Assessment of tire technologies and practices for tire wear and energy use reduction

Andrew Burke
University of California-Davis, Institute of Transportation Studies
afburke@ucdavis.edu

Marc Melaina
University of California-Davis, Institute of Transportation Studies
melaina@ucdavis.edu

Keywords

tires, rolling resistance, tire pressure, fuel economy, wear, nitrogen inflation

Abstract

Various aspects of the effects on tire usage and markets of new laws and regulations in the United States and California are analyzed and discussed. Special attention is given to the effects on tire rolling resistance and maintenance as they relate to vehicle fuel economy and tire wear. Detailed data are given on the rolling resistance of tires especially those classified as low rolling resistance tires with a rolling resistance coefficient (RRC) less than .008. Vehicle simulation results indicated that vehicle fuel economy will increase by 1.5 % for a 10 % reduction in RRC. Hence if the RRC is reduced from .01 to .008, a fuel economy increase of about 3 % would be expected. The price, RRC, and mileage life trade-offs are technology dependent and difficult to assess. Both rolling resistance and mileage life are critically dependent on tire maintenance especially proper tire inflation. It was found that a 6 psi under-inflation (about a 17 % deviation from the correct value of pressure) results in a 10 % increase in RRC which would result in a 1.5 % reduction in fuel economy for the vehicle. Tire pressure monitoring systems are available that display to the driver both the pressure and temperature of the tires on the vehicle and alert the driver if there is a problem with one or more of the tires. The use of these monitoring units should result in both safer and more efficient vehicle operation. Another approach that is being considered to improve tire performance and life is to utilize nitrogen inflation rather than air. Little meaningful data are available to evaluate with confidence the effect of nitrogen inflation on tire performance, especially tire pressure and temperature. An analysis of the properties of air and nitrogen as they relate to tires indicate that only the permeability of rubber varies significantly for the two inflation gases.

Introduction

The safe, efficient and environmentally friendly operation of vehicles is highly dependent on the proper selection and maintenance of the tires on the vehicles. In recent years both the State of California (California 2001) and the United States Federal government (United States 2000) have passed laws and/or issued regulations that significantly affect the tires that can be marketed and how the performance of the tires on the vehicle are to be monitored and disposed of after they have worn out. This paper is concerned with tires for light duty vehicles (passenger cars, vans, and light trucks) and how the new laws/regulations are likely to affect vehicle fuel economy and tire wear if new tire technologies such as tire pressure monitoring and nitrogen inflation are implemented and car owners/drivers are properly informed about tire maintenance.

It is widely recognized that there are trade-offs in the design of tires with respect to rolling resistance (fuel economy), safety (tire durability and vehicle handling), tire wear (mileage life), and cost. Measurements of tire performance in these areas are complex and expensive and the results difficult to relate to tire usage in the real world on vehicles of different types. Cost is always a key issue from the point-of-view of consumers when they initially purchase the vehicle and refuel it and replace the tires later in the vehicle's life. The situation becomes even more complex when one considers the disposal of the tires and the effect of tire rolling resistance on fuel usage (petroleum consumption) and greenhouse gas emissions.

In this paper, the various issues of vehicle efficiency (fuel economy), tire maintenance, and tire wear and discard are considered in detail along with the related cost to the consumer. Of particular interest is the advent of tire monitoring and possibly nitrogen inflation and the expected greater attention to tire maintenance. All issues have been investigated for California in a recent report (ITS 2006) prepared by the University of California-Davis, Institute of Transportation Studies for the California Integrated Waste Management Board (CIWMB). This paper is based in large part on the research done for the CIWMB study.

Vehicle and tire statistics in California

Vehicle statistics (Caltrans 2003) for California are shown in Table 1 starting in 2004 and projecting to 2025. It is possible to estimate from the vehicle statistics the volume of waste tires that would be generated in California for an assumed tire mileage life. It is often stated that the present mileage life of tires is about 40,000 miles. If this were the case, the volume of waste tires generated in California in 2004 would be about 27 million rather than the 39 million determined by the California Integrated Waste Management Board in CIWMB 2005. In reality, it appears the effective life of the average set of tires in California is only about 28,000 miles. This is consistent with the information given in CIWMB 2003 that less than 50 % of the tires replaced were discarded because the tread had been completely worn down. Most of the tires had been discarded because of uneven wear or other reasons. Tires are presently warranted by the manufacturers for 35,000-80,000 miles if the tire is properly maintained (exhibits even tread wear). Hence proper maintenance of tires, particularly inflation pressure, would result in a significant increase in tire life and a large reduction in the number of discarded tires each year. The vehicle statistics given in Table 1 indicate that the number of tires discarded per year in California could increase by 50 % by 2025 unless the tire mileage life is increased by improving the quality of tires and/or tire maintenance.

Effects of tire pressure and wheel alignment on rolling resistance and fuel economy

It is well known that under-inflation of the tires and wheel non-alignment result in higher rolling resistance (RRC). It is generally accepted (Kelly 2002) that RRC varies as the inverse of the square root of the tire pressure ($RRC = RRC_o\ (P/P_o)^{-.5}$). The increase in rolling resistance with under-inflation for a typical tire is shown in Table 2. The pressure shown is gage pressure-not absolute pressure. Based on Table 2, the rolling resistance increases by about 1.6 % for each psi of under-pressure.

The non-alignment of the tires can also increase the rolling resistance. According to Duleep 2005, the effect of toe-in alignment is a 1 % increase in RRC per 0.15 deg; the effect of the slip angle is larger being 5 % for 0.5 deg and 16 % for 1.0 deg slip of the tires.

The effect of rolling resistance on vehicle fuel economy can be estimated using vehicle simulation results. A series of vehicle simulations were run using the **Advisor** vehicle simulation program (Advisor 2002) developed at NREL. Simulations were run for compact and mid-size passenger cars and a mid-size SUV on the FUDS and FHW driving cycles. Calculations were made for RRC values between .006 and .013. The fuel economy results for the various values of RRC were normalized using the parameter Δ mpg/mpgo /Δ RRC/ RRCo based on the fuel economy for RRCo = .01. The results are given below in Table 3.

