

NHTSA TIRE ROLLING RESISTANCE TEST DEVELOPMENT PROJECT – PHASE 2

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ABSTRACT

In December 2007, the United States Congress enacted the Energy Independence and Security Act (EISA) that mandated the USDOT-NHTSA to establish a national tire fuel efficiency rating system for motor vehicle replacement tires. The rolling resistance of each tire results in an energy loss for the vehicle and thus affects the vehicle's overall fuel economy. However, improvements in one aspect of tire performance, such as rolling resistance, may lead to reductions in other performance aspects, such as traction and treadwear.

As part of the development of the tire fuel efficiency rating system, NHTSA initiated two phases of research. The Phase 1 research focused on identifying the best rolling resistance test method for use in a rating system, with results being published in a full agency report and summarized in a paper at ESV 2009 (09-0300). The Phase 2 research examined possible correlations between tire rolling resistance levels and vehicle fuel economy, wet and dry traction, outdoor and indoor treadwear, and tread rubber properties. The Phase 2 results were published in a full agency report and are summarized in this paper.

Overall, the Phase 2 results indicate statistically significant improvements in vehicle fuel economy when using low rolling resistance tires and proper inflation pressure, with no expected impact on tire dry traction or treadwear rate. However, the tire models tested exhibited a strong and significant relationship between better rolling resistance and poorer wet slide friction. The wet peak friction displayed the same tendency, but the relationship was much weaker. An analysis of tire tread rubber compounds indicated that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

INTRODUCTION

Rolling resistance is defined as the “*loss of energy (or energy consumed) per unit of distance traveled.*” [1] Approximately 80 to 95 percent of this loss is attributed to viscoelastic behavior of tire rubber compounds as they cyclically deform during the rotation process. Rolling resistance is reported in units of force (RRF), or as a coefficient when normalized to the applied normal load (RRC). In vehicle and powertrain dynamics, it is included as a force at the tire/surface contact area opposing the direction of vehicle motion. This simplifies the analysis of energy loss and the derivations of the equations of motion, and should not be understood as a loss at the contact surface such as Coulomb friction. Since vehicle fuel consumption calculations require tire inputs in units of energy, rolling resistance is reported in Newton-meter/meter (reduced to Newtons) in this paper rather than as the dimensionless rolling resistance coefficient.

The National Academy of Sciences (NAS), Transportation Research Board report of April 2006 concluded that a 10% reduction of average rolling resistance of replacement passenger vehicle tires in the United States was technically and economically feasible within a decade, and that such a reduction would increase the fuel economy of passenger vehicles by 1 to 2%, saving about 1 to 2 billion gallons of fuel per year.[2] The NAS report suggests that safety consequences from this 10% improvement in tire rolling resistance “were probably undetectable.” However, the committee’s analysis of grades under the Uniform Tire Quality Grading Standards (UTQGS) (FMVSS No. 575.104) for tires in their study indicated that there was difficulty in achieving the highest wet traction and/or treadwear grades while achieving the lowest rolling resistance coefficients. This was more noticeable when the sample of tires was constrained to similar designs (*i.e.*, similar speed ratings and diameters).

The NAS committee also concluded that the effects of improvements in rolling resistance on tire wear life and the waste tire stream were difficult to estimate because of the various means by which rolling resistance can be reduced (e.g., initial tread depth, tire dimensions, tread compounding, tread pattern, etc.). However, due to the importance U.S. motorists place on long wear life, as reflected by the emphasis on mileage warranties in tire marketing, the committee deemed it improbable that tire manufacturers would sacrifice wear life to any major degree.

One of the primary recommendations of the NAS committee in their report was that:

“Congress (US) should authorize and make sufficient resources available to NHTSA to allow it to gather and report information on the influence of individual passenger tires on vehicle fuel consumption.”

In anticipation of possible congressional legislation, NHTSA began a large-scale research project to select a rolling resistance test procedure that would be best for a regulation, and to examine correlations between tire rolling resistance levels and tire safety performance. The first phase of the project evaluated five test procedures from SAE or ISO, two of which were single-point tests (a single set of test conditions) and three of which were multi-point tests (measured over a range of conditions). The variability of the rolling resistance results from lab to lab, machine to machine, and for multiple tests on the same tire was compared.

The five tests studied were all capable of providing data to accurately assess the rolling resistance of the tires surveyed. The variability of all tests was low, with coefficients of variation below 2 percent. The rank order grouping of tire types was statistically the same for each of the rolling resistance test methods evaluated. However, the analysis showed that there was a significant offset between the data generated by the two labs that is not consistent between tests, or even between tire types within the same test in some cases. Therefore, a rating system must institute a methodology to account for the lab-to-lab variation.

It was concluded that while multi-point rolling resistance test methods are necessary to characterize the response of a tire’s rolling resistance over a range of loads, pressures, and/or speeds, either of the two shorter and less expensive single-point test methods were deemed sufficient for the purpose of simply assessing and rating individual tires in a common

system. The draft single-point ISO 28580 method had the advantage of using defined lab alignment tires to allow comparison of data between labs on a standardized basis. The use of other test methods would require extensive evaluation and definition of a method to allow direct comparison of results generated in different laboratories, or even on different machines in the same laboratory. The Phase 1 research results were published in a full agency report (DOT HS 811 119) [3] and summarized in a paper at ESV 2009 (09-0300).[4]

In December 2007, the United States Congress enacted the Energy Independence and Security Act (EISA) that mandated the USDOT-NHTSA to establish a national tire fuel efficiency consumer information program to educate consumers about the effects of tires on automobile fuel efficiency, safety, and durability.[5] The program was to include:

“A national tire fuel efficiency rating system for motor vehicle replacement tires to assist consumers in making more educated tire purchasing decisions;

Requirements for providing information to consumers, including information at the point of sale and other potential information dissemination methods, including the Internet;

Specifications for test methods for manufacturers to use in assessing and rating tires to avoid variation among test equipment and manufacturers; and

A national tire maintenance consumer education program including, information on tire inflation pressure, alignment, rotation, and tread wear to maximize fuel efficiency, safety, and durability of replacement tires.”

