NHTSA TIRE ROLLING RESISTANCE TEST DEVELOPMENT PROJECT – PHASE I

Dr. M. Kamel Salaani, Larry R. Evans, John R. Harris
Transportation Research Center Inc.

James D. MacIsaac Jr.
U.S. Department of Transportation - National Highway Traffic Safety Administration
United States of America

Paper Number 09-0300

ABSTRACT

This paper presents research results from the first phase of a project to develop a tire fuel efficiency consumer information program for passenger vehicle replacement tires. In this phase of the project, the agency completed a test program using 600 tires of 25 model/size combinations to evaluate five different rolling resistance test methods. These test methods were derived from two SAE and two ISO standards. The test matrix included two separate test laboratories to examine lab-to-lab variation.

The results indicated that all of the five test methods had very low variability and all methods could be cross-correlated to provide the same information about individual tire types. 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 single-point ISO 28580 draft international standard has an advantage over the single-point SAE J1269 recommended practice because it contains a lab-to-lab measurement result correlation procedure. There was a significant offset observed in the data generated by the two laboratories when using the identical test, even when testing the same tire, which must be accounted for in a rating system. Results show that for all the tests conducted, lab-to-lab variation can be statistically minimized if data from each lab is normalized to the test results of a Standard Reference Test Tire (SRTT). Two additional retests of a given tire did not produce statistically different rolling resistance values from the first test. So the concept of limited retesting of the same tires for lab alignment or data quality monitoring appears valid.

INTRODUCTION

Rolling resistance is the effort required to keep a given tire rolling at steady speed to compensate for the amount of energy dissipated within the volume of the tire. 80 to 95 percent of this loss is attributed to viscoelastic behavior of tire rubber compounds as they cyclically deform during the rotation process. It is reported in units of force, or as a coefficient when normalized to the applied normal load. This notation indicates the amount of force measured by the testing machine at the tire and test drum interface to keep the tire rolling at steady state conditions. 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 another loss at the contact surface similar to Coulomb friction. In this paper the rolling resistance is reported in units of force (Newton or lb) rather than as a coefficient, since the divisor of the coefficient can be determined from one of many varied load formulas.

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, 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 [1]. One of the primary recommendations of the 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 response to the NAS recommendation, NHTSA embarked on a large-scale research project in July 2006 to evaluate existing tire rolling resistance test methods and to examine correlations between tire rolling resistance levels and tire safety performance. The first phase is composed of the following research milestones:

- Benchmark the current rolling resistance levels in modern passenger vehicle tires in terms of actual rolling force, rolling resistance coefficient, as well as indexed against the ASTM F2493-06 Standard Reference Test Tire (SRTT).
- Analyze the effect of the input variables on the testing conditions for non-linear response.
- Examine the variability of the rolling resistance results from lab to lab, machine to machine.
- Evaluate the effects of first test on a tire versus multiple tests on the same tire.
- Select a test procedure that would be best for a regulation.

The NAS report suggests that safety consequences from a 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 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 (similar speed ratings and diameters) [1].

In December 2007, Congress enacted the Energy Independence and Security Act of 2007 that mandated that USDOT/NHTSA establish a national tire fuel efficiency rating system for motor vehicle replacement tires within 24 months. The rulemaking was to include a replacement tire fuel efficiency rating system, requirements for providing information to consumers, specifications for test methods for manufacturers, and a national tire maintenance consumer education program [2]. To address these requirements, 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, and outdoor and indoor treadwear.

Since tire traction can be characterized by mechanical properties that play a fundamental role in defining vehicle handling and control performances, direct measurements were made to characterize the force generation process of tires in comparison to rolling resistance.

The mechanical properties estimated from tire data measured on a Flat-Trac® tire testing machine (dry testing only) are longitudinal, lateral, vertical, and torsional stiffnesses, peak longitudinal and lateral frictions and their decay coefficients, and moment arms (first derivatives of moments to the principal force). These are the fundamental constituents of steady tire forces and moments [3]. The correlation between these properties and rolling resistance will be studied for all tires measured in this project.

In addition to the steady force and moment data, tread viscoelastic (dynamic mechanical) properties of all tires used in this project were measured. The tread compound has been reported to be a major contributor to rolling resistance. The dynamic measurements of the tread consisted of measuring the viscoelastic behavior, notably the tangent delta (tan δ) of the compounds over a range of temperatures. Tan δ, referred to as the loss modulus, is the phase angle between which the strain lags behind the applied stresses. It is predictive of the rolling resistance and wet traction/handling characteristics of a tire. In a later phase of the project, rolling resistance will be correlated with tires' static and dynamic properties to study the marginal effects on rolling resistances.

This paper focuses on summarizing the findings of phase 1. The full details of this study and subsequent phases of the project will be reported in agency technical reports as they are completed. This paper provides a brief introduction to the standards evaluated in phase 1 of the research program, the list of all the tires tested, and test location. A summary of the statistical analysis is introduced where each rolling resistance test method is analyzed for consistency, and then all the test methods are compared to each other. Lab-to-lab variations for each method are analyzed. Finally, the normalized data is analyzed and the recommended test for rolling resistance rating program is discussed.

ROLLING RESISTANCE EXPERIMENTS

The test program utilized an assortment of approximately 600 new tires of 25 different models. 15 tire models were passenger, 9 were light truck tire models, and one was the ASTM F2493-06 P225/60R16 97S Standard Reference Test Tire

(SRTT). Five different test methods were used that included single- and multi-point SAE J1269, SAE J2452, ISO 18164:2005 (E) -Annex B.4, and ISO 28580 (Draft). The testing was conducted under contract by two independent organizations: The Smithers Tire and Automotive Test Center in Ravenna, Ohio, USA and the consortium of Akron Rubber Development Lab, in Akron, Ohio USA and Standards Testing Labs in Massillon, Ohio, USA. In this paper, these two test organizations are referred as SSS and ARDL-STL respectively.