The sensitivity of fuel economy to changes in rolling resistance was found to vary only slightly with vehicle type. For most of the cases considered, the value of the normalized parameter also was only slightly different for increases in RRC as compared to decreases in RRC. The values shown in the table are for decreases in RRC between .01 and .006. The results given in Table 3 are close to those reported in Kelley 2002, NRC

Table 1: Projected vehicle/tire statistics for California (2004-2025)

Year	Number of Vehicles (106)*	Miles traveled per year (109)*	Miles/Year per vehicle (103)	Tire life (yr.) if mileage 40K**	Tires discarded per year (106)
2004	21.5	270.6	12.5	3.2	26.9
2005	21.8	270.8	12.6	3.17	27.5
2010	24.0	301.1	12.7	3.15	30.5
2015	26.3	339.6	13.1	3.05	34.5
2020	28.7	373.8	13.2	3.03	37.9
2025	30.9	406.2	13.4	2.99	41.3

* Vehicle/miles statistics from Caltrans (Reference 4)

** A mileage life of 40,000 miles is often assumed for tires in 2004

Table 2: Variation of RRC with tire pressure

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

Table 3: The effect of changes in rolling resistance on vehicle fuel economy for various types of vehicles

	Δ mpg/mpgo /Δ RRC/ RRCo	
Vehicle type	FUDS	FHW
Compact car CdA=.60 m2 wt=1295 kg	.097	.17
Mid-size car CdA=.645 m2 wt=1650 kg	.097	.18
Mid-size SUV CdA=1.09 m2 wt=2045 kg	.106	.16

2006 for decreases in the rolling resistance. Hence as rule of thumb, one can assume that a 10 % change in RRC will result in a 1 % change in fuel economy in city driving and a 1.8 % change in fuel economy in highway driving. For combined driving, a reasonable assumption is a 1.5 % change in fuel economy for a 10 % change in rolling resistance. Since it was found previously that 6 psi under-inflation in the tires results in a 10 % increase in rolling resistance, it follows that the 6 psi under-inflation will result in a 1.0 % and 1.8 % reduction in fuel economy for city and highway driving, respectively. The 6 psi under-inflation represents a 17 % deviation in tire pressure from a placard value of 35 psi.

Tire pressure monitoring approaches

In 2000, the United States Congress passed the Transportation Recall Enhancement, Accountability, and Documentation Act (TREAD) in response to tire safety problems on light-duty trucks and SUVs (United States 2000). As part of the implementation of that act, the National Highway Traffic Safety Administration (NHTSA) issued a ruling in December 2001 that after November 2003, all light-duty vehicles must have a dashboard light to warn drivers if their tire pressure was low. Multiple legal actions by industry and consumers challenging the ruling and how it would be implemented delayed its implementation until the 2008 model year (NHTSA 2005). Most of the 2008 models will detect the presence of low pressure tires by an indirect tire pressure monitoring system (TPMS) integrated with the anti-lock braking system (ABS) of the vehicle.

The indirect TPMS uses wheel speed sensors that are part of the ABS system and infers inflation levels from the differences in rotational speeds of the tires. This approach relies on training the TPMS to tire conditions that are assumed to be uniform. Unfortunately, the accuracy of this approach can be compromised by road conditions or uneven wear and has a poor ability to detect discrepancies in tires on different axles (Grygier 2001). In general, ABS systems have trouble detecting more than one tire with pressure loss, under inflation warning thresholds vary by axle and the detectable pressure threshold varies between 10-40 per cent of the cold inflation pressure level. Also, the vehicle's loading influences the pressure loss threshold for these systems and the time required to recognize a low tire pressure condition varies from one to 10 minutes, depending on the system and type of driving. This indirect approach meets the requirements of the NHTSA rule requiring the ability to detect a pressure that is 25 % (about 8 psi) or greater below the proper inflation pressure of the tire, but it does not give a direct, quantitative measurement of inflation pressure.

The approach taken in this paper is to relate the degree (absolute or fractional pressure changes) of under-pressure to changes in tire performance and mileage life. Projections have been made of the effects of reducing the average pressure defect markedly below the present values of 4-8 psi by direct tire pressure monitoring and consistent driver response to system warnings. Several direct tire pressure monitoring systems (TPMS) that range in complexity from screw-on valve stem indicators to integrated automatic inflation systems are available. The criteria for the system of choice were that it is robust and the output display be visible from the seated driver's position. Otherwise, it would be ignored by the driver and be ineffectual. It was decided that an aftermarket TPMS that measured the pressure and temperature of each tire and relayed it to a central receiver on the dash made the most sense.

Another important requirement for the TPMS is that it output a temperature compensated pressure, since vehicles could be operating in climatic conditions as extreme as Lake Tahoe and Death Valley. The gauge pressure in a tire varies 0.6 psi for each 10° F change in tire temperature. The potential error for pressure measurements from -20° F in Lake Tahoe to 110° F in Death Valley would be about 8 psi, an unacceptable variance. For this reason, the system offered by Smart Tire (Smartire) was selected for further study and installation in the California DGS fleet. Similar systems are manufactured by Beru, Dakota Digital, Schrader, and Bosch, but Smart Tire was the only one to offer an aftermarket option that performs temperature compensation to the pressure. In addition, Smart Tire was willing to provide support in adapting their system to our project needs, including data logging.

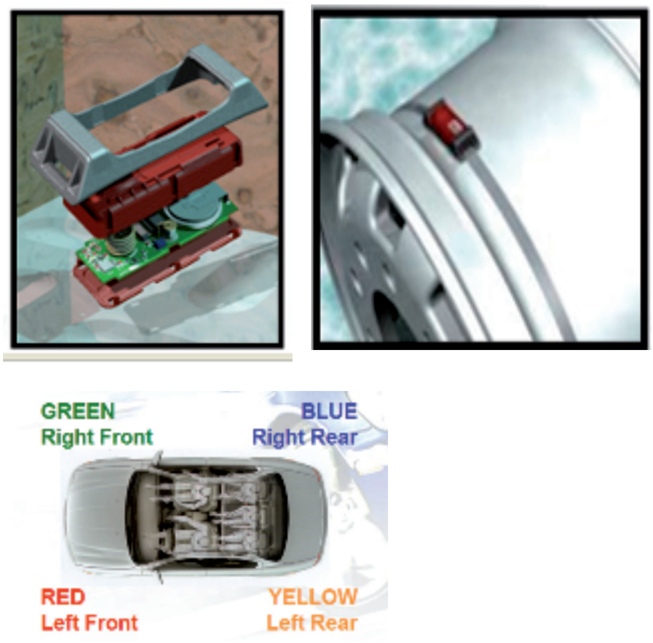


Figure 1: Tire pressure and temperature sensors and mounting positions of the Smart Car system

The Smart Car system shown in Figure 1 consists of a pressure and temperature sensor mounted in each wheel that communicates wirelessly with a receiver in the cab of the vehicle. The sensor utilizes solid state calibrated components and a proprietary battery design to achieve eight-year replacement intervals. The tire location of each sensor is uniquely identified through communications software with the receiver.

