron is the processed product from smelting (i.e. metallurgical extraction) of iron ore with coke. Iron ore is a natural material found in rocks and minerals that are used for extracting metallic iron. The vast majority of steelmaking globally is conducted in basic oxygen furnace where oxygen in blown on the molten pig iron to lower its carbon content transforming it into low-carbon steel. The entire process is mostly exothermic.

Modern steelmaking began in 1855 with open-hearth furnaces (OHFs), which dominated the production process until 1960 [24] where they were replaced with basic oxygen furnaces (BOF). By year 2000, more than 60% of world's steel is from basic oxygen furnaces [24]. The subsequent major advancement to steelmaking is the origination of electric arc furnace, which made it possible to establish steelmaking plants independent of taking into account the supplies of ore, coal, and limestone [24]. By the year 2000, nearly one-third of the world's steel was produced from electric arc furnace [24]. Currently, after steelmaking the output products are sent to continuous casting whereby molten metal is solidified into a semi-finished steel billet or slab. Typical energy cost of making 1 Kg of ordinary steel from pig iron is about 20-25 MJ [24]. For specialty alloy steel the energy cost of producing 1 Kg of the end product from raw materials varies between 30 to 60 MJ [24]. In this study the energy cost for producing ordinary steel is assumed to be 25 MJ per Kg.

Plasticizers and Fillers

Fillers and elastomer products are supplied in tire manufacturing to increase plasticity of tires. More specifically fillers are developed to mate with the beads to be a cushion between bead and the inner liner of the tire. Typically these items are produced from mineral oil. Lutsey et al. provides the energy required for this group of product, which is around 42 MJ per Kg (e.g. energy cost associated to producing residual oil (39.5 MJ) in addition to energy cost associated to extracting and refining crude oil (2.96 MJ)) [22].

Fabric

The body ply of a tire consists of multiple sheets, which is typically one layer of rubber, one layer of reinforcing fabric, and a second layer of rubber. The fabric utilized in earlier times was cotton, but recently this has changed to materials such as rayon, nylon, polyester, and Kevlar. In this study the fabric is assumed to be nylon with production energy cost of 43.49 MJ per Kg [19]. Table 6 below is the summary of energy intensity for raw material extraction and production of core components in vehicle tires.

Table 6. Energy intensity of raw materials assembled in a tire

Tire Material	**Energy Intensity (MJ/Kg Material)**
Natural Rubber	9.3
Synthetic Rubber	119.8
Carbon Black	126.5
Steel	25
Plasticizers	42

Fabric	43.5

5.2 Tire Manufacturing Phase

Tire manufacturing is the process of producing the tread and the casing and assembling the core parts to build a unit of tire. At this stage, the raw materials especially for the rubber compound are mixed together at a pre-determined temperature depending on the integrity of the rubber compound generated [4], [5].

The mixed compound is transported to the processing facility where the cooled rubber undergoes the following production stages:

- Milling: thick slabs of rubber are continuously fed between pairs of rollers that mix the compound

- Extruding: The tire compounds are directed into a die (i.e. mold) for generating various components (i.e. tread, sidewall, etc)

- Calendaring: The finished-rubber is coated with different kinds of fabrics to increase strength (e.g. polyester, rayon, nylon, steel, etc)

A cutting machine is utilized for cutting the rubber compound into appropriate sizes for the manufacturing stage. Furthermore, the finished products are fed into a tire building machine, that pre-shape the various components of the tire (i.e. sidewalls, inner walls). Consecutively, a second machine applies the tread and belt to the prior components. A successful completion of these processes produces a tire without any tread patterns.

In order to print the desired tread patterns the tire is vulcanized. Tire vulcanizing or tire curing is the process of placing an un-cured tire in a mold, applying high temperature and pressure, and producing engraved tread patterns. The finishing process is the last stage of tire production, whereby the tire is inflated to appropriate pressures, trimmed, and balanced. Subsequently, the manufactured tire is rigorously tested and inspected based on strict safety standards and regulations.

The energy cost of tire manufacturing is reported in Amari et al. as 11.7 MJ per 1 Kg of tire [19]. In this study 11.7 MJ per Kg is chosen as the energy intensity for manufacturing a tire.

5.3 Tire Remanufacturing Phase

The remanufacturing process of tires is an industrial process, which requires industrial machines, skilled labors, and high quality development process. This study reflects upon a conventional tire retreading process. The operation at each retreading plant may be different due to the requirements and objectives for the finished products.

The entire retreading process of tires is listed as follows (NHTSA):

Step 1: Casing Submission

Used casings (cores) arrive at the retreading plant. Each casing is stamped with a unique identification code for distinguishing it from other casings based on type, conditions, and required processes for the casing to undergo.

Step 2: First Stage Inspection

A skilled technician visually inspects the tire by glancing at different parts of the tire to determine whether there are any physical defects on the tires (e.g. bruises, holes, cuts, punctures, nails, etc). Also, the technician makes judgment calls based on whether the tire is retreadable based on the plant and industry quality and safety standards. Tires that do not meet the expected inspection protocols such as extensive side damaging are rejected from the retreading stream.

Step 3: Second Stage Inspection

The casings that make it to this stage undergo a more rigorous and detailed testing process to assess defects and damages that are invisible to the eye. There are testing equipments such as fluoroscopic x-rays and ultrasound that are utilized for assessing the internal defects of casings. In addition, other non-destructive testing such as shearography is carried out to detect internal casing defects using laser. The purpose is to ensure the good condition of the bead, the sidewall, and the shoulder. Michelin utilizes inter-liner inspection to test the inter-lining penetration for potential air leaking in the tire.

Step 4: Buffing

The buffing process is where the remaining tread of the casings that have passed testing are shaved. This is performed to cut out the old worn tread design and to prepare the casing for the new tread. The buffing process is streamlined to buff the tire to a desired tire radius, profile, and crown width.

Step 5: Casing Preparation and Repair

Upon the completion of the buffing process the shaved casing is inspected once again to assure that the casing has not been damaged in the process and that no defects are detected on the shaved casing. Any casing that does not meet the required testing standards is rejected at this stage.

Step 6: New Tread Application

The new tread is added and prepared for chemically bonding to the casing. The new tread is aligned and centered to the casing.

Step 7: Enveloping

The applied tread and the casing are wrapped around a rubber envelope and a vacuum is generated.

Step 8: Curing (Vulcanizing)

The curing process occurs as the casing and the tread inside the rubber envelope are placed in a curing chamber and exposed to a pre-determined temperature and pressure. The purpose of the curing process is to chemically bond the tread to the casing by enabling cross-linking of rubber polymeric chains between the tread and the casing. Predominantly, there are two conventional processes for applying the new tread to the tire for retreading: (1) mold-cure process; (2) pre-cure process.

In mold-cure process, the uncured tread is applied and strip wound to the casing. Then, the casing and the tread are placed in a rigid mold together and heated to nearly 300 degrees Fahrenheit to cure the tread rubber and mold the tread design on the unvulcanized rubber.

In pre-cure process, a previously cured tread rubber, which encompasses the tread design is applied and strip wound to the shaved casing. Upon fully containing the circumference of the casing, the remaining tread is spliced. A thin layer of uncured rubber is place between the tread and the casing and it is cured to provide chemical bonding between the casing and the tread.

Step 9: Final Inspection

The cured tires are sent to a final inspection platform where the retreaded tires are tested according to industry standards. More specifically, retreaded tires are tested to reject tires that have anomalies or separation between tread and casing.

Step 10: Preparation for Shipping

The retreaded tires that pass the final stage of testing are painted and marked with required industry and federal identification mark and are sent to the officials responsible for shipping the items.

5.3.1 Energy Requirements for Tire Remanufacturing Phase

Tire retreading is a remanufacturing process that effectively utilizes the core value of a used tire at end of its lifetime and by doing so extends its use phase roughly by another full lifetime. As reported by industry sources, only 10 to 20 percent of a tire gets consumed during its first lifetime. Nearly all of the material consumption is from the tread, which can be replaced by a retreading process.

Light Duty Passenger Car Tires

Ferrer et al. reveals that it takes on average 26.4 liters of oil to produce a new passenger car tire. Moreover, it conveys that by retreading the passenger car tire only 9 liters of oil is required (34% of new).

Heavy Duty Truck Tires

The Tire Retread and Repair Information Bureau claims that a retreaded truck tire consumes 7 gallons of oil compared to production of new truck tire, which takes up 22 gallons of oil [15]. Therefore, we will assume that the remanufacturing (retreading) energy for truck tires is approximately 32% (7/22) of raw materials processing and manufacturing.

Given the above information, it appears that tire remanufacturing is an energy savings strategy. It is important to stretch the scope of analysis boundary such that it encompasses the use phase. This would provide the analyst with the opportunity to perform a life cycle assessment of tires and evaluate the impact of retreading on use phase of products.

5.4 Use Phase

In order to quantify the use-phase energy consumption of tires it is critical to first understand the sources of heat dissipation and energy losses associated to a tire in operation. More specifically, the issue to address is the impact of rolling resistance on energy performance of tires. As such, the next section provides detailed introduction to rolling resistance, rolling resistance coefficient, and their respective impacts on tires and vehicle fuel economies in use.

5.4.1 Components affecting energy use of automobiles

The total fuel consumption of a vehicle can be broken into the following categories [25].

$$E_T = E_{\text{Rolling Resistance}} + E_{\text{Drivetrain Losses}} + E_{\text{Aerodynamic Drag}} + E_{\text{Inertia}} + E_{\text{Accessories}} \qquad \text{Equation 1}$$

According to the equation above, the fuel input in a vehicle is expended to overcome rolling resistance ($E_{\text{Rolling Resistance}}$), accelerate and stop the vehicle (E_{Inertia}), to overcome energy losses in the transmission, engine and drivetrain ($E_{\text{Drivetrain Losses}}$), to power auxiliary components such as compressors, air conditioners, and heaters ($E_{\text{Accessories}}$), and aerodynamic resistance ($E_{\text{Aerodynamic Drag}}$) [25].

5.4.2 Rolling Resistance: Relation to Energy Consumption and Tire Efficiency

Understanding the energy consumption to overcome rolling resistance of tires demands a clear illustration of the meaning of rolling resistance as a physical phenomenon. As a tire rolls on the road, it undergoes repeated viscoelastic (rubber) compression and tension as it deforms under the vehicle's load. Due to viscoelastic nature of rubber, only a portion of the compression energy is stored as the tire deforms. Upon changing energy state, the remaining unrecovered energy by the rubber is dissipated as heat [26]. The conversion of absorbed energy to dissipated heat, along with the internal friction between the tread, the casing, and the tire and its rim, generates what is defined as hysteresis losses [18]. Hysteresis losses are one (and the largest) of the contributing losses associated with rolling resistance. Hysteresis losses accompanied by the tire-road friction losses as well as tire aerodynamic drag are irrecoverable energies, and combine to generate a total resistive force on a moving vehicle. This drag force is commonly defined as rolling resistance (or rolling resistance force). In the case of a free rolling tire, the rolling resistance can be defined as a force that opposes vehicle motion [18]. Tire rolling resistance is also defined as the energy a tire consumes per unit distance of travel [18]. The standard metric units of rolling resistance are Joules per meter (J/m) or Newtons (N); the comparable English unit for rolling resistance is pounds [18].

Equation below shows rolling resistance of tires as a function of hysterises, tire-road friction, and aerodynamic drag:

$$\text{Rolling Resistance} = F_{RR} = F\,(\text{Hysterises Losses, Road Frictional Losses, Tire Aerodynamic Drag})$$

Given that tires operate under various loading conditions based on the particular vehicle in use, rolling resistance is often divided by the vehicle weight (distributed based on the load undertaken by each individual tire) in order to come up with a dimensionless measure of tire efficiency, known as the rolling resistance coefficient [18]. In other words, rolling resistance coefficient is a dimensionless parameter that can be conveyed in terms of rolling resistance force generated per unit load applied. The following equation and graphical representation sums up the definition of rolling resistance and rolling resistance coefficient [27].

$$C_{RR} = \frac{F_{RR}}{Z}$$

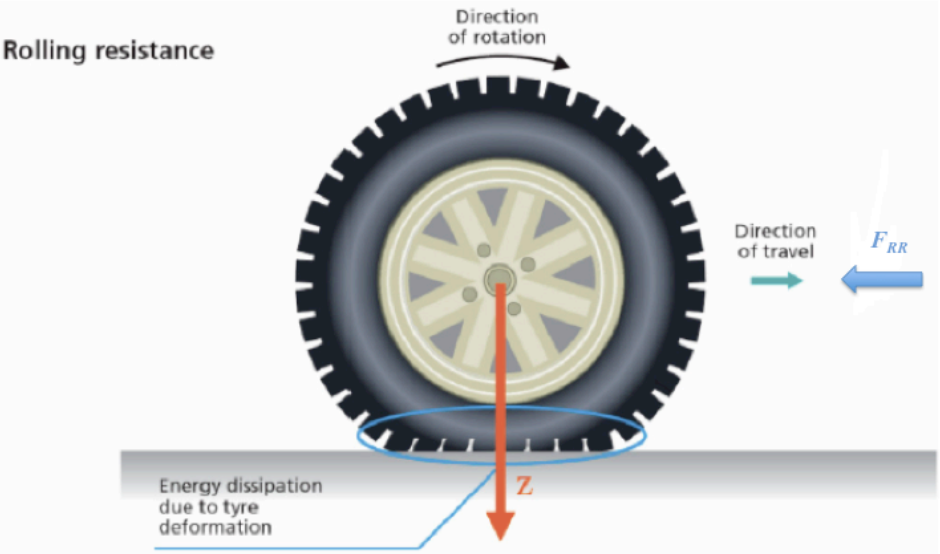

Figure 8. The Inter-dependence Relation between Rolling Resistance Coefficient (C_{RR}), Rolling resistance Force (F_{RR}), and Vehicle Load (Z).

The Society of Automobiles Engineers (SAE) defines rolling resistance force and rolling resistance coefficient as follows [28]:

“F_{RR} = Rolling Resistance Force:

Rolling resistance of the free-rolling tire is the scalar sum of all contact forces tangent to the test surface and parallel to the wheel plane of the tire.

C_{RR} = Coefficient of Rolling Resistance:
Rolling resistance coefficient is the ratio of the rolling resistance to the load of the tire."

In the U.S. tire industry rolling resistance coefficient is becoming more identified as a parameter for tire efficiency. According to this, the Rubber Manufacturers' Association (RMA) states, "Rolling resistance coefficient, is an appropriate expression of efficiency and suitable as the basis for a consumer tire energy efficiency rating system."

In the U.S. tire industry, rolling resistance coefficient is commonly expressed in formats listed below [18]:

(1) Fractional value between 0 and 1 with lower values corresponding to higher measures of efficiency (i.e. pounds rolling resistance per pounds vehicle load)
(2) Kg per 1000 Kg (i.e. Kg/ton). The purpose of this is to express rolling resistance in whole numbers (e.g. 0.001 rolling resistance coefficient is 1 Kg/ton)

5.4.3 Factors Contributing to Rolling Resistance

The heat loss generated in motion of tires is distributed heterogeneously across tire's body. The design and architecture of tire components places a critical role in the performance of tires. As such, section below provides and introduction to the components utilized in tires.

5.4.3.1 Tire Components and Nomenclature

The Figure below is a graphical representation of the anatomy of a conventional tire [29].

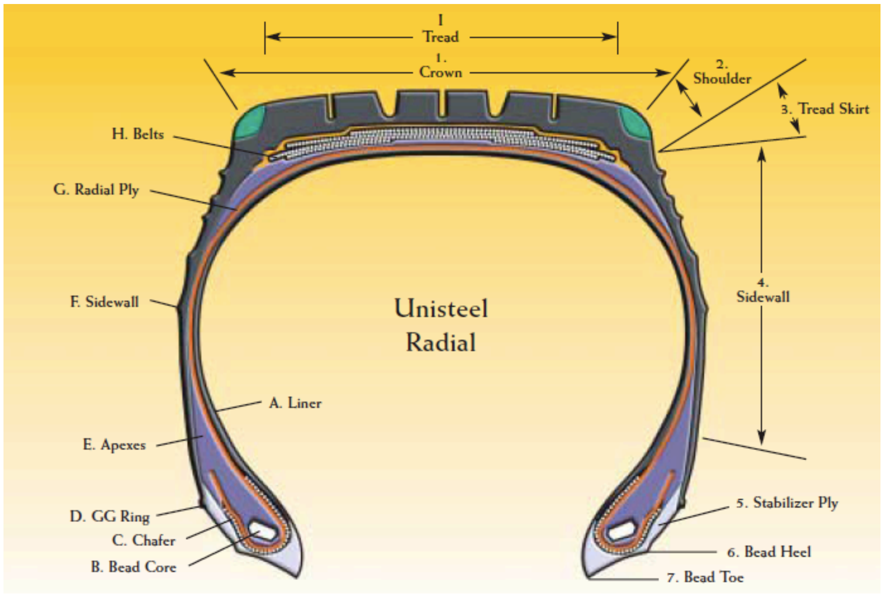

Figure 9. Radial Truck Tire Components and Nomenclature [29].

Rolling resistance is influenced by the interaction of the vehicle with the road based on tire characteristics as well as the nature of the road surface [25].

According to Figure 9 a tire consist of the following components:

- A. Liner
    - A layer or layers of rubber in tubeless tires designed for resisting air diffusion.

- B. Bead Core
    - Bead Core is typically made of high-tensile wire such as steel, which are aligned in the plane of the rotation of the wheel. It provides structural rigidity and uniformity in maintaining tire diameter on the rim.

- C. Chafer
    - Chafer is utilized for resisting chafing between the bead and the wheel. Chafer is made from stripes of protective fabric in the outer region of the tire carcass and it is meant to reduce damaging effects on carcass plies when mounting and dismounting.

- D. GG Ring
    - Utilized as a reference point for situating the bead area on the rim [4], [5].

