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16. Abstract

Following a 2006 report to Congress on passenger vehicle tire rolling resistance by the National Academies, the agency initiated a research project to evaluate existing tire rolling resistance test methods and to examine correlations between tire rolling resistance levels and tire safety performance. The subsequent Energy Independence and Security Act of 2007 mandated that within 24 months of enactment, the USDOT/NHTSA shall establish a national tire fuel efficiency consumer information program for replacement tires to educate consumers about the effect of tires on automobile fuel efficiency, safety, and durability. Some of the technical challenges involved in development of the new system included: (1) selecting the best rolling resistance test method for a rating program; (2) specifying a test method that avoids variation among test equipment and manufacturers; (3) examining possible tradeoffs between improved tire rolling resistance and tire safety; And (4) determining how to present and disseminate tire rolling resistance information to consumers. This report documents the results of the first phase of the project that used 600 tires of 25 different model/size combinations to evaluate five rolling resistance test methods at two different laboratories. A one-way ANOVA analysis was carried out to evaluate the effects on rolling resistance of tire type, lab-to-lab variability, inflation maintenance, and repeat testing on the same tire.

Results indicated that all of the rolling resistance test methods could be cross-correlated to provide the same information about individual tire types. Within the variables analyzed, individual tire type had the most significant effect on the statistical model. A significant offset occurred in the data generated by the two laboratories used in this study. Therefore, development of a method to account for lab-to-lab data offset is required, either by (1) the use of lab-to-lab correlation equation, based on a reference laboratory, or (2) the use of a Standard Reference Test Tire (SRTT), to normalize data across labs. Considering this factor, the adoption of the ISO 28580 test, which contains a laboratory cross-correlation procedure, is recommended. NHTSA also examined differences resulting from the method of inflation maintenance, specifically whether inflation pressure was capped or regulated. In the capped test, inflation pressure rose as the tire was tested and resulted in slightly lower rolling resistance versus regulated pressure. Finally, two additional tests of the same tire did not produce statistically different values from the first test, indicating that the concept of limited retesting of the same tires for lab alignment or data quality monitoring appears valid.

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Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
km^2	square kilometers	0.4	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

ii

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

EXECUTIVE SUMMARY

The National Highway Traffic Safety Administration evaluated five test methods to measure the rolling resistance of 25 light-vehicle tire models. These test methods included two versions of the SAE J1269 and three additional methods. The methods were:

1. SAE J1269 - Sep 2006-09; Rolling Resistance Measurement Procedure for Passenger Car, Light Truck and Highway Truck and Bus Tires,
    a. Multi-Point,
    b. Single-Point;
2. SAE J2452 - Jun 1999; Stepwise Coastdown Methodology for Measuring Tire Rolling Resistance, Multi-Point;
3. ISO 18164:2005(E); Passenger car, truck, bus and motorcycle tyres -- Methods of measuring rolling resistance, Multi Point (Annex B.4);
4. ISO/DIS 28580; Passenger car, truck and bus tyres -- Methods of measuring rolling resistance -- Single point test and correlation of measurement results, Single-Point.

The test matrix was duplicated at two independent laboratories to study lab-to-lab variability. Tires of each model were purchased with identical or similar build dates and were tested in triplicate in each test method, and in triplicate at each laboratory. Depending on the individual rolling resistance standard, there can be up to four methods allowed for measurement of tire rolling resistance: force, torque, power and deceleration. Of these, the force and torque methods are the most commonly used. One test laboratory used in the study evaluated all five rolling resistance standards on one "force measurement method" test machine. The second test laboratory evaluated SAE J2452 on one "torque measurement method" test machine and the other four methods on a second "force measurement method" test machine. In this study, all work was done using machines with 1.707-m (67.23-in) roadwheels with grit surface, which is typical for the United States. (Internationally some laboratories use a 2-m (78.34-in) roadwheel, often with a bare steel surface.)

NHTSA's evaluation showed that all of the rolling resistance test methods have very low variability and all methods can be cross-correlated to provide the same information about individual tire types. The rank order grouping of tire types was statistically the same for each of the rolling resistance test methods evaluated. However, the relative rankings of the tires within the population of the 25 models tested shifted considerably when tires were ranked by rolling resistance force (RRf) as opposed to rolling resistance coefficient (RRc). 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.

A one-way ANOVA analysis was carried out on the data using the General Linear Models procedure of SAS software to estimate effects on rolling resistance. The independent variables analyzed in this study are tire type (i.e., each individual model), lab-to-lab variability, inflation maintenance, and the effect of repeat testing on the same tire. For all of the variables analyzed, tire type had the most significant effect on the statistical model. There was a significant offset in the data generated by the two laboratories used in this study. Therefore, development of a method to account for lab-to-lab data offset is required, either by; (1) the use of lab-to-lab correlation equation, based on a reference laboratory, or (2) the use of a Standard Reference Test Tire (SRTT), to normalize data across labs. NHTSA also examined differences resulting from the method of inflation maintenance, specifically whether inflation pressure was capped or regulated. In the capped test, inflation pressure rose as the tire was tested and resulted in slightly lower rolling resistance versus regulated pressure for the same tire in the same test. Finally, NHTSA analyzed the effect of repeating tests on the same tire and found that this had little to no effect on test results.

It is recommended that the agency adopt the ISO 28580 single-point test procedure, when issued in its final version, as the standard test for rolling resistance of light vehicle tires. All tests provided equivalent information about the rank-order of tire rolling resistance. A single-point test is the most cost effective option. A major advantage of the ISO 28580 method is the use of defined reference tires to allow comparison of data between labs on a standardized basis. The use of any other procedure 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. Finally, the Commission of the European Communities (EU) has selected ISO 28580 international standard as the basis of their rolling resistance rating system. Use of ISO 28580 would allow international harmonization of US and European test practices.

The next phase of the project will examine possible correlations between tire rolling resistance levels and wet and dry traction, indoor and outdoor treadwear, and vehicle fuel economy as measured on a dynamometer.

DEFINITIONS

SAE – "The Society of Automotive Engineers International is an international standards organization providing voluntary standards to advance the state of technical and engineering sciences." SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel 877-606-7323, www.sae.org

ISO – "The International Organization for Standardization is a worldwide federation of national standards bodies that prepares standards through technical committees comprised of international organizations, governmental and non-governmental, in liaison with ISO." ISO Central Secretariat, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211 Geneva 20, Switzerland, Telephone +41 22 749 01 11, Fax +41 22 733 34 30, www.iso.org

SAE J1269 (REV. SEP2006) – "SAE multi-point standard: Rolling Resistance Measurement Procedure for Passenger Car, Light Truck and Highway Truck and Bus Tires: This procedure is intended to provide a standard method for gathering data on a uniform basis, to be used for various purposes (for example, tire comparisons, determination of load or pressure effects, correlation with test results from fuel consumption tests, etc.)." A single-point test condition (SRC or standard reference condition) is included. The rolling resistance at this condition may be calculated from regression of the multi-point measurements or measured directly at the SRC.

SAE J2452 (ISSUED JUN1999) – "Stepwise Coastdown Methodology for Measuring Tire Rolling Resistance: This SAE Recommended Practice establishes a laboratory method for determination of tire rolling resistance of Passenger Car and Light Truck tires. The method provides a standard for collection and analysis of rolling resistance data with respect to vertical load, inflation pressure, and velocity. The primary intent is for estimation of the tire rolling resistance contribution to vehicle force applicable to SAE Vehicle Coastdown recommended practices J2263 and J2264."

ISO 18164:2005(E) – "Passenger car, truck, bus and motorcycle tires -- Methods of measuring rolling resistance: This International Standard specifies methods for measuring rolling resistance, under controlled laboratory conditions, for new pneumatic tyres designed primarily for use on passenger cars, trucks, buses and motorcycles."

ISO 28580 Draft International Standard (DIS) – "Tyre Rolling Resistance measurement method – single-point test and measurement result correlation – designed to facilitate international cooperation and, possibly, regulation building. Passenger Car, Truck and Bus Tyres: This recommendation specifies methods for measuring rolling resistance, under controlled laboratory conditions, for new pneumatic tyres designed primarily for use on passenger cars, trucks and buses. Tyres intended for temporary use only are not included in this specification. This includes a method for correlating measurement results to allow inter-laboratory comparisons. Measurement of tyres using this method enables comparisons to be made between the rolling resistance of new test tyres when they are free-rolling straight ahead, in a position perpendicular to the drum outer surface, and in steady-state conditions."

Rolling Resistance (Also referred to as "RRF")

Rolling Resistance (F_R) (SAE J1269) – "Rolling resistance of the free-rolling tire is the scalar sum of all contact forces tangent to the test surface and parallel to the wheel plane of the tire."

Rolling Resistance (RR) (SAE J2452) – "Rolling resistance is the energy consumed per unit distance and is equivalent to the scalar sum of all contact forces tangent to the test surface and parallel to the wheel plane of the tire. Units are newtons (lbf)."

Rolling Resistance (F_r) (ISO 18164) – "Loss of energy (or energy consumed) per unit of distance traveled. NOTE: The SI unit conventionally used for the rolling resistance is the newton meter per meter (N m/m).This is equivalent to a drag force in newtons (N)."

Rolling Resistance (Fr) (ISO 28580 Draft) – "Loss of energy (or energy consumed) per unit of distance travelled. NOTE 1: The SI unit conventionally used for the rolling resistance is the newton metre per metre (N m/m). This is equivalent to a drag force in newtons (N)."

Rolling Resistance Coefficient (Also referred to as "RRC")

Rolling Resistance Coefficient (C_R) (SAE J1269) – "Rolling resistance coefficient is the ratio of the rolling resistance to the load on the tire."

Rolling Resistance Coefficient (SAE 2452) – Not used (see MERF/SMERF).

Rolling Resistance Coefficient (C_r) (ISO 18164) – "Ratio of the rolling resistance, in newtons, to the load on the tire, in newtons."

Rolling Resistance Coefficient (Cr) (ISO 28580 Draft) – "Ratio of the rolling resistance, in newtons, to the load on the tire, in knewtons. This quantity is dimensionless."

Mean Equivalent Rolling Force (MERF) (SAE 2452) – "The average rolling resistance of a tire, at a given load/inflation condition, over a driving cycle with a specified speed-time profile. This implicitly weights the rolling resistance for each speed using the length of time spent at that speed during the cycle. For the purpose of this document, MERF is a combined weighting of MERFs calculated using the standard EPA urban and highway driving cycles. Specifically, this weighting is 55% for the EPA Urban (FTP) Cycle and 45% for the EPA Highway Fuel Economy Cycle."