The sensors transmit data at an interval based on a random number generator to avoid confusion in the data stream. The interval varies from three to seven minutes. The transmission is comprised of 11 bytes and relays the state of pressure, temperature, time stamp, sensor ID number, sensor life span, battery voltage, counter, transmission interval, and packet count. Not all parameters are reported in each transmission. The number of states is given by the packet count variable.

There are two types of TPMS receivers used: a data receiver and a basic and functional display receivers. The data receiver, Figure 2, acquires the parameters from the sensors and encodes them into a digital RS-232 signal. This receiver can be mounted under the passenger seat. It can work in conjunction with the data acquisition system to record real time pressures and temperatures for all tires.

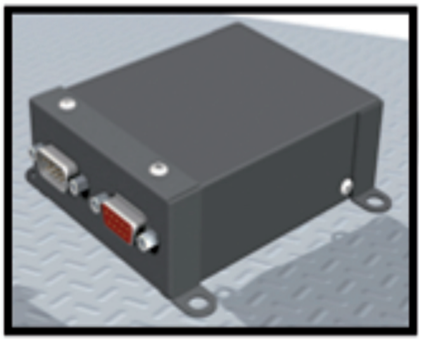


Figure 2: The data receiver

Figure 3: The basic and full-function display units

The basic display and the full function units available with the Smart Tire system are shown in Figure 3. All of the displays give an auditory alarm when pressure or temperature is outside of a specified range. The base display is a small plastic readout that is mounted within the view of the vehicle operator. Each tire is represented by an indicator light. If the pressure or temperature in any of the tires exceeds the preset limit, an indicator light will shine and an audible alarm will sound. In Figure 3, the light above the blue marker is indicating a pressure or temperature out of range on the right rear tire.

Another approach to tire monitoring is a passive tire pressure indicator like that shown in Figure 4. This device, which simply threads on to the valve stem in place of the cap, might be termed a "tire minder" as it indicates to the driver when the tire pressure falls below a set value. Devices can be purchased for set pressures between 26-40 psi. The driver could notice the color of the devices on the tires as they enter the vehicle. The device shows green when the pressure is at or above the set value and red when the pressure is less than the set value. These devices are low cost (less than $ 20 for a set of five) and have been found by personal experience to function very well giving the driver a good sense of security regarding their tires. With the tire minder type devices, tire maintenance should become easier and less time consuming as one knows when and where to add air to the tires. The devices themselves require no maintenance.

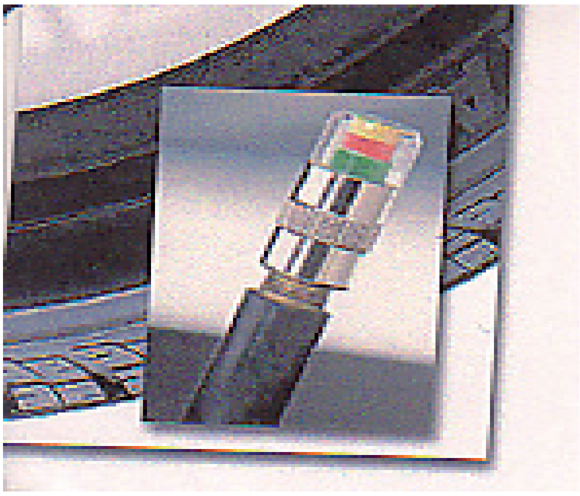


Figure 4: Passive tire pressure monitoring device

The need to monitor tire pressure can be eliminated by utilizing a self-inflating tire system. While there are systems available for high pressure tires and large trucks, only one was found for passenger vehicles. The "Auto-Pump" system manufactured by Cycloid has been used on some of the Jeep Grand Cherokee vehicles. This system utilizes a centrifugal pump mounted in the rim of each wheel to maintain tire pressure. It is unknown if this company is still in existence and whether this approach is applicable to the mass car market.

Tire technology assessments

LOW ROLLING RESISTANCE (LRR) TIRES

Low rolling resistance tires (LRR) are tires whose rolling resistance coefficient (RRC) is significantly less than the average of tires customarily installed on vehicles of the same type/class. In most cases, the designation as LRR is applied to replacement tires available for purchase by consumers. The OEM tires on new vehicles are selected by the auto manufacturers to meet their requirements for ride, handling, and fuel economy. In re-