Tire fuel efficiency is assessed by measuring the rolling resistance of each tire. The level of rolling resistance measured represents an energy loss for the vehicle during operation, and thus affects the vehicle’s overall fuel economy. Lower rolling resistance therefore contributes to improved vehicle fuel economy. However, improvements in one aspect of tire performance, such as rolling resistance, may lead to reductions in other performance aspects. This tendency is normally expressed in the tire industry as the “Magic Triangle” as shown in Figure 1. Any improvement in one of the vertices’ properties of rolling resistance, wet traction, or treadwear may cause a decrease in performance for one or both of the remaining properties.

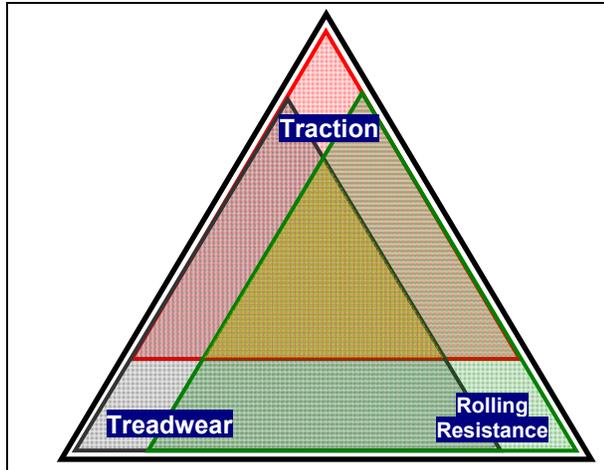


Figure 1. “Magic Triangle” Illustration of Tire Performance Tradeoffs.

In order to understand the possible effects of the EISA requirements on tire performance, the agency conducted a second phase of the project to examine possible correlations between tire rolling resistance levels and vehicle fuel economy, wet and dry traction, outdoor and indoor treadwear, and tread-rubber properties. The specific questions that Phase 2 research was structured to explore were:

1. How sensitive is the overall fuel economy of a typical passenger vehicle to changes in tire rolling resistance and inflation pressure?
2. Do current low-rolling-resistance production tires exhibit any tradeoffs in wet or dry traction?
3. Do the properties of the tread rubber compound affect tire rolling resistance, traction, or treadwear performance?
4. Do current low-rolling-resistance production tires exhibit any tradeoffs in initial tread depth or treadwear rate?

The results were published in a full agency report (DOT HS 811 154) [6] and are summarized in this paper.

EXPERIMENTAL METHODOLOGY

Fifteen passenger tire models that were previously measured for rolling resistance in Phase I of this work, along with the tires that were original equipment on the fuel economy test vehicle, were used in this work. As described in the ESV 2009 paper, [4] the tires were selected to represent a cross-section of manufacturers and performance levels of all-season tires, as well as summer, winter, and run-

flat type tires. The tires are described in detail in Table 8 in the Appendix. Because of cost and time constraints for the project, not every test could be conducted on every tire. Table 8 also shows which tests were completed for each tire model.

Rolling Resistance

The rolling resistance for each tire was measured using the conditions of the then draft ISO 28580 test procedure, which was later finalized in equivalent form as ISO 28580:2009(E) *Passenger car, truck and bus tyres – Methods of measuring rolling resistance – Single point test and correlation of measurement results*. The conditions of 80% of maximum tire rated load, 80 km/h (49.7 mph), and 210 kPa (30.5 psi) inflation for standard load tires, or 250 kPa (36.3 psi) for extra load tires are a reasonable approximation of average on-vehicle tire service conditions.

On-Vehicle Dynamometer Fuel Economy

The effects of tire rolling resistance on automobile fuel efficiency were evaluated by installing fifteen different tire models on a new 2008 Chevrolet Impala LS using the 2008 five-cycle EPA fuel economy test.[7] This procedure measures fuel consumption under simulated conditions of city and highway driving, and adds a highway driving cycle which includes higher speeds and harder acceleration, a city cycle with air conditioning use, and a city cycle at cold (-7°C or 20°F) conditions. A summary of the five-cycle test conditions is given in Table 9.

Testing was completed under contract by the Transportation Research Center Inc.'s emissions laboratory. The test apparatus and vehicle are shown in Figure 2.



Figure 2. Vehicle on Fuel Economy Dynamometer.

Since tire inflation pressure affects the operational rolling resistance of a tire, the vehicle fuel economy measurements were conducted at two different tire inflation pressures. All 15 tire models were tested at the vehicle placard pressure of 210 kPa (30 psi). Six models were re-tested at 158 kPa (23 psi), which represents the Tire Pressure Monitoring System (TPMS) activation threshold of 25% inflation pressure reduction. It is important to note that these tests were research and not official EPA fuel economy ratings of the test vehicle. The many tire sets and repeats of test for statistical analysis/dual inflation pressure resulted in the new test vehicle acquiring nearly 6,000 miles by the end of testing. The EPA estimates that new vehicles will not obtain their optimal fuel economy until the engine has broken in at around 3-5 thousand miles.[7] Therefore the fuel economy of the test vehicle was expected to improve slightly during the course of testing, a factor that was tracked and accounted for by the repeated testing of the control and original equipment (OE) tires at regular intervals throughout the testing.

In order to minimize the mileage accumulated on the vehicle, as well as the limitations of time and budget for the project, it was not possible to run a separate coast-down measurement for each set of tires prior to the dynamometer testing. This measurement is used to correct the dynamometer force for the effects of the rolling resistance of the non-driven wheels as well as to correct for inertia and aerodynamic effects. Thereby all vehicle tests were conducted using the dynamometer input for the original equipment tires on the Impala. Coast-down measurements were run for a second set of tires with a significantly higher rolling resistance and equations were developed to correct the fuel economy for these effects.