Standard Mean Equivalent Rolling Force (SMERF) (SAE 2452) – "For any tire is the MERF for that tire under standard load/inflation conditions defined in 3.10. For this document, the final SMERF is also calculated by weighting the SMERF obtained for the EPA urban and highway cycles, as discussed previously for MERF calculation."

Illustrative Definitions (A Single Source Referenced)

Loaded Radius (SAE J1269) – "Is the perpendicular distance from the axis of rotation of the loaded tire to the surface on which it is rolling."

Maximum Load (SAE J1269) – "Is the load molded on the tire sidewall and listed as the load limit in the tire load tables of the current Tire and Rim Association, Inc. (T&RA) Yearbook or in corresponding tables published by similar organizations concerned with standardization. For light truck tires, maximum load is defined as the maximum load (or load limit) given for single tire operation. For highway truck and bus tires, maximum load is defined as maximum load (or load limit) given for dual tire operation."

Base Inflation Pressure (SAE J1269) – "Is the inflation pressure corresponding to the maximum load listed in the load in the tire load tables of the current Tire and Rim Association, Inc. (T&RA) Yearbook or in corresponding tables published by similar organizations concerned with tire and wheel technology standardization."

Capped Inflation (SAE J1269) – "Is achieved by inflating the tire to the required pressure prior to testing, while the tire is at ambient temperature of the test area, and then sealing the air in the tire during testing with a valve, cap or some other seal."

Regulated Inflation Pressure (SAE J1269) – "Is achieved by inflating the tire to the required pressure independent of its temperature, and maintaining this inflation pressure during testing." Note: usually performed by using a regulated air (gas) supply external to the spindle or axle and connected with a low friction rotary union.

Standard Reference Condition (SRC) (SAE J2452) – "A single value of tire load, regulated inflation pressure, and speed specified such that tires can be compared at a single condition." (SRC can also be used as the test conditions for a single point test.)

Ambient Temperature (SAE J1269) – "The temperature of the air measured during a rolling resistance test at a fixed location near the tire. The location of the ambient temperature measurement is to be fixed at a lateral distance of 0.4 m (16 inches) from a point on either rim flange farthest from the test surface." (Note: ISO location is 1m from the nearest sidewall plane on the rotational axis.)

Ambient Reference Temperature (SAE J1269) – "All rolling resistance data are referred to an ambient temperature of 24°C (75°F)." (Note: ISO reference temperature is 25°C)

Test Surface – The area of the roadwheel that the tire contacts during the test. The surface is either medium-coarse (80 grit) texture or bare steel.

Skim Test Reading (ISO 18164) – "A parasitic loss measured, in which the tire is kept rolling, without slippage, while reducing the tire load to a level at which energy loss within the tire itself is virtually zero."

Machine Reading (ISO 18164) – "Type of parasitic loss measurement, involving losses of the test machine, exclusive of losses in the rotating spindle bearing, which carries the tire and rim, and aerodynamic losses."

Force Method (ISO 18164) – "The reaction force measured at the tire spindle. This measured value also includes the bearing and aerodynamic losses of the wheel and tire that are also to be considered for further data interpretation."

Torque Method (ISO 18164) – "The torque input measured at the test drum. This measured value also includes the bearing and aerodynamic losses of the wheel, the tire and the drum losses."

Power Method (ISO 18164) – "The measurement of the power input to the test drum. This measured value also includes the bearing and aerodynamic losses of the wheel, the tire and the drum losses."

Deceleration Method (ISO 18164) – "The measurement of deceleration of the test drum and tire assembly. This measured value also includes the bearing and aerodynamic losses of the wheel, the tire and the drum losses."

1.0 INTRODUCTION

Reducing energy consumption is a national goal for many reasons, from economic and national security to improving air quality and reducing green house gas emissions. Also, rising energy prices are having their effect on consumers and businesses, and have contributed to increases in the Consumer Price Index in recent years. Hall and Moreland (2001) define tire rolling resistance "as the energy consumed per unit distance of travel as a tire rolls under load."[1] A vehicle's fuel economy is affected by tire rolling resistance, therefore, fuel saving could be achieved by reducing tire rolling resistance. Low rolling resistance Original Equipment (OE) tires are used by auto manufactures to help meet the federal fuel economy standards for new passenger cars and light trucks. However, consumers often purchase less fuel efficient tires when replacing their vehicle's OE tires, as well as when purchasing the many subsequent sets of replacement tires. For example, during 2007 there were an estimated 51 million OE passenger and light truck tires sold in the US, as opposed to an estimated 237 million replacement passenger and light truck tires.[2] Therefore, the rolling resistance of replacement tires could have a significant impact on the fuel economy of the US light vehicle fleet.

In the Consolidated Appropriations Act of 2004, Congress provided funding through the US-DOT/NHTSA to the National Academy of Sciences (NAS)[1] to develop and perform a national tire fuel efficiency study and literature review.[3] The NAS was to consider the relationship that low rolling resistance replacement tires designed for use on passenger cars and light trucks have on vehicle fuel consumption and tire wear life. The study was to address the potential of securing technically feasible and cost-effective fuel savings from low rolling resistance replacement tires that do not adversely affect tire safety, including the impacts on performance and durability or adversely impact tire tread life and scrap tire disposal, and that does fully consider the average American ''drive cycle''. The study was to further address the cost to the consumer including the additional cost of replacement tires and any potential fuel savings.

The resulting NAS Transportation Research Board report of April 2006 concluded that reduction of average rolling resistance of replacement tires by 10 percent was technically and economically feasible, and that such a reduction would increase the fuel economy of passenger vehicles by 1 to 2 percent, saving about 1 to 2 billion gallons of fuel per year nationwide.[4] The report also 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] Ultimately the "Committee for the National Tire Efficiency Study" of the Transportation Research Board, a division of the National Research Council that is jointly administered by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

One of the primary committee recommendations in TRB Special Report 286 (2006) was[4]:

> "Congress 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, the 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. 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 should include replacement tire fuel efficiency rating system, requirement for providing information to consumers, specifications for test methods for manufacturers, and a national tire maintenance consumer education program.[5] This report documents the first phase of the test program, the evaluation of the tire rolling resistance test methods and their variability. Specifically, 600 tires of 25 different model/size combinations were used to evaluate five different laboratory rolling resistance test methods at two separate labs. Tires of each model were purchased with identical or similar build dates and were tested in multiple times in each test method, and in multiple times at each laboratory. The post-test analysis was to focus on the following areas:

- 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 second test on the same tire
- Select a test procedure that would be best for a regulation
- Investigate methods for reporting the data to consumers

2.0 METHODOLOGY

This study includes the use and evaluation of the four current and one draft tire rolling resistance test methods. 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 even a different number of test points in the set of conditions. The term “single point” refers to a method that uses a single set of test conditions. However, the set of single point test conditions may differ for passenger and light truck tires.

The test methods evaluated were:

1. SAE J1269 - Sep 2006-09; Rolling Resistance Measurement Procedure for Passenger Car, Light Truck and Highway Truck and Bus Tires
    a. Multi Point
    b. Single Point
2. SAE J2452 - Jun 1999; Stepwise Coastdown Methodology for Measuring Tire Rolling Resistance
    a. Multi Point
3. ISO 18164:2005(E); Passenger car, truck, bus and motorcycle tyres -- Methods of measuring rolling resistance
    a. Multi Point (Annex B.4)
4. ISO/DIS 28580; Passenger car, truck and bus tyres -- Methods of measuring rolling resistance -- Single point test and correlation of measurement results
    a. Single Point

2.1 SAE J1269 Multi Point Test

SAE J1269 was originally approved in 1979 as a method of determining rolling resistance at four different load and pressure conditions for Passenger car (P) tires, six test conditions for Light Truck (LT) tires, and five test conditions for truck and bus tires. This study evaluated P and LT tires only, therefore truck and bus test conditions are not considered nor reported. This test method uses a 1.707 m (67.23 inch) roadwheel with grit surface and allows the measurement of rolling resistance by the force, torque or power method. The force method measures the reaction force generated at the axle or spindle supporting the tire specimen. A multi-axis load cell measures the radial load and force tangential to the contact or test surface. With the torque method, a torque cell is located between the drive motor and the roadwheel that measures the input torque required to maintain the roadwheel speed. The power method measures the electrical energy needed to maintain the roadwheel speed. Based on the equipment installed at the two test labs available for this study, all J1269 single and multi-point testing was conducted on machines that utilize the force method of measurement.

In J1269, it is recommended to test in steadily decreasing values of rolling resistance. Generally, tests are conducted in the following order: high load, low inflation first, then low load and high inflation. This test contains Standard and Alternate test plans for Passenger and Light Truck tires. The standard 4-point Passenger (Figure 1) and 6-point Light Truck (Figure 2) test were evaluated in this study. These test procedures were labeled “*J1269_M*”. (Designations ultimately included the lab initials to identify where the data was generated, i.e. "*J1269_M_xxx*" (with the "*xxx*" equal to "*SSS*" for Smithers Scientific Services, Inc. or "*ARDL*" for the test contract consortium of Akron Rubber Development Laboratory, Inc. and Standards Testing Labs). The test load (F_z) is determined from the maximum load molded on the tire sidewall that corresponds to the load rating from Tire and Rim Association (T&RA) tables or other standardizing bodies such as European Tire and Rim Technical Organization (ETRTO), etc. Light Truck tire loads are based on the single tire load listed in the standards or on the sidewall.