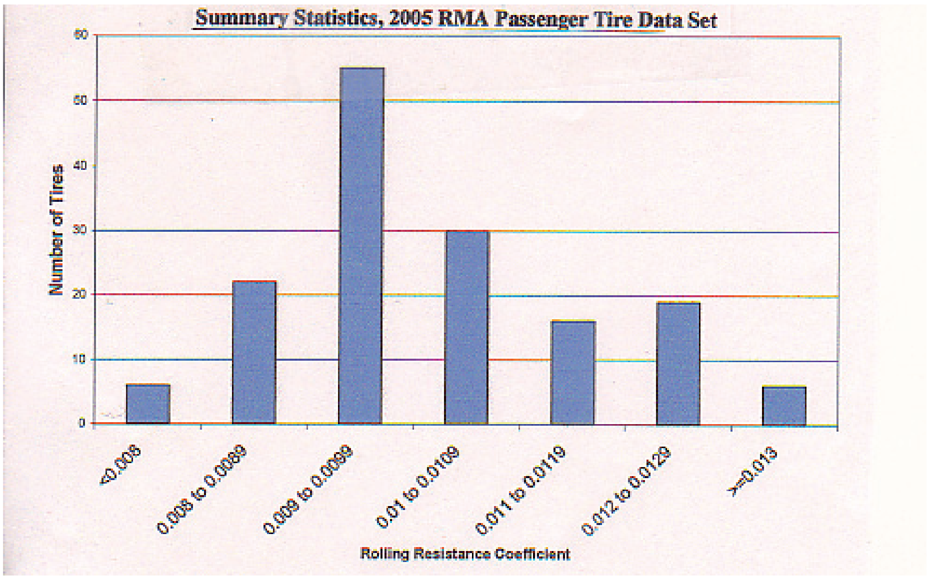
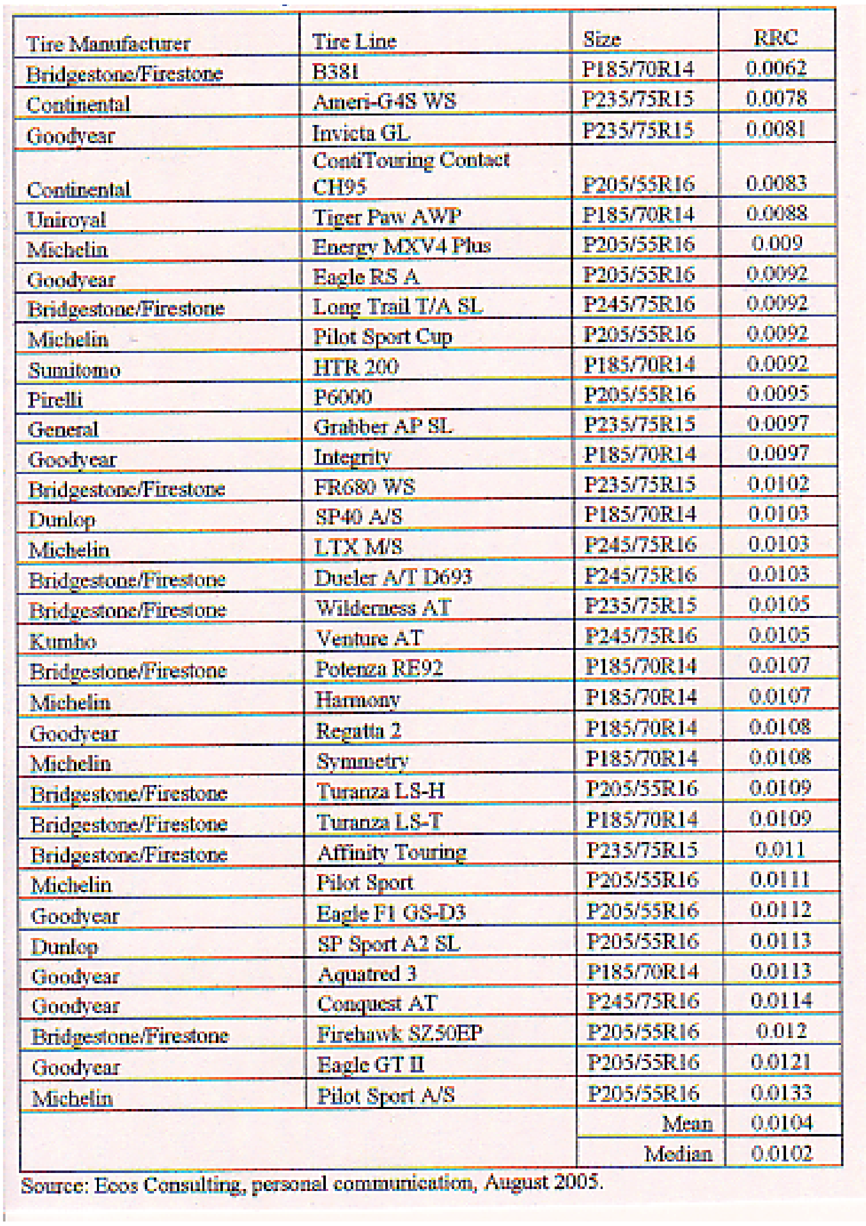


Figure 5: Distribution of the RRC for tires based on RMA data (NRC 2006)

Table 4: Rolling Resistance coefficients for new passenger car tires (NRC 2006)



Tire Manufacturer	Tire Line	Size	RRC
Bridgestone/Firestone	B381	P185/70R14	0.0062
Continental	Ameri-G4S WS	P235/75R15	0.0078
Goodyear	Invicta GL	P235/75R15	0.0081
Continental	ContiTouring Contact CH95	P205/55R16	0.0083
Uniroyal	Tiger Paw AWP	P185/70R14	0.0088
Michelin	Energy MXV4 Plus	P205/55R16	0.009
Goodyear	Eagle RS A	P205/55R16	0.0092
Bridgestone/Firestone	Long Trail T/A SL	P245/75R16	0.0092
Michelin	Pilot Sport Cup	P205/55R16	0.0092
Sumitomo	HTR 200	P185/70R14	0.0092
Pirelli	P6000	P205/55R16	0.0095
General	Grabber AP SL	P235/75R15	0.0097
Goodyear	Integrity	P185/70R14	0.0097
Bridgestone/Firestone	FR680 WS	P235/75R15	0.0102
Dunlop	SP40 A/S	P185/70R14	0.0103
Michelin	LTX M/S	P245/75R16	0.0103
Bridgestone/Firestone	Dueler A/T D693	P245/75R16	0.0103
Bridgestone/Firestone	Wilderness AT	P235/75R15	0.0105
Kumho	Venture AT	P245/75R16	0.0105
Bridgestone/Firestone	Potenza RE92	P185/70R14	0.0107
Michelin	Harmony	P185/70R14	0.0107
Goodyear	Regatta 2	P185/70R14	0.0108
Michelin	Symmetry	P185/70R14	0.0108
Bridgestone/Firestone	Turanza LS-H	P205/55R16	0.0109
Bridgestone/Firestone	Turanza LS-T	P185/70R14	0.0109
Bridgestone/Firestone	Affinity Touring	P235/75R15	0.011
Michelin	Pilot Sport	P205/55R16	0.0111
Goodyear	Eagle F1 GS-D3	P205/55R16	0.0112
Dunlop	SP Sport A2 SL	P205/55R16	0.0113
Goodyear	Aquatred 3	P185/70R14	0.0113
Goodyear	Conquest AT	P245/75R16	0.0114
Bridgestone/Firestone	Firehawk SZ50EP	P205/55R16	0.012
Goodyear	Eagle GT II	P205/55R16	0.0121
Michelin	Pilot Sport A/S	P205/55R16	0.0133
		Mean	0.0104
		Median	0.0102

Source: Ecos Consulting, personal communication, August 2005.

cent years, fuel economy has been an important issue for the auto manufacturers as they struggle to meet the CAFE standards. The RRC of the OEM tires are thought to be significantly lower (as much as 20 %) than those of the same size replacement tires for most passenger vehicles (CEC 2003). RRC values in the range .007-.009 were quoted by the auto manufacturers for new vehicle tires. If designation as LRR for a tire means that its RRC is significantly less than that of the tires on the vehicle when it was new, then LRR would require the tire to have a RRC in the range .006-.008. Only a small fraction of tires available would fall into this category. The required RRC for LRR would be less demanding if it is to be compared to that of the average replacement tire. In this case, tires equivalent in rolling resistance to those on new vehicles would qualify as LRR.