Rolling Resistance Tests

Figure 1 shows an example of a laboratory rolling resistance test machine. Test standards include the provision of testing tires on different wheel diameters and correcting for the diameter with a mathematical equation. In this project, all tests were conducted on 1.707-m roadwheels. This practice eliminated the use of an approximation formula that corrects for the curvature of the footprint contacts between the tires and drum surface. Comparing measured values versus adjusted measured values to account for road wheel diameter variation might add variations not originating from the physical process itself, but from the empirical corrections.

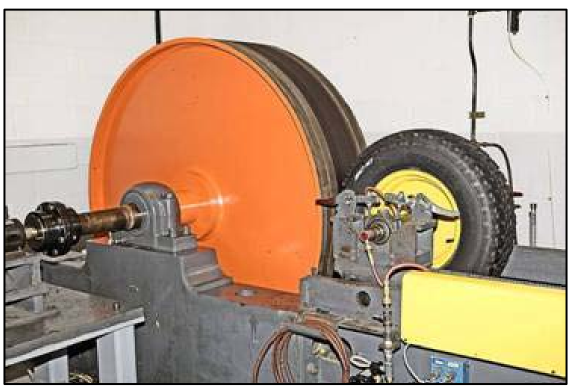

Figure 1. Example of Laboratory Tire Rolling Resistance Test Machine (Torque-Measurement Style).

Table 3 provides a detailed comparison of the tests used in phase 1 and the standard conditions followed for each test. The term "single point" refers to a method that uses a single set of test conditions. The term "multi point" refers to a method that uses more than one set of conditions to test a tire, usually varying speed, pressure, and/or load. Passenger and light truck tires generally have different test conditions and can have a different number of test points in the set of conditions.

Depending on the rolling resistance test method, the rolling resistance force can be measured by up to four different means: Force method, torque method, power method, or deceleration method. Of the five rolling resistance test methods evaluated at the two test laboratories, all testing was completed on machines utilizing the force measurement method, with the exception of the SAE J2452 test at Standards Testing Labs, which used the torque measurement method. Therefore, the results of the study cannot characterize testing completed on machines that use power or deceleration methods of measurement, which are permitted in some rolling resistance test standards (Table 3).

Test Tires

The national tire fuel efficiency rating system will apply to replacement passenger car tires only. The system will not apply to deep tread tires (i.e. LT-designated tires), winter-type snow tires, space-saver or temporary use spare tires, tires with nominal rim diameters of 12 inches or less, and limited production tires. However, because this research project initiated more than a year prior (July, 2006) to the enactment of the legislation, the mix of 25 tire models includes 2 winter-type passenger tire models and 9 light truck tire models. The 16 passenger tires were selected to provide a three-dimensional variation in terms of size, construction, and manufacturers. The details of the passenger tires are included in Table 4. A similar testing approach is used for the 9 DOT-approved light truck tire models. Details of these tires are included in Table 5.

In an attempt to minimize variability in the experiments, tires of each model were purchased with identical (or very similar) build dates. Tires were tested on wheels of the corresponding "measuring rim width" for their size. Wheels of each size used in the test program were purchased new, in identical lots to minimize wheel-to-wheel variation. Tires participating in multiple tests at the same lab or between two labs were mounted once on a single wheel and continued to be tested on that same wheel until completion of all tests.

The ASTM F2493 - *Standard Specification for P225/60R16 97S Radial Standard Reference Test Tire* (SRTT) provides specifications for a tire "for use as a reference tire for braking traction, snow traction, and wear performance evaluations, but may also be used for other evaluations, such as pavement roughness, noise, or other tests that require a reference tire." The standard contains detailed specifications for the design, allowable dimensions, and storage of the SRTTs. The F2493 SRTT is a variant of a modern 16-inch Uniroyal TigerPaw radial passenger vehicle tire and comes marked with a full USDOT Tire Identification Number (TIN) and UTQGS grades. The details of the SRTT tire are included in Table 6.

The SRTTs were used extensively throughout the test programs at both labs as the first and last tire in each block of testing in order to track and account for the variation in machine results. In theory, by monitoring first and last tests for each block of testing at each lab with a SRTT, and referencing rolling resistance results for each tire back to the SRTT results for that block of testing, the results should be corrected for variations in the test equipment over that time period, as well as variations in test equipment from lab to lab.

Table 7 lists all the rolling resistance experiments for the tires listed in Tables 4, 5, and 6 and for the standard tests included in Table 1. Due to its large similarity with SAE J1269 multi-point conditions, only ten tires were tested to ISO 18164. The list on Table 5 was designed to study variation from lab-to-lab, correlations between standards within the same lab, and experimental repeatability "or consistency" for a typical tire within a specific testing standard.

Additional testing using single point J1269 and ISO 28580 with a smaller selection of tire models are listed in Table 8. This addition was designed to investigate the following conditions:

- Capped versus regulated inflation pressure
- Nitrogen versus air inflation
- Smooth versus textured (grit) surfaces

The combined list of experiments specified in Tables 7 and 8 resulted in more tires of a model being tested in one test in one lab than another. The collected data is unsymmetrical. Multivariate statistical analysis was used to evaluate the effects of the input variables and different labs.

As the findings of this project are presented next, we should note that each tire is designed and manufactured for its specific market niche. The ranking of tires as presented in this paper is solely based on rolling resistance experimental values and does not by any means reflect NHTSA's preferences of one tire over the others. Rolling resistance is very important, likewise tire traction, load capacity, durability, ride quality, and other aspects are important too, and this paper does not address them.