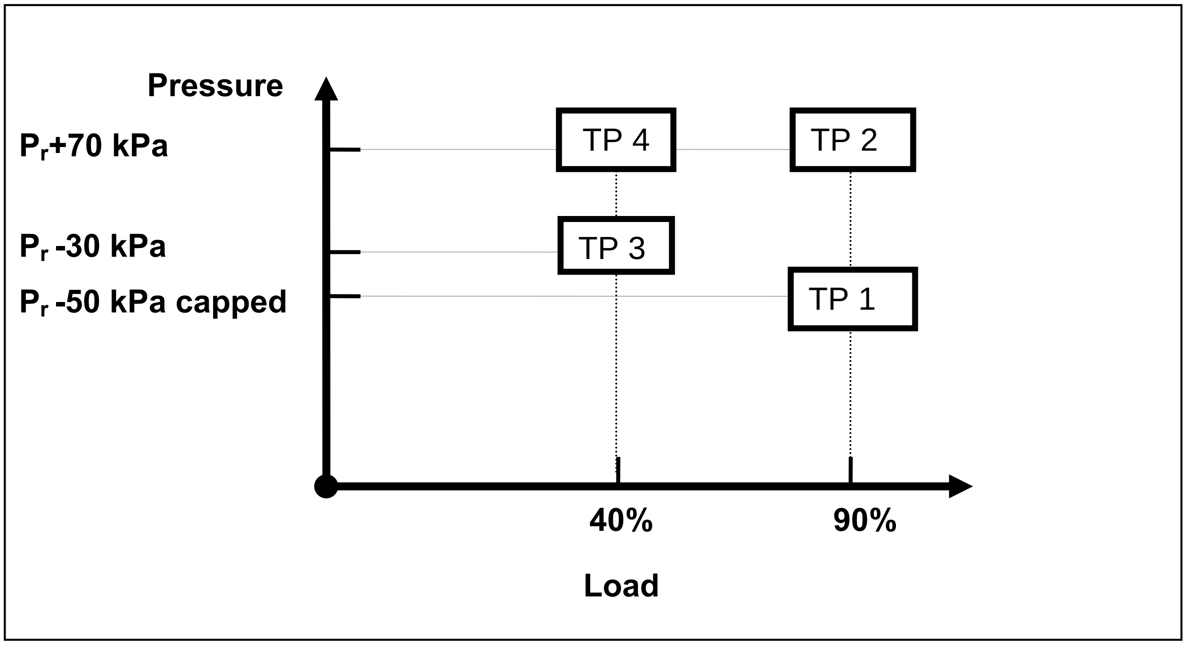


Figure 1. Test Order for J1269 Multi-Point Measurement of Passenger Tires

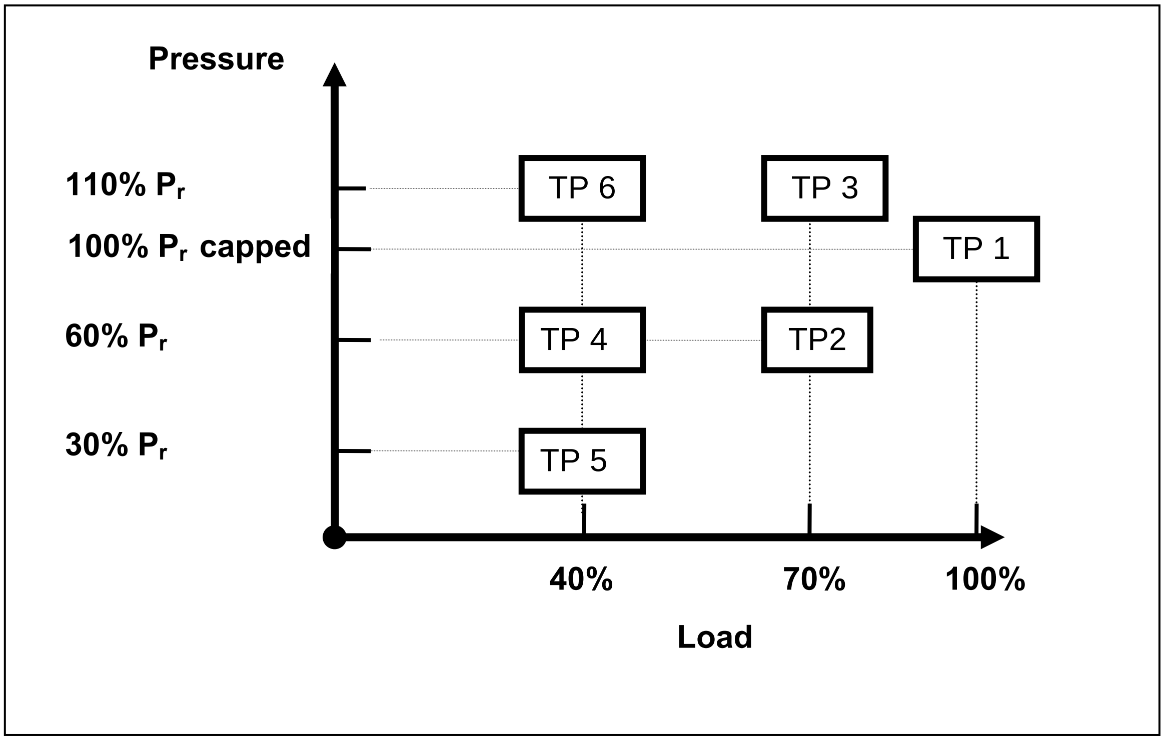


Figure 2. Test Order for J1269 Multi-Point Measurement of Light Truck Tires

The "Alternate" Passenger (4 point) and Light Truck (6 point) test methods were not evaluated, as the major difference in the alternate method is the use of regulated inflation pressure for all test points, including the first one. In the standard J1269 test, the first test point is determined using capped (i.e. sealed) tire inflation pressure set at the ambient laboratory temperature. The use of capped inflation pressure for the first test point is thought to be representative of on-highway operation, during which the initial temperature of the tire's internal inflation gas, and therefore its pressure, will rise during operation. Since different tires may generate different increases in internal temperature, and therefore different increases in internal pressure, the capped pressure rise may affect results. Whereas the use of regulated inflation pressure for the first point of the alternate test results in the increased pressure being bled-off during the test. In both the standard and alternate test approaches, all subsequent test points are conducted with regulated inflation pressure throughout the test (as allowing the tires to cool back down to the ambient laboratory temperature condition between each test point is not practical).

Prior to the 2006-09 version of J1269, the pressure used during the test was the maximum pressure found molded on the tire sidewall. These pressures were not always consistent with the maximum pressures from the standardizing bodies for the maximum load. In September 2006, a revision was made to the Recommended Practice for 2007 version of the SAE Handbook. (It should be noted this change was made after the National Academies (NAS) report was issued.) The change revised the definition of "Base Inflation Pressure" (P_r) to specify the inflation pressure corresponding to the maximum load listed in the tables of current T&RA Yearbook or in corresponding tables published by similar organizations. This meaning of Base Inflation Pressure was used in this study.

2.1.1 SAE J1269 Test Procedure

An optional break-in of 1 hour is used for tires suspected of significant dimensional change at the first test point. This is to stabilize the physical and material properties of the new tire. However, most modern radial tires do not change significantly. Therefore, the optional break-in is not often used and was not used in this study. After the break-in, a 2-hour minimum conditioning period at room temperature is required for Passenger and Light truck tires.

The tire must be in the test environment for a minimum of 2 hours to reach equilibrium temperature before testing. All tires require a warm-up period before the first or only test point. The warm-up time for P tires is 30 minutes, and for LT tires is 60 minutes (which effectively serves as the break-in period for radial tires). Between test points, stabilization times required for the tire prior to data acquisition are 10 minutes for P tires and 15 minutes for LT tires.

The test is then conducted using the specified test points and monitored until steady state is realized before recording gross data. Force method data is taken in clockwise and counter clockwise directions. Direction of the roadwheel may be maintained in one direction through all the steps and then reversed, or alternating clockwise and counterclockwise at each test point can be employed. A typical test sequence is:

Test Plan 1

Break-in tire = 1 hours (tires suspected of significant dimensional change only)

	Cool tire to room temperature = 2 hours
	Set pressure P_{1c}
	Warm-up tire at Fz_1 and P_{1c} = 30 minutes
TP 1	Data run at Fz_1 and P_{1c}
	Warm-up at Fz_2 and P_2 = 10 minutes
TP2	Data run at Fz_2 and P_2
	Warm-up at Fz_3 and P_3 = 10 minutes
TP 3	Data run at Fz_3 and P_3
	Warm-up at Fz_4 and P_4 = 10 minutes
TP 4	Data run at Fz_4 and P_4
	Reduce load and acquire skim (tare) data
Reverse direction	
	Warm-up tire at Fz_1 and P_{1c} = 10 minutes
TP 1	Data run at Fz_1 and P_{1c}
	Warm-up at Fz_2 and P_2 = 10 minutes
TP2	Data run at Fz_2 and P_2
	Warm-up at Fz_3 and P_3 = 10 minutes
TP 3	Data run at Fz_3 and P_3
	Warm-up at Fz_4 and P_4 = 10 minutes
TP 4	Data run at Fz_4 and P_4
	Reduce load and acquire skim (tare) data

Test Plan 2

Break-in tire = 1 hours (tires suspected of significant dimensional change only)

	Cool tire to room temperature = 2 hours
	Set pressure P_{1c}
	Clockwise Direction
	Warm-up tire at Fz_1 and P_{1c} = 30 minutes
TP 1	Data run at Fz_1 and P_{1c}
	Counter Clockwise Direction
TP 1	Data run at Fz_1 and P_{1c}
	Clockwise Direction
	Warm-up at Fz_2 and P_2 = 10 minutes
TP2	Data run at Fz_2 and P_2
	Counter Clockwise Direction
TP2	Data run at Fz_2 and P_2
	Clockwise Direction
	Warm-up at Fz_3 and P_3 = 10 minutes
TP 3	Data run at Fz_3 and P_3
	Counter Clockwise Direction
	Warm-up at Fz_3 and P_3 = 10 minutes
TP 3	Data run at Fz_3 and P_3
	Clockwise Direction
TP 4	Data run at Fz_4 and P_4
	Counter Clockwise Direction
TP 4	Data run at Fz_4 and P_4
	Reduce load and acquire skim (tare) data

Parasitic losses can be determined in two manners: Skim reading and Machine offset reading. To determine the Skim reading the load is reduced to 100N (20 lbf) for P tires and 150 N (35lbf) for LT tires, brought to steady state and data is taken. Skim readings are then subtracted from the test point readings to eliminate the friction of the axle bearings and rotary unions. Machine offset reading is measured by removing the test specimen from the roadwheel and measuring the power or torque required to maintain the test speed. (Note: this cannot be used with the force method). Spindle force must be recorded in both directions at each test point. Data is taken in both rolling directions and averaged to determine the rolling resistance of the tire.

The data reduction is done using the equations found in sections 7.3.1, 7.3.2, and 7.3.3 of the standard. The calculations are:

Force Method (7.3.1)

$$F_R=F_X(1+R_L/R)$$

Where:

F_R = Rolling Resistance, N (lbf)
F_X = magnitude of net tire spindle force, N (lbf)
R_L = Loaded Radius, m (in)

R = test wheel radius, m (in)

Torque Method (7.3.2)

$$F_R = T/R$$

Where T is the net input torque, N·m (lbf·in)

Power Method (7.3.3)

$$F_R = c \cdot P/V$$

Where:

c = 3.60 for speed in km/h
c = 0.503 for speed in mph
P = Net power input, W
V = test surface speed, km/h (mph)

Data adjustment to Ambient Reference Temperature:

$$F_{RR} = F_R\{1 + k(T_A - T_R)\}, \text{ N (lbf)}$$

Where:

F_{RR} = rolling resistance at Ambient Reference temperature, N (lbf)
T_A = average ambient temperature measured at the test point, C (F)
T_R = Ambient Reference Temperature
k = temperature adjustment factor, $0.0060(°C)^{-1}$ or $0.0033(°F)^{-1}$

Data can be directly compared using newtons (N) or pounds force (lbf) for the units. Multiple linear regressions are used to calculate the SRC or F_R at any set of conditions within the tested conditions boundaries. The standard provides a conversion to Rolling Resistance Coefficient (RRc). The RRc is determined by dividing the rolling resistance at ambient reference temperature (F_{RR}) by the load on the tire during the test point. Finally, SAE J1269 has an equation for converting the values from the roadwheel to a flat surface condition if desired. The Clark equation as found in the standard contains a typographical error. What is indicated to be -1/2 should be to the -1/2 power. The correct formula is:

$$F_{Rf} = F_{RW}(1 + r/R)^{-1/2}$$

Where F_{Rf} is the rolling resistance in a flat surface and F_{RW} is the rolling resistance in the roadwheel. The data in this study was not corrected to flat.