The major motivation to reduce the rolling resistance of tires has been to increase fuel economy. In 2001, the Legislature in California passed SB1170 (California 2001) directing the California Energy Commission (CEC) to make recommendations to increase the fuel economy of the state fleet by 10 % and for product labeling so consumers would purchase more LRR tires. The initial report (Reference 14) resulting from SB1170 was prepared for the CEC by TIAX Corp. The major conclusion of the report was that the use of low rolling resistance tires in California could increase average fuel economy and reduce fuel consumption by 3 %. This would require a reduction of about 20 % in the rolling resistance of replacement tires. The limited tire test data available for the TIAX study indicated that the rolling resistance coefficient of most of the tires was in the range .01-.011. Hence a 20 % reduction in rolling resistance would put the low rolling resistance tires in the range .0083 to .0092. Correlations of rolling resistance and other tire characteristics (traction, wear, price, etc.) did not show that decreasing rolling resistance adversely affected the other tire characteristics. The study concluded that fuel savings could pay for the additional cost of low rolling resistance tires in about one year and that it is not likely that the mileage life of the low rolling resistance tires would be significantly less than the tires presently being purchase and discarded. It was also concluded that maintaining proper inflation pressure in tires would reduce fuel consumption by about 1 % and improved tire maintenance should be encouraged in conjunction with the switch to low rolling resistance tires. The CEC initiated a tire program in 2003 to test both OEM and replacement tires, but the results of that program are not yet available.

In February 2005, the National Research Council (NRC) and NHTSA initiated a study of tires and vehicle fuel economy in response to a request from the U.S. Congress. The report (NRC 2006) resulting from that study was published in March 2006. Considerable tire rolling resistance data from the tire industry and the Rubber Manufacturer Association (RMA) were made available to the NRC Tire Committee, which improved the available information. Selected portions of that data are given in Table 4 and Figure 5. As a result, the situation regarding the rolling resistance of available tires is relatively clear. Based on the tires available in 2005, it is reasonable to classify tires with RRC less than .009 as LRR tires with the expectation that in the future that requirement could be reduced to .008 or even .007 if the tire industry is given time to develop and certify those tires. These LRR tires could reduce rolling resistance by 10-30 % and increase fuel economy by 1.5-4.5 % if the tires are assumed to be properly maintained.

NITROGEN INFLATION

There are many articles (Tiredealer 2005, Miller 2004) in the automotive literature discussing the advantages of nitrogen inflation for tires both for passenger cars and commercial trucks. Many claims are made concerning the differences between tire behavior on vehicles with air and nitrogen inflation. Unfortunately, there is very little data or quantitative information cited to substantiate the claims. Most of the information is anecdotal in character, being plausible and reasonable but not verifiable independently. Nitrogen inflation is commonly used in race car and aircraft tires. The primary reason that nitrogen is used in these applications is for safety. In the case of an accident, the gas escaping from the tires would tend to extinguish a fire and not provide oxygen for it. In this section, the claims for nitrogen inflation for passenger cars are reviewed and linked to the differences between the fundamental properties of air, nitrogen, and oxygen.

When inflating with nitrogen, the tires are filled with pure nitrogen which is essentially moisture free. One of the claims made for nitrogen inflation is that the nitrogen leaks from the tires much slower than air – up to six (6) times slower in high pressure truck tires. As a result, the tires remain near the proper inflation pressure for much longer periods of time and require much less attention from the vehicle owner. The consequences of maintaining more uniform tire pressure are improved fuel economy and reduced tire wear. A second claim ia that tire life is longer (up to 25 %) with nitrogen due to reduced oxidation of the tire inner liner and steel cords. The oxygen and water vapor in the air result in a gradual deterioration of the inner materials and seals of the tire leading to more rapid tire wear and in some instances tire failure. In addition, rust of the wheel rims is reduced. It is also claimed that tires inflated with nitrogen run cooler than tires inflated with air due to less heat being generated in the tires and the ability of the tire and nitrogen to absorb the heat with a smaller temperature rise. It should be possible to substantiate these claims by well planned and documented field tests, but that does not appear to have been done to date.

Selected fundamental properties of air, nitrogen, and oxygen are compared in Table 5. These properties are taken from Lange's Handbook of Chemistry, Edition 14. The properties listed are those most pertinent to the discussion of tire inflation. Note that except for the permeability in rubbers, the properties of the three gases are not very different especially when one considers that air is 78 % nitrogen by volume and molecular fraction.