Skid Trailer Traction Testing

UTQGS Wet Traction FMVSS No. 575.104, *Uniform tire quality grading standards* (UTQGS) requires manufacturers to provide a (wet slide) traction grade for all tires subject to the standard and manufactured after April 1, 1980. Per UTQGS literature:

“Traction grades are an indication of a tire’s ability to stop on wet pavement. A higher graded tire should allow a car to stop on wet roads in a shorter distance than a tire with a lower grade. Traction is graded from highest to lowest as “AA”, “A”, “B”, and “C”. ”[8]

The UTQGS skid-trailer traction testing for the project was performed at the NHTSA test facility on Goodfellow Air Force Base in San Angelo, Texas. The traction grading tests are now performed on a purpose-built oval at the base rather than the original test surface diagram shown in 575.104. The test pavements are asphalt and concrete skid pads constructed in accordance with industry specifications for skid surfaces. ASTM E501 [9] reference (control) tires are used to monitor the traction coefficient of the two surfaces (which varies based on environmental conditions, surface wear, etc.). During a normal wet traction test, a vehicle tows a skid-trailer, shown in Figure 3, at 40 mph across the test surfaces. Water is dispersed ahead of the tire from a water nozzle just before the brake is applied. Instrumentation measures the horizontal force as the brake is applied to one wheel of the trailer until lock-up, and then held for a few seconds and released. The tests are repeated for a total of 10 measurements on each surface. The candidate test tires are conditioned by running for 200 miles on a pavement surface. The candidate tires are then fitted to the trailer, loaded to a specified load and pressure, then subjected to the same testing completed on the control tires. The average sliding coefficient of friction for the candidate tire on each surface is corrected using the coefficients of the control tire to yield an adjusted traction coefficient for the candidate tire on each test surface.



Figure 3. NHTSA San Angelo Skid Trailer.

Phase 2 traction tests were conducted with tires of 16 different models. Two tires had the highest traction grade “AA”, and 14 tires were graded “A”. Since these tires experienced some break-in during the 50 to 70 mile rolling resistance tests, these tires were only conditioned for 70 miles on a pavement surface rather than the normal 200 miles. Since the tires were previously tested for rolling resistance, and had a

reduced break-in, the results generated are for research purposes and are unofficial.

Peak Friction Measurement of Traction The San Angelo trailer is instrumented to provide continuous monitoring of the traction and slip during the test procedure. Since modern anti-lock braking systems (ABS) and electronic stability control (ESC) systems operate in the lower slip and higher friction region, the peak coefficient recorded during the traction testing was also used for comparisons in Phase 2 in addition to the traditional slide values used for UTQGS wet traction.

Dry Traction Measurement The San Angelo skid trailer was also used to repeat the test matrix on dry asphalt and concrete test surfaces. Both the peak and sliding coefficient of friction was recorded. However, the number of measurements on the dry surfaces was reduced to five in order to preserve the limited test surface area from rubber buildup.

On-Vehicle Treadwear Testing

FMVSS No. 575.104, *Uniform tire quality grading standards* (UTQGS) requires manufacturers to provide a treadwear grade for all tires subject to the standard and manufactured after April 1, 1980. Per UTQGS literature:

“Treadwear grades are an indication of a tire's relative wear rate. The higher the treadwear number is, the longer it should take for the tread to wear down. A control tire is assigned a grade of 100. Other tires are compared to the control tire. For example, a tire grade of 200 should wear twice as long as the control tire.”[8]

Additional tires from five models were tested in the UTQGS treadwear test. The five tire models, with treadwear grades ranging from 300 to 700, were mounted and balanced on 16 x 7.0" rims. The groove depths of the tires were then measured. The tires were then installed on five Mercury Marquis vehicles for testing on the UTQG test route near San Angelo, Texas. The vehicles were loaded to 1182 pounds per wheel within +/-1 percent. The vehicles were aligned to center of manufacturer's specifications for caster, camber, and toe.

Indoor Treadwear Testing

Advances in radial tire tread compounding since 1980 have resulting in longer life treads that exhibit only a marginal amount of wear after running the

7,200-mile UTQGS treadwear course. To evaluate the effects of bulk treadwear on tire rolling resistance, additional tires of the five tire models subjected to on-vehicle treadwear, as well as the original equipment tires from the Impala fuel economy vehicle, were subjected to a more aggressive indoor treadwear test developed by Smithers Scientific in Ravenna, Ohio.

The testing was completed on an MTS 860 Durability Machine (Figure 4) 3.048-meter (120-inch) diameter drum covered with 3M 180 μ film with servo hydraulic control of tire radial load, tire slip angle and/or slip load, tire camber angle, roadway speed, and braking torque. A powder spray system is used to prevent rubber buildup on the drum 3M surface. The machine was programmed with a drive file that allows for consistent application of energy. The machine was run in force control so that the amount of energy input to the tire/wheel assembly was consistent between test specimens.



Figure 4. MTS 860 Durability Machine.

Two test methods were conducted: one was a 25% Fz (radial load) test and the other was a 20% Fz test. Two tires of each of the six tire models were tested using the 25% test. One each tire model was tested using the less demanding 20% test. The tires were of two load indexes and therefore tested using two different load and force levels to match the rolling resistance load differences. Table 1 lists these test conditions for two of the tested models.

Table 1. Indoor Wear Test Parameters

Tire Model Code	G12	G8
Radial Load (80% max)	5,725 N	5,882 N
Camber Angle	0°	0°
Speed	80 km/h	80 km/h
Inflation Pressure	210 kPa	210 kPa
25% Fy (Lateral) Amplitude	1,431 N	1,471 N
20% Fy (Lateral) Amplitude	1,145 N	1,176 N

A frictional work or work rate approach was conducted in which the side force was the controlled parameter and was varied throughout the wear test. The 25% Fz test consisted of 1,641 lateral force cycles. The input cycle was a sine wave of the following form, where Fz is the radial load and t is the time in seconds:

$$F_y = (25 \% F_z) \sin \left(\frac{1}{15} \pi t \right) \quad (1)$$

A similar cycle was used for the 20% Fz profile. Data that were collected as part of the wear testing were tire/wheel assembly weight, and laser profilometry using a precision scale and a Bytewise CTWIST machine. The CTWIST machine collects 4,096 data points per tire revolution every millimeter across the tire. The data were collected at the new or pre-test point, at the half way point, and at the end of the test. This allows for wear rate to be evaluated. After the final wear cycle the tires were again weighed and measured for rolling resistance in their final state.