- E. Apexes
    - A Transitioning region between stiffer lower inner-walls and the upper more flexible sidewalls

- F. Sidewall
    - This is a rubber cover on the side of the tire, which protects the side of the carcass plies. Sidewalls contain anti-oxidants to protect the tire from ultra-violet and ozone damages. Also, the sidewall is constructed to withstand continuous flexing and weathering

- G. Radial Ply
    - Binding layers that are situated below the tread withstanding internal pressure, external load, frictional, and hysteresis forces. Radial ply are an improved version of bias-ply, which are aligned perpendicular to the direction of motion of tire

- H. Belts
    - Steel cord belts are constructed to provide tread stability, structural strength and sturdiness, and protection from air chamber punctures

- I. Tread

    - The contacting surface between tire and the road surface. The tread is designed to extract heat, provide traction and driving stability, and wear

In addition the tire can be broken into various regions/areas in terms of construction:

- 1. Crown
    - This is the entire area of the tire that is in contact with the surface and wears in time

- 2. Shoulder
    - The outer edge of the tire that is between the crown and the tread skirt

- 3. Tread skirt
    - This section is an intersection between the tread and the side wall

- 4. Sidewall
    - This is a rubber cover on the side of the tire, which protects the side of the carcass plies. Sidewalls contain anti-oxidants to protect the tire from ultra-violet and ozone damages. Also, the sidewall is constructed to withstand continuous flexing and weathering

- 5. Stabilizer ply
    - Region between radial ply, bead, and the chafer, which reinforces bead-to-sidewall zone

- 6. Bead Heel
    - This is the area of the tire that touches the rim

- 7. Bead Toe
    - The inner-end of the bead

5.4.3.2 Distribution of Losses in a Tire

In general, the level of impact for the three main loss contributors associated with tire rolling resistance (Eq. 1.2 above) is as follows [17], [30]:

(1) Tire hysteresis losses in the sidewall and tread: 80 to 95 per cent
(2) Tire-road interaction and surface frictional losses: 0 to 15 per cent
(3) Tire aerodynamic drag and air circulations: 0 to 5 per cent

In addition, each tire component has a distinct impact on heat dissipation and rolling resistance. For light-duty passenger car tires the component impacts associated with rolling resistance are as follows [31]:

(1) Tread: 60 to 70 per cent

(2) Sidewall (the portion of the tire between the tread and the bead): 10 to 20 per cent
(3) Bead Core (continuous high-tensile wire wound in the plane of tire rotation to form high-strength unit): 15 to 20 per cent

For truck tires, 35 to 50 per cent of the rolling resistance is caused by the tread design and tread compounding while 50 to 65 percent of the rolling resistance is cause by the design and compounding of the casing (including sidewalls, bead, and belts) [32]. The distribution of losses is for tires operating in steady-state conditions. Dynamic changes in driving cycle, low tire inflation pressure, etc. may change the contribution of each tire component.

This study assumes that tires operate with proper tire inflation pressure and constant vehicle load. Low tire inflation, as well as heavy vehicle load, can also affect vehicle fuel economy (CEC). Lower inflation pressure or heavier vehicle load leads to higher tire distortion, increased friction, and greater energy absorbed by the tires, hence reducing vehicle fuel efficiency. According to the Rubber Manufacturers' Association, when a tire is under-inflated by 1 pound per square inches (psi), the tire's rolling resistance increases by approximately 1.1%.

5.4.4 Measuring Rolling Resistance: Testing Methodologies

In order to further elaborate on rolling resistance and tire use-phase energy consumption, it is important to discuss how rolling resistance and rolling resistance coefficient are measured from rolling resistance testing.

Rolling resistance is measured on a specialized dynamometer in a controlled laboratory setting. The laboratory test procedures are constructed such that environmental influences (i.e. road surface texture, temperature, aerodynamic drag) are controlled or eliminated. Moreover, the procedures must adhere to strict standards placed on allowed variations in test speeds, slip angle, applied load, and test inflation pressure. Such controls provide test repeatability assurance while reflecting an accurate representation of a tire's rolling resistance [33], [34]. Rolling resistance measurements are conducted by specialized dynamometers, which enables accurate measurement of tire forces required under various loads and inflations [18].

Currently, there are two methodologies in the United States established by the SAE mainly for assessing light-duty vehicle (i.e. passenger car and light truck) tire rolling resistance, one endorsed by the International Standards Organization (ISO), and a recent global testing mechanism established by ISO. These testing methodologies are described below:

SAE J1269

Title: Rolling Resistance Measurement Procedure for Passenger Car, Light Truck, and Highway Truck and Bus Tires

SAE J1269 test is designed such that the measurements are performed as a single run test at the Standard Reference Condition (SRC) while enabling variation in four or six sets of test condition (NHTSA).

Established in 1979, this SAE recommended practice is a standardized method for laboratory measurement of rolling resistance of pneumatic passenger car, light truck, and highway truck and bus [35]. This testing is performed on a single-point of a tire at the fixed speed of about 50 miles per hour (80 km/h) under steady-state conditions. The advantages of this test are the wide-use in the tire manufacturing industry enabling a common testing methodology for the basis of effective comparison. The drawbacks of this testing scheme are that its predictive capabilities are not highly correlated with the actual road performance across a wide range of speeds [18], [31].

In relation to this, the Society of Automobiles Engineers (SAE) states the following passage [35]:

> "The procedure applies only to the steady-state operation of free-rolling tires at zero slip and inclination angles; it includes the following three basic methods: Force Method--Measures the reaction force at the tire spindle and converts it to rolling resistance. Torque Method--Measures the torque input to the test machine and converts it to rolling resistance. Power Method--Measures the power input to the test machine and converts it to rolling resistance."

SAE J2452

Title: Stepwise Coast Methodology for Measuring Tire Rolling Resistance

SAE J2452 was developed to enable additional assessment of the impact of rolling resistance on driving cycles used for federal vehicle emissions and fuel economy regulatory compliance [36].

This SAE recommended practice provides a standardized testing methodology within normal operating ranges of vertical load and inflation for testing tire rolling resistance in simulation of a coast down from 115 km/h (71 mph) to 15 km/h (9 mpg) [31]. This testing is applicable to pneumatic passenger car tires and light truck tires. Also, the tests are conducted at five distinct fixed speeds. The objective of this testing methodology is to replicate the range of speeds published in EPA's Supplemental Federal Test Procedure (SFTP) for vehicle fuel economy. SAE J2452 is widely utilized by auto manufacturers for vehicle fuel economy calculations over a range of speeds [4], [5]. The advantage of this testing methodology is its multi-point speed testing capability reflecting a more realistic testing scenario to assess the performance of tire on the overall vehicle fuel economy. More specifically, the speed-adjusted measurements outputted by SAE J2452 can be input into simulated driving cycles for testing new vehicle compliance with CAFE standards [36]. The disadvantage of this test is that it is not as commonly utilized as SAE J1269 by independent laboratories [18].

ISO 18164

This ISO endorsed practice measures rolling resistance of passenger car, truck, bus and motorcycle tires under normal operating steady conditions. The testing equipment utilizes a dynamometer with a smooth steel or textured drum operating at steady-state conditions and at fixed speed and load. ISO 18164 is capable of measuring various output parameters such as torque, power, reaction force, etc in order to measure rolling resistance [31].

ISO 28580

Recently, the International Standard Organization has developed an advanced version of ISO 18164, which is becoming a new global standard for tire characterization comparison. ISO 28580 is capable of pre-testing alignment calibration of the testing apparatus [28]. The greatest advantage of the new ISO 28580 is that it provides an effective mechanism for comparison of pre-testing apparatus set-up amongst different testing facilities [28].

5.4.5 Tire Rolling Resistance Major Technological Advancement in the Past Few Decades

Prior to analyzing the change evolution in rolling resistance of passenger car and truck tires, it is important to describe the two greatest technological advancements in tire rolling resistance improvements: transforming from tube tires to tubeless; transforming from bias-ply tires to radials.

Technology advancement in tires: Tubeless vs. Tube

According to Goodyear, by transforming from tube type truck tire to tubeless tires on all wheels, an over-the-road tractor-trailer can gain 2 per cent in fuel economy at 80,000 gross curb weight (GCW) [29].

Technology advancement in tires: Bias Ply vs. Radial Ply

Figure 10 below shows the differentiation in structuring of bias-ply tires and radial-ply tires.

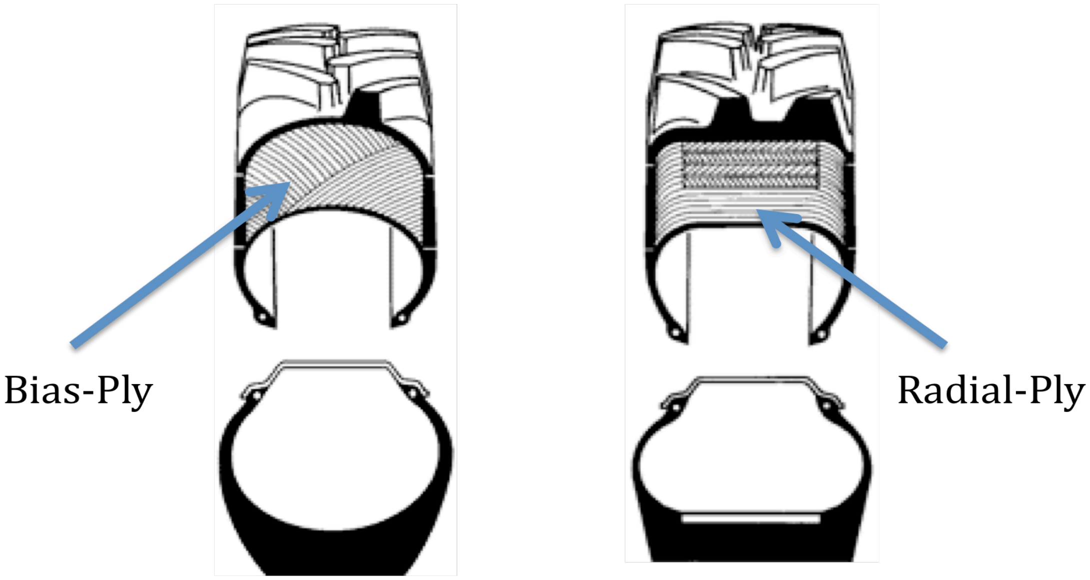

Figure 10. Illustration of the design comparison between bias-ply and radial-ply construction [37].

Radial-ply tires were introduced in the U.S. tire market in the 1970s and mass-produced in the 1980s; since then, it has steadily replaced bias-ply tires fully [36]. The bias-ply tires were the predominant passenger tires used in the United States prior to 1980s but no-longer produced due to the advancement of tires to radial-ply configuration [36]. Bias-ply tires were pneumatic tires in which the ply cords that extend to the tire beads (refer to Figure 10 above) are laid at alternate angles of +60 and -60 degrees to the centerline of the tread [36].

Comparatively, radial-ply tires are constructed by extending the ply cords at approximately 90 degrees (perpendicular) to the centerline of the tread (refer to Figure 10 above). Patented and introduced by Michelin in 1946, radial-ply tires were first introduced to the market in Europe in 1950s, and penetrated into the U.S. tire market in the 1970s [36], [37].

In bias-ply tires, the tread and the sidewalls share the same casing plies, which results in direct transmission of sidewall flexing motion to the tread causing tread distortion (buckling) throughout the contact patch. This phenomenon causes disadvantages such as [37]:

- Large deformations in tread contact patch
- Rapid wear
- Reduction in traction
- Higher shear effects from the surface
- Increased rolling resistance coefficient and fuel consumption

On the other hand, the radial-ply configuration has the following advantages [37]:

- Superior traction capabilities enabling flat stable tread crown
- Better distribution of air pressure leading to reduced soil compaction
- Reduction in chances of tire slip
- Reduced rolling resistance coefficient
- Longer tread life
- Better comfort and handling while on the road

A study conducted by Williams shows that on average, radial tires have 25 per cent reduction in rolling resistance coefficient in comparison to bias-ply tires for passenger car tires [38]. Moreover, according to Goodyear, new radial ply tires on average can provide fuel savings of six percent or greater compared to bias ply wheels in over-the-road tractor-trailer application [29].

Despite the fact that bias-ply tires no longer exist in the U.S. tire market, it is still heavily produced in developing countries such as Mexico, and emerging economies such as China[I].

[I] Source: Michelin Industry Standards and Government Regulations, personal communication with Mike Wischhusen, Director, July, 2009.

Therefore, the discussion around the energy performance degradation of bias-ply compared to radial tires is still an important topic for the global tire supply industry.

5.4.6 Rolling resistance: Literature Review

In order to provide a conclusive literature review, this section is broken into two sections, namely, passenger cars and heavy trucks. For each section, the literature review is broken into distinct studies spanning from scientific publications, governmental reports, consulting briefings, and industrial analyses. It is critical to represent the viewpoints of all the above groups in order to appreciate the diversity in characterizing and analyzing rolling resistance and its impact on vehicle fuel consumption.

Rolling Resistance: Light-Duty Passenger Vehicles

Shuring et al., 1990, [39]

[39] conducted a comprehensive review of rolling resistance data, from more than a dozen studies published prior to 1990. The study concludes by suggesting a linear relationship between changes in rolling resistance and fuel economy [39]. According to the authors, rolling resistance coefficient for new tires from 1970 to 1980 were mostly above 0.01.

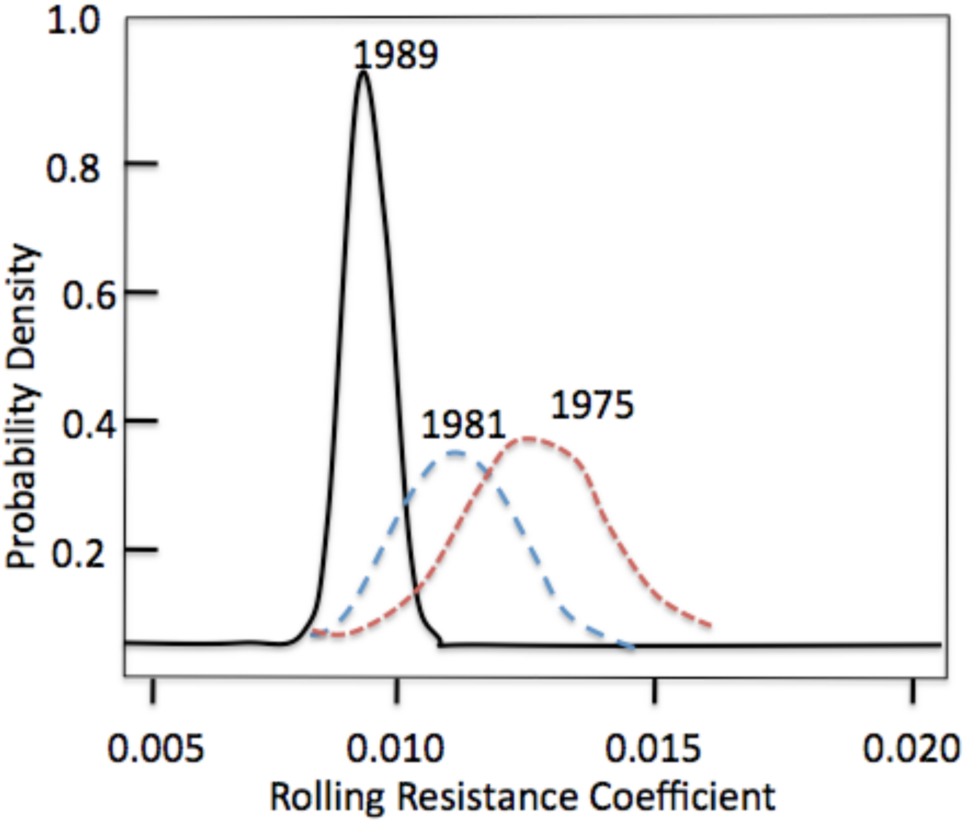

Figure 11. Rolling Resistance Coefficient of three passenger care tire samples tested in 1979, 1981, and 1989. Each test sample pool is less than 200 tires. All sample tires were tested for rolling resistance coefficient at 80 per cent maximum load and maximum pressure on a 67-inch (170 cm) road wheel [39].

Note that despite Schuring's conclusive summarization of rolling data of rolling resistance coefficient during 1970s and 1980s, it is not wise to directly compare Figure 11 with the forthcoming results since the testing parameterization for above analysis may not have met the protocols of SAE J1269.

National Research Council (NRC), [36]

In February 2005, in response to a congressional request with funding provided from the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation, the National Research Council (NRC) formed the committee for the National Tire Efficiency Study. The committee was given the charge to assess the impact of tires on passenger vehicle fuel economy [36]. The committee compiled a comprehensive literature review of rolling resistance data in the past two decades measured by SAE including the very first SAE J1269 rolling resistance values published by the Environmental Protection Agency (EPA 1982-1983) [36].

More specifically, the committee reviewed the publicly available data sets beginning with EPA testing sample in 1982 and 1983 (EPA 1982-1983), consumer reports (Michelin 1994-1995), private research consultants (Ecos. 2002), submissions to NHTSA and U.S. Department of Transportation (CEC), and three major tire companies supported by rubber manufacturers association (RMA).

Table 7 below and Figure 12 illustrate in detail the compiled study for rolling resistance data from 1982 to 2005.

Table 7. Summary of Data Set Containing Rolling Resistance Measurements for Original Equipment (OEM) and Replacement Passenger Tires between 1982 and 2005 [36].

Data Set	Tire Lines	Tire Sizes	RRC Range	RRC Average
Replacement Tires				
EPA 1982–1983	36 from several tire makers (four to six tires tested for each model) (note: RRC values for bias-ply tires have been omitted)	195/75/R15	0.00979 to 0.01381	0.01131

Michelin 1994	37 from several tire makers	Not given	0.0087 to 0.01430	.01117
Goodyear 1994	Not given	Not given	0.0073 to 0.0131	Not Given
Michelin 1995	6 from three tire makers	215/70/R15, 235/75/R15	0.0997 to 0.0102	0.0108
Ecos Consulting 2002	34 from several tire makers	185/70/R14 205/55/R16 235/75/R15 245/75/R16	0.0062 to 0.0133	0.0102
RMA 2005	154 from three tire makers, mostly Michelin Brands	Various	0.0065 to 0.0133	0.0102

OE Tires

Michelin 1994	9 from several tire makers	Not given	0.0073 to 0.0105	0.0091
Goodyear 1994	Not given	Not given	0.0067 to 0.0152	Not Given
Michelin 1995	24 from michelin brands	Various	0.0077 to 0.0114	0.0092
OEM interviews 2005	Multiple tire lines			
	All-season		0.005 to 0.007	
	Touring		0.0058 to 0.008	
	Performance		0.0065 to 0.01	
	Light truck (passenger tires)		0.0075 to 0.0095	
RMA 2005	8 from Bridgestone and Goodyear brands	Various	0.007 to 0.0095	0.00838

Note: All of the rolling resistance values in the table were derived by using the SAE J1269 test procedure with the exception of the ranges given by automobile manufacturers for current OE tires. These values are estimates by OEMs on the basis of the SAE J2452 test procedure.