RESULTS AND DISCUSSION

Tables 9-13 list the results of the SAS General Linear Model (GLM) analysis of all the standard tests done. The ability of the model to explain the data is shown by the F Value and the R^2 value. The F Value is based on the ratio of the variance explained by the model to the variance due to error. Its significance is given by the Pr > F, where values less than 0.050 are considered significant. The R^2 value is a measure of the distance between the points predicted by the model and the measured points, values of R^2 greater than 0.95 were considered significant. The influence of each factor is shown by the Sums of Squares for the individual terms, their significance is shown by the Pr > F, where a Pr > F less than 0.050 is considered significant.

All models produced high R^2 values, above 0.98, and high F values with Probability > F of 0.0001. The most significant variable as measured by any test is the individual tire model. This variable was at least an order of magnitude more important to the statistical model than all other variables combined. For each tire type the variability within the group of tires was very low, approximately 2 percent of the mean value.[1]

The test sequence (ordering of testing the same tire: first, second or third) is statistically insignificant for SAE J1269 single-point (Table 9), ISO 28580 single-point, and SAE J1269 Multi-point. For SAE J2452 the test sequence is statistically significant but with a small effect as can be seen by the 'sum of squares'. ISO 18164 test sequence could not be analyzed due to insufficient data and data covariance.

For the test of capped versus regulated pressure done for SAE J1269 standard only, Table 9 shows that the Sums of Squares for the individual terms indicate that (capped vs. regulated) is the third significant term after tire type and lab to lab variations. The F value and the sum of squares are very close to lab-to-lab variations and very small when compared to tire type. The capped tires showed a mean predicted rolling resistance of 49.42 N (11.11 pounds) compared to 51.64 N (11.61 pounds) for the regulated tires. The term was significant with a Pr > F of 0.0001. The lower rolling resistance for the capped tires is expected due to the increase in inflation pressure as the tire cavity temperature rises during the test. This pressure rise is vented during a regulated test.

[1] One tire of type C9 was excluded from the analysis since it had abnormally high values on multiple tests compared to the rest of the type C9 tires.

For each of the testing methods the Coefficient of Variation (C.V.) is about 2%, except for the ISO 18164 multi-point experiments with only 10 tires tested, which had a C.V. of 5.25%.

The potential for discrimination within each test is an estimate of the ability of a test measure to classify the entire range of tire data into groups. It is calculated as the range of the means of the data (maximum mean value - minimum mean value) divided by three times the root mean square error for the test. For most tests, tire models could be divided from five to six groups. This analysis indicates that all standards can be used to distinguish rolling resistance values of tires, but these tests were done at different pressure, load and speed values, as detailed in Table 5. Moreover, some of these tests that are based on single-point measurements are a direct measure of rolling resistance; while rolling resistance from a multi-point measure uses regression equations to estimate a single value.

To determine if these values are measures of the same physical phenomena we compare them to each other. A simple method is to test if these measures are collinear and have linear relations by preserving the same ordering of clusters or groups. We hypothesize that if each group contains the same tires measured by different standards then we can conclude that the measures report the same physical phenomena.

Using Duncan’s statistical method for hypothesis testing of pair-wise comparison, the results showed that all tested tires were divided into 7 groups that are made of the same tire list independent of the testing standard used. Within each group the ranking of the rolling resistance is not the same but it is within the expected variation of each test. Table 14 lists all these groups for each standard test and the ordering from lowest to highest, and Figure 2 plots their linear relations. Therefore all standard tests are equivalent measures for rolling resistance force.

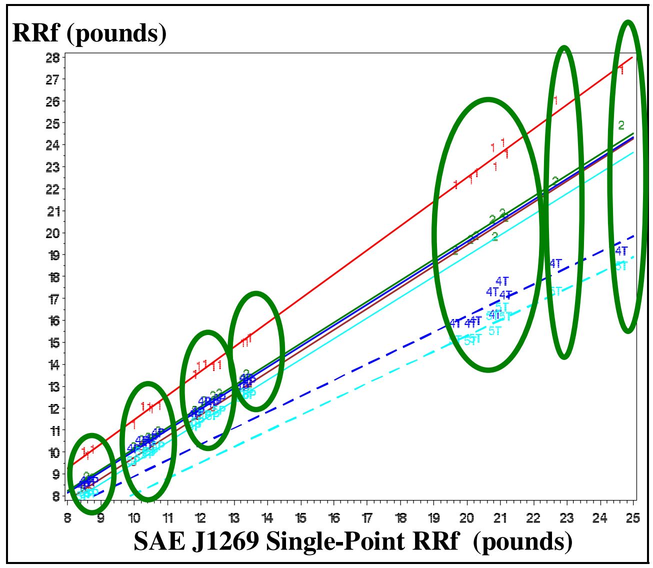

Figure 2. Comparing Standards: 1=ISO 28580 value; 2 = SAE J1269 multi-point value at SRC; 3 = ISO 18164 value at SRC; 4P = SAE J2452 value @ SRC for Passenger Tires; 4T = SAE J2452 value @ SRC, Light Truck Tires; 5P = SAE J2452 SMERF value for Passenger Tires; 5T = SAE J2452 SMRF value for Light Truck Tires.

But how do these testing standards compare when compared from lab to lab? To understand the significance of the different measures between labs, each testing standard is correlated between the SSS and ARDL-STL labs. Table 1 lists all the regression equations. These equations produced a fit with R^2>0.97. The intercepts range from nearly zero to ±10% of the average force value, and the slopes range from 0.9 to 1.17. A slightly better fit was produced with a second order. There is no data to suggest that these equations remain unchanged over time, or there won’t be a drift or offset that require additional standardizations.