Tread Rubber Property Analysis

The tread rubber of the 15 tire models was analyzed for the type of polymer, the fillers and extender, and for dynamic mechanical properties using a variety of analytical procedures. The analysis is outside the scope of this report and was reported in the full DOT report.[6]

RESULTS AND DISCUSSION

Dynamometer Fuel Consumption Testing

Table 2 shows the results of the analysis of variance for the various fuel economy tests studied. The fuel consumption measured during each EPA cycle was modeled as a linear function of tire rolling resistance. The tires ranged in rolling resistance from approximately 40 to 65 N. It should be noted that although rolling resistance is actually an energy loss measured in N-m/m, the meter terms are customarily cancelled.

Table 2. Analysis of Variance for Change in Vehicle Fuel Economy versus Change in Tire Rolling Resistance

Highway FET	64.4	0.0001	0.764	+0.0142	0.0001
City FTP	48.5	0.0001	0.651	+0.0310	0.0001
High Speed US06	48.6	0.0001	0.511	+0.0292	0.0001
Air Conditioning SC03	16.0	0.0005	0.597	+0.0228	0.0005
Cold City FTP	45.7	0.0001	0.420	+0.0273	0.0001

The highway (HWFET) drive cycle was sequentially repeated three times for each tire model inflation pressure combination to provide a measure of repeatability. In addition, the ASTM F2493 Standard Reference tire (SRTT) was run periodically throughout the procedure to verify consistency of the test procedure and apparatus over time. The following analysis was conducted on the verified values, which include some retests to account for anomalous data. The raw data is available in the complete DOT report. The F values are significant indicating that the overall trend toward lower fuel economy with increasing tire rolling resistance is statistically significant. Values in the column “Probability > |t|” that are less than 0.05 indicate that tire rolling resistance has a significant effect on estimated fuel economy of the vehicle. Increases in fuel consumption range from 0.014 to 0.031 L/100 km for each Newton of increased tire rolling resistance.

The average fuel economy for each of the drive cycle tests versus the tire rolling resistance is shown in Figure 5 to Figure 9. The trend toward increased fuel consumption as tire rolling resistance increases is clearly evident for each of the EPA drive cycles.

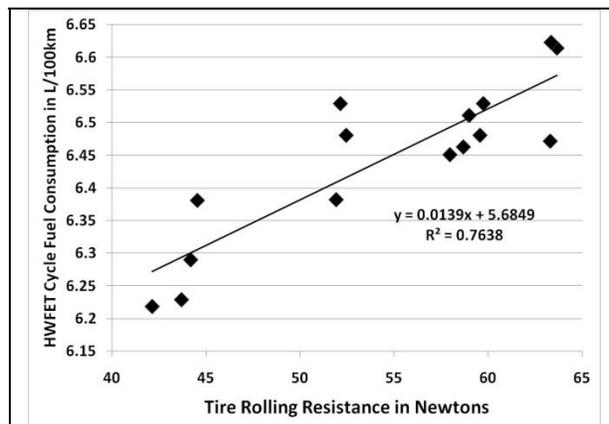


Figure 5. Highway Cycle (FET) Fuel Consumption versus Tire Rolling Resistance.

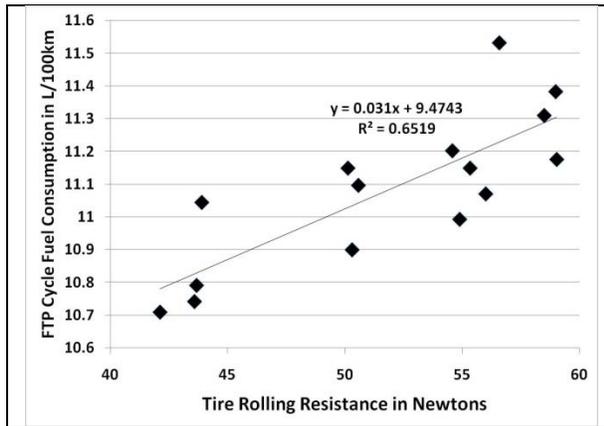


Figure 8. Air Conditioning Cycle (SC03) Fuel Consumption versus Tire Rolling Resistance.

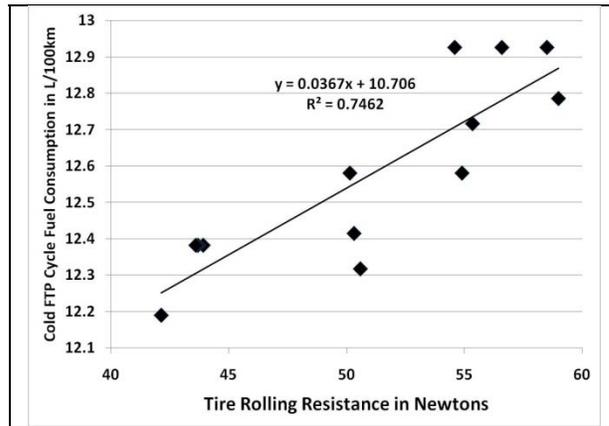


Figure 6. City Cycle (FTP) Fuel Consumption versus Tire Rolling Resistance.

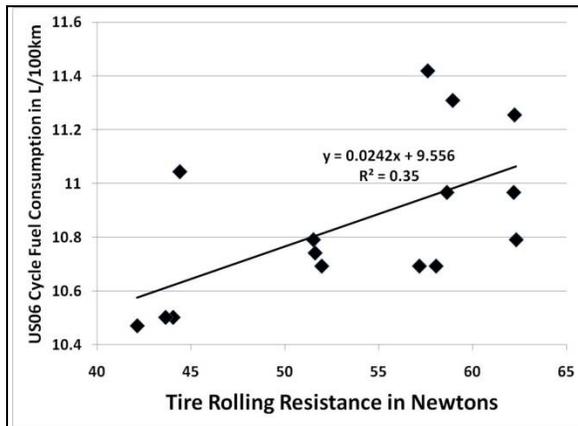


Figure 9. Cold City (FTP) Cycle Fuel Consumption versus Tire Rolling Resistance.