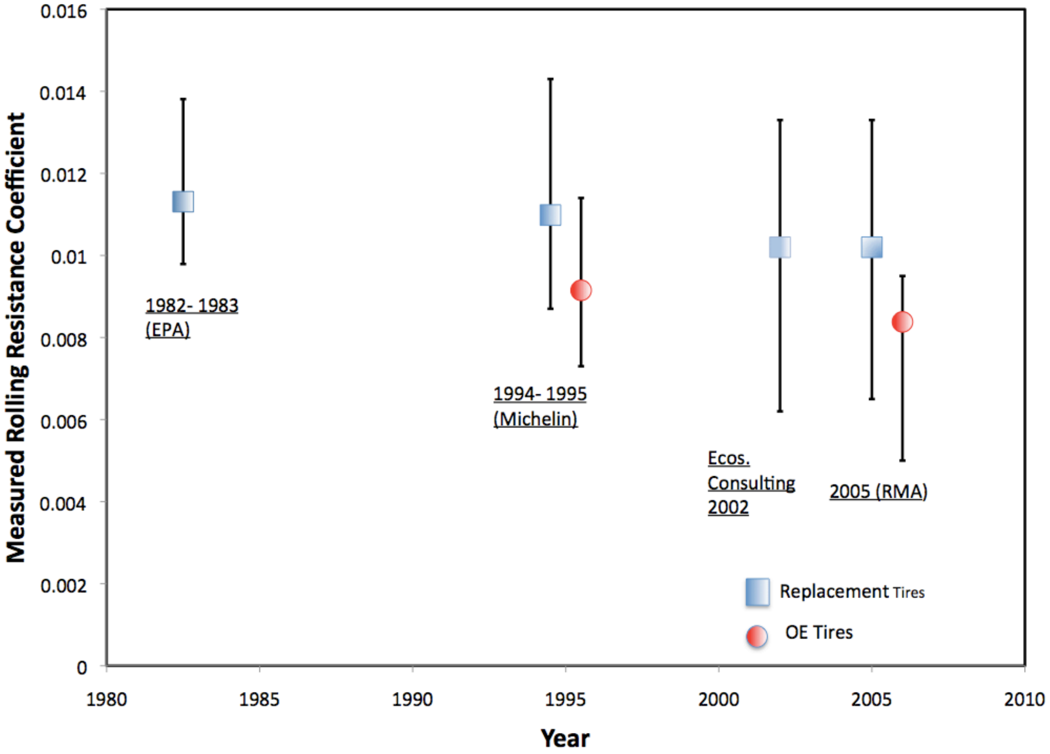

Figure 12. Rolling Resistance Measurements for Original Equipment (OEM) and Replacement Passenger Tires between 1982 and 2005 [36].

The committee reflected on the variability in testing results for determining rolling resistance coefficient by discussing variability in tire testing equipment, applied correction factors, testing apparatus alignment, and the reference conditions assumed in reporting the specific values of rolling resistance coefficient [36], [28]. The authors elaborate on the response of tire OEMs in relation to variability in testing inconsistency [36]:

“Variability in tire testing equipment alone could result in rolling resistance coefficient differentials of as much as +/- 20 per cent among the ranges reported by each company and in comparison with rolling resistance coefficients observed among replacement tires.”

In addition, this study claims that proliferation of tire sizes, speed rating, rim diameter, aspect ratio impacts the variation in rolling resistance measurements.

Interestingly, this study reflects upon a critical discussion in the tire industry about the stark difference between the rolling resistance coefficient of tires produced for Automotive manufacturers and the tire replacement market. This may have stemmed from the stringent fuel efficiency standards (i.e. Corporate Average Fuel Economy (CAFE)) that the automotive industry has to follow. The newly announced CAFE standards put-forth by the Obama Administration for automotive vehicles may make this difference even greater. There is a heated discussion within the tire and rubber manufacturing industry in relation to making tires in the replacement market as efficient as tires delivered to automotive OEMs.

Perhaps, the most comprehensive data set in Figure 12 above is from three major tire manufacturers, namely, Michelin, Goodyear, and Bridgestone published by Rubber Manufacturers Association in 2005 [33]. These OEMs provided the committee with rolling resistance measurements, Uniform Tire Quality Grading (UTQG) system grades, and speed rating for 162 passenger tires of varying sizes and affiliated brands (i.e. Firestone, BFGoodrich, etc) [36]. Figure 13 below illustrates the distribution of replacement tires (154 samples) rolling resistance coefficient in the RMA data set [36]. The range of rolling resistance coefficient observed for the 154 replacement tire samples was 0.0065 to 0.0133, with a mean and median of 0.0102 and 0.0099, respectively [36].

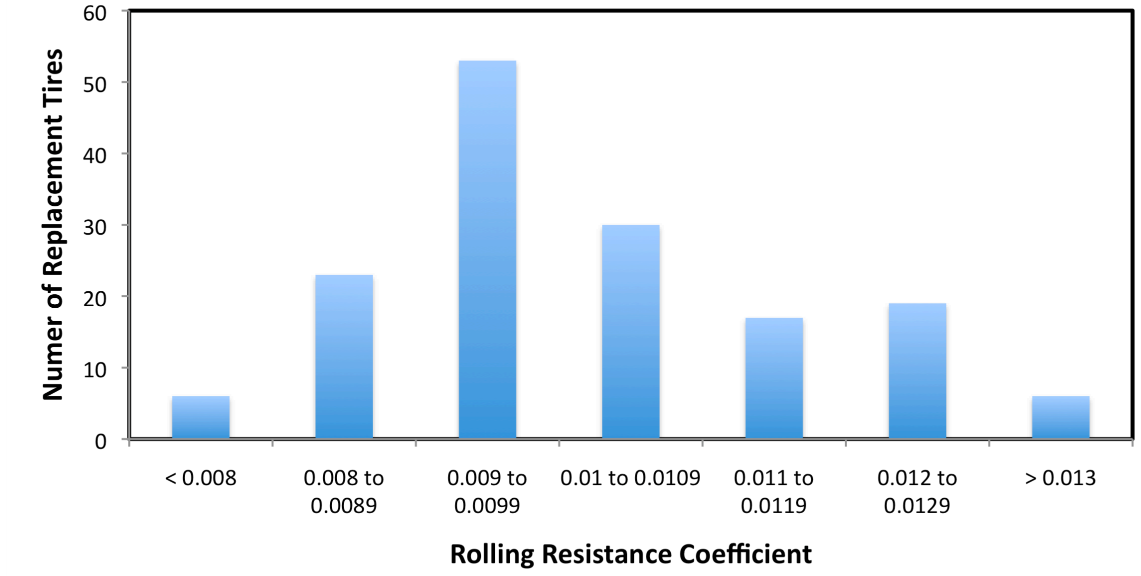

Figure 13. Distribution of tires in the RMA data set by Rolling Resistance Coefficient [33].

According to figure above RMA states, “In all seven groupings [in Figure 13], the difference between the highest and lowest value is at least 18 per cent, and most of the differentials exceed 25 per cent.” [36].

The conclusions of RMA study based on sorting of the above data are as follows [33]:

1. Design elements intended to augment performance have an impact on rolling resistance coefficient (i.e. speed rating, performance rating)
2. Geometric differences in tires may contribute to tire rolling resistance differentials (i.e. rim diameter, tread width)

An effective methodology to analyze the improvement in rolling resistance coefficient in the past 25 years (refer to Figure 12) is to assess the improvement in the most energy-efficient portion of the sample population. The EPA study reports that all rolling resistance coefficient for radial tires in 1982-1983 exceeded 0.009. In comparison to this in the two most recent data sets [33], [18] nearly 20 per cent of the rolling resistance coefficient measurements were 0.009 or less. More specifically, the top 25 percentile for most efficient radial tires in 1982-1983 data set had an average rolling resistance coefficient of 0.0103. The combined data in 2002 and 2005 for the top 25 percentile for most efficient radial tires conveyed average rolling resistance coefficient of 0.0085 (18% reduction from 25 years prior) [36].

Despite the evolution of rolling resistance measures published by [36], it does not capture the two greatest advancements in tire rolling resistance coefficient in the past few decades, namely, transformation from tube to tubeless tires, and the progression from bias-ply to radial-ply in construction of tire[1]. In other words, the data sets included in NRC have intentionally filtered out rolling resistance measurements for bias-ply tires since it no longer exists in the U.S. market place. In other words, the intention of the National Research Council was to assess the technological advancement of radial tubeless tires between 1980 and 2000 only, which was the dominant tire sold during 2006 (when this study became publicly available) in the U.S. tire industry.

California Energy Commission/ Michelin Center of Technologies, Research and Development

Figure 5 illustrates the reduction in rolling resistance coefficient of Original Equipment Manufacturer (OEM) passenger car tires (bias-ply as well as radial-ply) between 1975 and 2004 [17], [18].

In comparison to the National Research Council study reporting similar rolling resistance coefficient for replacement radial tires, this study illustrates a much greater reduction in rolling resistance coefficient of OEM passenger tires. More specifically, the reduction trend can be broken into two distinct phases: (1) 1975-1986; (2)1986-2004. According to the results, average coefficient of rolling resistance was halved between 1975 and 1986. Moreover, between 1986 and 2004, rolling resistance was reduced more moderately.

This phenomenon can be explained by the policy standards enforcing minimum efficiency performance for vehicles under the Corporate Average Fuel Economy (CAFE) standard. First enacted by the U.S. congress in 1975, the purpose of CAFE standards are to reduce the energy consumption of passenger car vehicles and light trucks. The standards were implemented in year 1978 under the responsibility of National Highway Traffic Safety Administration (NHTSA). As a result, automakers began providing explicit rolling resistance design parameters to their tire suppliers. More specifically, automakers demanded improved technology for OEM tires as a key strategy for achieving CAFE across vehicles they sell. This led to substantial improvements in tire technology between 1975 and 1986 and increased demand for radial tires over bias tires. However the pace in reduction of coefficient of rolling resistance for OEM tires was more moderate there after. This correlates directly with the change in CAFE standards, as shown in Figure 6. After 1985, CAFE standards for passenger vehicles have remained steady at around

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[1] Source: Environmental Protection Agency, personal communication with Smartway partnership managing director, Cheryl Bynum, June, 2009.

27.5 miles per gallon. As a results automakers have steadily improved the technology of vehicles between 1986 and 2004, including OEM tires, and without much change in stringency of CAFE standards.

Under President Obama's administration, the CAFE standards will increase by five percent each year, reaching 35.5 mpg by 2016. In other words, in 7 years the national average CAFE has to increase by 8 mpg per vehicle. Therefore, change in fuel standards can potentially cause OEM tires to become more efficient at a faster rate, perhaps similar to improvements observed during 1975-1985 era.

Rolling Resistance: Heavy-Duty Large Trucks

Argonne National Laboratory

A study published by Office of Heavy Vehicle Technologies at DOE's Argonne National Laboratory titled "Life-cycle Analysis for Heavy Vehicles" claims that the greatest sources of reduction in rolling resistance (as mentioned earlier above) is due to moving from conventional bias ply tire to the first generation of radial tires [40]. In addition, further reduction in rolling resistance of radial truck tires has been observed due to improvements in tire technology. The next giant leap in trucking industry appears to be the transformation from dual-tire feature to single-wide (i.e. super single) tires.

This study shows the following data for evolution of rolling resistance coefficient for heavy truck tires (i.e. Class 7 and Class 8) [40]:

Table 8. Three major improvement in truck tire design since bias-ply tires, and its impact on coefficient of rolling resistance.

Tire Type	Coefficient of Rolling Resistance	% Improvement (Bias and Radial Combined)	% Improvement (Radial Only)
Conventional Bias Ply	0.0097	100	NA
Initial Radial Ply	0.0068	70	100
Improved Radial Ply (including Low Rolling Resistance)	0.0061	63	90
Single-Wide Radial Tire	0.0054	56	80

Goodyear

Goodyear has published a service manual titles “Radial Truck Tire And Retread,” which provides a graph illustrating the comparison between radial-ply truck tires and bias-ply truck tires in relation to rolling resistance coefficient and wear [29].

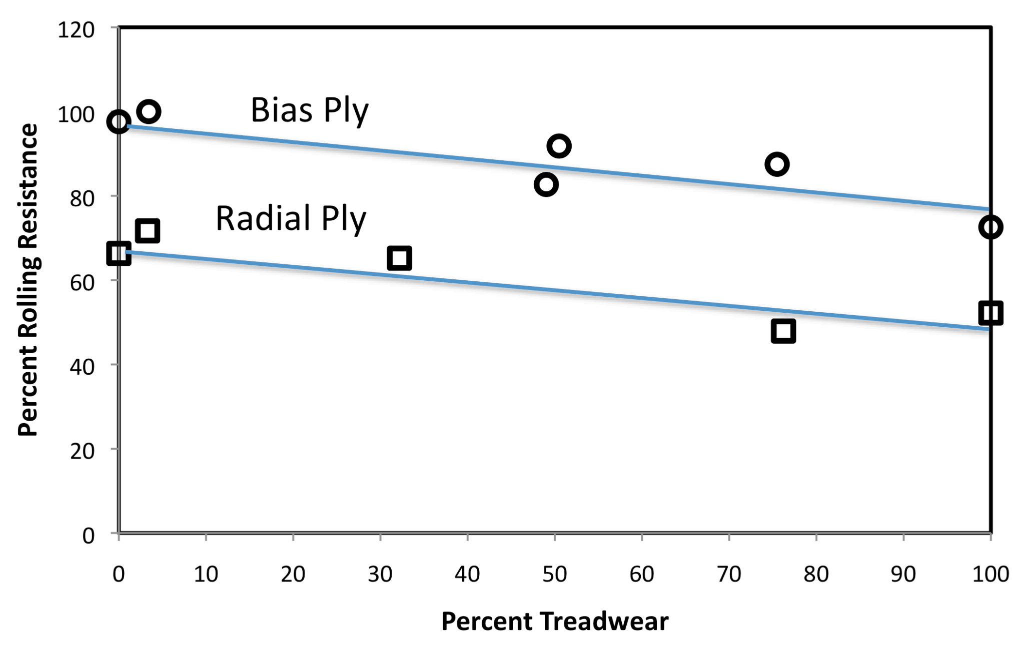


Figure 14. Effect of Treadwear on Truck Tire Rolling Resistance Laboratory Data (Goodyear fuel Tests, 1986).

According to Figure above, for newly purchased truck tire (0% treadwear), radial ply tires have a 30 per cent reduced rolling resistance compared to bias tires. This figure is in agreement with Table 8.

U.S. EPA SmartWay Transport Partnership

Accoring to Cheryl Bynum, Manager at Environmental Protection Agency’s SmartWay Transport Partnership, the rolling resistance coefficient of line haul off-the-road tractor-trailer currently has the following coefficient of rolling resistance:[I]

- Steer Axle: 0.006 to 0.007
- Drive Axle: 0.008 to 0.009
- Trailer Axle: 0.006 to 0.007
- Combined full vehicle: 0.007

Michelin Center of Technologies, Research and Development

[I] Source: Environmental Protection Agency, personal communication with Smartway partnership managing director, Cheryl Bynum, June, 2009.

In a separate presentation to Federal Highway Administration, Michelin's R&D group presented the following historical evolution of rolling resistance coefficient for passenger car, truck, bus tires and railroad wheels [37].

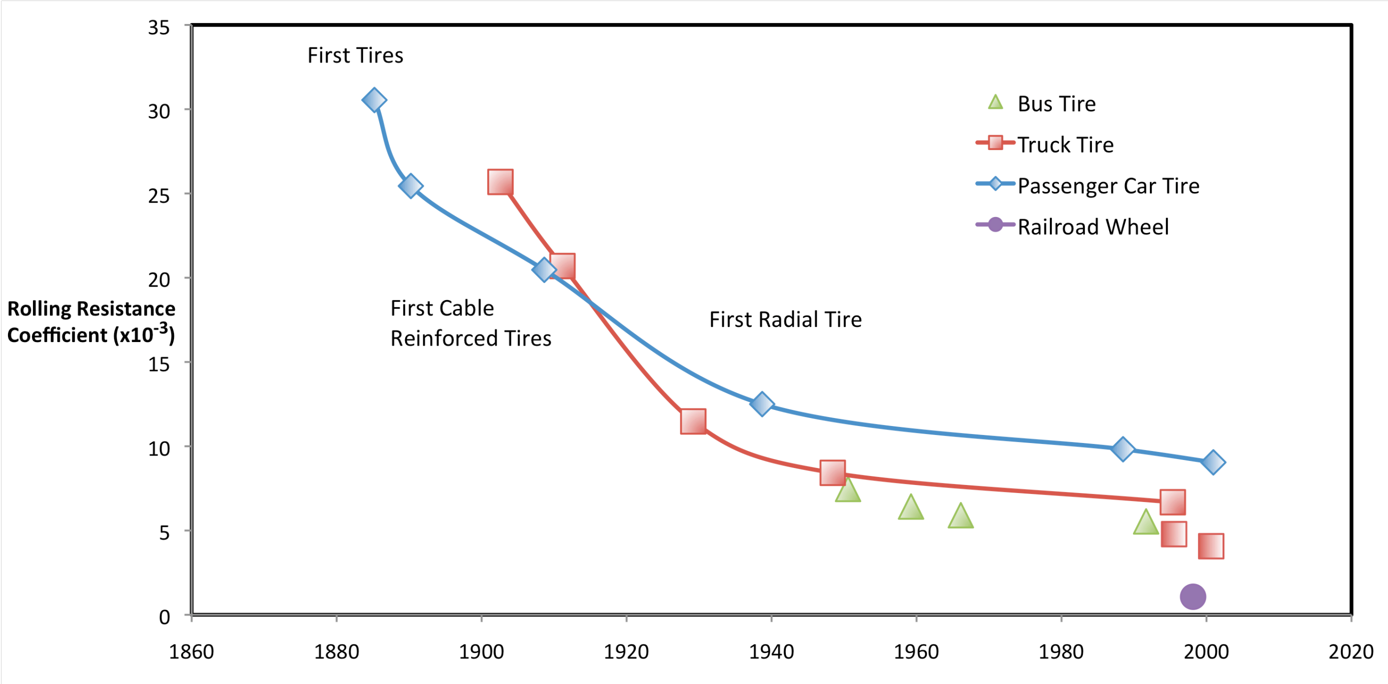


Figure 15. Evolution of tires technological advancement since its invention 1890 to 2001[37].