2.2 SAE J1269 as a Single Point Test

Included in the J1269 2006-09 version is a "Standard Reference Condition" (SRC) that when calculated from the multiple data points sets a rolling resistance value for each tire. These conditions are compared to the standard J1269 test conditions in Figure 3 and Figure 4 for Passenger and Light Truck tires. This rolling resistance value can then be used to compare tires. To evaluate the possibility using just the SRC load and inflation as a more efficient means of running the test, a modified version of J1269 was evaluated. Data from this set of conditions is labeled "*J1269_S_xxx"* in the report and dataset (with the *"xxx"* equal to "*SSS*" for Smithers Scientific Services, Inc. or "*ARDL*" for the test contract consortium of Akron Rubber Development Laboratory, Inc. and Standards Testing Labs). With exception to using only the single load of 70 percent of maximum and single inflation pressure of Base +70 kPa (2.9 psi), the tests were conducted in the same manner as other J1269 test (i.e. the standard multi-point test). The comparison of the loads, pressure speeds and air control specifics can be found in Table 1 below. In the analysis, the SRC calculated from the multi-point J1269 test was compared to the value measured at the actual SRC test conditions in the single-point J1269 test.

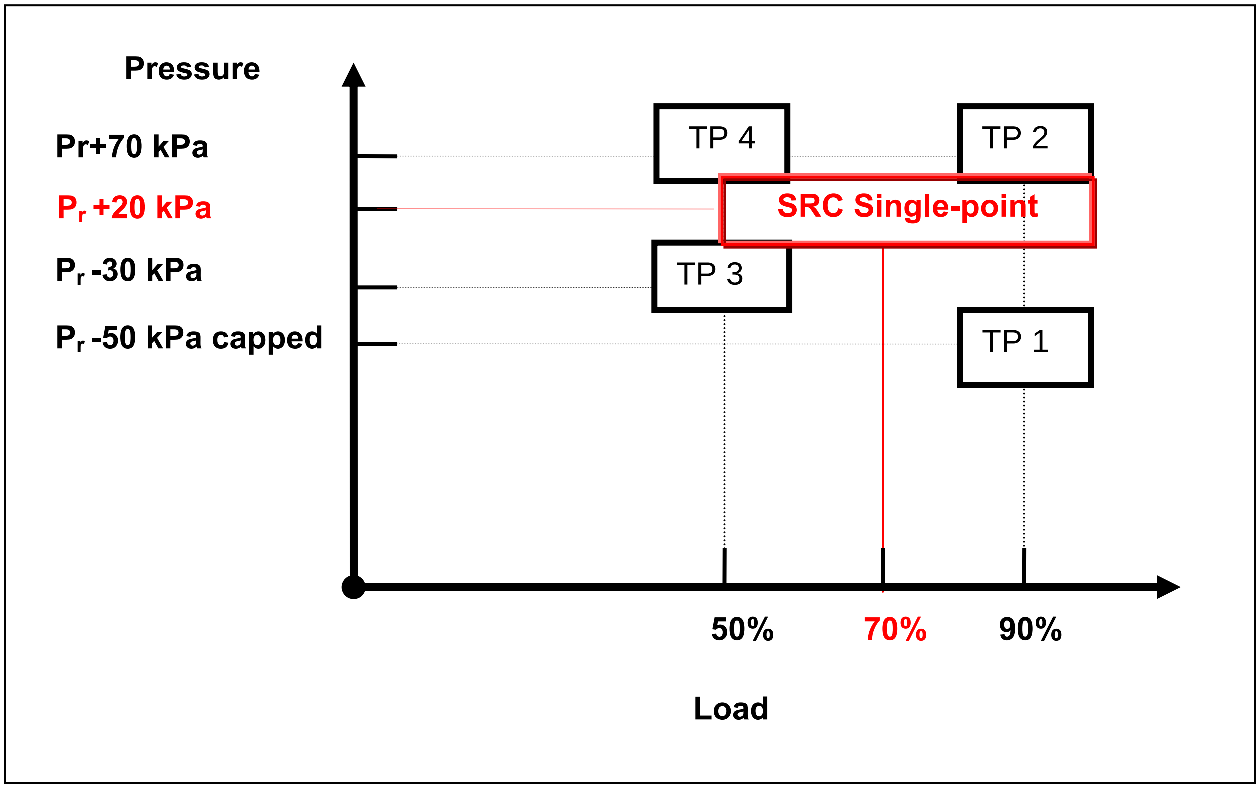


Figure 3. Standard Reference Condition for J1269 Single-Point Test Measurement of Passenger Tires

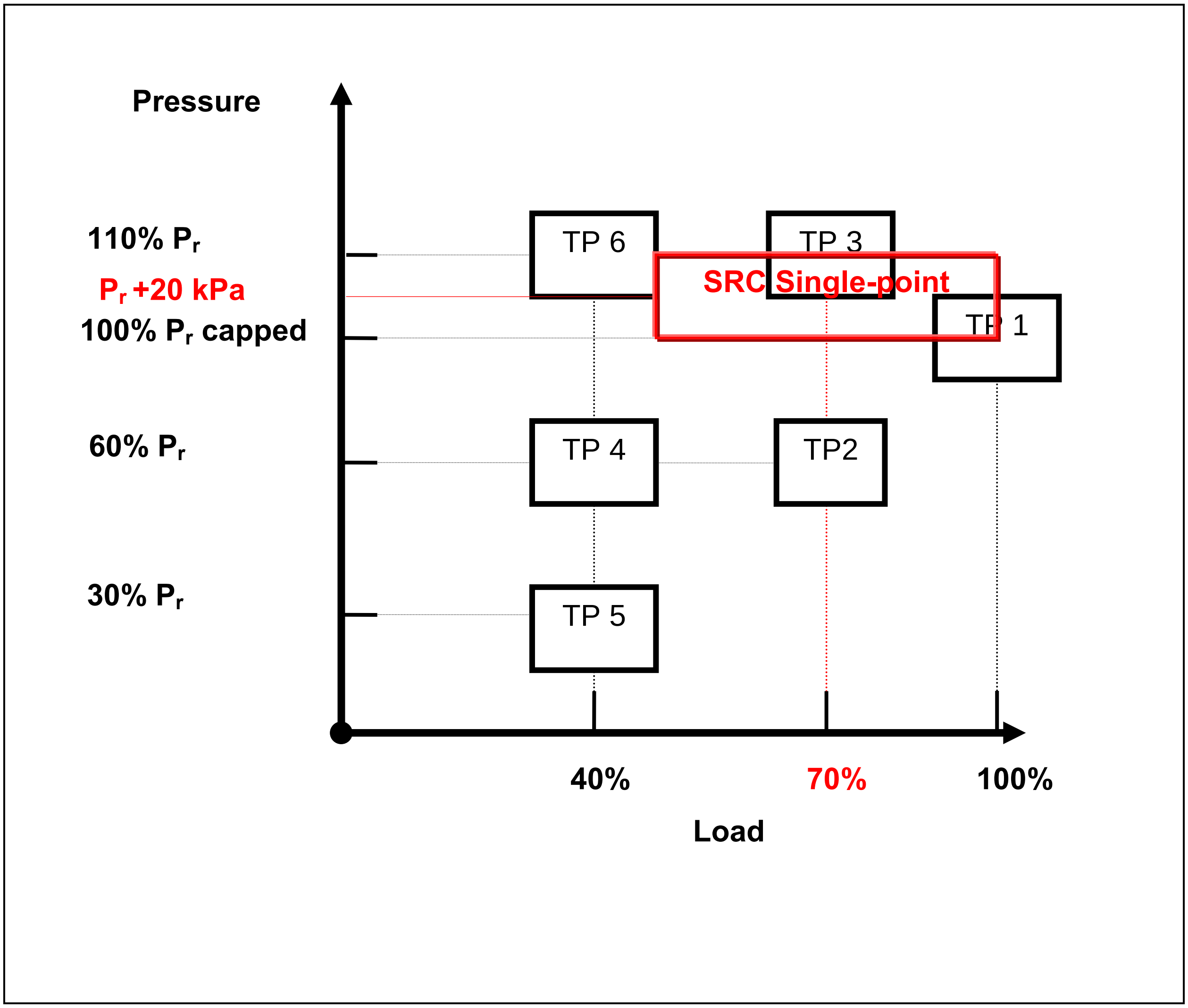


Figure 4. Standard Reference Condition for J1269 Single-Point Test Measurement of Light Truck Tires

Table 1. Test Load and Inflation for SAE J1269 Tests

Test Point Number	Passenger Tires		Light Truck Tires	
	Load	**Pressure**	**Load**	**Pressure**
1	90%	-50 kPa, capped*	100%	100%, capped*
2	90%	+70 kPa	70%	60%
3	50%	-30 kPa	70%	110%
4	50%	+70 kPa	40%	60%
5			40%	30%
6			40%	110%
SRC (single-point condition)	70%	+20 kPa	70%	+20 kPa

* All other test conditions are run with regulated pressure for this test

Though the test speed in J1269 is 80 km/h (50 mph nominal), the two US commercial laboratories use an exact conversion to 49.7 mph (80 km/h). Again, all SAE J1269 testing was completed using machines that utilize the force method of measurement.

Ambient temperature during testing may range from 20 °C (68° F) to 28° C (82° F). An average temperature is measured during the testing. All rolling resistance values must then be adjusted to the Ambient Reference Temperature of 24°C (75° F). The conversion equation can be found in section 7.4 of the standard.

2.3 SAE J2452 Stepwise Coastdown Test

The J2452 Stepwise Coastdown Test Method was developed by tire industry, automotive manufacturers and laboratory representatives in the late 1990's. Popio, J. & Luchini, J. (2007) stated[6]:

> "The SAE undertook the effort to create a transient test procedure for assessing the speed dependence of tire-rolling resistance, and SAE J2452 for measuring tire-rolling resistance was first published in 1999."