Using regression equations to relate results at different labs might produce accurate results, which is the case in this research. However, making this method as a standard for reporting rolling resistance values is not practical due to the possibility of changes of the machine/tire system over time, and the amount of data required for setting up conversion equations each time when the system is re-calibrated.

Table 1.
Correlation Equations for Conversion of Pounds Force Values Obtained at ARDL-STL to Estimated SSS Lab Data

Test	To Convert ARDL-STL Value (A) to SSS Value (S)
SAE J1269 Single-point	S = 0.2568 + 1.0239*A
ISO 28580 Single-point	S = -0.0994 + 1.0120*A
SAE J1269 Multi-point	S = -1.7463 + 1.1732*A
SAE J2452 SRC	S= -0.02306 + 1.0769*A
SAE J2452, SMERF	S= -0.1425 + 1.0772*A

A better approach is to normalize each lab data with a reference tire. This research used the aforementioned 16-inch ASTM SRTT for both control and lab-to-lab normalization purposes. Table 2 lists all the regression equations. The linear relationships between labs, and between all tests for passenger tires, indicate that this tire may be used as an internal standard for test reference. Accordingly, all values for passenger tires were normalized to the average value of the SRTT tested at the same conditions. For ease, the values were multiplied by 100 to give an index of rolling resistance (RRIndex). Figures 3-8 show a direct comparison between the two labs for all the tests performed. All correlations between labs are nearly one-to-one for each test, with an average of 1.0022, with a standard deviation within the limits of the accuracy of the test.

Normalization to the SRTT value is a valid method of maintaining correlation between labs. The use of the SRTT as a reference, and for statistical process control techniques within each lab will give results that can be directly compared. Within the scope of data collected in this project, none of the test methods outperformed the other when the SRTT normalization method is employed. Many tires from all models in the study, including the SRTT, were retested two additional times and did not produce statistically different values from their first test. Therefore, the limited retesting of control and lab alignment tires appears to be a viable concept.

Table 2.
Correlation between Labs using RRIndex Normalized to SRTT

Test	SSS Index = ARDL-STL Index
SAE J1269 Single-Point	0.9884
ISO 28580 Single-Point	0.9911
SAE J1269 Multi-Point @ SRC	1.0046
ISO 18164 Multi-Point (All Conditions)	0.9966
SAE J2452, Calculated @ SRC	1.0163
SAE J2452, SMERF	1.0167
Average	**1.0022 ± 0.0112**

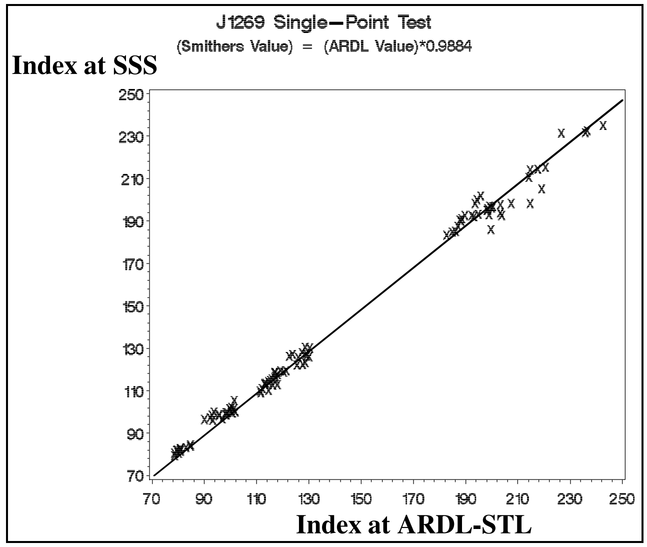

Figure 3. Lab-to-Lab Correlation of SAE J1269 Single-Point Test Using RRIndex (Normalized to SRTT).

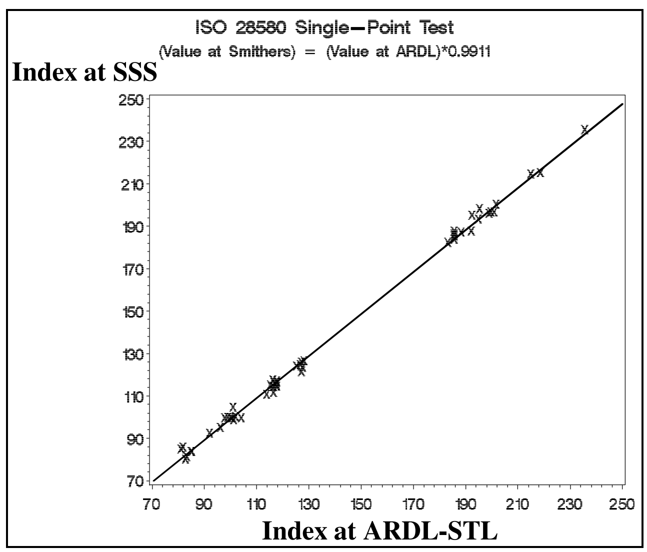

Figure 4. Lab-to-Lab Correlation of ISO 28580 Test Using RRIndex (Normalized to SRTT).

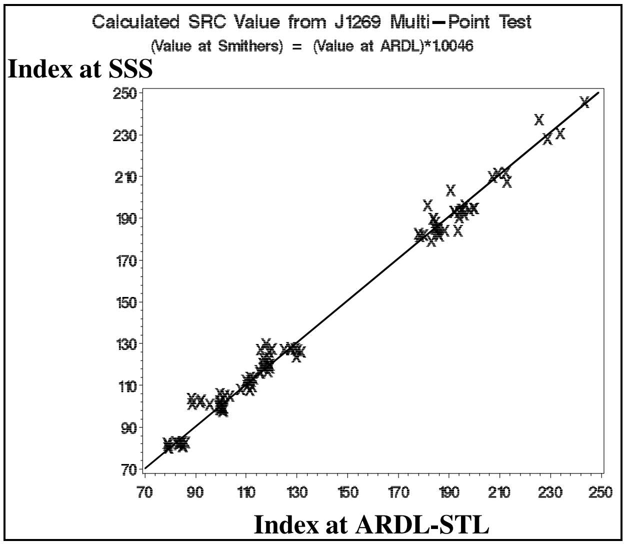

Figure 5. Lab-to-Lab Correlation of SAE J1269 Multi-Point Test Using RRIndex (Normalized to SRTT).