According to the figure above, since 1980, the rolling resistance coefficient for truck tire and passenger tire has been reduced by 42% and 25 % respectively.

5.4.7 Impact of Rolling Resistance on Vehicle Fuel Consumption: Literature Review

After conducting an extensive literature review of the impact of tires on vehicle fuel economy for passenger cars, mid-size and heavy-duty trucks, it was concluded that the rolling resistance contributions are mainly represented in literature in three distinct formats:

1. Contribution Factor: Fraction of the total vehicle fuel consumption (i.e. overcoming tire rolling resistance accounts for X% of the total fuel intake).

$$\text{Contribution of Rolling Resistance on Vehicle Fuel Consumption} = \frac{E_{RR}}{E_{T}} = \frac{\text{Rolling Resistace Energy}}{\text{Total Vehicle Energy Consumption}}$$

2. Return Factor or Return Ratio: Change in fuel consumption due to change in rolling resistance (e.g. X% change in tire rolling resistance results in Y% change in vehicle fuel consumption). Return factor can be used to determine the change in fuel consumption due to change in tire rolling resistance as shown below:

$$\text{Return Factor} = \frac{\%\ \text{Change in Fuel Consumption}}{\%\ \text{Change in Rolling Resistance}} \qquad \text{Equation 2}$$

There are various methodologies used for producing rolling resistance contribution values such as numerical simulations, experimental testing, etc. Typically the contribution values provided in the form of 1 are smaller than the values in the form 2. NRC et al. claims that the reasoning for this is because "reducing rolling resistance, and thus reducing mechanical energy demand, by a given amount will translate into a larger reduction in total fuel consumption because less fuel energy will need to be sent to the engine in the first place." However, as a first order approximation, we assume that both 1 and 2 can be used as a measure of the contribution of rolling resistance of tires on the vehicle fuel consumption.

Our literature review concludes that there is a wide variation in the results published for contribution of tires. The reasoning for this could be due to the boundary conditions, assumptions, test samples, context of analysis (e.g. driving cycles), difference in methodology, and technical details beyond the scope of this report.

The results compiled through literature review are expressed in the same format as published. For comparison purposes, the return factor (RF) and the contribution factor (CF) for each study has been computed, as shown below.

5.4.7.1 Effects of Tires on Passenger Car Fuel Consumption

Transport and Road Research Laboratory, 1980 [41]

A study by UK's Transport and Road Research Laboratory (TRRL) [41] published in 1980, suggested that a 20 per cent reduction in over tire rolling resistance would reduce the total fuel consumption by nearly 3 per cent for both urban and rural driving cycles [41]. This translates to return factor (RF) of 1:6.7 and contribution factor (CF) of 0.15.

Energy Efficiency Office, Department of Energy, London, UK, 1989 [42], [25]

This study conveys that of the energy used by the car, 72% is lost by thermodynamic heat rejection of the combustion process, 2% by frictional losses and transmission, and 8% by power auxileries. Of the 18% remaining energy, Martin et al. claims, 6% is used to overcome rolling resistance. This translates to RF of 1:16.7 and CF or 0.06.

California Energy Commission, 2003, [18]

In this report gathered by Ecos Consulting titled "California State-Fuel Efficient Tire," it is stated that tire rolling resistance has different impacts on vehicle fuel consumption under various driving conditions and driving speeds [18]. The recommendation of Ecos Consulting about the impact of tires on passenger car fuel consumption is as follows [18]:

"The highway fuel economy test yielded a return ratio (RF) of 1:5.3, or more than 2% fuel economy change for every 10% change in rolling resistance. The urban fuel economy test yielded a return ratio (RF) of 1:9.6, or about 1% fuel economy change for every 10% change in rolling resistance." This translates to CF of 0.1 to 0.2.

U.S. National Research Council, 2006

As discussed earlier, this study provides a comprehensive analysis of the impact of tires on passenger vehicle fuel economy [36].

This report claims that most of the input energy- about two-thirds- is lost to converting into mechanical work at the engine. For both urban and highway driving conditions, the mechanical energy that makes its way to turn the wheels, is consumed by three sinks: aerodynamic drag, rolling resistance, and braking. NRC claims that rolling resistance directly consumes about 4 to 7 percent of the total energy expended in tires. However, NRC argues, "reducing rolling resistance, and thus reducing mechanical energy demand, by a given amount will translate into a larger reduction in total fuel consumption because less fuel energy will need to be sent to the engine in the first place." As such, this report shows that a 10 per cent reduction in rolling resistance coefficient of passenger car tires will yield a 1 to 2 per cent increase in passenger vehicle fuel economy [36]. This translates to RF of 1:10 to 1:5. NRC explains that this result applies to the impact of coefficient of rolling resistance on fuel economy.

This translates to RF of 1:5 to 1:10 and CF of 0.04 to 0.07. Note that this report claims that RF and CF provide different contribution values in terms of impact of rolling resistance on fuel consumption of the vehicle.

5.4.7.2 Effects of Tires on Heavy-load Trucks

Transport and Road Research Laboratory, 1980 [41]

This study calculates the contribution of energy use for a 36-ton truck as

Engine losses	62%
Accessories	3%
Transmission losses	4%
Rolling resistance	15%
Aerodynamic drag	12%
Acceleration and braking	4%

This translates to RF of 1:6.7 and CF of 0.15.

Transport and Road Research Laboratory [43]

Another report published in 1994, by TRRL measured the effect of rolling resistance on fuel consumption of a five-axle tractor-trailer. The results from the study show a linear relationship between fuel consumption and the total rolling resistance of the tires.

In addition, this report suggests that to reduce vehicle fuel consumption of a heavy commercial vehicle by 1%, the tire-rolling resistance has to be reduced by 2.7 to 3.7 per cent for full load, and 5 to 6.6 per cent for an empty load. [43]. This translates to RF of 1:3 to 1:6 and CF of 0.16 to 0.33.

Office of Heavy Vehicles Technologies of U.S. Department of Energy, 2000 [30]

This report prepared by DOE's Office of Heavy Vehicles Technologies shows an energy audit of a typical Class 8 vehicle operating on a level road at a constant speed of 65 mph with a Gross Vehicle Weight (GVW) of 80,000 lbs (36,280 Kg). Moreover, it show results in terms of kWh of energy used per hour illustrating that rolling resistance consumes 51 kWh out of total 400 kWh, or roughly 13% of the total energy.

Authors of this report claim that the variations in speed, load, temperature, driving cycles, and pressure would typically lead to the following range of return factors for Class 8 Trucks [30]:

- Line-haul Class 8 Truck RF → 1:3 to 1:4
- Regional use Class 8 Truck RF → 1:5 to 1:6

More generally, the Office of Heavy Vehicles Technologies establishes a consensus between industry officials and government research groups in regards to the impact of tire rolling resistance of a typical class 8 tractor-trailer [30]:

"Industry experience indicates that for a typical class 8 tractor-trailer combination running on an interstate circuit, a 30% decrease in total vehicle tire-rolling resistance, would improve fuel consumption by approximate 10%."

This translates to RF 1:6 to 1:3 and CF of 0.13.

GHK Consulting report prepared for European Policy Evaluation Consortium (EPEC), 2008, [31]

This report claims that a 15 per cent reduction in the rolling resistance value leads to a 4 per cent reduction in fuel consumption in urban driving, and 7 per cent in highway driving [31]. This translates to RF of 1:3.75 to 1:2.14 and CF of 0.26 to 0.47. The upper RF value is the highest contribution of truck tire rolling resistance (i.e. 47%) in the published data in this literature review.

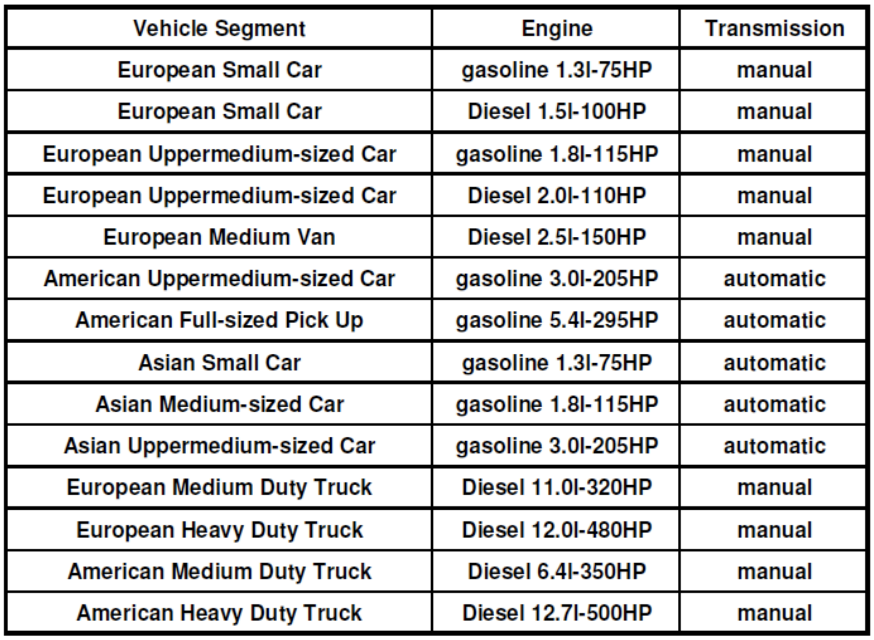
Bridgestone, 2008 [32]

In a Bridgestone report titled "real questions, real answers: Tires and Trucks Fuel Economy," the Bridgestone officials reflect upon the dynamic interaction between contribution of tires as well as other resistive components (such as aerodynamic resistance) to vehicle fuel economy [32]. The report claims that despite advancement in tire efficiency in the past decades, the contribution of rolling resistance for some models of trucks have increased from 15-20% to 25-35% due to higher rates of advancement in reducing internal frictional losses, aerodynamics losses, etc [32]. The report concludes by stating that "for each 3 per cent change in rolling resistance, fuel economy changes by about one per cent" [32]. This translates to RF of 1:3 and CF of 0.15 to 0.33.

Michelin Center of Technologies, 2009 [27]

In a technical report published by Society of Automotive Engineers titled "Reducing Tire Rolling Resistance to Save Fuel and Lower Emissions," the authors illustrate the variation in % contribution of overcoming rolling resistance by utilizing fuel economy simulations with AVL Cruise software for multiple gasoline and diesel vehicles and heavy trucks [27]. The simulations were conducted over multiple usage ranges including standardized cycles endorsed by governmental agencies such as EPA Federal Test Procedure (EPA FTP-75), and New European Driving Cycle (NEDC). Table 9 below shows the type of vehicles tested for this study:

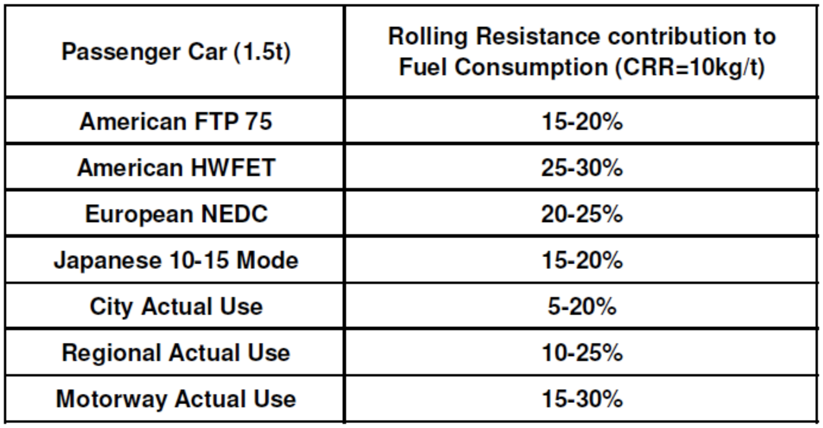
Table 9. Vehicle Models used for Cruise Simulations conducted in Michelin laboratory [27]



Vehicle Segment	Engine	Transmission
European Small Car	gasoline 1.3l-75HP	manual
European Small Car	Diesel 1.5l-100HP	manual
European Uppermedium-sized Car	gasoline 1.8l-115HP	manual
European Uppermedium-sized Car	Diesel 2.0l-110HP	manual
European Medium Van	Diesel 2.5l-150HP	manual
American Uppermedium-sized Car	gasoline 3.0l-205HP	automatic
American Full-sized Pick Up	gasoline 5.4l-295HP	automatic
Asian Small Car	gasoline 1.3l-75HP	automatic
Asian Medium-sized Car	gasoline 1.8l-115HP	automatic
Asian Uppermedium-sized Car	gasoline 3.0l-205HP	automatic
European Medium Duty Truck	Diesel 11.0l-320HP	manual
European Heavy Duty Truck	Diesel 12.0l-480HP	manual
American Medium Duty Truck	Diesel 6.4l-350HP	manual
American Heavy Duty Truck	Diesel 12.7l-500HP	manual

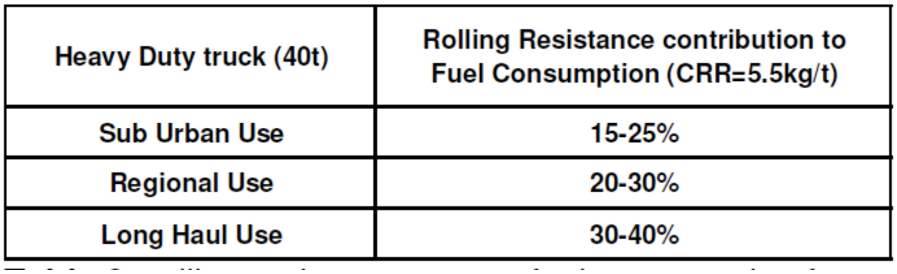
The report computed the change in tire's contribution to fuel consumption for both passenger cars as well as heavy duty trucks for various driving conditions, as shown in Table 10 and Table 11.

Table 10. Contribution of Rolling Resistance to Fuel Consumption: Passenger Car [27]



Passenger Car (1.5t)	Rolling Resistance contribution to Fuel Consumption (CRR=10kg/t)
American FTP 75	15-20%
American HWFET	25-30%
European NEDC	20-25%
Japanese 10-15 Mode	15-20%
City Actual Use	5-20%
Regional Actual Use	10-25%
Motorway Actual Use	15-30%

Table 11. Contribution of Rolling Resistance to Fuel Consumption: Heavy-duty Trucks [27].



Heavy Duty truck (40t)	Rolling Resistance contribution to Fuel Consumption (CRR=5.5kg/t)
Sub Urban Use	15-25%
Regional Use	20-30%
Long Haul Use	30-40%

The study illustrates the vast range of rolling resistance contribution (CF of 0.05 to 0.30 for passenger cars; CF of 0.15 to 0.40 for heavy-duty vehicles). The study also concludes that the tire contribution to fuel consumption is not constant but variable, and most dependent on driving characteristics, vehicle specifications, and the tire's energy efficiency (i.e. rolling resistance coefficient) [27].

At last, the study concludes by stating that, "on average it can be assumed that 1 tank of fuel out of 5 [20%] is consumed due to the tires of passenger cars, and 1 tank out of 3 [i.e. 33%] for heavy trucks." [27]. This translates to RF of 1:5 and 1:3 for passenger cars and heavy truck, respectively.

The summary of the literature review for contributions of tire rolling resistance on total vehicle energy requirements is compiled and shown in Table 12 below.

Table 12 Summary of literature review for contribution of total tire rolling resistance on the total fuel consumption of the vehicle

	Light Duty Passenger Cars	Reference: Author/ Year Published
Rolling Resistance Contribution to Fuel	15% 6%	Waters et al., 1980 Martin et al., 1989

Consumption (Contribution Factor)	10% to 20% 4% to 7% 10% to 20% 5% to 30%	Calwell et al., 2003 NRC, 2006 NRC, 2006 Barrand et al., 2009
	Heavy Trucks	
Rolling Resistance Contribution to Fuel Consumption (Contribution Factor)	15% 13% to 33% 13% 13% to 33% 26% to 47% 15% to 40%	Waters et al., 1980 Schuring et al., 1982 DOE, 2000 DOE, 2008 Bozeat et al., 2008 Barrand et al., 2009

In this study, we take the contribution of rolling resistance on vehicle fuel consumption to be on average 15% for passenger cars, and 24% for heavy trucks. Furthermore, we illustrate the results based on the range for the contribution of rolling resistance on vehicle energy expenditure. We consider the range of contribution to be 10 to 20% for passenger cars and 15 to 33% for heavy trucks.

5.4.8 Use Phase Energy Analysis: Methodology and Approach

How can one quantify the energy losses during use of a tire? Industry officials, researchers, and tire manufacturers have been studying this for decades in order to improve the energy performance of tires. The assessments encompass varieties of testing approaches such as experimental observations using standardized testing procedures, stress-strain simulations, numerical modeling, etc.

One common approach for conveying the contribution of tire rolling resistance on fuel consumption is to determine the changes in total vehicle fuel consumption based on the changes in rolling resistance of tires. Reports publish this unit of measure and commonly refer to it as 'return factor', 'return ratio', 'energy return', etc (refer to 5.4.7 above for detailed information on return factor and rolling resistance contribution).

$$\mathrm{Z} = \text{Return Factor} = \frac{\left(\Delta E_T \middle/ E_T \right)}{\left(\Delta F_{RR} \middle/ F_{RR} \right)} = \frac{\left(\dfrac{E_T^{'} - E_T^{o}}{E_T^{o}} \right)}{\left(\dfrac{F_{RR}^{'} - F_{RR}^{o}}{F_{RR}^{o}} \right)} \qquad \text{Equation 3}$$

where E_T^o, $E_T^{'}$, F_{RR}^o, $F_{RR}^{'}$, Z are the vehicle fuel energy consumption with initial set of tires (taken as the reference), modified vehicle fuel energy consumption due to modified tires, rolling resistance of initial set of tires, rolling resistance of the modified set of tires, and return factor.