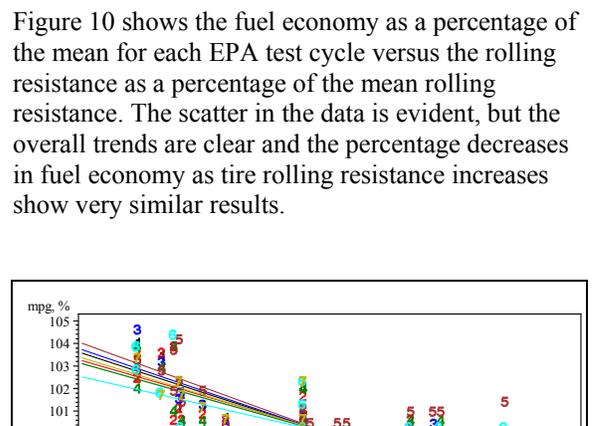


Figure 7. High Speed Cycle (US06) Fuel Consumption versus Tire Rolling Resistance.

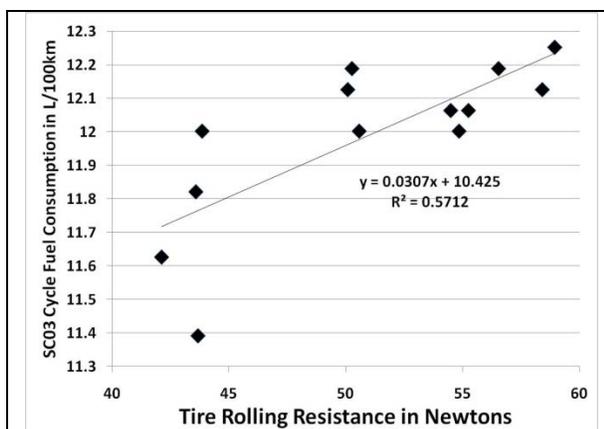


Figure 10 shows the fuel economy as a percentage of the mean for each EPA test cycle versus the rolling resistance as a percentage of the mean rolling resistance. The scatter in the data is evident, but the overall trends are clear and the percentage decreases in fuel economy as tire rolling resistance increases show very similar results.

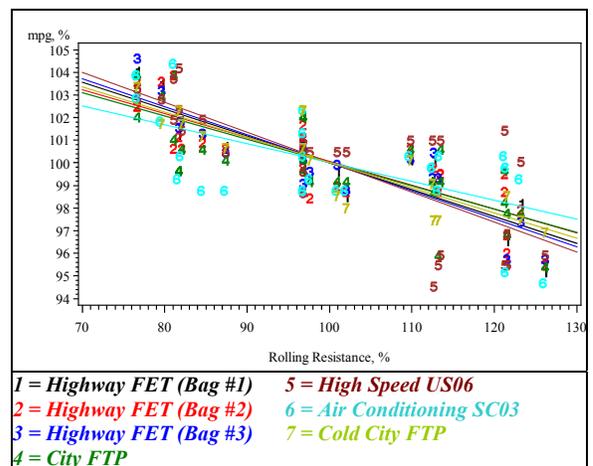


Figure 10. Normalized Fuel Economy versus Tire Rolling Resistance.

Table 3 shows the regression results for the percentage change in vehicle mileage which results from a 10 percent change in rolling resistance of the tires. The increase in mileage for a 10% decrease in rolling resistance is approximately 1.3%, ranging from a low of 1.2% for the Air Conditioning SC03 cycle, to a high of 1.6% for the High Speed US06

cycle. These results agree with the calculated values of a 0.7% to 2.0% change in fuel economy for a 10% change in rolling resistance that are shown in the Transportation Research Board, Special Report 286.

Table 3. Percentage Change in Vehicle Fuel Economy for a 10% Change in Tire Rolling Resistance

EPA Drive Cycle	% Change in Fuel Economy for a 10% Change in Rolling Resistance
Highway FET	1.29
City FTP	1.48
High Speed US06	1.62
Air Conditioning	1.20
SC03	
Cold City FTP	1.61

Under-inflated tires have been shown to be a prevalent issue for passenger vehicle safety. In 2001, NHTSA released the results of the *Tire Pressure Special Study*, showing that 28% of passenger cars had at least one tire under-inflated by 8 psi or more.[10] Recently NHTSA published the results of a sample of vehicles surveyed with and without tire pressure monitoring systems (TPMS).[11] Although the number of vehicles with underinflated tires was less with TPMS, there were still approximately 20% of vehicles equipped with TPMS systems that had at least one tire underinflated by 25% or more. While the primary safety issue for under-inflation of tires is reduced vehicle control and possible tire failure due to cumulative damage, studies have shown that underinflation increases the rolling resistance of a tire, thus increasing vehicle fuel consumption.

The effect of reduced inflation pressure was estimated from comparison of the dynamometer fuel economy of the vehicle with the tires inflated to the placard pressure of 210 kPa (30 psi), to tests with the same tires inflated to 158 kPa (23 psi). The lower pressure represents the 25% reduced pressure activation threshold of the tire pressure monitoring system (TPMS) specified in FMVSS No. 571.138. Six tire models that spanned the range of rolling resistances were chosen for the experiment. There was a trend for tires at the lower inflation pressure to generate lower fuel economy in all tests. Table 4 shows the results of the ANOVA analysis for the tests. All but one of the tests showed an increase of 0.3 to 0.6 percent in fuel consumption for all fuel economy cycles for a 10 kPa decrease in tire pressure. The High Speed US06 test showed no significant change in fuel economy, possibly due to

the large effect of aerodynamic drag on the total fuel consumption.