It seems clear from Table 5 that the major difference between nitrogen and air is the permeability through rubbers. The permeability constant Pm is given as

Pm = amount permeated/ (area)* (time)*(pressure difference)

The values of Pm shown in the table are relative values and are presented to show the significantly higher permeability of oxygen compared to nitrogen. A detailed table for Pm is given in Section 10.68 of Lange's Handbook for various gases and rubber materials. Note also the very high permeability of water vapor through rubbers which would add to the potential for normal air leakage in air inflated tires. Since the leakage of air

Table 5: Selected properties of Air, Nitrogen, and Oxygen

Property	Air	Nitrogen	Oxygen
Molecular weight	29	28	32
Composition	78 % N_2 , 22 % O_2	100 % N_2	100 % O_2
Molecular diameter (nm)	----	.315	.292
Specific heat (kJ/kg ^{o}K)	1.007	1.039	.919
Heat conductivity (mW/m ^{0}K)	26.2	26.0	26.3
Gas permeability thru rubbers	*---	9.43	23.3

* permeability coefficient of water vapor is 2290

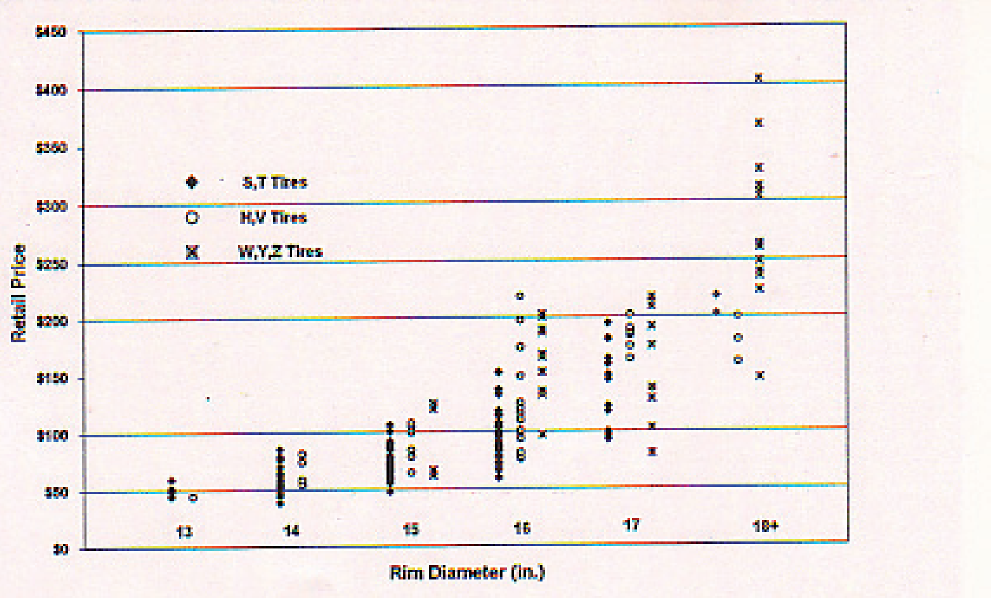


Figure 6: Retail prices by rim diameter and speed rating (NRC 2006)

is proportional to pressure and the surface area of the tire, the effects of permeation leakage would be greater for large, high pressure truck tires than for passenger car tires.

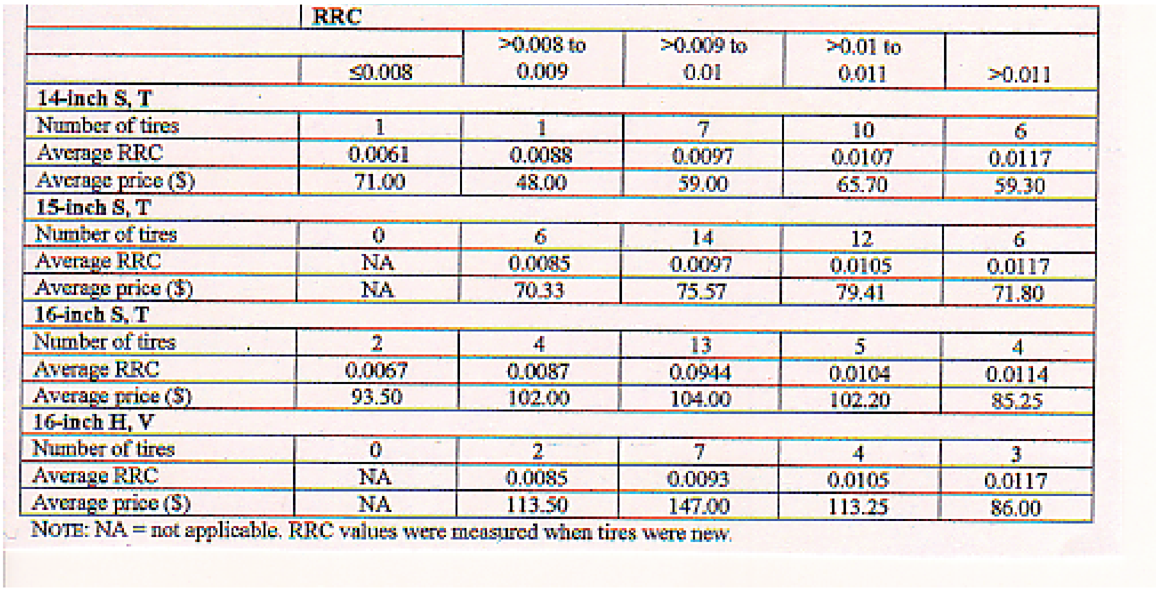
The previous discussions indicate that the key potential advantage of nitrogen inflation is the lower permeability of the nitrogen through rubbers and the absence of oxygen and water vapor in the nitrogen. The water vapor enhances the oxidation and rust due to the presence of the oxygen and likely adds to the leakage characteristic of the air. It appears that the thermal properties of the air and nitrogen are not sufficiently different to affect the temperature of the tires on the road. The nitrogen inflated tires could run cooler due to the reduced loss of air and as result, less generation of heat. It is difficult to estimate quantitatively the improvement in fuel economy, tire wear and mileage life that could result from the use of nitrogen inflation. The magnitudes of the improvements certainly depend on the attention given to tire maintenance using air. However, without verifiable test data, it is difficult to explain or accept the large improvements claimed in the literature for nitrogen inflation.