In this study, E_T^o is computed based on the following equation,

$$E_T = \frac{\text{Miles Travelled [miles]}}{\text{Vehicle Fuel Economy [miles per gallon of fuel]}} \times \text{Fuel Heat Content} \qquad \text{Equation 4}$$

Return factor provides a relation between the changes in rolling resistance and its corresponding energy impacts on vehicle energy consumption. Rolling resistance is conceived as an energy loss per unit distance travelled (J/m or N), where the higher the value the more vehicle fuel input required for overcoming tire energy losses (refer to 5.4.2 for detailed information).

In this study, we are interested, however, in the energy impacts of changes in coefficient of rolling resistance of tires on vehicle fuel energy consumption. Coefficient of rolling resistance is a dimensionless measure of tire efficiency that can be conveyed in terms of rolling resistance force generated per unit load applied (RMA). Therefore, coefficient of rolling resistance is linearly correlated to rolling resistance as expressed below (refer to section X for more information),

$$C_{RR} = \frac{F_{RR}}{W} \qquad \text{Equation 5}$$

where C_{RR} and W are the tire coefficient of rolling resistance and vehicle load on tires. Based on this relation, we can postulate that rolling resistance, tire energy loss, and coefficient of rolling resistance are linearly proportional (refer 5.4.2 for more information). Therefore, we can illustrate that fractional changes in coefficient of rolling resistance is equivalent to fractional changes in rolling resistance,

$$\Delta C_{RR} / C_{RR} = \frac{C_{RR}^{'} - C_{RR}^o}{C_{RR}^o} \approx \frac{F_{RR}^{'} - F_{RR}^o}{F_{RR}^o} = \Delta F_{RR} / F_{RR} \qquad \text{Equation 6}$$

where C_{RR}^o and $C_{RR}^{'}$ are the coefficient of rolling resistance of the initial set of tires (reference case) and the modified set of tires. Based on this, we can re-write Equation 3 as follows,

$$\text{Z} = \text{Return Ratio} = \frac{\left(\Delta E_T / E_T\right)}{\left(\Delta C_{RR} / C_{RR}\right)} = \frac{\left(\frac{E_T^{'} - E_T^o}{E_T^o}\right)}{\left(\frac{C_{RR}^{'} - C_{RR}^o}{C_{RR}^o}\right)} \qquad \text{Equation 7}$$

The equation above can be re-arranged to solve for the modified vehicle fuel energy consumption, $E_T^{'}$, as a result of utilizing the modified set of tires,

$$E_T^{'} = E_T^o + Z.E_T^o.(\frac{C_{RR}^{'} - C_{RR}^o}{C_{RR}^o}) \qquad \text{Equation 8}$$

By taking a first-order approximation, it can be articulated that Z (return factor) is the contribution factor of rolling resistance on total vehicle fuel consumption. Based on this, the energy required for overcoming rolling resistances of all tires on a vehicle can be expressed as,

$$E_{RR}^o = Z.E_T^o \qquad \text{Equation 9}$$

where E_{RR}^o is the use phase energy consumption of all tires operating on a vehicle.

The total energy consumption of a vehicle, E_T^o, consists of a combination of energy expending components. In this study we break them into energy losses due to rolling resistance of tires, E_{RR}^o, and losses due to all the other components $\overline{E}_{RR}^o$ (i.e. engine losses, transmission losses, aerodynamic losses, etc.).

$$E_T^o = E_{RR}^o + \overline{E_{RR}^o} \qquad \text{Equation 10}$$

Utilizing Equation 9 for E_{RR}^o we end up with the following equation,

$$E_T^o = Z.E_T^o + (1-Z).E_T^o \qquad \text{Equation 11}$$

We assume that the changes in rolling resistance of the tires do not change the energy requirements of other vehicle components. In other words,

$$\overline{E}_{RR}^o = \overline{E}_{RR}^{'} \qquad \text{Equation 12}$$

Based on the above assumption, we can compute the use phase energy cost of a new set of tires by taking into account the following expression,

$$E_T^{'} = E_{RR}^{'} + \overline{E_{RR}^{'}}$$

$$E'_{RR} = E'_{T} - \overline{E'_{RR}} = E'_{T} - \overline{E^{o}_{RR}} = E'_{T} - (1-Z).E^{o}_{T} \qquad \text{Equation 13}$$

Using Equation 8, we Plug in for E'_{T} to come up with the following equation,

$$E'_{RR} = Z.E^{o}_{T}.(\frac{C'_{RR} - C^{o}_{RR}}{C^{o}_{RR}} + 1) = E^{o}_{RR}.(\frac{C'_{RR}}{C^{o}_{RR}}) \qquad \text{Equation 14}$$

where E'_{RR} is the energy requirement for overcoming rolling resistance energy losses of the modified set of tires on a vehicle.

Use: Passenger Car Tires

Given average annual travel miles of passenger car vehicles in the U.S., a replacement tire would last for about 3 to 4 years (assuming proper operation and maintenance of the tire) [45]. We take the fuel economies of 1977 and 2001 passenger vehicles to be around 15.8 and 28.8 mpg, respectively [45].

The wear life of the passenger car OEM tire is taken to be 41,500 miles [46]. The mileage lifetime of such tires have changed considerably in the past few decades. But for simplicity we keep the mileage lifetime to be the same for both 2004 as well as 1980 analysis. In addition, low heat value (LHV) gasoline was chosen as the fuel input during the operational lifetime of the passenger vehicle. The primary production and feedstock energy of LHV gasoline is estimate to be 142.4 MJ per 1 U.S. gallon [45]. Table 13 provides a breakdown of the gross calorific value as well as primary production energy cost of gasoline.

Table 13. Gasoline fuel feedstock energy value [45]

	Energy Content (Typical Gross Calorific Value) MJ/Gallon	Fuel Production Plant Efficiency (%)	Production Energy (MJ/Gallon)	Total Fuel Energy (MJ/Gallon)
Gasoline (Lower Heating Value)	121.75	85.5%	20.65	142.40
Gasoline (Higher Heating Value)	131.88	85.5%	22.37	154.25

Values for Z is taken to be on average 0.15, with a range of 0.1 to 0.2 [36], [25]. We assume that the contribution factor has remained in the same range between 1977 and 2001. Finally the results for passenger car analysis are showcased in terms of relative lifecycle energy savings due to retreading OEM tires.

Use: Heavy Truck Tires

We assume that the truck analyzed has an average vehicle fuel economy of 5.5 mpg. This is the average value for mpg of trucks between years 1970 and 2005 (mean: 5.5; std. deviation +/- 0.34). Also, we assume that the truck consumes conventional diesel fuel with volumetric heating content of 146.34 MJ per gallon of fuel [45].

Truck tire lifetime has greatly improved as tires transformed from bias to radial, some estimating doubling the tire lifetime[I]. Moreover, the current pace of improvements in wear performance of radial tires have been steady[I]. The typical lifetime of a heavy truck tire may range from 80,000 to 100,000 miles. Some high performing truck tires under proper maintenance are capable of travelling for more than 200,000 miles during one lifetime[I]. In this analysis, the average mileage lifetime of a replacement heavy truck tire is taken as 100,000 miles[I]. In addition, for energy analysis, we assume that retreaded tires and new tires have comparable mileage lifetime (refer to detailed discussion and justification of this assumption in 7.2).

For the analysis, the base case (reference) is considered to be for retreading old radial tires to like-new and re-using them for another 100,000 miles. In other words, it is assumed that retreading the old radial tires to like-new conditions would have no impact in terms of changing fuel economy of the truck (keeping the fuel economy at 5.5 mpg across multiple driving cycles).

Also, as discussed above, we assume that on average 24% of input fuel is expended (range: 15 to 33%) for overcoming rolling resistance energy losses of all tires on a heavy load tractor-trailer combination truck [30]. We use this parameter to determine the relative changes in truck fuel consumption and rolling resistance energy losses of tires.

Lastly, the energy analysis is performed such that the impact of rolling resistance is analyzed per total vehicle tires for a tractor-trailer with 3 axles (steer axle; drive axle; and trailer axle). The values for coefficient of rolling resistance for bias ply, radial, advanced radial, and single wide-base tires are average industrial values taken from DOE 2000.

Assumptions

We assume that by remanufacturing the tires will be brought back to like-new conditions. In other words, based on this assumption, the retreading process doesn't degrade or enhance energy performance of a tire casing relative to when it was first manufactured. In reality, depending on the quality of the retreading process, tires can be degraded in performance during use phase [16], [47]. This notion is contested in the sensitivity analysis.

[I] Source: Argonne National Laboratory, personal communication Tim LaClair, June, 2009.

In addition, we assume that retreaded tires can be utilized on the drive and trailer axles only. In reality, the steer axle cannot be equipped with retreaded tires for safety precautions. As such, for decisions 1, 2, and 3, where the choices are in favor of utilizing/procuring retreaded truck tires, we assume that the steer axle is equipped with two new tires. Moreover, we assume that these new tires are of similar construction and performance attributes as the retreaded tires. For example, for decision 1, we assume that the drive and trailer axles will utilize retreaded bias ply tires while the steer axle will be equipped with new bias ply tires (with similar coefficient of rolling resistance as the retreaded ones).

For single wide-base tires, only 8 single wide-base tires are required for the drive and trailer axles (instead of 16 for dual radial tires). Since single wide-base tires cannot be used on the steer axle we assume that the steer axle utilizes two radial tires of similar rolling resistance attributes as the single wide-base tires.

The energy demands for producing the required number of tires for decision 6 is determined as follows:

$$E_{\text{Production}}^{\text{Total Tires}} = 2E_{\text{Radial}} + 8E_{\text{Single Wide}} \qquad \text{Equation 15}$$

where $E_{\text{Production}}^{\text{Total Tires}}$, E_{Radial}, and $E_{Single-Wide}$ are total production energy costs for all tires utilized for the truck, production energy demands for a radial tire, and production energy demands for a single wide-base tire, respectively.

5.4.9 Tire Retreading Decision Analysis

5.4.9.1 Light Duty Passenger Vehicle

Figure 12 reveals that the average coefficient of rolling resistance for replacement tires has changed only slightly between 1994 and 2005 (data encompasses radial tires only). Therefore, based on this fact, we presume that by retreading an old replacement tire to like-new conditions, it would save energy compared to purchasing a new replacement tires (assuming that the retreaded tire performance in use phase is similar to that of a new tire). Some recent studies, however, reflect on the energy savings benefits of the new low rolling resistance fuel-efficiency enhancing (eco-efficient) tires. According to CEC, low rolling resistance replacement tires can reduce fuel consumption of a vehicle by about 4% compared to current radial tires. Therefore, if the retreaded tires are of conventional type and are being compared to new low rolling resistance replacement tires, then the conclusions may be that new low rolling resistance replacement tires are more energy savings. This requires quantitative assessments in order to achieve concrete conclusions; due to lack of data, we refrain from quantitative assessment of energy savings potential of replacement tire retreading.

The industry efforts for promoting energy efficient replacement tires have been less pronounced than for Original Equipment Manufacturer (OEM) tires. Since the enacting of CAFE standards in 1975, tire manufacturers have improved the energy efficiency of OEM tires in order to comply with automotive fuel efficiency standards. Also, consumers in general have been less keen on the environmental incentives for procuring more efficient replacement tires; instead the primary focus in the replacement tire market has been to optimize the decision choice based on the quality of performance and the desire to save on upfront costs. According to LaClair, average coefficient of rolling resistance of OEM tires has been reduced by more than 60% from 1975 to 2004. Therefore, the consumer choice between remanufacturing OEM tires and purchasing new OEM tires may or may not lead to energy savings. Therefore, the objective of analysis for OEM tires is to reveal the energy savings benefits of retreading despite improvements in tire efficiency.

Consider a scenario where by a consumer has purchased a new passenger car vehicle in 2001 (i.e. 2001 model), which came with OEM tires produced in 2001. After 3 years of use (average operational life of OEM tire [45], [46]) the OEM tires reach end of life and must be replaced. For the purpose of addressing retreaded OEM tires performance only, we assume that the options available are only based on utilizing OEM tires. This is not a realistic representation since in majority of instances worn tires are replaced with replacement tires. However, due to scarcity of data and for effective comparison, we establish the scenario based on OEM tire choices only. Therefore, as the set of old OEM tires of the vehicle become worn-out, the owner of the vehicle has a decision to make:

1. To remanufacture the set of four old OEM tires and re-use them (2001 model tires)
2. To dispose the set of old OEM tires and replace it with a set of four new OEM tires (2004 model tires)

We determine the energy impacts of changes in rolling resistance coefficient between 2001 and 2004 models by utilizing Equation 14. Since the comparison is between tires that are only 3 years apart in terms of production year, the outcomes of the energy savings evaluations will be in the scope of transitional technological changes in OEM tires (refer to section X for more information).

As shown in **Error! Reference source not found.**, the improvements in rolling resistance coefficient of OEM tires in 2000's have been relatively moderate compared to the improvements during the 70's an the 80's. According to **Error! Reference source not found.**, the rate of reduction in coefficient of rolling resistance of OEM tires has been about 1.5% annually between 1995 and 2005. Comparatively, the rate of reduction during 1975-1985 and 1985-1995 has been 4.5% annually and 2.2% annually, respectively. In order to capture the dynamic changes in rate of efficiency improvements in tires, we perform the same analysis retrospectively during 1975-1980 timeline. We consider a situation where a consumer has purchased a1977 model passenger vehicle in year 1977, which came with OEM tires that were produced in 1977. After 3 years of use, the tires have reached end of life and must be replaced. The owner of the vehicle has a decision to make:

1. Remanufacture the old set of four OEM tires and re-use them (1977 model tires)
2. Dispose the set of old tires and replace with a set of four new OEM tires (1980 model)

Figure 16 below illustrates the decision tree for evaluating the energy benefits of retreading OEM tires.

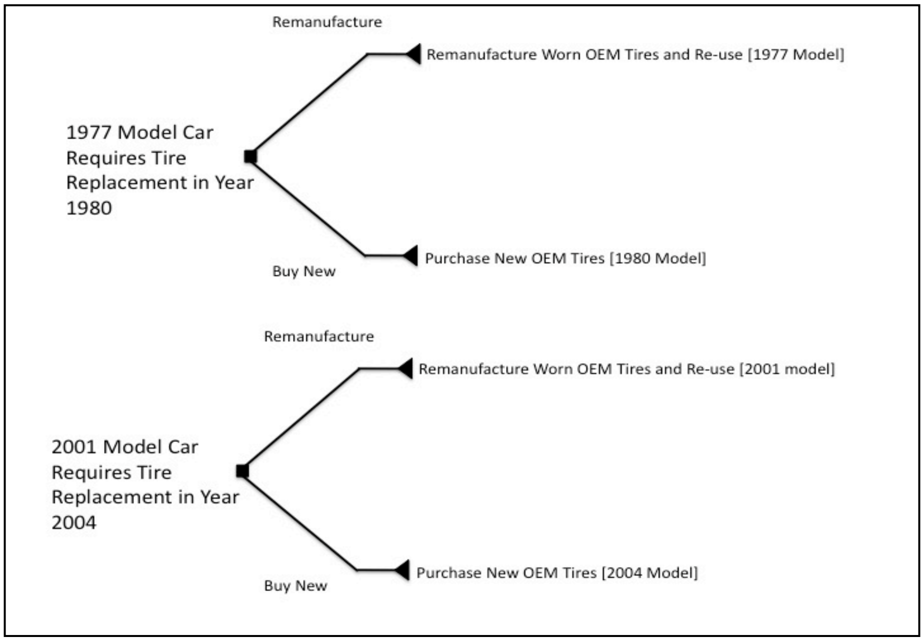


Figure 16 Decision-Tree Analysis: Consumer Decision for Replacing worn Tires

Each decision has particular consequences including lifecycle energy requirements. If the consumer decides to remanufacture old tires and re-use them, then the lifecycle energy cost is taken to be the energy to remanufacture old tires and the energy demands in use-phase. If the consumer chooses to purchase new tires, then the energy consequences to be taken into account are for producing raw materials, manufacturing the tires, and using them.

5.4.9.2 Heavy Duty Truck Tire

The objective of the analysis for truck tires is primarily to evaluate lifecycle energy savings potential of remanufacturing radial tires (most utilized tires). The assessments are performed in the scope of transformational technological advancements in tires. For truck tires, the evolution of tire advancements can be broken into three critical transformation steps [30]:

1. Transformation from Bias-Ply tires to Radial-Ply tires (past)
2. Progression in Technological advancement and efficiency gains in Radial-Ply tires including low rolling resistance tires (present)
3. Transformation from efficient radial tires to single wide-base tires (most recent)

According to DOE, the technological advancements from bias-ply tires to single-wide tires has led to an average reduction of 44% on average in coefficient of rolling resistances [30].

We establish a decision scenario for evaluating lifecycle energy savings potential of truck tire remanufacturing. The scope of this analysis is based on evaluating tire retreading in the context of transformational technological changes in tires. Consider a Class 8 tractor-tailor combination truck, which is reaching a point where all tires are worn-out and have to be replaced at once. We assume that the tires that were used and now reached end of life are radial tires (conventional tires currently used in the market).

The truck owner has to make two decisions in series. The first decision is whether to utilize remanufactured tires or to utilize new tires. The second decision that follows is, which tire technology to choose for replacing the tires. For the case where the owner chooses to utilize remanufactured tires, we assume that there are three options available:

1. To purchase remanufactured bias-ply tires.
2. To remanufacture the worn radial tires and re-use them.
3. To dispose worn radial tires and purchase remanufactured radial tires.

For the case where the owner decides to dispose the old tires and purchase new tires, we assume that there are three other options available:

4. To purchase new radial tires.
5. To purchase new advanced radial (low rolling resistance) tires.
6. To purchase new single wide-base tires.

Figure 17 below illustrates all the options available to the consumer in the form of a decision tree.