Table 4. Decrease in Vehicle Fuel Economy for Decreases in Tire Inflation Pressure

EPA Drive Cycle	% Change in Fuel Economy / 10 kPa Reduction in Tire Inflation
Highway FET	-0.300
City FTP	-0.464
High Speed US06	-0.019
Air Conditioning	-0.560
SC03	
Cold City FTP	-0.364

Dry Traction Skid Trailer Testing

Sixteen tire models representing a range of rolling resistance and of other characteristics were tested for dry traction by NHTSA. The data is reported as Slide Number (coefficient of friction x 10²). The ASTM E501 Standard Reference Test Tire is run along with the test tires. The coefficient of variation for the data ranged from 4% to 6%. There appears to be no significant correlation between dry peak or slide friction values on asphalt or concrete to rolling resistance for the tires studied. Table 5 shows the Pearson Product Moment Correlation of the values for dry traction to the tire rolling resistance. The Pearson value indicates the strength and direction of the correlation with values ranging from -1 for complete negative correlation, to +1 for complete positive correlation, with values near zero indicating no correlation between the measures. It is evident in Figure 11, that there is very little correlation between the dry traction and rolling resistance for these tires. For a value to be statistically significant the probability > |r| would have to be less than 0.050, and no value approaches that number.

Table 5. Correlation of Skid Trailer Dry Traction to Tire Rolling Resistance

	Asphalt		Concrete	
	Peak Value	Sliding Value	Peak Value	Sliding Value
Pearson Product Moment Correlation	0.209	-0.158	0.056	0.069
Probability > r	0.2518	0.3886	0.7602	0.7059

Figure 11 displays that the peak and sliding traction conducted on dry asphalt and concrete surfaces have

no systematic change as tire rolling resistance changes.

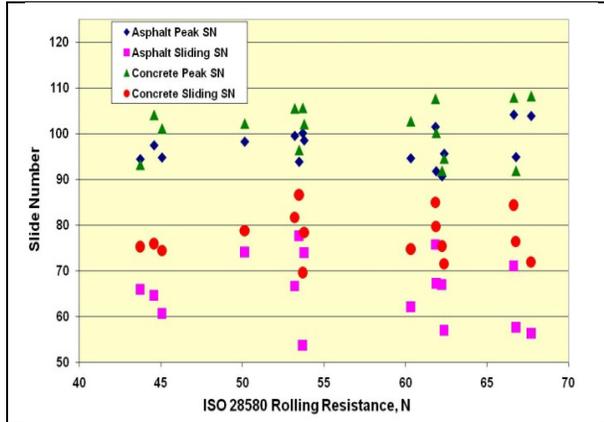


Figure 11. Dry Traction Slide Numbers versus ISO 28580 Rolling Resistance.

Skid Trailer Traction Testing on Wet Surfaces

Table 6 shows the Pearson Product Moment Correlation of the values for wet traction to the tire rolling resistance. The sliding values all have a strong and significant relationship between better rolling resistance and poorer wet traction. The peak values display the same tendency but the relationship is much weaker.

Table 6. Correlation of Skid Trailer Wet Traction to Tire Rolling Resistance

	Asphalt		Concrete	
	Peak Value	Sliding Value	Peak Value	Sliding Value
Pearson Product Moment Correlation	0.299	0.739	0.465	0.700
Probability > r	0.0965	<0.0001	0.0070	<0.0001

Even though these tires were not new, having been previously tested for rolling resistance in the laboratory, the UTQGS procedure was used for this testing and the results should display the same trends seen in new tires. The UTQGS traction rating is based on the wet sliding value on asphalt and concrete. Figure 12 displays the wet traction slide number on the asphalt surface with the critical values to achieve an A or AA traction rating. Figure 13 displays the data for the concrete surface. While most of these tires were labeled A traction and tested as such, it is clear that the values increase within the range as rolling resistance increases. From these data,

it appears that the tires with lower rolling resistance values will have poorer wet traction performance in the sliding region. This will be particularly significant to consumers without ABS systems on their vehicles, since the sliding value will relate most closely to emergency stopping maneuvers.

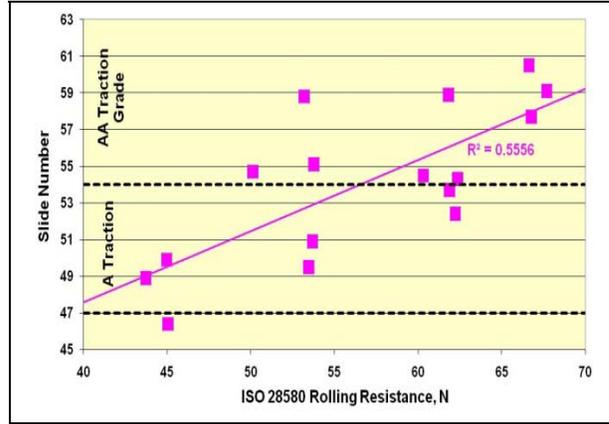


Figure 12. Slide Number on Wet Asphalt versus Tire Rolling Resistance.

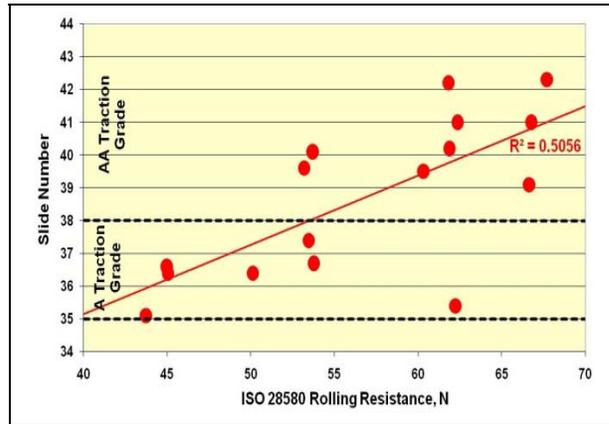


Figure 13. Slide Number on Wet Concrete versus Tire Rolling Resistance.

The wet traction versus rolling resistance for the peak measured traction on both asphalt and concrete surfaces are shown in Figure 14. The decrease in traction as rolling resistance improves is much less pronounced. Hence, for newer vehicles with ABS or ESC systems, the tradeoff is expected to be much less significant.