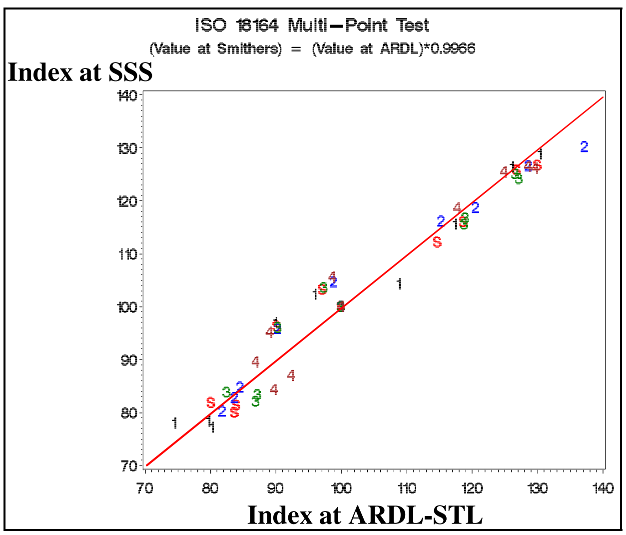

Figure 6. Lab-to-Lab Correlation of ISO 18164 Multi-Point Test at Various Conditions Using RRIndex (Normalized to SRTT). 1= 50% load and +70 kPa; 2 = 50% load and -30 kPa; 3 = 90% load and +70 kPa; 4 = 90% load and -30 kPa; 5 = Standard Reference Calculation (70% load and + 20 kPa).

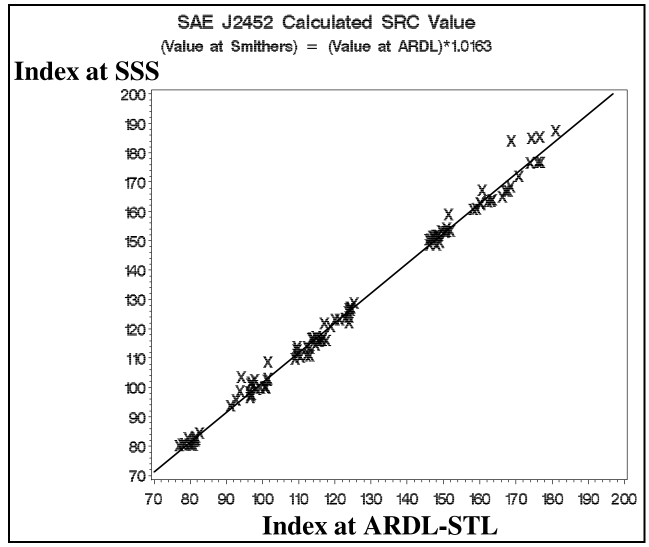

Figure 7. Lab-to-Lab Correlation of SAE J2452 SRC Value Using RRIndex (Normalized to SRTT).

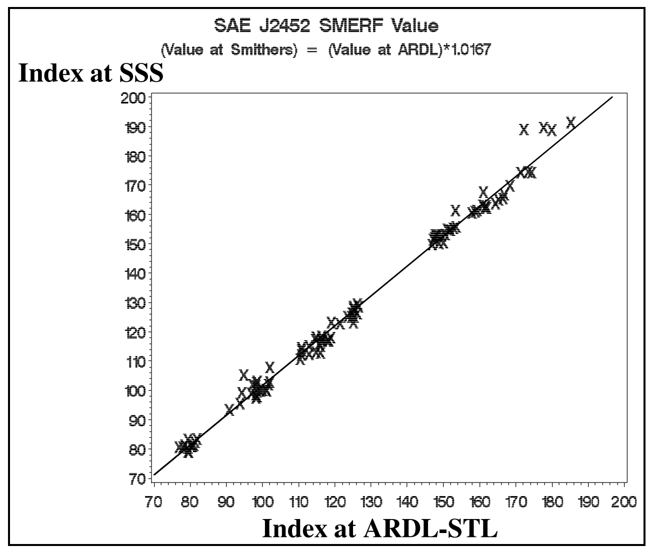

Figure 8. Lab-to-Lab Correlation Using RRIndex (Normalized to SRTT).

Figures 3-8 show that using RRIndex, the correlations between labs for the SAE and ISO single-point tests are nearly identical. More importantly, each standard test is capable of discriminating tires, and when they are compared to each other, the reported rolling resistance values are consistent and do provide a measure of the same physical phenomena, and when they are normalized to SRTT, rolling resistance index between the different tests and labs are well correlated and very accurate.

Figure 6 shows the values for the ISO 18164 test performed at the range of load and inflation conditions indexed to the SRTT values at those same conditions. Use of the RRIndex gives similar values for each tire over this broad range of conditions.

CONCLUSIONS

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, it should be noted that the relative rankings of the tires within the population of the 25 models tested shifted considerably when tires were ranked by either rolling resistance force or rolling resistance coefficient.

Empirical equations were derived that allowed accurate conversion of data from any one test to the expected data from any other test. However, these equations are only valid for those specific test machines at that point in time. These equations must be periodically validated and adjusted for possible drifts in machine output due to mechanical, electrical and environmental changes over time.