This test method is presented by SAE as being "applicable to pneumatic Passenger Car "P" Type, Light Truck Metric, and Light Truck High Flotation tires, or similar tires approved by bodies other than Tire & Rim Association." It is acceptable for use on 1.2 meter (48 in.) or greater roadwheels. In this study, all work was done using machines with 1.707 m (67.23 inch) roadwheels with grit surface, with the exception of limited smooth roadwheel testing to gauge surface effects. The machines at Smithers and STL (ARDL's contract consortium partner) have been in operation for many years and use the force method. An additional machine was installed at STL during the contract period that uses the torque method. Unlike the other test methods, J2452 can only be accomplished on Force or Torque machines. No provision is allowed for Power or Deceleration methods.

As indicated in the J2452 title, the test consists of a coastdown approach where the tire is brought up to an operating speed and then the initial measurement is made, then the roadwheel speed is reduced over a specified period of time and held at the next speed to measure the rolling resistance at that speed. This procedure is repeated until the minimum of six (6) measurements are made. This procedure is followed for four steps (P) and five steps (LT) varying the test load and pressure in each step. The test load is a percentage of the maximum load stamped on the tire sidewall. The Base Inflation Pressure for Passenger tires are:

Table 2. SAE J2452 Passenger Tire Base Inflation Pressures

Inflation Pressure (Marked on tire sidewall) kPa (psi)	Base Inflation Pressure kPa
240 (35) Standard Load	240
300 (44) Standard Load	240
350 (51) Standard Load	350
280 (41) Extra Load	280
340 (49) Extra Load	340

For LT and High Flotation tires, the base inflation pressure is defined as the inflation pressure corresponding to the maximum load for single tire operation, i.e. Load Range E = 550 kPa (79.8 psi).

The standard 4-point Passenger and 5 point LT tests were evaluated in this test program. The test conditions are described in Figure 5 and Figure 6 below. All the data was then corrected to a standard reference temperature of 24°C ±4°C.

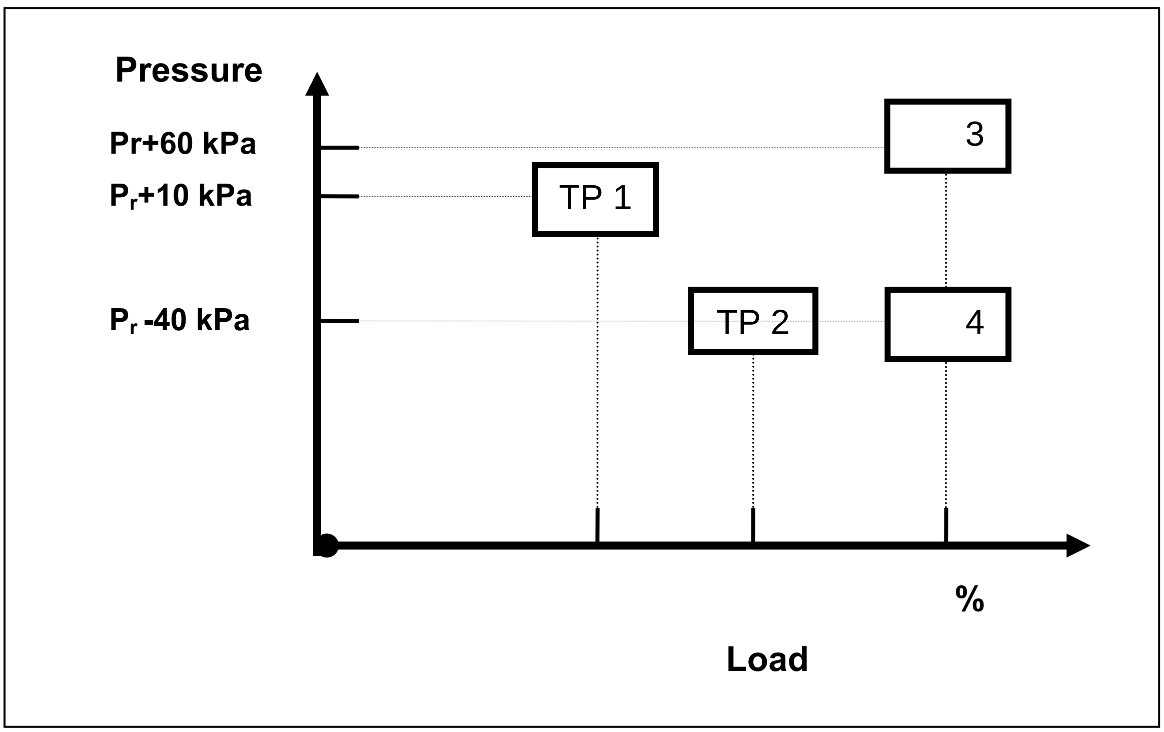


Figure 5. Passenger Tire Measurement Conditions for SAE J2452 Test

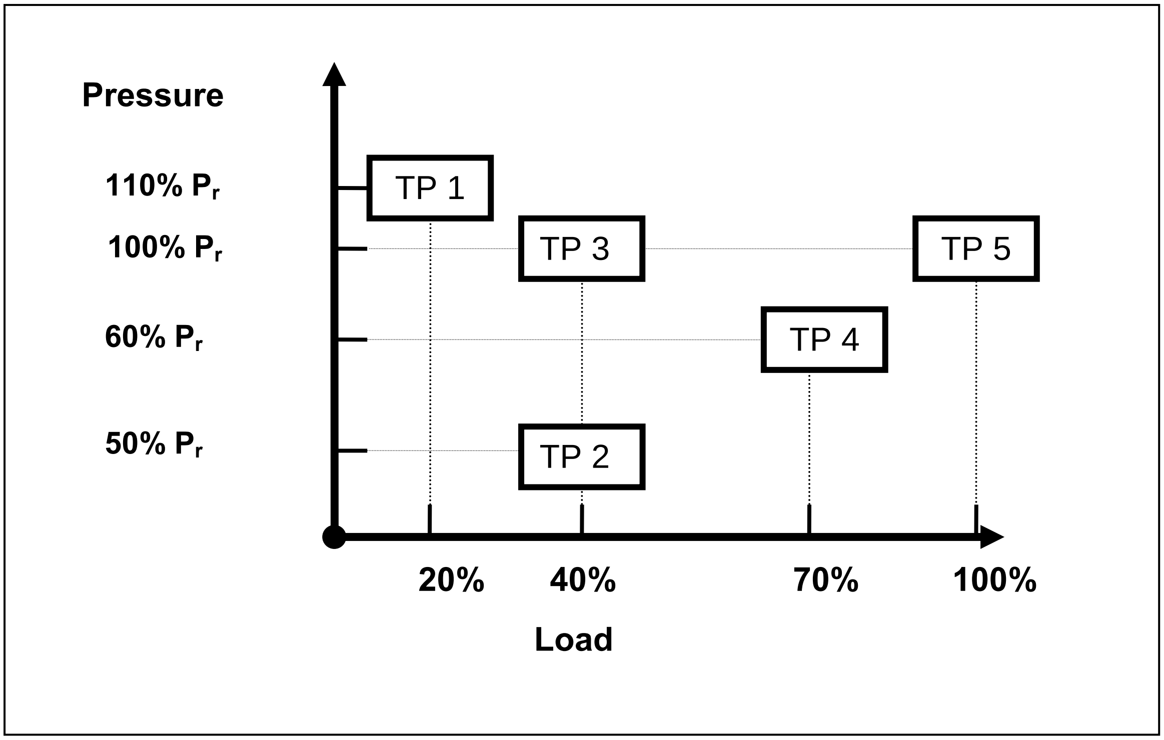


Figure 6. Light Truck Tire Measurement Conditions for SAE J2452 Test

2.3.1 SAE J2452 Test Procedure

The procedure specifies an optional break-in of 1 hour at 80 km/h followed by a cool down period of at least 2 hours for tires known to undergo significant permanent change in their dimensions. An alternative is specified where a tire can be to run the first 30 minutes of operation of the test as adequate break-in for the measurement of a new tire, which is the procedure used for this test program.

The tire is then brought up to equilibrium at a test speed of 80 km/h (50 mph) prior to the beginning of the stepwise coastdown sequence. This warm-up may be accomplished by running the tire at the first load/pressure condition for 30 minutes for the P tires, or 60 minutes for LT tires before acquiring the first Test Point value. Subsequent load/pressure (Test Points) conditions can then be considered to equilibrate when run for 10 minutes for P tires and 15 minutes LT for the next load/pressure combination. When the rolling resistance has stabilized at 80 km/h for the Test Point 1 (TP 1) load and inflation, the roadwheel is accelerated to 115 km/h. The test sequence is started when the speed/load and pressure are stabilized and the first the data are acquired. The roadwheel is then decelerated in less than 60 seconds to the next lower target speed, stabilized and data are taken. This is repeated until the slowest speed data are required. Skim reading and Machine offset values are determined after the test and used in the data reduction.

A very complicated data reduction process is required in SAE J2452. First, a model is developed using the measured data that describes the dependence on load, pressure and speed. Then Mean Equivalent Rolling Force (MERF) (the average rolling resistance of a tire, at a given load/inflation condition, over a driving cycle with a specified speed-time profile) is calculated for each load/pressure test condition. Standard Mean Equivalent Rolling Force (SMERF) for any tire is the MERF for that tire under standard load/inflation conditions defined in Standard Reference Condition table below:

Table 3. SAE J2452 Standard Reference Conditions

	Load	Pressure	Speed
Passenger "P" Tires	70% T&RA 240 kPa	260 kPa	80 km/h
Metric LT	70% T&RA 350 kPa	370 kPa	80 km/h
Flotation LT	70% T&RA 35 psi	260 kPa	80 km/h

Data from this set of conditions is labeled "*J2452_xxx*" in the report and dataset.

2.4 ISO 18164 2005(E) Annex B.4 Multi Point Test

The ISO 18164:2005(E) Annex B.4 multi-point test is very similar to SAE J1269, therefore only the major differences will be discussed. Like J1269, this method has the possibility to measure rolling resistance with the Force, Torque and Power methods. However, ISO 18164 also includes a Deceleration method. During this study, ISO 18164 was only evaluated on machines that utilize the force method of measurement.

ISO 18164 normally specifies a smooth roadwheel 1.5 meter or greater and then uses a 1.7 meter as the reference. ISO 18164 section B.4 specifies the test conditions to be used with the 1.707 m (67.23 inch) roadwheel with grit surface. Testing by Smithers and ARDL-STL were carried out using Annex B.4 of the test method on 1.707 m roadwheels with grit surface.

This method recommends obtaining the test data in increasing values of the rolling resistance for passenger tires, the opposite of J1269. That is the light load/high pressure TP1 is first, followed by decreasing the pressure for TP2, increase the load and pressure for TP3 then decrease the pressure for TP4 completes the order of running the data points. Figure 7 graphically represents this concept.