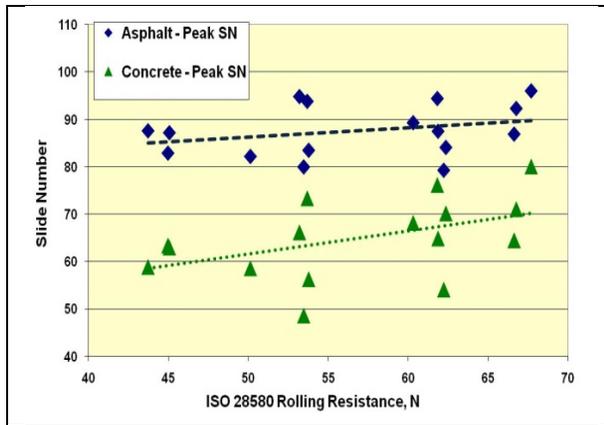


Figure 14. Peak Traction Results on Wet Surfaces versus Tire Rolling Resistance.

Technical literature indicates that the tradeoff between tire fuel economy and traction performance can be significantly reduced or eliminated with advanced compounding technologies, which are usually more expensive and proprietary. An analysis of tire tread rubber compounds, which was beyond the scope of this paper, confirmed that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

On-Vehicle Treadwear Testing

Five tire models, including the ASTM F2493SRTT, that were selected to represent the range of rolling resistance of the models studied were tested according to the UTQGS testing protocol for treadwear. Measurements were taken across the tire at six locations in each groove (1 through 4). Data were analyzed by tire type, by groove, by shoulder (grooves 1 and 4) or tread center (grooves 2 and 3). The coefficients of variation for the wear rates are approximately 0.5% for all tire types indicating that comparisons between tire types at these conditions are reliable.

Table 7 shows the treadwear rates and projected mileage to 1.59mm (2/32^{nds} in) tread depth for the tires. For each model the wear rates for the shoulder and tread center were compared along with the projected lifetime for each area. For tire type B11 the wear rate in the shoulder area was significantly faster than the wear rate in the tread center, with a corresponding decrease in projected mileage. For tire type M14 the wear rate in the tread center was significantly faster than in the shoulder area, with significantly shorter projected tread life in this area. Tire type M13 had faster wear rates in the tread

center, but this was partially offset by a lesser groove depth in the shoulder area in projecting tire lifetime.

Table 7. Projected Mileage to Wearout for Tires with Varying Rolling Resistance

Tire Type	Rolling Resistance, Newtons	Reported Wear Rate, mil/1000 mi	Average Projected Tread Life, km	Projected Life, km (Shoulder)	Projected Life, km (Tread Center)
B11	45.1	5.16	88,254	78,132	101,708
B13	66.8	6.46	83,716	83,346	87,771
G8	43.7	6.45	73,046	74,768	73,770
M13	53.7	5.45	66,480	72,660	65,177
M14	53.2	5.56	72,419	91,296	63,133

Figure 15 shows the projected average tire mileage to wear out and the minimum projected mileage, versus the rolling resistance for the tire. From the outdoor test data, there is no evidence that a tire with reduced rolling resistance will necessarily have reduced tread life.

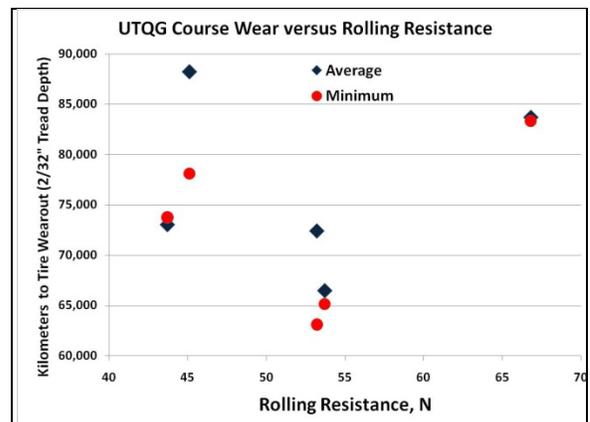


Figure 15. On-Vehicle Tire Test Miles to Wear-out versus Tire Rolling Resistance.

Indoor Treadwear Testing

The indoor treadwear test was designed to provide a faster rate of wear on the tire by minimizing the straight-ahead driving time where little tire wear takes place. The same tires that were tested on the on-vehicle wear test, along with the original equipment tires from the Impala fuel economy test vehicle were

tested in the laboratory. At the severe conditions (25% Fz) the tire shoulders wore very quickly and were nearing complete wearout at the conclusion of the 1350 km test sequence. At the mild conditions (20% Fz) the shoulder area still wore significantly faster than the tread center. As seen in Figure 16, the indoor test data does indicate a trend towards shorter treadlife for the tires with lower rolling resistance.

The results for the indoor treadwear testing are contrary to results for the on-vehicle testing. However, given the large difference in the severity of the two tests (the on-vehicle test was minimal in severity and the indoor test was aggressive), it is likely that the tests were evaluating different wear regimes for the tire treads. In other words, the rank ordering of wear rates for individual tires at minimal wear conditions can change at more severe conditions.

Additional analysis of tire wear patterns was conducted using the data points provided by the Bytewise CTWIST machine and are provided in the full DOT report.[6]

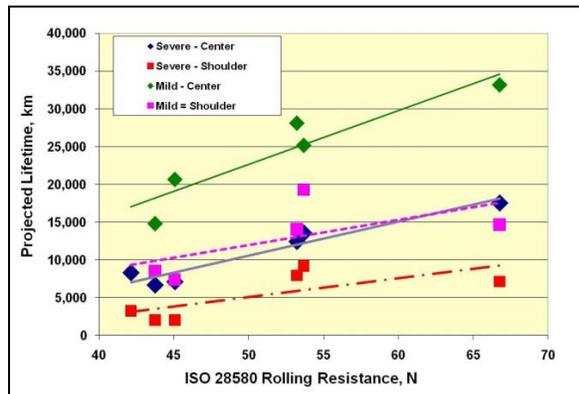


Figure 16. Indoor Treadwear - Projected Tire Tread Life versus Rolling Resistance.