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. The rating system must institute a methodology to account for the lab-to-lab variation. Results show that for all the tests conducted, lab-to-lab variation can be statistically minimized if data from each lab is normalized to the test results of a Standard Reference Test Tire (SRTT). Two additional retests of a given tire did not produce statistically different rolling resistance values from the first test. So the concept of limited retesting of the same tires for lab alignment or data quality monitoring appears valid.

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 has 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 lab alignment procedure in ISO 28580, which for passenger tires uses two dissimilar tires to calibrate a test lab to a master lab, states that it will compensate for differences induced from tests conducted using different options under the test standard. These options include the use of one of four measurement methods (force, torque, power, or deceleration), textured or smooth drum surface, correction of data to a 25°C reference temperature, and correction of data from tests conducted on a test drum of less than 2.0-m in diameter to a 2.0-m test drum. The variability in test results induced by allowing the various test options, as well as the effectiveness of the temperature and test drum correction equations has not been determined by the agency.

ACKNOWLEDGEMENTS

The agency would like to thank its contractors at the Akron Rubber Development Laboratory, Inc., Smithers Scientific Services, Inc., Standards Testing Laboratories, Inc., and Transportation Research Center, Inc. for their contributions to the project.

REFERENCES

[1] Transportation Research Board Special Report 286, Tires and Passenger Vehicle Fuel Economy, National Research Council of the National Academies (2006).
[2] Section 111, Consumer Tire Information, of the H.R. 6: Energy Independence and Security Act of 2007.
[3] Salaani, M. K., "Analytical analysis of tyre forces as a function of normal pressure distributions," Int. J. Heavy Vehicle systems, Vol. 16, Nos. ½, 2009.

Table 3.
Comparison of the Five Laboratory Rolling Resistance Test Methods Evaluated (Passenger and Light Truck Conditions with Speed of 80 kph, 50 mph)

	ISO 28580 Draft		ISO 18164:2005(E)		SAE J1269				SAE J2452	
	Single Point		Multi Point		Single Point		Multi Point		Multi Point	
Note	Ref. ISO 28580 Draft		Annex B		SRC Conditions					
Roadwheel Diameter	2.0 m or > 1.7 m corrected to 2.0 m		1.5 m or greater		1.7 m commonly used		1.7 m commonly used		1.219 m or greater	
Measurement Methods	Force		Force		Force		Force		Force	
	Torque		Torque		Torque		Torque		Torque	
	Power		Power		Power		Power			
	Deceleration		Deceleration							
Roadwheel Surface	Smooth (Texture optional)		Smooth (Texture optional)		Medium-coarse (80-grit) texture		Medium-coarse (80-grit) texture		Medium-coarse (80-grit) texture	
Temperature Range	20 to 30 C		20 to 30 C		20 to 28 C		20 to 28 C		20 to 28 C	
Reference Temperature	25 C		25 C		24 C		24 C		24 C	
Speed	80 km/h		80 km/h (Optional passenger multiple speeds of 50 km/h, 90 km/h and 120 km/h. Optional truck/bus multiple speeds 80km/h & 120 km/h)		80 km/h		80 km/h		SRC = 80 km/h ; Coast downs (115 to 15 km/h range)	
Base Pressure					Molded sidewall load@ T&RA pressure		Molded sidewall load@ T&RA pressure		Reference table in standard	
Test Load and Pressure	**Passenger**		**Passenger (Table B.1)**		**Passenger & LT**		**Passenger**		**Passenger**	
	Load	Pressure	Load	Pressure	Load	Pressure	Load	Pressure	Load	Pressure
	SL 80%	210 kPa Capped	50%	+70 kPa reg.	70%	+20 kPa Regulated	90%	-50 kPa (-7.3 psi) Capped	30%	+1.4 psi reg.
	XL 80%	250 kPa Capped	50%	-30 kPa reg.			90%	+70 kPa (10.2 psi) reg.	60%	-5.8 psi reg.
			90%	+70 kPa reg.			50%	-30 kPa (-4.4 psi) reg.	90%	+8.7 psi reg.
			90%	-30 kPa reg.			50%	+70 kPa (10.2 psi) reg.	90%	-5.8 psi reg.
	C, Truck/ Bus (single) ≤Li 121		**≤Li 121 Highway Truck and Bus (Table B.1)**				**Light Truck (single)**		**Light Truck (single)**	
	85%	100 % Capped	100%	Pressure			100%	100 % Capped	20%	110 % reg.
			100%	100 % Capped			70%	60 % Reg.	40%	50 % Reg.
			75%	95 % Reg.			70%	110 % Reg.	40%	100 % Reg.
			50%	70 % Reg.			40%	30 % Reg.	70%	60 % Reg.
			25%	120 % Reg.			40%	60 % Reg.	100%	100 % Reg.
							40%	110 % Reg.		