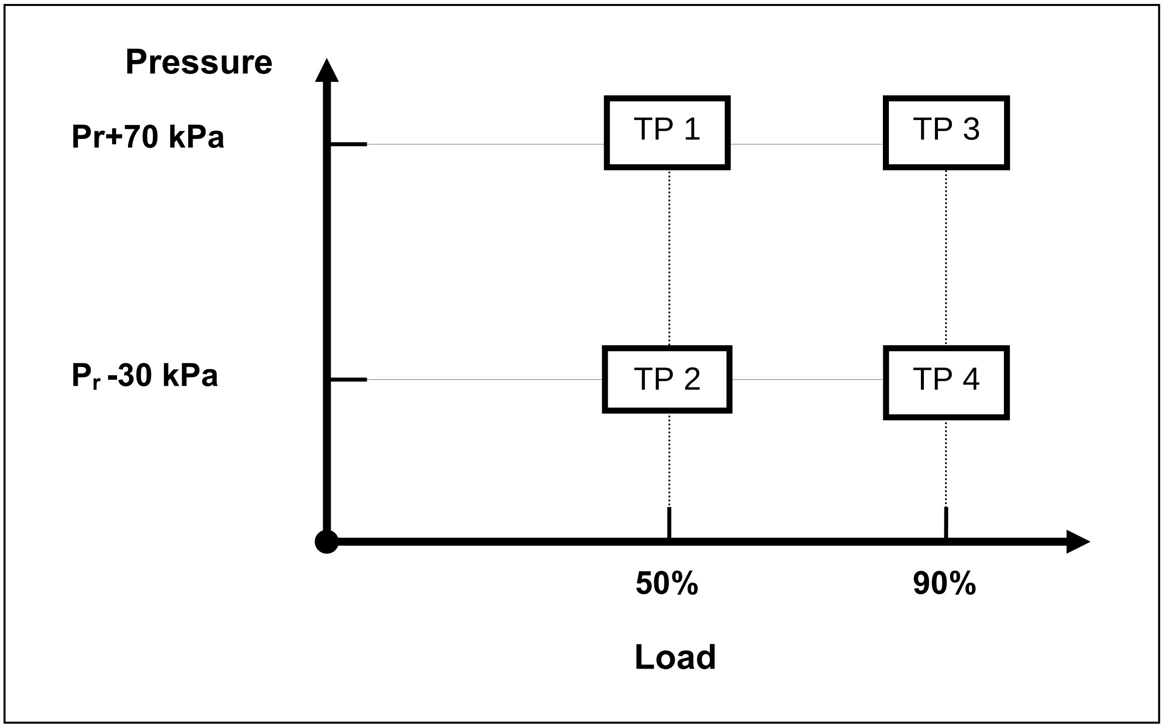


Figure 7. Test Order for Measurement of Passenger Tires Using ISO 18164 Annex B

Light Truck (Load Index less than or equal to 121) does not follow this scheme and includes a fifth data point equivalent to J1269. Figure 8 illustrates the relationships of the loads and pressures used.

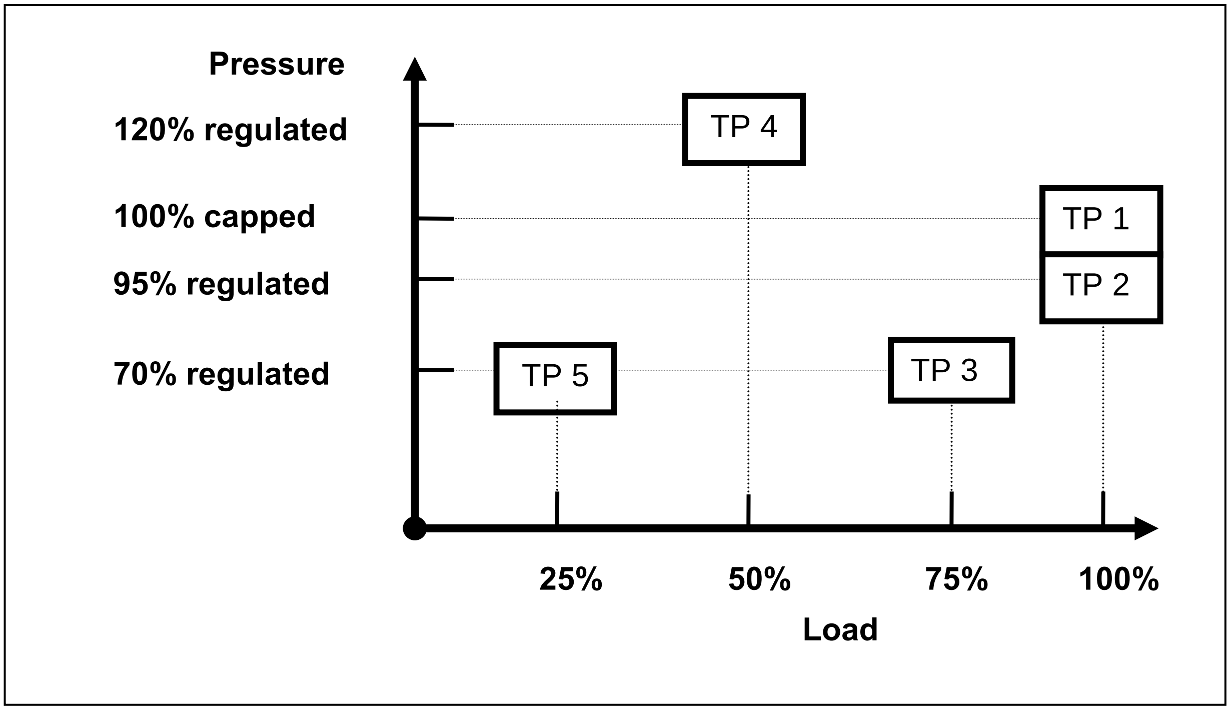


Figure 8. Test Order for Measurement of "C" or LT ≥121 Load Index Tires Using ISO 18164 Procedure

The test load is based on the maximum load for the Li (Load index) of the tire. The inflation pressure is 210 kPa for standard load (SL) or 250 kPa for reinforced (XL) +70 kPa (2.9 psi) or -30 kPa and all pressures are run regulated (per Annex B.4 of the standard) for passenger tires. Light Truck tires are tested in five steps (Annex B.4 of the standard) and are also run regulated. The B2 version of the test uses capped inflation, but it is for smooth roadwheel not used in this study. Multiple speeds are permitted in the test standard. However in this study only 80 km/h (actual is running speed at 80 km/h is 49.7 mph) was examined to provide a direct comparison to the SAE test methods.

Test temperature range is specified as 20°C to 30°C. The test temperature is corrected to 25°C using the formula $F_{r25}= F_r[1+K(t_{amb}-25)]$ where:

F_{r25} is the rolling resistance corrected to the reference temperature
F_r is the rolling resistance, in newtons
T_{amb} is the ambient temperature, in degrees Celsius
K is equal to:
0.008 for passenger tires
0.010 for truck and bus with load index less than 121
0.006 for truck and bus tires with load index 122 and above

2.4.1 ISO 18164 Test Procedure

The procedure follows much the same practice as others with an optional one-hour break-in. The tire must be then conditioned in the test environment for three hours for passenger tires, and six hours for light truck tires, before beginning the testing. Annex B.4 recommends warm-up times based on whether multiple speeds are used or if multiple loads are used in the testing. In this study, multiple loads required a 30-minute warm-up for passenger and 10 minutes between conditions. Light Trucks required 90 minutes for the first data point and 30 minutes between data points. These times assure equilibrium and stabilization of the sample before acquiring data.

The test sequences are then performed in the order as shown in the respective Figure 7 and Figure 9. The same pattern is followed as outlined in SAE J1269. Measurements of the parasitic losses are at skim readings. The force or torque measurements are taken when at the specified reduced load (with no slippage on the roadwheel) and subtracted similar to SAE J1269. The calculations for raw Rolling Resistance value F_r are:

Force Method:

$$F_r = F_t\{1+(r_L/R)\}-F_{pl}$$

Where

F_t is the tire spindle force in newtons
F_{pl} is the parasitic losses
r_L is the distance from the tire axis to the drum outer surface under steady state conditions, in meters
R is the test drum (roadwheel), radius in meters.

Torque Method:

$$F_r = (T_t/R)-F_{pl}$$

Where

T_t is the input torque, in Newton-meters
F_{pl} is the parasitic losses
R is the test drum (roadwheel) radius in meters

From these equations the raw Rolling Resistance value F_r in newtons or pounds are obtained. For reporting purposes, the tire industry prefers to use Rolling Resistance Coefficient (C_r). C_r is calculated with the following formula:

$$C_r = F_r / L_m$$

Where

F_r is the raw rolling resistance data in newtons (N) or pounds (lbf)
L_m is the test load in newtons (N) or pounds (lbf)

There is a drum (roadwheel) diameter correction formula available but since all data in this study were run on 1.707m roadwheel, it is not considered. Consult the test standard for details.

Data from this set of conditions is labeled "*ISO_xxx_M*" in the report and dataset. The test method explains the parameters in more detail than is presented in this report.

2.5 ISO 28580 Single Point Test

At the inception of this study, an advanced copy of the ISO 28580 test standard was provided for evaluation. Since that time, some changes have occurred in the standard being balloted. These items will be addressed by noting how this study was conducted, and if a change has been made it will be noted.

The four types of machines noted in ISO 18164 are also available for use in ISO 28580. The types of methods to measure rolling resistance are Force, Torque, Power and Deceleration. During this, study all ISO 18164 testing was conducted on machines that utilized the force method of measurement.

ISO 28580 specifies a roadwheel of at least 1.707 meters and both smooth and optional grit surface as long as it is kept clean. Testing for this study used a 1.707 m (67.23 inch) roadwheel with grit surface. The Passenger and Light Truck testing was performed at 80km/h as was found in ISO 18164. The single point test load is based on the tire Load index (Li) with SL and XL tires being multiplied by 80 percent. LT or "C" tires have the load adjusted to 85 percent of the Li maximum load. These are shown in Figure 9 and Figure 10 below. The original ISO 18164 test points are included to allow a quick comparison of the relative loads and pressures in ISO 28580.