Cost and tire characteristics trade-offs

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

Information on tire characteristics including price is readily available on the web for most of the tire manufacturers. Many of the large tire dealers have web-sites that list the tires available by size, characteristics, and price using the USDOT rating designations. If rolling resistance was included in the ratings,

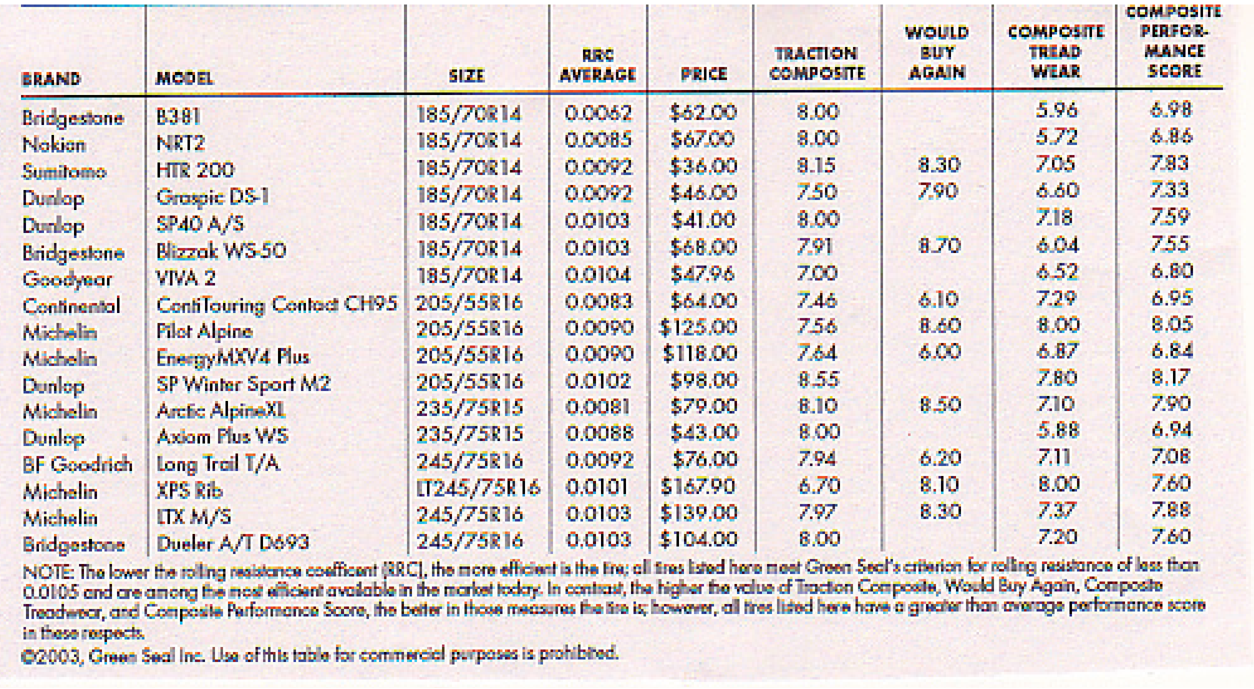
Table 6: Average tire prices by RRC distribution for groupings of tires having the same rim size and speed rating (NRC 2006)



	RRC				
	≤0.008	>0.008 to 0.009	>0.009 to 0.01	>0.01 to 0.011	>0.011
14-inch S, T					
Number of tires	1	1	7	10	6
Average RRC	0.0061	0.0088	0.0097	0.0107	0.0117
Average price ($)	71.00	48.00	59.00	65.70	59.30
15-inch S, T					
Number of tires	0	6	14	12	6
Average RRC	NA	0.0085	0.0097	0.0105	0.0117
Average price ($)	NA	70.33	75.57	79.41	71.80
16-inch S, T					
Number of tires	2	4	13	5	4
Average RRC	0.0067	0.0087	0.0944	0.0104	0.0114
Average price ($)	93.50	102.00	104.00	102.20	85.25
16-inch H, V					
Number of tires	0	2	7	4	3
Average RRC	NA	0.0085	0.0093	0.0105	0.0117
Average price ($)	NA	113.50	147.00	113.25	86.00

NOTE: NA = not applicable. RRC values were measured when tires were new.

Table 7: Characteristics and cost for selected low rolling resistance tires (Greenseal 2006)



BRAND	MODEL	SIZE	RRC AVERAGE	PRICE	TRACTION COMPOSITE	WOULD BUY AGAIN	COMPOSITE TREAD WEAR	COMPOSITE PERFORMANCE SCORE
Bridgestone	B381	185/70R14	0.0062	$62.00	8.00		5.96	6.98
Nokian	NRT2	185/70R14	0.0085	$67.00	8.00		5.72	6.86
Sumitomo	HTR 200	185/70R14	0.0092	$36.00	8.15	8.30	7.05	7.83
Dunlop	Graspic DS-1	185/70R14	0.0092	$46.00	7.50	7.90	6.60	7.33
Dunlop	SP40 A/S	185/70R14	0.0103	$41.00	8.00		7.18	7.59
Bridgestone	Blizzak WS-50	185/70R14	0.0103	$68.00	7.91	8.70	6.04	7.55
Goodyear	VIVA 2	185/70R14	0.0104	$47.96	7.00		6.52	6.80
Continental	ContiTouring Contact CH95	205/55R16	0.0083	$64.00	7.46	6.10	7.29	6.95
Michelin	Pilot Alpine	205/55R16	0.0090	$125.00	7.56	8.60	8.00	8.05
Michelin	EnergyMXV4 Plus	205/55R16	0.0090	$118.00	7.64	6.00	6.87	6.84
Dunlop	SP Winter Sport M2	205/55R16	0.0102	$98.00	8.55		7.80	8.17
Michelin	Arctic AlpineXL	235/75R15	0.0081	$79.00	8.10	8.50	7.10	7.90
Dunlop	Axiom Plus WS	235/75R15	0.0088	$43.00	8.00		5.88	6.94
BF Goodrich	Long Trail T/A	245/75R16	0.0092	$76.00	7.94	6.20	7.11	7.08
Michelin	XPS Rib	LT245/75R16	0.0101	$167.90	6.70	8.10	8.00	7.60
Michelin	LTX M/S	245/75R16	0.0103	$139.00	7.97	8.30	7.37	7.88
Bridgestone	Dueler A/T D693	245/75R16	0.0103	$104.00	8.00		7.20	7.60

NOTE: The lower the rolling resistance coefficent (RRC), the more efficient is the tire; all tires listed here meet Green Seal's criterion for rolling resistance of less than 0.0105 and are among the most efficient available in the market today. In contrast, the higher the value of Traction Composite, Would Buy Again, Composite Treadwear, and Composite Performance Score, the better in those measures the tire is; however, all tires listed here have a greater than average performance score in these respects.