Table 4.
Specifications for Passenger Tire Models

Test Program Axis #	Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	UTQGS Treadwear	UTQGS Trac.	UTQGS Temp.	Measured Tread Depth (1/32")	Performance Level
1	**G10**	Goodyear	P205/75R15	97	S	Integrity	460	A	B	9	Passenger All Season
	G11	Goodyear	P225/60R17	98	S	Integrity	460	A	B	8	Passenger All Season
	G8	Goodyear	225/60R16	98	S	Integrity	460	A	B	9	Passenger All Season
	G9	Goodyear	P205/75R14	95	S	Integrity	460	A	B	9	Passenger All Season
	U3	Dunlop	P225/60R17	98	T	SP Sport 4000 DSST	360	A	B	11	Run Flat
2	**B10**	Bridgestone	225/60R16	98	Q	Blizzak REVO1	-			9	Performance Winter
	B15	Dayton	225/60R16	98	S	Winterforce	-			14	Performance Winter
	B13	Bridgestone	P225/60R16	97	T	Turanza LS-T	700	A	B	11	Standard Touring All Season
	B14	Bridgestone	P225/60R16	97	V	Turanza LS-V	400	AA	A	11	Grand Touring All Season
	B11	Bridgestone	P225/60R16	97	H	Potenza RE92 OWL	340	A	A	11	High Performance All Season
	B12	Bridgestone	P225/60R16	98	W	Potenza RE750	340	AA	A	7	Ultra High Performance Summer
3	**M13**	Michelin	225/60R16	98	H	Pilot MXM4	300	A	A	7	Grand Touring All Season
	D10	Cooper	225/60R16	98	H	Lifeliner Touring SLE	420	A	A	11	Standard Touring All Season
	P5	Pep Boys	P225/60R16	97	H	Touring HR	420	A	A	11	Passenger All Season
	R4	Pirelli	225/60R16	98	H	P6 Four Seasons	400	A	A	11	Passenger All Season

Table 5.
Specifications for Light Truck Tire Models

Test Program Axis #	Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	Measured Tread Depth (1/32")	Performance Level
4	**D7**	Cooper	LT235/85R16	120(E)	N	Discoverer ST-C	19	All terrain on/off road
	D8	Cooper	LT245/75R16	120(E)	N	Discoverer ST-C	19	All terrain on/off road
	D9	Cooper	LT265/75R16	120(E)	N	Discoverer ST-C	19	All terrain on/off road
5	**M10**	Michelin	LT245/75R16	120(E)	R	Michelin LTX A/S	15	All season on-road
	M11	Michelin	LT245/75R16	120(E)	R	Michelin LTX M/S	16	All season on-road
	M12	Michelin	LT245/75R16	120(E)	R	Michelin X RADIAL LT	15	All season on-road
6	**P4**	Pep Boys	LT245/75R16	120(E)	N	Scrambler A/P	15	All season on-road
	C9	General	LT245/75R16	120(E)	Q	AmeriTrac TR	15	All terrain on/off road
	K4	Kumho	LT245/75R16	120(E)	Q	Road Venture HT	15	All season on-road

Table 6.
Specifications for ASTM F2493-06 SRTT

Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	UTQGS Treadwear	UTQGS Trac.	UTQGS Temp.	Measured Tread Depth (1/32")	Performance Level
M14	Uniroyal	P225/60R16	97	S	ASTM 16" SRTT	540	A	B	8	ASTM F 2493-06 Reference

Table 7.
Rolling Resistance Tests

Tire Type	J2452				J1269 - Single-point					J1269 - Multi-point				ISO 28580			ISO 18164		Total
	ARDL-STL		SSS		ARDL-STL		SSS			ARDL-STL		SSS		ARDL-STL	SSS		ARDL-STL	SSS	
	1st Run	3rd Run	1st Run	3rd Run	1st Run	2nd Run	1st Run	2nd Run	3rd Run	1st Run	2nd Run	1st Run	2nd Run	1st Run	1st Run	2nd Run	2nd Run	1st Run	
B10	3	1	3	1	1	3	3		1	3	1	3	1	2	2				**28**
B11	3	1	3	1	1	3	3		1	3	1	3	1	2	1	1	1	1	**30**
B12	3	1	3	1	1	3	3		1	3	1	3	1	2	1	1	1	1	**30**
B13	3	1	3	1	1	3	3		1	3	1	3	1	2	1	1	1	1	**30**
B14	3	1	3	1	1	3	3		1	3	1	3	1	2	1	1	1	1	**30**
B15	3	1	3	1	2	2	3	1		3	1	3	1	2	2				**28**
C9	3	1	3	1	3	1	3	1		3	1	3	1	2	2				**28**
D10	3	2	3	1	1	2	2			3	1	3	1	2	3				**27**
D7	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
D8	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
D9	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
G10	3	1	3	1	3	1	3	1		3	1	3	1	2	1	1	1	1	**30**
G11	3	1	3	1	3	1	3	1		3	1	3	1	2	1	1	1	1	**30**
G8	3	1	3	1	1	3	3		1	3	1	3	1	2	1	1	1	1	**30**
G9	3	1	3	1	2	2	3	1		3	1	3	1	2	1	1	1	1	**30**
K4	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
M10	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
M11	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
M12	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
M13	3	1	3	1	2	2	3	1		3	1	3	1	2	2				**28**
M14	3	1	3	1	3	1	3	1		3	1	3	1	1	3	2	1	1	**32**
P4	3	1	3	1	3	1	3	1			1	3	1	2	2				**25**
P5	3	1	3	1	1	3	3		1	3	1	3	1	2	2				**28**
R4	3	1	3	1	2	2	3	1		3	1	3	1	2	2				**28**
U3	1	1	3	1	3	1	2	1		3	1	1	1	2	6	1	1	1	**30**
Total	**73**	**26**	**75**	**25**	**55**	**44**	**73**	**17**	**7**	**51**	**25**	**73**	**25**	**49**	**48**	**11**	**10**	**10**	**697**