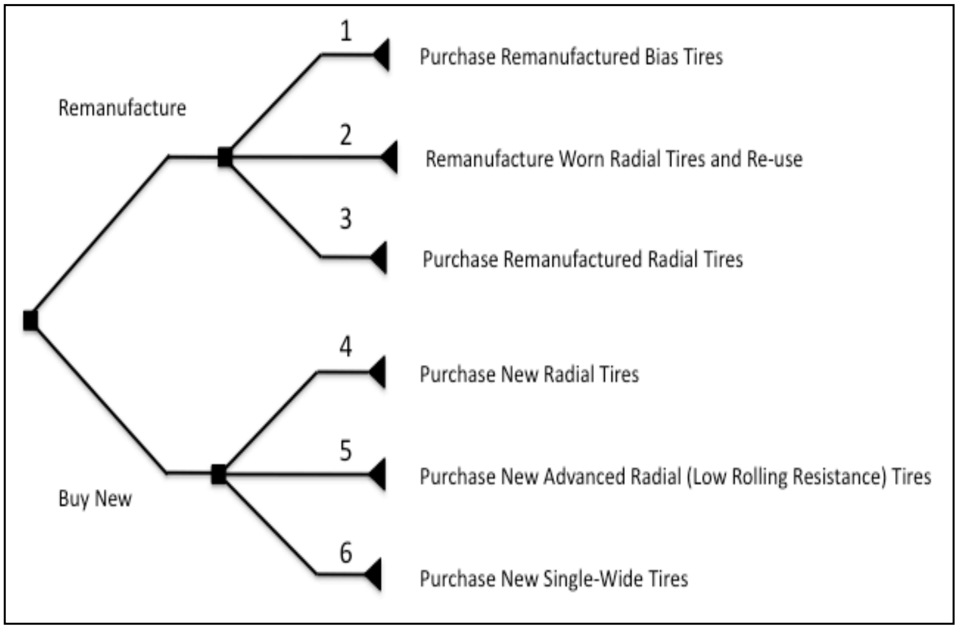


Figure 17 Decision-Tree Analyses: Consumer Decision for Replacing Worn Tires.

We assume that the energy performance of retreaded radial tires in decision 2 and decision 3 are similar in the use phase. Another decision studied in this report is about utilizing remanufactured bias tires (decision 1). Note that decision 1 is not necessarily a realistic decision in the U.S. given that bias tires have become obsolete. However, in order to capture the past transformational changes in tire designs and architectures, we keep decision 1 included in the evaluations.

We assume that the retreading processes bring worn tires back to like-new conditions. We also assume that the rolling resistance attributes of new radial tires are similar to those of older radial tires. This is a realistic assumption given that truckers go through the full lifetime of their tires in a much faster rate than passenger car owners. Fleets use trucks more often and travel longer distances than passenger cars. Therefore, we presume decisions 2, 3, and 4 to have similar energy impacts in use phase.

5.5 Data Sources

5.5.1 Passenger Car Vehicles

The data sources for each phase is as follows:

Raw materials processing Phase

Bill of materials: [48].
Energy intensity values for each raw materials: [22], [20], [19], [23], [24].

For tire mass, we assume that radial and bias ply tires have similar mass of 9.1 Kg [22].

Manufacturing Phase

We rely on the literature data to reveal the energy requirements for manufacturing a passenger car tire: Manufacturing: [19], [21].

Remanufacturing Phase

Remanufacturing [14].

Use Phase

Passenger vehicle fuel economy for 1977 and 2001 models [45].

Return Factor (Z) [36].

Lifetime mileage of tires [46].

Fuel embedded energy [45].

5.5.2 Heavy Duty Trucks

The data sources for each phase is as follows:

Raw materials processing Phase

Bill of materials and tire mass: [48]

For tire mass, we assume that radial and bias ply tires have equivalent masses (55 Kg) [48] while single-wide tires have a mass of 81 Kg [49].

Energy intensity values for each raw materials: [22], [20], [19], [23], [24].

Manufacturing Phase

We rely on the literature data to reveal the energy requirements for manufacturing a truck tire: Manufacturing: [19], [21].

Remanufacturing Phase

Energy requirements [15].

Use Phase

Truck Fuel Economy [45].
Fuel Heat Content [45].
Z [30]
Mileage [Argonne National Laboratory]
Coefficient of rolling resistance for bias ply, radial ply, advanced radial, and single-wide [40].

6. Results

6.1 Lifecycle Assessments for Light-duty Passenger Car Tires

Raw Materials Processing and Manufacturing Phase

A conventional passenger car tire is typically made of synthetic rubber, plastic rubber, carbon black, fabric-type materials, plasticizers and other additives. There are various numbers cited for the material compositions of tires in the literature. For example, Ferrer et al. breaks down the material composition of an 8 Kg passenger car tire into 21 % synthetic rubber (styrene-butadiene rubber), 21 % natural rubber, 23% carbon black, 13% steel, 12% rubber chemicals, 4% bead wire, and 5% rayon and nylon cords [14]. Lutsey et al. assesses the life cycle energy cost of a light duty vehicle tire that weighs about 9.1 Kg. The material composition of the functional unit analyzed consist of 26% synthetic rubber (styrene-butadiene rubber), 9% natural rubber, 33% carbon black, 2% silica, 15% steel, 10% plasticizers, and 5% fabric [22]. RMA provides information about tire weight and a breakdown of raw materials for light duty and heavy vehicles. More specifically, the tire represented by RMA weighs about 11 Kg and its embedded raw materials consist of 14% natural rubber, 27% synthetic rubber, 28% carbon black, 15% steel, and 16% fabric and fillers [48]. Figure 18 below illustrates the comparison between material compositions as stated in the above studies.

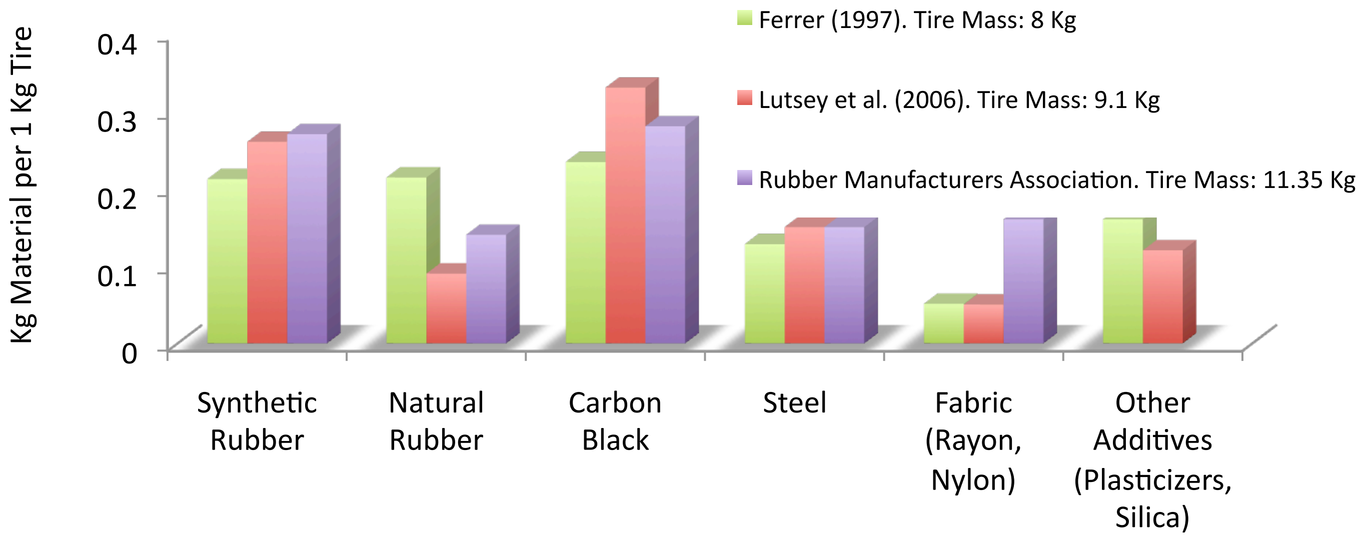


Figure 18. Raw Material Composition in Passenger Car Tire

We have used the raw materials composition provided by the Rubber Manufacturers Association (RMA) for determining passenger car tire raw materials processing and manufacturing energy. Table 14 below reveals the materials compositions of a passenger car tire, energy intensity, and total raw materials processing and manufacturing energy.

Table 14. Raw materials processing and manufacturing energy consumption: passenger car vehicle

Tire Material	Composition %	Energy Intensity (MJ/Kg Material)	Energy (MJ/Kg Tire)
Natural Rubber	14	9.3	1.3
Synthetic Rubber	27	119.8	32.3
Carbon Black	28	126.5	35.4
Steel	15	25	3.8
Plasticizers (Fillers)	5	42	2.1
Fabric (Rayon, Nylon, Polyester)	11	43.49	4.8
Average Mass (New) Kg	11.3	**Raw Materials Processing (MJ/Tire)**	**903.7**
		Manufacturing (11.7 MJ/Kg tire)	**132.7**
		Total (MJ/Tire)	**1036.4**

Therefore, for a set of four new passenger car tires, it would take about 4,145 MJ to extract the raw materials, process it, and manufacture the tires.

$$E_{\text{New Tire Raw Materials Processing and Manufacturing}} = 4{,}145 \text{ MJ per set of four tires}$$

We assume that energy values for raw materials processing and manufacturing of new tires have remained similar between 1977 and 2004.

Remanufacturing Phase

According to Ferrer et al. retreading a passenger car tire takes up 34% of the total energy required for producing a new tire. This translates to 352.4 MJ of energy required for remanufacturing a passenger car tire. Therefore, by retreading a passenger car tire, 684 MJ of the energy that is otherwise required for processing the raw materials and manufacturing a new tire is saved. Therefore, retreading a set of four used tires would require about 1,380 MJ, as shown below.

$$E_{\text{Tire Remanufacturing}} = 1{,}380 \text{ MJ per set of four tires}$$

We assume that energy values for tire remanufacturing have not changed between 1977 and 2004.

Use Phase

The objective of use-phase analysis, as expressed earlier, is to determine the relative energy savings potential of retreaded tires (produced 3 years prior) that has been restored to ‘like-new’ conditions compared to new tires (produced today).

Based on the data gathered by National Research Council, the average rolling resistance coefficients of replacement tires have remained steady between 1982 and 2005 (refer to Figure 12). Therefore, these values suggest that by restoring replacement tires to like-new conditions, on average, there is no additional energy expenditure in use-phase compared to new replacement tires (assuming no degradation in energy losses associated to overcoming tire rolling resistance).

For OEM passenger car tires, we perform the assessment by computing the relative changes in the vehicle fuel energy consumption of vehicle by choosing to purchase a set of four new tires as oppose to remanufacture and re-use the set of four old tires. To start, we compute the total fuel consumption of the 2001 vehicle. We take this to be the total fuel consumption of the vehicle with ‘like-new’ retreaded 2001 OEM tires ($C_{RR}^{o} = 0.0094$).

$$E_{T2001}^{o} = \frac{41{,}500 \text{ miles}}{28.8 \text{ miles per gallon}} .142 \, {}^{MJ}\!/_{\text{Gallon Fuel}} = 204{,}618 \text{ MJ/Vehicle}$$

Given C_{RR}^{o}, $C_{RR}^{'}$, and Z, to be 0.0094, 0.0089, and 0.15, respectively we can determine $E_{T}^{'}$ by using Equation 8.

$$E_{T2001}^{'} = 203{,}608 \text{ MJ/car}$$

This is the modified vehicle fuel energy consumption by utilizing a set of four new OEM tires produced in 2004 ($C_{RR}^{'} = 0.00899$).

We perform the calculation for a 1977 model vehicle that requires tire change in year 1980. The base case for vehicle fuel consumption is the decision to retread, bring to like-new, and re-use 1977 old OEM tires.

$$E_{T1977}^{o} = \frac{41{,}500 \text{ miles}}{15.8 \text{ miles per gallon}} .142 \, {}^{MJ}\!/_{\text{Gallon Fuel}} = 372{,}975 \text{ MJ/Vehicle}$$

Given C_{RR}^{o}, $C_{RR}^{'}$, and Z to be 0.0222, 0.01888, and 0.15, respectively, we determine the modified total fuel consumption, $E_{T}^{'}$ by using Equation 8,

$$E_{T1977}^{'} = 289{,}488 \text{ MJ/car}$$

Life Cycle Assessment

Results for Decision Analysis in Year 2004

According to the results, the vehicle's fuel energy requirements reduce on average by 1,339 MJ for the 41,500 miles of tires' lifetime. This reduction has been caused by utilizing a set of four new tires (2004 OEM tires) instead of remanufacturing and re-using a set of four 2001 OEM tires. Given the range of return factor (0.1 to 0.2), by choosing to use new tires in 2004, the vehicle owner saves around 0.5% to 1% in fuel energy consumption of the vehicle during the service lifetime of the tires.

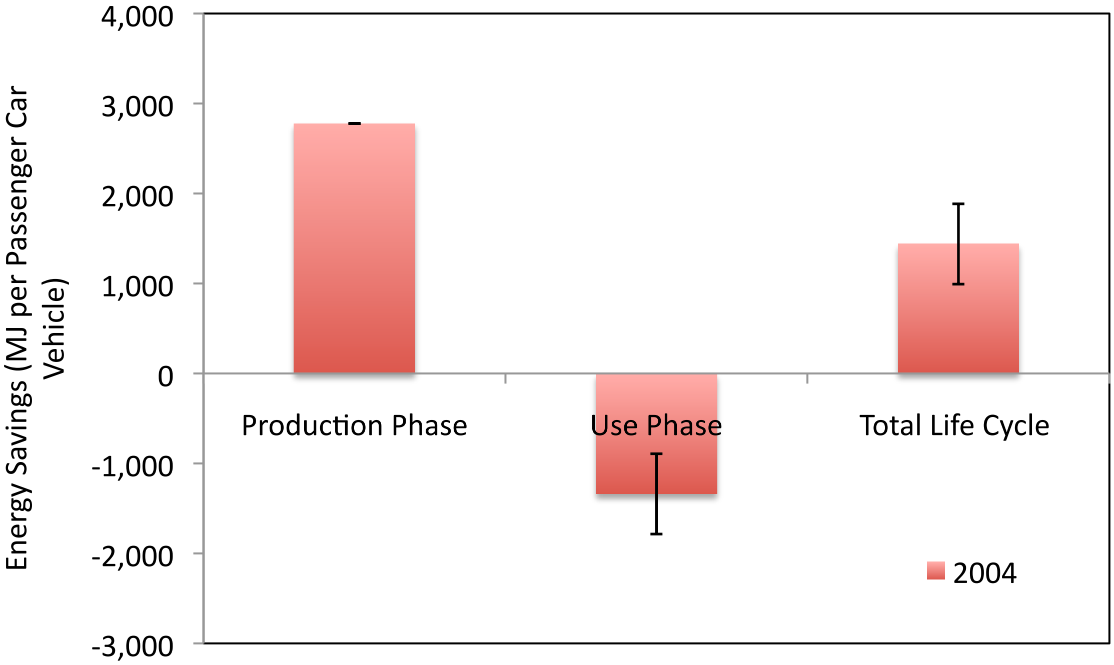


Figure 19 Lifecycle Energy Savings by Retreading and Re-using Old Passenger Car Tires. The Energy Comparison in This Figure is Between a Set of Four Retreaded 2001 OEM tires and a Set of Four New 2004 OEM Tires.

According to Figure 19 above, by remanufacturing and re-using a set of four passenger car tires in 2004 it saves about 2,777 MJ in production phase compared to a set of four new tires. Moreover, the retreaded tires expend on average about 1,339 MJ more in use phase than new tires. Therefore, the savings in the production phase dominates the over-expenditure in the use phase. As such, from a total life cycle perspective tire retreading saves on average 1,439 MJ per set of four tires in year 2004. The results conclude that improvements in tire rolling resistance coefficient for OEM tires between 2001 and 2004 have not been as substantial, hence making tire retreading an energy savings end of life option.

Results for Decision Analysis in Year 1980

By remanufacturing and re-using a set of four passenger car tires in 1980 it saves about 2,777 MJ in the production phase compared to a set of four new tires. In the use phase, the choice of utilizing a set of four new OEM tires (1980 models) instead of retreading and re-using old OEM tires (1977 models) saves the consumer on average 6,643 MJ. Given the range of return factor (0.1 to 0.2), by choosing to use new tires in 1980, the vehicle owner saves around 1.5% to 3% in fuel energy consumption of the vehicle during the service lifetime of the tires.

The energy over-expenditure of retreaded 1977 tires in the use phase cancels out the savings in the production phase. The analysis concludes that in year 1980, from a total life cycle perspective, retreading will cost on average 3,865 MJ more per set of four passenger car tires compared to purchasing new. Figure 20 below showcases the results for year 1980.

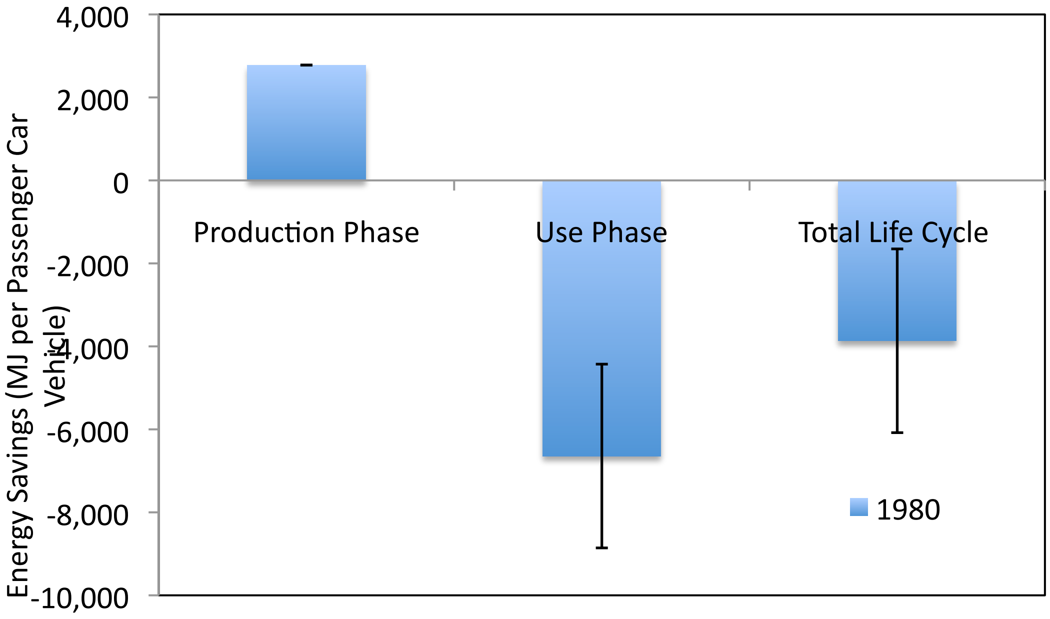


Figure 20 Lifecycle Energy Savings by Retreading and Re-using Old Passenger Car Tires. The Energy Comparison in This Figure is Between a Set of Four Retreaded 1977 OEM tires and a Set of Four New 1980 OEM Tires.