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it would be rather straightforward to make the traction, wear, rolling resistance, and price trade-offs that would be appropriate. Researching the tire lists on the web, it soon becomes apparent that any trade-offs must be done for a fixed tire size and manufacturer as each manufacturer seems to have a "price niche". In general, the tire price increases as the size (rim diameter and tread width) increases (see Figure 6). In addition, tires with higher speed and traction ratings are more expensive. Except for tires with very low wear rating (< 300) and high wear rating (> 600), there does not seem to be a strong correlation between wear rating and price. Other rating and marketing factors seem to be more important in the mid-range of wear rating. The manufacturer's mileage warranty for these tires is 40,000 to 60,000 miles. In most cases, tires in the low range of wear rating have no mileage warranty indicated and tires in the high wear range are warranted for 70,000 to 90,000 miles. These high mileage tires are usually significantly more expensive than other tires. Cost/performance trade-offs were considered in some detail in the recent report of the NRC (NRC 2006). A key issue was the trade-off between rolling resistance, wear, and tire price. One of the key findings of that study is summarized in Table 6.

Based on the information in the table, the NRC Tire Committee concluded that there was no clear correlation between rolling resistance and price when size and speed ratings were fixed.

Table 6 does not address the question of the influence of tire wear on the trade-off between rolling resistance and price. The NRC Tire Committee discusses this trade-off, but does not reach any firm conclusion. There are clearly approaches (for example, reduce the tread thickness) to lower the rolling resistance and price, but that also reduces the tire mileage life. A more promising approach is to improve the tire design and/or tread compounds so that rolling resistance can be lowered without compromising tire wear. The data shown in Table 7 indicate that some tires on the market exhibit both low rolling resistance and good tire life. This is especially true for 16" rim tires for which low aspect ratio (55) tires are available. Such designs seem to favor low rolling resistance. Since the wear rating of most tires sold are in the range 400-600 and those tires have mileage warranties of 40,000-60,000 miles, it seems likely that a reduction of at least 10 % in rolling resistance (RRC) can be achieved without reducing tire life. This would reduce RRC from about .01 to .009 in replacement tires. Future developments on tread compounding could lead to further reductions to .008 or .007 without compromises in mileage life and significant increases in price. If the tire labeling would include a rolling resistance designation, there would be competition between tire manufacturers in that area and improvements in rolling resistance would likely follow. Rolling resistance labeling would also result in the development of a standard test procedure and a large increase in the availability of rolling resistance data.

Summary and conclusions

Various aspects of the effects on tire useage and markets of new laws and regulations in the United States and California are analyzed and discussed. Special attention is given to the effects on tire rolling resistance and maintenance as they relate to vehicle fuel economy and tire wear. Detailed data are given on the rolling resistance of tires especially those classified as low rolling resistance tires with a rolling resistance coefficient (RRC) less than .008. Vehicle simulation results indicated that vehicle fuel economy will increase by 1.5 % for a 10 % reduction in RRC. Hence if the RRC is reduced from .01 to .008, a fuel economy increase of about 3 % would be expected. Available tire price information indicates that there is no clear relationship between rolling resistance and price for fixed size and tire rating. The price, RRC, and mileage life trade-offs are technology dependent and difficult to assess. Both rolling resistance and mileage life are critically dependent on tire maintenance especially proper tire inflation. It was found that a 6 psi underinflation (about a 17 % deviation from the correct value of pressure) results in a 10 % increase in RRC which would result in a 1.5 % reduction in fuel economy for the vehicle. Relatively low cost tire pressure monitoring systems are available that display to the driver both the pressure and temperature of the tires on the vehicle and alert the driver if there is a problem with one or more of the tires. The use of these monitoring units should result in both safer and more efficient vehicle operation. Another approach that is being considered to improve tire performance and life is to utilize nitrogen inflation rather than air. Little meaningful data are available to evaluate with confidence the effect of nitrogen inflation on tire performance, especially tire pressure and temperature. An analysis of the properties of air and nitrogen as they relate to tires indicate that only the permeability of rubber varies significantly for the two inflation gases.

References

Advisor 2002, **Advisor** (Advanced Vehicle Simulator)**, Version 2002,** developed by the National Renewable energy Laboratory (NREL)

California 2001, Legislation, Senate Bill 1170, 2001 mandating California State Fuel-Efficient Tire Program no later than January 31, 2003

Caltrans 2003, california motor vehicle stock, travel, and fuel forecast report, Caltrans, Division of Transportation Systems Information, November 2003

CEC 2003, California State Fuel-Efficient Tire Report: Volume II, California Energy Commission Report 600-03-001, January 2003

CIWMB 2005, California Waste Tire Generation, Markets, and Disposal: Staff report, California Integrated Waste Management Board (CIWMB) Publication # 620-05-007, June 2005

CIWMB 2003, Weissman, S.L. and Sackman, J.L., Extending the Lifespan of Tires: Final Report, Prepared for the California Integrated Waste Management Board, July 2003

DOTire, United States Department of Transportation (DOT) passenger car tire rating terminology, www.tireguides.com

Duleep 2005, Duleep, K.G., Tires, technologies, and energy consumption, presentation to the NRC Tire Committee in Davis, California, March 2005

Greenseal 2006, Rolling Resistance Report, accessed May 8, 2006, www.green seal.org

Grygier 2001, Grygier, P., etals., An Evaluation of Existing Tire Pressure Monitoring Systems, National Highway Traffic Safety Administration Report DOT 809 297, July 2001

ITS 2006, Assessment of tire technologies and practices for potential waste and energy use reduction, report prepard for the California Integrated Waste Management Board

Kelly 2002, Kelly, K.J., Modeling tools for predicting the impact of rolling resistance on energy usage and fuel economy for realistic driving cycles, International Tire Exhibition and Conference-2002, Paper No. 31C

Miller 2004, Miller, C., Pump up the use of nitrogen to help deflate fleet expenses, Aftermarket Business, www.findarticles.com , July 2004.

NHTSA 2005, National Highway Traffic Safety Administration (NHTSA), Department of Transportation, Final Rule, TREAD Act, 49 CFR Part 571, published February 2005, Effective June 1, 2007

NRC 2006 Tires and passenger vehicle fuel economy, National Research Council (NRC), Transportation Research Board Report No. 286, 2006

Smartire, Web page for Smart Tire Systems, Inc., www.smartire.com

Tiredealer 2005, Manges, M., More than a passing fad: tire dealers pump up bottom lines with nitrogen inflation, Modern Tire Dealer, www.moderntiredealer.com, August 2005

United States 2000, Congress passed the Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act in August 2000, Final Rule March 2005