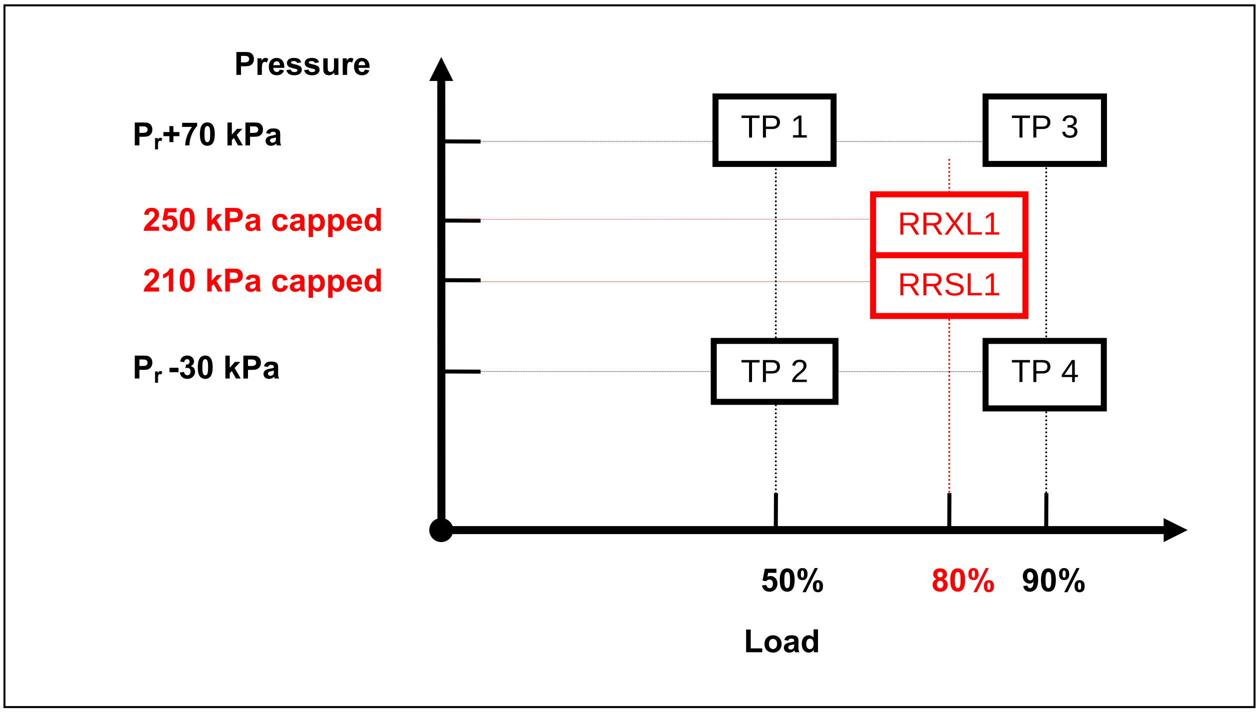


Figure 9. ISO 28580 Test Conditions for Standard Load (RRSL1) and Extra Load (RRXL1) Passenger Tires

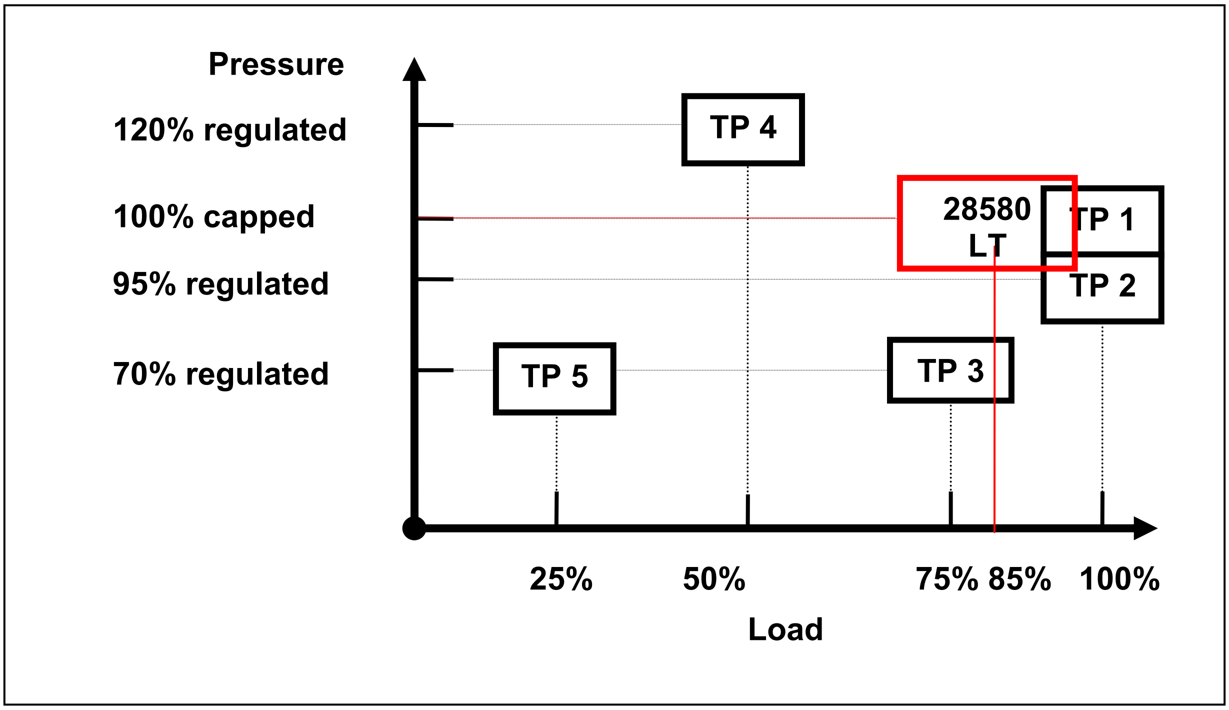


Figure 10. ISO 28580 Draft Standard Test Conditions for "C" or LT, Li ≥ 121 Tires

The Base Inflation Pressure for ISO 28580 does not have the pressure adjustment for testing on the grit surface, as does ISO 18164. The capped pressures are the same as was specified by ISO 18164 for smooth surface roadwheel. The nominal test speed in ISO 28580 is 80 km/h (50 mph nominal). The test temperature range is specified as 20°C to 30°C. The test temperature is corrected to 25°C using the formula $F_{r25}= F_r[1+K(t_{amb}-25)]$ where:

> F_r is the rolling resistance, in newtons
> T_{amb} is the ambient temperature, in degrees Celsius
> K is equal to:
> > 0.008 for passenger tires
> > 0.010 for truck and bus with load index less than 121
> > 0.006 for truck and bus tires with load index 122 and above

2.5.1 <u>ISO 28580 Test Procedure</u>

This procedure varies from all the others in not having an optional break-in. The tire must be in the test environment for 3 hours for passenger tires and 6 hours for light truck tires before beginning the testing. There is a 30-minute warm-up for passenger tires and 50 minutes for light truck tires. These times assure equilibrium and stabilization of the sample before acquiring data. The test sequences are then performed at the load and pressure in Figure 9 or Figure 10. Measurement of the parasitic losses is done by a skim reading. The force or torque measurement is taken when at the specified reduced load and subtracted. A maximum skim load of 200 N and minimum of 150 N for passenger tires, and 200 N to 500 N for LT or "C" tires to LI 121 are to be used in measuring the parasitic losses. The calculations for raw Rolling Resistance value Fr are the same as ISO 18164.

For reporting the Rolling Resistance Coefficient (Cr) is calculated using the formula:

$$Cr = F_r / L_m$$

Where

F_r is the raw rolling resistance data in newtons

L_m is the test load in kilonewtons.

There is a drum (roadwheel) diameter correction formula available, but since all tests in this study were run on 1.707m roadwheel, it was not considered. Consult the test standard for details. The June 2008 version of the DIS (Draft International Standard) will require the Fr or Cr values to be expressed relative to a 2.0-meter roadwheel diameter. Data from this test is labeled "*ISO_xxx*" in the report and dataset. The test method explains the parameters in more detail than is presented in this report.

Laboratory Alignment

ISO 28580 contains a detailed method of lab alignment. The initial draft contained a round robin with 15 tire sizes being sent through a lab certification program. The DIS draft has revised this system. The new system will require two (2) reference tires (currently under development) for passenger and smaller (less than Li 121) LT or "C" tires. The tires will be tested on a reference machine then sent to the candidate lab. The lab will then use these tires to "align" its measurement with the reference lab. The correlation develops an alignment equation to correct the data to the reference lab. The equation is in the following form:

$\mathbf{Cr_{aligned} = A \times Crc + B}$ and is qualified with a standard deviation estimate of σ_m

The reference machine control tire must then be run (3 separate measurements) at a maximum interval of one month to maintain alignment. The full alignment process must be repeated every 2 years.

Table 4. Comparison of the Five Laboratory Rolling Resistance Test Methods Evaluated

	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 ; Coastdowns (115 to 15 km/h range)	
Base Pressure					Molded sidewall load at T&RA pressure		Molded sidewall load at 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)**	
	Load	Pressure	Load	Pressure			Load	Pressure	Load	Pressure
	85%	100 % Capped	100%	100 % Capped			100%	100 % Capped	20%	110 % reg.
			100%	95 % Reg.			70%	60 % Reg.	40%	50 % Reg.
			75%	70 % Reg.			70%	110 % Reg.	40%	100 % Reg.
			50%	120 % Reg.			40%	30 % Reg.	70%	60 % Reg.
			25%	70 % Reg			40%	60 % Reg.	100%	100 % Reg.
							40%	110 % Reg.		

3.0 TEST TIRES

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). The Energy Independence and Security Act (EISA) of December 2007 required that the National Tire fuel Efficiency Consumer Information Program *"apply only to replacement tires covered under section 575.104(c) of title 49, Code of Federal Regulations* (UTQGS)*, in effect on the date of the enactment of the Ten-in-Ten Fuel Economy Act."* Per 575.104(c), the Uniform Tire Quality Grading System (UTQGS) does not apply to deep tread (which is interpreted as light truck tires), winter-type snow tires, space-saver, or temporary use spare tires, or tires with nominal rim diameters of 12 inches or less, or to limited production tires. However, because this research project initiated more than a year prior (July, 2006) to the enactment of EISA, the mix of 25 tire models includes 2 winter-type passenger tire models and 9 light truck tire models.

3.1 ASTM F2493 Radial Standard Reference Test Tire (SRTT)

The ASTM F2493 - *Standard Specification for P225/60R16 97S Radial Standard Reference Test Tire* 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. As can be observed in Figure 11, 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 and UTQGS grades (Table 5). 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.