The figure below illustrates the retrospective lifecycle assessment for years 1980 and 2004 combined in a single plot.

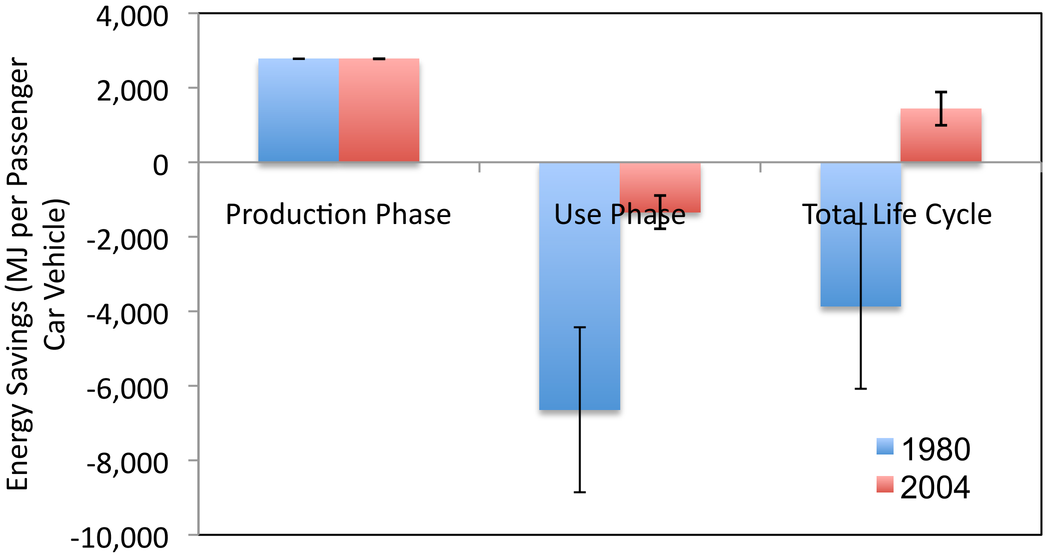


Figure 21 Lifecycle Energy Savings by Retreading and Re-using Old Passenger Car Tires. The Energy Comparison in This Figure is Between a Set of Four Retreaded 1977 (2001) OEM tires and a Set of Four New 1980 (2004) OEM Tires.

Conclusions for Tire Retreading Energy Savings Potential for Passenger Car Vehicles

- Given that coefficient of rolling resistances for replacement tires have remained similar on average since 1994 [36], we conclude on qualitative basis that replacement tire retreading is a potentially feasible energy savings end of life option [36].
- By retreading and remanufacturing old OEM tires instead of purchasing new it saves energy in production phase. Moreover, depending on the rate of enhancement of tire efficiency (i.e. coefficient of rolling resistance), retreaded tires may expend more energy in use phase than new tires.
- Retreading and re-using old OEM tires in year 2004 saves energy from a total lifecycle perspective.
- Retreading and re-using old OEM tires in year 1980 costs energy from a total lifecycle perspective.
- Given lesser energy savings by retreading in 1980, it illustrates that the pace of technology improvements in improving efficiency of tires between years 1975 and 1980 were much more substantial than in years 2001 to 2004. Furthermore, our analysis reflects upon the impact of the pace of technological changes and efficiency improvements on the energy savings potential of tire retreading.
- Conclusion remarks on the importance of considering transitional technological improvements in tires, and its impact on tire remanufacturing energy savings potential.
- The life cycle inventory analysis conveys that the use-phase energy consumption of the tire is a critical factor to take into account when evaluating the energy savings potential of tire retreading.

6.2 Heavy-Duty Truck Tire LCA

Raw Materials Processing and Manufacturing Phase

The material composition, specific energy of material, and total raw material and manufacturing energy consumption of a typical heavy-size truck tire is presented in Table 15 below.

Table 15. Material consumption and energy expenditure for raw material processing and manufacturing of a new heavy truck tire

Tire Material	Material Composition (%) [48]	Specific Energy (MJ/Kg Tire)	Total Raw Material Production Energy (MJ/Kg tire)	Percent of Total Energy (%)

Natural rubber [22]	27	9.3	2.5	3.8
Synthetic rubber [19], [20]	14	119.8	16.8	25.5
Carbon black [23]	28	126.5	35.4	53.8
Steel [24]	15	25	3.8	5.7
Fabric, fillers, accelerators, antioxidants [19]	16	43.5	7.4	11.2
Average Mass:	New 55 Kg			
			Total Raw Material Processing per Tire [MJ]:	3,622
			Manufacturing Energy Intensity [MJ/Kg] [19], [21]:	11.7
			Manufacturing per Tire [MJ]:	643.5
			Production Process Total per Tire [MJ]:	4,265

According to Table 15, it takes about 4,265 MJ of energy to process raw materials and manufacture a heavy-duty truck tire . As a result for a tractor-trailer combination heavy-duty truck, the total production energy consumption for a set of 18 tires would be 65,780 MJ.

Note that the above bill of materials is for a conventional radial tire that weighs about 55 Kg. We assume that bias ply and advanced radial tires have approximately similar material compositions and sizes. For single wide-base tire, we assume it has similar materials composition as radial tires. We determine the mass of a single wide-base tire to be on average around 81 Kg (50% heavier than a radial tire) [49]. Therefore the total raw materials processing and manufacturing for a single wide-base tire is estimated by multiplying the production energy requirements for a radial tire by 1.5. This makes the energy requirements for raw materials processing and manufacturing for a single wide base tire to be around 6,281 MJ/Tire.

The energy requirements for raw materials processing and manufacturing phase for the three decisions related to purchasing new tires are (refer to Figure 17),

$E_{\text{Raw Materials Processing and Manufacturing}}$ (decision 4) = 76,770 MJ/Truck
$E_{\text{Raw Materials Processing and Manufacturing}}$ (decision 5) = 76,770 MJ/Truck
$E_{\text{Raw Materials Processing and Manufacturing}}$ (decision 6) = 58,221 MJ/Truck

Note that the raw materials processing and manufacturing energy for decision 6 is less than decisions 4 or 5, because only 8 single wide-base tires is needed for drive and trailer axles as opposed to 16. Even though a single wide-base tires are heavier than a single radial tire, it is lighter than two conventional radial tires.

Remanufacturing Phase

The Tire Retread and Repair Information Bureau claims that a retreaded truck tire consumes 7 gallons of oil compared to production of new truck tire, which takes up 22 gallons of oil [15]. Therefore, we will assume that the remanufacturing (retreading) energy for truck tires is approximately 32% (7/22) of manufacturing energy consumption, or 1,365 MJ per conventional truck tire. Equivalently, the total energy requirements for remanufacturing 18 tires (for a truck) is as follows:

$$E_{\text{Remanufacturing}}(1, 2, 3) = 24{,}570 \text{ MJ/Truck}$$

This value is taken to be same for all three decisions related to utilizing remanufactured tires (refer to Figure 17).

Use Phase

The objective of the analysis for use-phase is to quantify the impact of technological changes on energy performance of truck tires. The evolution of truck tire advancements in this study is broken into three critical transformation steps [30]:

1. Transformation from Bias-Ply tires to Radial-Ply tires
2. Progression in Technological advancement and efficiency gains in Radial-Ply tires including low rolling resistance tires
3. Transformation from efficient radial tires to single-wide tires

We establish the base case for the use-phase to be for retread and re-use of old radial tires. Assuming, that the radial tires perform like-new, then the fuel economy of the truck will remain unchanged. Given 5.5 MPG truck fuel economy, 100,000 tire wear life, 146.34 MJ/gallon heat content of diesel fuel, we compute the total energy consumption of a heavy truck during the mileage lifetime of truck tires. Where E_T^o is the total energy consumption of the heavy truck with retreaded radial tires.

$$E_T^o = 18{,}182 \text{ gallons of fuel} = 2{,}654{,}545 \text{ MJ}$$

Considering an average return factor of 0.24, we compute the total rolling resistance losses for a heavy truck with retreaded radial tires to be,

$$E_{RR}^o = Z.E_T^o = 641{,}515 \text{ MJ per all tires on a truck}$$

This is taken as the average value for energy consumption of retreaded radial tires in the use phase (Decision 2/3 in Figure 17). Given that we assume new radial truck tires to be similar in performance to old radial truck tires, then the use phase energy for decision 4 would be equivalent to decision 2/3. In short, for decisions 2, 3, and 4 (Figure 17), the average use phase energy for all tires is taken as 641,515 MJ.

Given C^{o}_{RR}, C'$_{RR}$, and Z we can determine the relative energy for decision 1, 5, and 6.

$E^{'}_{RR}$ (decision 1) = 915,102 MJ per entire tires operating for a truck
$E^{'}_{RR}$(decision 5)=575,477 MJ per entire tires operating for a truck
$E^{'}_{RR}$(decision 6) = 509,439 MJ per entire tires operating for a truck

The average change in energy consumption for overcoming rolling resistance due to improvement in rolling resistance coefficient is presented in Table 16 and below:

Table 16. Use-phase energy requirements for truck tires

Tire Type	Coefficient of Rolling Resistance	% Change in Coefficient of Rolling Resistance	% Change in Vehicle Fuel Consumption	Total Energy Consumption (MJ)	Use Phase Energy Consumption: Total Tires (MJ)
Conventional Bias tires	0.0097	42.6%	10.31%	2928133	915,102
Radial tires	0.0068	0.0%	0.00%	2654545	641,515
Improved Radial tires (including Low Rolling Resistance tires)	0.0061	-10.3%	-2.49%	2588507	575,477
New Single-Wide Tire	0.0054	-20.6%	-4.98%	2522469	509,439

Life Cycle Assessment

Given the information above, the total lifecycle energy requirements for each consumer decision is plotted (refer to Figure 17). The plot reveals a range allotted for the results. This variation is due to performing the analysis by taking the range for the contribution of overcoming truck tires rolling resistance on truck fuel consumption (15 to 33% of total energy). Moreover, the average values, illustrate the case where overcoming truck tire rolling resistance consumes 24% of the truck fuel consumption. The lower-bounds and upper-bounds reveal rolling resistance losses to be 15% and 33%, respectively of total input fuel energy expenditure for truck.

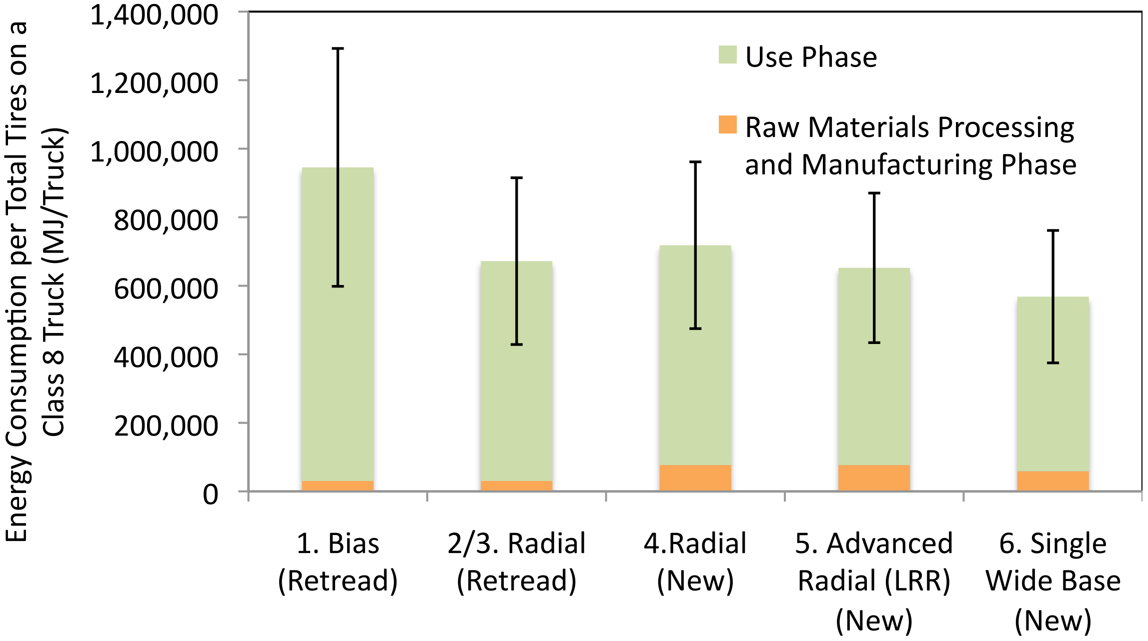


Figure 22. Life Cycle Assessment of Truck Tires Performing for a Tractor-Trailer (Class 8) Heavy Duty Vehicle. This Figure Illustrates Changes in Lifecycle Energy Consumption of Heavy Truck Tires Due to Technological Improvements in Tires.

Conclusions for Tire Retreading Energy Savings Potential for Heavy Trucks

According to Figure 22, the lifecycle energy consumption of truck tires is dominated by use phase. Based on the assumptions and data provided, the analysis concludes that a trucking fleet will save energy in production phase by retreading or purchasing retreaded truck tires. However, depending on the technology transitioning stages, the fleet will expend additional incremental energy in use phase by purchasing retreaded tires. Based on the decision-making options available (refer to Figure 17), the following conclusions can be made:

- Bias tire technology is the least efficient tire technology, and using remanufactured bias tires is not an effective energy savings options since it leads to the highest life cycle energy requirements compared to other options.
- Remanufacturing and re-using old radial tires compared to purchasing new radial tires leads to lifecycle energy savings. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis concludes that by challenging this assumption it makes the lifecycle energy savings to be nuanced between these two options.
- Remanufacturing and re-using old radial tires leads to negligible energy savings compared to the decision to purchase new low resistance radial tires. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis concludes that degradation in coefficient of rolling resistance due to retreading (7-9% increase in C_{RR}) makes utilizing low rolling resistance tire more favorable in terms of lifecycle energy savings.

- Replacing old radial tires with new single wide-base tires leads to lifecycle energy savings compared to remanufacturing and re-using old radial tires. More specifically, by utilizing new single wide base tires instead of retreading old radial tires, the lifecycle energy requirements would decline by 11.3 to 16%.

7. Sensitivity Analysis

7.1 Passenger Car Tires

Increase in Rolling Resistance Due to Remanufacturing

The core assessments for lifecycle assessment of passenger car tires are conducted by assuming that retreaded tires perform like-new. This is a biased assumption in favor of tire remanufacturing. Depending on the quality of retread, some retreaded tires may experience an increase in rolling resistance (reduction in efficiency). In relation to this, Continental et al. reveals a case where the rolling resistance coefficient of retreaded tires may increase by 3 to 10%. Similarly, we perform a sensitivity analysis for life cycle energy savings of retreading where by we assume three scenarios: (1) no degradation in coefficient of rolling resistance due to retreading (i.e. like-new), (2) 4% increase in coefficient of rolling resistance due to retreading, (3) 10% increase in coefficient of rolling resistance due to retreading. Figure 23 below reveals the results for all three scenarios.

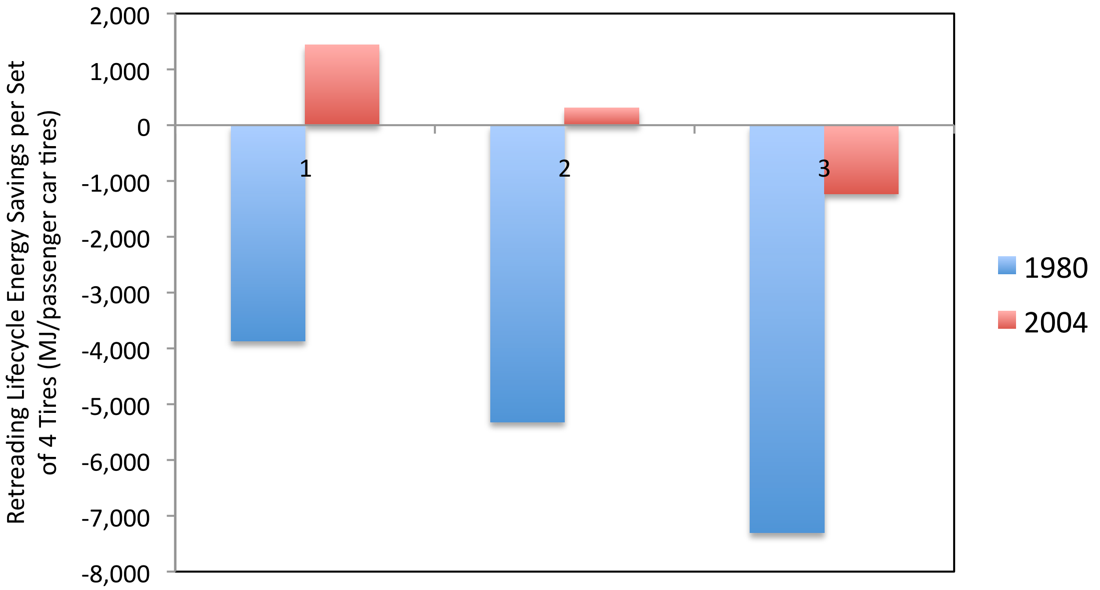


Figure 23 Sensitivity Analysis: Life cycle Energy Savings Potential of Passenger Car Retreading. 1. Retreaded tires that perform like-new.2. retreaded tires with increase in coefficient of rolling resistance of 4%. 3.retreaded tires with increase in coefficient of rolling resistance of 10%.