CONCLUSIONS

Based on five different fuel economy cycles, a 10 percent decrease in tire rolling resistance resulted in an approximately 1.3 percent increase in fuel economy for the vehicle. This result was within the range predicted by technical literature. Reducing the inflation pressure by 25 percent resulted in a small but statistically significant increase of approximately 0.3 to 0.5 L/100km for four of the five fuel economy cycles, excluding the High Speed US06 cycle. This value was also within the range predicted by technical literature.

For the tires studied, there appeared to be no significant relationship between dry peak or slide numbers and rolling resistance. However, these tire models exhibited a strong and significant relationship between better rolling resistance and poorer wet slide numbers. The peak wet slide number displayed the same tendency, but the relationship was much weaker. This may be significant to consumers without anti-lock braking systems (ABS) on their vehicles since the wet slide value relates most closely to locked-wheel emergency stops. For newer vehicles with ABS or electronic stability control systems, which operate in the earlier and higher wet peak friction range, the tradeoff is expected to be less significant. The tire models were selected to represent a broad range of passenger tires in the marketplace and the authors feel that these results are generally applicable to the current tire market.

Technical literature indicates that the tradeoff between tire fuel economy and traction performance can be significantly reduced or eliminated with advanced compounding technologies, which are usually more expensive and proprietary. An analysis of tire tread rubber compounds, which was beyond the scope of this paper, confirmed that the type of polymer, type of filler, and amount of filler can influence both rolling resistance and wet traction properties.

For the subset of five tire models subjected to on-vehicle treadwear testing (UTQGS), no clear relationship was exhibited between tread wear rate and rolling resistance levels. For the subset of six tire models subjected to more aggressive inputs in the indoor treadwear tests, there was a trend toward faster wear for tires with lower rolling resistance.

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APPENDIX

Table 8. Specifications for Passenger Tire Models and Tests Completed for Correlation with Rolling Resistance

Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	UTQGS Treadwear	UTQGS Traction	UTQGS Temp.	Performance Level	Dynamometer Fuel Economy	Skid Trailer Dry Traction	Skid Trailer Wet Traction	On-Vehicle UTQGS Treadwear	Indoor Treadwear	Dynamometer Fuel Economy at 25% Reduced Tire Inflation
G12	Goodyear	P225/60R16	97	S	Integrity	460	A	B	Passenger All Season, TPC 1298MS	✓				✓	✓
G10	Goodyear	P205/75R15	97	S	Integrity	460	A	B	Passenger All Season		✓	✓			
G11	Goodyear	P225/60R17	98	S	Integrity	460	A	B	Passenger All Season	✓	✓	✓			
G8	Goodyear	225/60R16	98	S	Integrity	460	A	B	Passenger All Season	✓	✓	✓	✓	✓	✓
G9	Goodyear	P205/75R14	95	S	Integrity	460	A	B	Passenger All Season		✓	✓			
U3	Dunlop	P225/60R17	98	T	SP Sport 4000 DSST	360	A	B	Run Flat	✓	✓	✓			
B10	Bridgestone	225/60R16	98	Q	Blizzak REVO1		-		Performance Winter	✓	✓	✓			
B15	Dayton	225/60R16	98	S	Winterforce		-		Performance Winter	✓	✓	✓			
B13	Bridgestone	P225/60R16	97	T	Turanza LS-T	700	A	B	Standard Touring All Season	✓	✓	✓	✓	✓	✓
B14	Bridgestone	P225/60R16	97	V	Turanza LS-V	400	AA	A	Grand Touring All Season	✓	✓	✓			
B11	Bridgestone	P225/60R16	97	H	Potenza RE92 OWL	340	A	A	High Performance All Season Ultra High	✓	✓	✓	✓	✓	✓
B12	Bridgestone	P225/60R16	98	W	Potenza RE750	340	AA	A	Performance Summer	✓	✓	✓			
M13	Michelin	225/60R16	98	H	Pilot MXM4	300	A	A	Grand Touring All Season	✓	✓	✓	✓	✓	✓
D10	Cooper	225/60R16	98	H	Lifeline Touring SLE	420	A	A	Standard Touring All Season	✓	✓	✓			
P5	Pep Boys	P225/60R16	97	H	Touring HR	420	A	A	Passenger All Season	✓	✓	✓			
R4	Pirelli	225/60R16	98	H	P6 Four Seasons	400	A	A	Passenger All Season	✓	✓	✓			
M14	Uniroyal	P225/60R16	97	S	ASTM F2493 SRTT	540	A	B	Passenger All Season	✓	✓	✓	✓	✓	✓

Table 9. 2008 EPA Fuel Economy 5-Driving Schedule Test (Source: US EPA, 2011)

Driving Schedule Attributes	Test Schedule(1)				
	City (FTP)	Highway (HwFET)	High Speed (US06)	Air Conditioning (SC03)	Cold Temp (Cold CO)
Trip Type	Low speeds in stop-and-go urban traffic	Free-flow traffic at highway speeds	Higher speeds; harder acceleration & braking	AC use under hot ambient conditions	City test w/ colder outside temperature
Top Speed	56 mph	60 mph	80 mph	54.8 mph	56 mph
Average Speed	21.2 mph	48.3 mph	48.4 mph	21.2 mph	21.2 mph
Max. Acceleration	3.3 mph/sec	3.2 mph/sec	8.46 mph/sec	5.1 mph/sec	3.3 mph/sec
Simulated Distance	11 mi.	10.3 mi.	8 mi.	3.6 mi.	11 mi.
Time	31.2 min.	12.75 min.	9.9 min.	9.9 min.	31.2 min.
Stops	23	None	4	5	23
Idling time	18% of time	None	7% of time	19% of time	18% of time
Engine Startup	Cold	Warm	Warm	Warm	Cold
Lab temperature	68-86°F	68-86°F	68-86°F	95°F	20°F
Vehicle air conditioning	Off	Off	Off	On	Off