Table 8.
Rolling Resistance Specialty Tests

Tire Type	J1269 - Single-point - Regulated - N_2		J1269 - Single-point - Capped - N_2		J1269 - Single-point – Capped - air	ISO 2850 Bare Surface - air		Flat-Trac Surface -air	Total
	ARDL-STL	SSS	ARDL-STL	SSS	ARDL-STL	SSS		SSS	
	1st Run	1st Run	1st Run	1st Run	1st Run	2nd Run	3rd Run	1st Run	
B10					2	1		2	**5**
B11					2		1	2	**5**
B12					2		1	2	**5**
B13					2		1	2	**5**
B14					2		1	2	**5**
B15					1	1		2	**4**
C9						1		3	**4**
D10					2	1		2	**5**
D7	1	1	1	1		1		3	**8**
D8	1	1	1	1		1		2	**7**
D9						1		2	**3**
G10							1	2	**3**
G11	1	1	1	1			1	2	**7**
G8	1	1	1	1	2		1	2	**9**
G9					1		1	2	**4**
K4						1		2	**3**
M10						1		2	**3**
M11						1		2	**3**
M12						1		2	**3**
M13					1	1		2	**4**
M14							1	2	**3**
P4								2	**2**
P5					2			2	**4**
R4					1	1		2	**4**
U3							1	2	**3**
Total	**4**	**4**	**4**	**4**	**20**	**13**	**10**	**52**	**111**

Table 9.
SAS GLM Analysis of SAE J1269 Single-Point Data

Dependent Variable: Rolling Resistance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	29	49358.72877	1702.02513	15122.2	<.0001
Error	191	21.49733	0.11255		
Uncorrected Total	220	49380.22610			

R-Square	Coeff Var	Root MSE	RR Mean
0.995985	2.371565	0.335487	14.14623

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Lab Where Tested	1	9.453262	9.453262	83.99	<.0001
Procedure for Inflation	1	2.995675	2.995675	26.62	<.0001
Test Order	2	0.072031	0.036015	0.32	0.7265
Type (Tire Model)	24	4871.637615	202.984901	1803.49	<.0001

Table 10.
SAS GLM Analysis of ISO 28580 Single-Point Data

Dependent Variable: Rolling Resistance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	27	30273.83087	1121.25300	8320.88	<.0001
Error	72	9.70213	0.13475		
Uncorrected Total	99	30283.53300			

R-Square	Coeff Var	Root MSE	RR Mean
0.996745	2.210444	0.367086	16.60687

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Laboratory where Tested	1	0.288688	0.288688	2.14	**0.1476**
Test Sequence	1	0.091518	0.091518	0.68	0.4126
Type (Tire Model)	24	2760.627024	115.026126	853.61	<.0001

Table 11.
SAS GLM Analysis of SAE J1269 Multi-Point Data @ SRC

Dependent Variable: Rolling Resistance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	27	46274.88079	1713.88447	15929.5	<.0001
Error	173	18.61335	0.10759		
Uncorrected Total	200	46293.49414			

R-Square	Coeff Var	Root MSE	rr Mean
0.995958	2.271922	0.328012	14.43763

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Laboratory where Tested	1	11.245985	11.245985	104.52	<.0001
Test Sequence	1	0.232031	0.232031	2.16	0.1438
Type (Tire Model)	24	4574.379431	190.599143	1771.51	<.0001

Table 12.
SAS GLM Analysis of ISO 18164 Multi-Point Data @ SRC

Dependent Variable: Rolling Resistance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	2197.142210	199.740201	2687.60	<.0001
Error	9	0.668873	0.074319		
Uncorrected Total	20	2197.811083			

R-Square	Coeff Var	Root MSE	rr Mean
0.989061	2.637529	0.272615	10.33602

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Type	9	60.15851716	6.68427968	89.94	<.0001
Lab	1	0.31936479	0.31936479	4.30	0.0680

Table 13.
SAS GLM Analysis of Rolling Resistance for J2452 Test – Pounds at SRC and SMERF Values

Dependent Variable: SRC Rolling Resistance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	26	33751.58386	1298.13784	23535.8	<.0001
Error	164	9.04555	0.05516		
Uncorrected Total	190	33760.62941			

R-Square	Coeff Var	Root MSE	SRCRR Mean
0.995310	1.814428	0.234853	12.94362

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Lab	1	41.707153	41.707153	756.17	<.0001
Test	1	1.164989	1.164989	21.12	<.0001
Type	23	1880.549151	81.763007	1482.40	<.0001

Dependent Variable: SMERF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	26	30622.39559	1177.78445	22051.3	<.0001
Error	164	8.75944	0.05341		
Uncorrected Total	190	30631.15503			

R-Square	Coeff Var	Root MSE	SMERF Mean
0.994955	1.874051	0.231109	12.33204

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Lab	1	29.074086	29.074086	544.34	<.0001
Test	1	1.419295	1.419295	26.57	<.0001
Type	23	1699.996725	73.912901	1383.85	<.0001

Table 14.
Grouping of Tires by Rolling Resistance Force – Lowest to Highest

Group #	Population					
	J1269 single-point	**J1269 multi-point@ SRC**	**ISO 28580**	**ISO 18164**	**J2452 @ SRC**	**J2452, SMERF**
1	B11 G8 G11	G11 B11 G8	G8 B11 G11	G11 G8 B11	G11 B11 G8	G11 G8 B11
2	G9 G10 M13 M14 B10*	G9 G10 M14 M13 B10*	G9 M13 M14 G10 B10*	G9 M14 G10	G9 M13 G10 M14 B10*	G9 M13 G10 M14 B10*
3	D10 U3 P5 B14 B15*	U3 D10 P5 B14 B15*	D10 B14 U3 B15* P5	U3 B14	D10 U3 B14 P5 B15*	D10 U3 B14 P5 B15*
4	R4 B13 B12	B12 R4 B13	R4 B13 B12	B13 B12	R4 B12 B13	R4 B12 B13
Passenger Light Truck	↑ Tires ↓ Tires					
5	M10 M12 M11 D8 K4 D7 P4	M10 M12 K4 M11 D8 P4 D7	M10 M12 M11 K4 P4 D8 D7		M12 M10 M11 K4 P4 D8 D7	M12 M10 M11 K4 P4 D8 D7
6	D9	D9	D9		D9	D9
7	C9	C9	C9		C9	C9

*Snow tires