Scenario 1 in Figure 23 reveals the base case results where retreaded tires perform like-new for both year 1980 and year 2004 analysis (refer to Figure 22).

According to figure above, for year 2004 analysis, increase in coefficient of rolling resistance, can lead to retreading life cycle energy savings to be nuanced or even negative. For 1980 analysis, degradation in coefficient of rolling resistance will make the life cycle energy cost of retreading even more substantial.

Decrease in Mileage Lifetime due to Remanufacturing

The analysis in this report makes the assumption that retreaded tires can last as long as new tires. This assumption is biased in favor of tire remanufacturing. Tire Retread Industry Bureau (TRIB) reveals that a retreaded tire can last anywhere between 75% and 100% of the lifetime of an equivalent new tire [15].

In order to contest the assumption for this study, we conduct a sensitivity analysis by assuming that the retreaded tire lasts shorter than an equivalent new tire. As such, it has to be retreaded once more to last as long as a new tire. The objective of this sensitivity analysis is whether an extra retreading energy cost would change the conclusions.

By performing another retreading, the total energy cost for a retreaded tire doubles to 705 MJ per tire.

Table 17 OEM Passenger Car Tire Retreading Relative Energy Savings

	Production Phase (MJ/Vehicle)	Use Phase (MJ/Vehicle)	Total Life Cycle (MJ/Vehicle)
1980	1,409	-6,643	-5,233
2004	1,409	-1,339	71

According to Table 17 above, the sensitivity analysis reveals that if lifetime mileage of retreaded tires in year 2004 are degraded compared to new, then retreading lifecycle energy saving is nuanced. Given that energy savings is production phase is reduced, retreading old tires becomes even more energy expending in 1980.

7.2 Heavy-Duty Truck Tire

Change in Rolling Resistance of Retreaded Truck Tires

The above analysis was conducted assuming that for a particular tire model, the retreaded-version would have no degradation in rolling resistance in comparison to a reference new tire. A more realistic scenario would be to analyze new radial tires (i.e. advanced and single-wide) against retreaded radial tires by taking into account the potential degradations in efficiency performance of retreaded tires.

In general, there are two elements to retreading that has to be taken into account when talking about increases in rolling resistance of retreaded tires[I]:

1. Due to the deep penetration effect of the buffing stage in the retreading process, some base rubber has to be added back to increase the thickness of the under-tread. This will generate additional heat in the retreaded tire use phase, in turn increasing the rolling resistance coefficient of retreaded truck tires.

2. As a result, the retreading industry has been utilizing treads that are shallower in depth than new tire treads in order to compensate for the extra heat generated. This would result in reduction of rolling resistance and relatively reduced lifetime mileage at times.

Due to the combination of these two effects, on average the rolling resistance coefficient of a retreaded truck tire in comparison to a new truck tire would increase by 0.0004 to 0.0005[I].

Michelin assesses the energy consumption of Michelin retreaded tires based on a tire model XZA1+ drive tire, which has a rolling resistance coefficient of 0.0054. As mentioned above, Michelin energy analysis concludes that due to retreading, the rolling resistance coefficient would increase by 0.0004 to 0.0005 (7- 9 per cent increase in C_{RR}) [I].

If we consider 8% increase in rolling resistance coefficient of remanufactured radial truck tires, we will get the following changes in total energy consumption of tires:

Table 18 Increase in tire energy consumption due to increase in rolling resistance of retreaded tire

Scenario 1 (Lower Bound): Return Factor Z=0.15

	Performance Condition	Production (MJ/Truck)	Use (MJ/Truck)	Life Cycle Energy (MJ/Truck)
Radial (retread)	8% increase in C_{RR}	30,370	430,036	460,406
Radial (retread)	Like-New	30,370	398,182	428,552
Radial (new)	-	76,770	398,182	474,952

Scenario 2 (Upper Bound): Return Factor Z=0.33

		Production	Use (MJ/Truck)	Life Cycle

[I] Source: Michelin Center of Technologies, Research and Development, personal communication with Don Baldwin, July, 2009.

		(MJ/Truck)		Energy (MJ/Truck)
Radial (retread)	8% increase in C_{RR}	30,370	1,262,210	1,292,580
Radial (retread)	Like-New	30,370	884,848	915,218
Radial (new)	-	76,770	884,848	961,618

According to the sensitivity analysis, for the case where return factor is 15%, an 8% increase in C_{RR} can make the lifecycle energy savings of retreaded radial tires nuanced compared to purchasing new radial tires.

On the other hand, for the case where return factor is 33%, an 8% increase in C_{RR} makes retreading an energy-expending end of life option.

Tire Lifetime Usage Mileage

In the analysis, we assumed that retreaded truck tires last as long as new tires. In a personal communication with the Technology Specialist at Michelin's R&D, Mr. Baldwin, he mentioned that[I],

> "In the past the retreaded tire would travel considerably less number of miles (in some cases as great as 50 per cent reduction in usage mileage). However, with technological advances in retreading processes, improvement in tread compounding, and casing being designed for retreading, retreaded tires can currently achieve comparatively similar mileage as their new counterparts."

Michelin Center of Technologies, Research and Development, claims that retreaded Michelin truck tire model XDN2 under proper maintenance and driving conditions can achieve mileage life of 200,000 to 250,000 miles[I]. As such, our assumption that current retreaded truck tires in the market can travel the same mile as equivalent new tires for the similar category of tires is credible and representative of current retreaded truck tires.

Product Variation and Its Impact on Analysis of Life Cycle Energy Savings Potential of Tires

One major limitation of the analysis above is the average-based nature of the assumptions and data considered. In order to reflect upon the limitation of average-based approaches on modeling and analysis, it is important to consider ranges, probabilities, and sensitivity analysis. For example, it is wise to ask how the conclusion above would change if energy savings of a retreaded tire with high rolling resistance dual radial tire casing is compared with a new low rolling resistance wide-base tire? In relation to this, Michelin has a plot comparing the rolling

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[I] Source: Michelin Center of Technologies, Research and Development, personal communication with Don Baldwin, July, 2009.

resistance coefficient of dual radial tires to single wide radial tires (XONE) as well as retreaded tires [37].

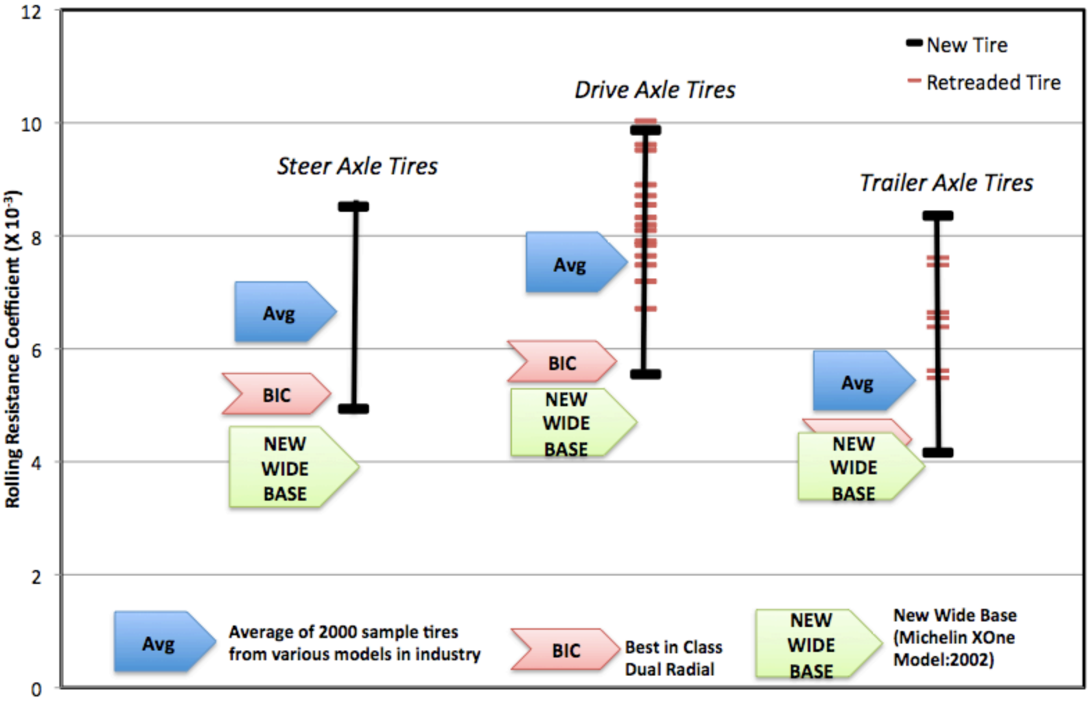

Figure 24. Tire Rolling Resistance Coefficient Ranges: Dual Radials and Wide-Base; New and Retread.The data for retreaded tire is most likely for Michelin tires only.

According to the same study, there is a difference between the rolling resistance coefficient of steer, drive, and trailer tires. This is partly due to the fact that, in reality, the weight of the truck is distributed unevenly between axles resulting in the following load distribution on tires [29]:

- Steer: 16% (8% per tire)
- Drive: 42% (5.25% per tire)
- Trailer: 42% (5.25% per tire)

The figure above depicts the rolling resistance coefficient of retread tires compared to the best-in-class (BIC) highly efficient dual radial tires, aggregated average tires, as well as single-wide base tires. On the other hand, the data shows that Michelin retreaded tires have rolling resistance coefficients that are within the industry range of rolling resistance coefficient for new tires. Therefore based on which tire casings are compared between new and retreaded tires, the conclusions for energy savings potential may alter.

According to Mike Wischhusen[I], Director of Industry Standards and Government Regulations at Michelin, one cannot find an industry-wide quantitative assessment of the performance of retreaded tires because of the complexity in the variables associated with producing a retreaded tires. In order to analyze the performance of retreaded tire, Wischhusen added, three distinct factors have to be analyzed:

1. Casing
2. Tread
3. Retreading Process

Moreover, Wischhusen states,

> “What makes quantitative assessment of retreaded tires daunting is the fact that there are 1000s of different casings, with dozens of tread material, with dozens to hundreds of different retreading processes (conventional as well as non-conventional). Also, the testing equipments add variation to the results as well. The combination of these factors makes the quantitative assessment of retreaded tires, from an industry standpoint, an ‘impossible task.’ This is why tire safety regulators do not make any comments in their report about the performance of retreaded tires [I].”

Therefore, in order to achieve concrete and insightful conclusions about the energy savings potential of tire retreading, it is important to compare the energy assessments based on similar casings, with similar characteristics, etc.

8. Conclusion and Discussions

Our assessments conclude that tire retreading, as an end of life option, can be both energy saving and energy expending. The conclusions for retreading energy savings strongly depend on the boundary conditions chosen for the analysis. If the analysis strictly focuses on the production process, then tire retreading is an energy savings end of life option. However, if the analysis takes into account use phase of tires, then tire retreading may or may not save energy from a total lifecycle perspective. Also, this case study evaluates energy savings potential of tire remanufacturing by analyzing it from four distinct scopes:

1. Transitional technological changes in tires.
2. Transformational technological changes in tires.
3. Degradation in performance due to retreading.
4. Tire casings variations and its corresponding impacts on conclusions for retreading energy savings potential.

If a retread tire exhibits more rolling resistance than a new tire, then it consumes more energy during its use phase. The increased consumption of energy in use phase can be more than offset by the savings attained in retreading process. In other words, the energy savings attained in

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[I] Source: Michelin Industry Standards and Government Regulations, personal communication with Mike Wischhusen, Director, July, 2009.

retreading process can be virtually canceled out by the higher petroleum (fuel) consumption in use phase.

Passenger Car Tires

Data suggest that since coefficient of rolling resistance for replacement tires has not improved substantially, then by retreading replacement tires, one can save energy in production phase.

For OEM tires, the analysis concludes that currently by retreading OEM tires, it would save energy. This is due to modest improvements in coefficient of rolling resistance of tires. Also, the sensitivity analysis shows how the conclusions drawn by average-based assessments could be nuanced if we consider degradation in performance of retreaded tires (between 4 to 10% increase in coefficient of rolling resistance).

Moreover, by performing the assessment retrospectively for OEM tires, we conclude that at times were pace of improvement in coefficient of rolling resistance were more aggressive (during 1975-1985) tire retreading was a net energy consuming end of life option. This retrospective assessment remarks on the impacts of macro-scale effects (i.e. pace of innovation in the tire industry, policies, mandates, market demand, etc.) on tire remanufacturing energy savings potential. For example, under President Obama's administration, the CAFE standards will increase by five percent each year, reaching 35.5 mpg by 2016. As shown in our retrospective assessments, changes in fuel standards can potentially cause OEM tires to enhance in efficiency at a faster rate. Perhaps if the pace of improvements is similar to those observed during 1975-1985, it could potentially make tire retreading a net energy expending option.

Heavy Truck Tires

A trucking fleet will save energy in production phase by retreading or purchasing retreaded truck tires. However, depending on the technology transitioning stages, the fleet will expend additional incremental energy in use phase by purchasing retreaded tires.

Based on the decision-making options available (refer to Figure 17), the following conclusions can be made:

- Bias tire technology is the least efficient tire technology, and using remanufactured bias tires is not an effective energy savings options since it leads to the highest life cycle energy requirements compared to other options.
- Remanufacturing and re-using old radial tires compared to purchasing new radial tires leads to lifecycle energy savings. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis concludes that by challenging this assumption it makes the lifecycle energy savings to be nuanced between these two options.
- Remanufacturing and re-using old radial tires leads to negligible energy savings compared to the decision to purchase new low resistance radial tires. This assessment is based on the assumption that retreaded tire would perform like-new. The sensitivity analysis concludes that degradation in coefficient of rolling resistance due to retreading (7-9% increase in C_{RR})

makes utilizing low rolling resistance tire more favorable in terms of lifecycle energy savings.

- Replacing old radial tires with new single wide-base tires leads to lifecycle energy savings compared to remanufacturing and re-using old radial tires. More specifically, by utilizing new single wide base tires instead of retreading old radial tires, the lifecycle energy requirements would decline by 11.3 to 16%.
- Figure 24 reveals the wide range of rolling resistances observed for both retreaded and new tires. In relation to this, we conclude that in order to draw insightful conclusions about tire remanufacturing energy savings potential the analysis should be conducted on a case-by-case basis. In other words, the conclusions on tire retreading energy savings can vary substantially depending on the types of casings compared between retread and new tires.

The assessments in this report conclude that tire retreading, as an end-of-life option, can be both energy saving and energy expending. The energy savings attribute of tire retreading strongly depends on the boundary conditions of the analysis. By considering only the manufacturing phase, retreading can be a very promising energy savings option. However, when taking use-phase into account, this case study concludes that there are a series of complex factors that is inter-related with the energy performance of tires in use-phase. We conclude that the evaluations for tire retreading and energy savings is more valuable and justified if conducted on a case-by-case basis.

9. Assumptions and Limitations

Though the intention is to be objective and concrete in evaluations, we acknowledge the limitations that stem from assumptions, data scarcity, and analysis approach. The following assumptions are made for the purpose of analysis that may be prone to scrutiny:

1. The use-phase energy consumption of tires was determined by utilizing return factor/energy ratio as opposed to experimental analysis.
2. The coefficient of rolling resistances stated in this report and in literature are determined in steady state laboratory settings; these are not necessarily similar to actual values for tires on the road.
3. The contribution of rolling resistance is equally distributed amongst tires. This may be true for passenger car tires, but it is not the case for truck-trailer combination tires.
4. The fuel economy of the vehicle is taken to be constant during the lifetime of the tire. In reality, the fuel economy of the vehicle changes considerably between different driving cycles. We have compensated for this by taking a range of return factor/energy ratio for contribution of rolling resistance to overall fuel consumption.
5. The experimental values produced by standardized procedures are prone to up to +/-20% in error due to the experimental setup and procedural errors.
6. The analysis above was conducted based on ideal and steady operational conditions. In reality, the change in rolling resistance is directly inter-related with other tire attributes such as wear, traction, inflation, temperature, driving behavior, speed, road effects.

7. The study assumes that tires operate with proper tire inflation pressure and constant vehicle load. Low tire inflation, as well as heavy vehicle load, can also affect vehicle fuel economy (CEC). Lower inflation pressure or heavier vehicle load leads to higher tire distortion, increased friction, and greater energy absorbed by the tires, hence reducing vehicle fuel efficiency. According to the Rubber Manufacturers' Association, when a tire is under-inflated by 1 pound per square inches (psi), the tire's rolling resistance increases by approximately 1.1%. Therefore, there are strong reasons for encouraging vehicle owners to maintain proper tire inflation pressure. This will not only lead to savings in fuel consumption, but may also contribute to longer tire lifetime and improvement in vehicle safety (CEC).
8. In the analysis for passenger car tires, we assume that raw materials processing and manufacturing energy consumptions are similar for tires produced between 1977 and 2004. In reality, raw materials processing and manufacturing steps may have become more efficient in the past few decades, making production energy expenditures less. However, due to data limitations we overlook the dynamic changes in energy demands for producing tires.
9. In the analysis for truck tires, we assume that bias ply, radial ply, advanced radial ply, and single wide-base tires to have similar materials compositions. This is a limitation given that the construction of each tire type is distinctly different from the rest. However, due to data limitations we overlook the variations in production energy costs.
10. In the analysis for truck tires, we assume that new radial truck tires have similar coefficient of rolling resistance than old retreaded tires. This assumption is true for cases where the fleet travels long-distances and has a high turnover rates for tires, hence, retreading used tires that are relatively up-to-date in terms of tire technology.
11. We perform the energy assessments for use phase on a relative basis. In other words, we consider a base case for the analysis, and modify it based on changes in coefficient of rolling resistance. This approach has considerable limitations because the absolute energy values are dependent on the choice of the base case. Therefore, the results are more credible when observing it in terms of relative changes in energy demands in use phase as opposed to observing it in absolute terms.

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Abbreviations

BTS	Bureau of Transportation Statistics
CEC	California Energy Commission
EIA	Energy Information Administration
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
RMA	Rubber Manufacturers Association
SAE	Society of Automobiles Engineers
TRIB	Tire Retread & Repair Information Bureau

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