Figure 11. ASTM F2493-06 Standard Reference Test Tire (SRTT)

Table 5. 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

3.2 <u>Passenger Tire Models</u>

Fifteen DOT-approved passenger tire models were purchased new for testing. Their specifications are detailed in Table 6. The passenger tires were separated into three axes in the test program:

- Axis #1
    - One Manufacturer - Goodyear
    - One Model - Integrity
    - Four Sizes
    - S Speed Rating
        - + One Dunlop[2] (Sumitomo) Run Flat Model

- Axis #2
    - One Manufacturer - Bridgestone
    - Six Models
    - One Size - P225/60R16
    - Q-W Speed Rating

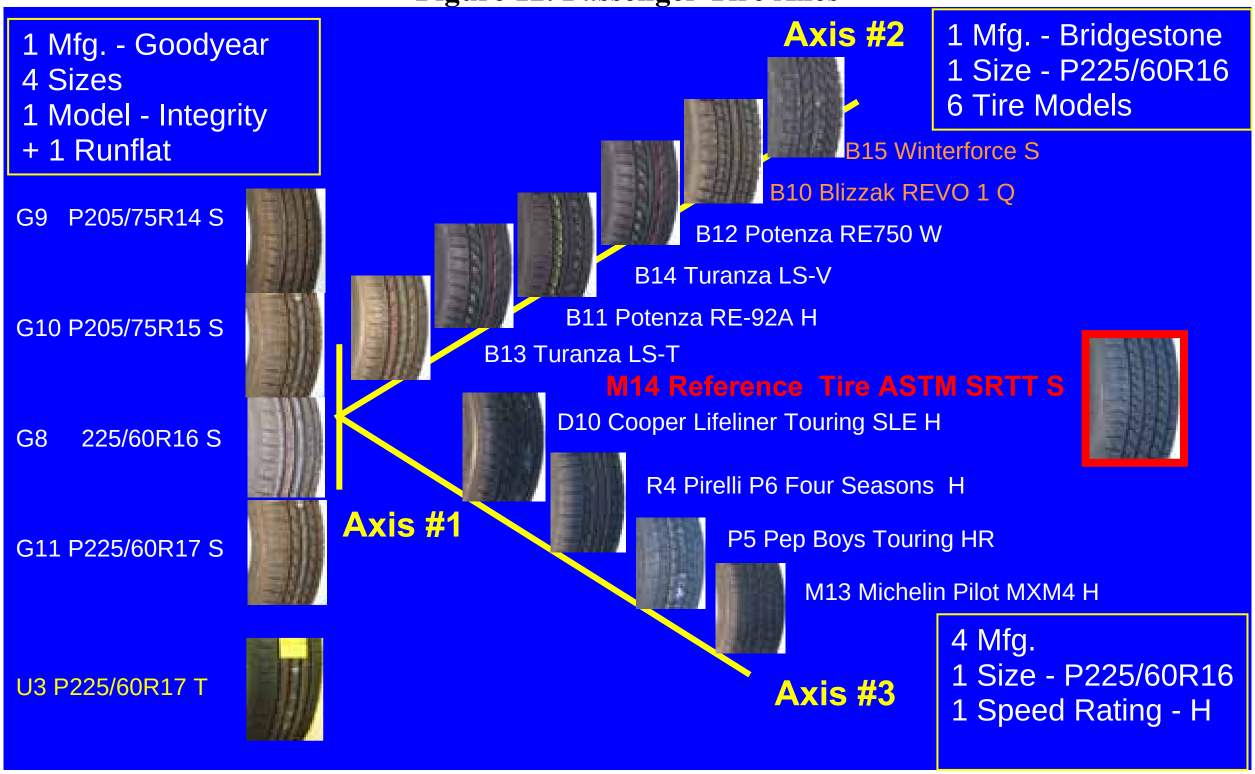
[2] Dunlop brand tires produced in Japan are part of a joint venture between Sumitomo (75%) and Goodyear (25%), and distributed, marketed, and sold by Goodyear in the US market. Therefore, this tire was considered representative of Goodyear and its global partners.

- Axis #3
  - Four Manufacturers
  - One Size - P225/60R16
  - One Speed Rating - H

Table 6. Specifications for Passenger Tire Models

Test Program Axis	Tire Model Code	MFG	Size	Load Index	Speed Rating	Model	UTQGS Tread-wear	UTQGS Trac.	UTQGS Temp.	Performance Level
1	**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
2	**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
	B12	Bridgestone	P225/60R16	98	W	Potenza RE750	340	AA	A	Ultra High Performance Summer
3	**M13**	Michelin	225/60R16	98	H	Pilot MXM4	300	A	A	Grand Touring All Season
	D10	Cooper	225/60R16	98	H	Lifeliner 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

Figure 12. Passenger Tire Axes



3.3 Light Truck Tires

Nine DOT-approved light truck tire models were purchased for testing. Their specifications are detailed in Table 7. The light truck tires were separated into three axes in the test program:

- Axis #4
  - 1 Manufacturer - Cooper
  - 3 Sizes
  - 1 Model - Discoverer ST-C

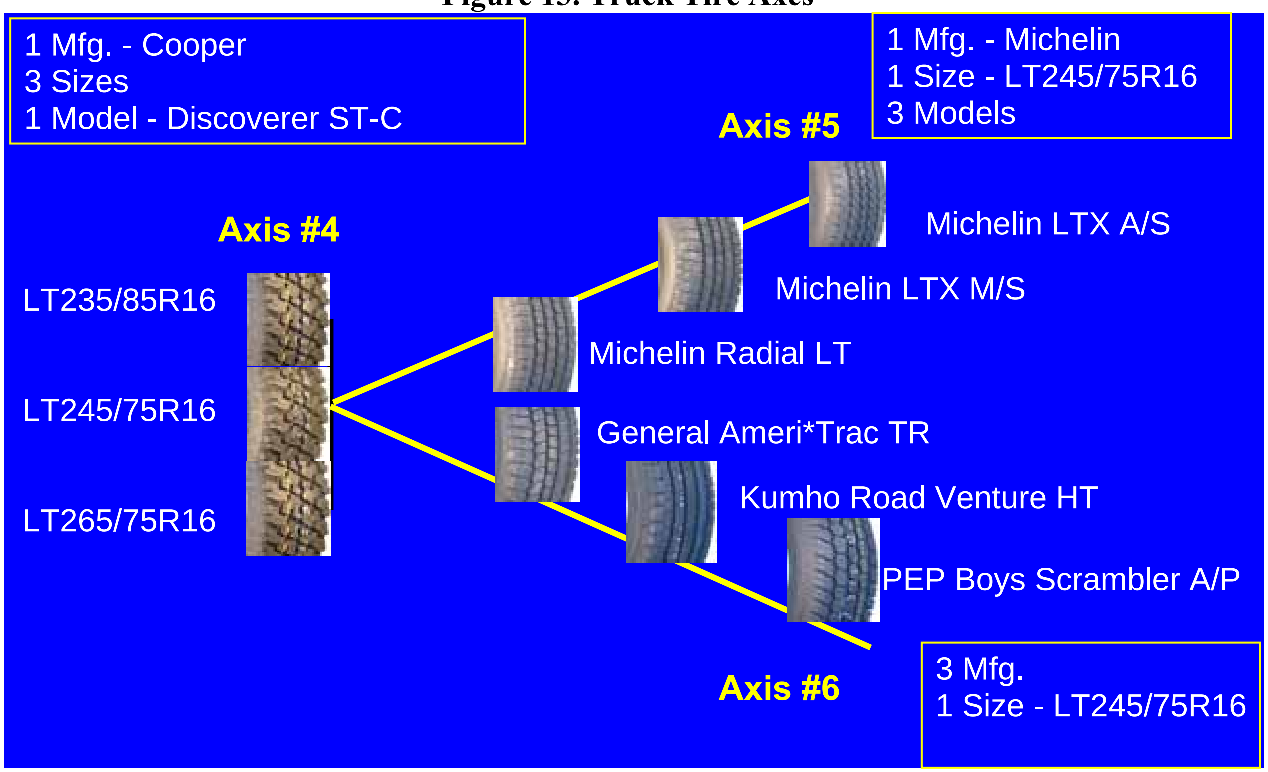
- Axis #5
  - 1 Manufacturer - Michelin
  - 1 Size - LT245/75R16
  - 3 Models

- Axis #6
  - 3 Manufacturers
  - 1 Size - LT245/75R16

Table 7. Specifications for Light Truck Tire Models

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

Figure 13. Truck Tire Axes



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.

4.0 STATISTICAL ANALYSIS

As described, each of the five test methods was used to measure the rolling resistance of the tires in two laboratories. Individual tires were systematically measured as a first test on a new tire, and as subsequent tests on the same tire after measurement on other tests and/or in other laboratories. General Linear Model analysis was carried out on the data using SAS software to estimate effects. An Analysis of Variance (ANOVA) model for the rolling resistance of the tires was carried out for each test using the three main variables of:

1. Tire Type – the model of tire in the study
2. Lab where tested, Smithers or ARDL (STL)
3. Test Order – whether the test was the first, second or third test carried out on a tire

This analysis assumes that the values are normally distributed and that the errors are homogeneous across the variables. No interaction effects were tested in the original analysis. All models produced high R^2 values, above 0.98, and high F values with Probability > F of 0.0001. A general description of the variables analyzed and the effect of each is shown in Table 8. The most significant variable as measured by any test is the tire type (i.e. 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.[3] There was a significant offset between data generated by the two labs used in the study of approximately 5 percent. This offset was not linear with force, nor was it uniform for all tests, showing a complete reversal for one test.

The method of inflation maintenance during the test was measured using the SAE J1269 single-point test. In the capped test, the inflation pressure was set to the specified value during the initial cold inflation of the tire and the pressure inside the tire cavity was allowed to rise during the roadwheel testing. In the regulated procedure, the inflation pressure was maintained at the specified pressure during the test using a rotary union coupling. As expected, the higher pressure inside the tire during the capped test produced slightly lower rolling resistance values. In order to study the feasibility of retesting the same tire periodically as a laboratory control tire, or in a possible dispute of test results, the testing involved the use of the same tire for multiple tests. The effect of test order was estimated by comparing the results of tires tested as a first test with tires of the same type that had been tested previously on other tests or in other labs. One test showed a very slight effect of test order, with a magnitude only slightly more than the random variability. Three tests showed no significant effect.

[3] 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.

Table 8: Variables Analyzed in Study and General Comments on Significance

Variable	Significance of Effect	Comments
Tire Type	Very High	Rank ordering of tires shows significant separation of tires by group using any test
Laboratory	High	Smithers showed higher results on four tests and lower results on one test than STL
Inflation Maintenance, (Capped vs. Regulated)	Significant	Only measured on SAE J1269 single-point test
Test Order (First vs. Subsequent Tests)	None/Slight	Three tests showed no statistical significance, one test showed significance with a very small effect, and one test could not be analyzed due to data covariance

Table 9 compares the variability for the six standard measures of rolling resistance studied using the five test methods. Variability of the tests is very low, as evidenced by the coefficient of variation (C.V.) values of approximately 2 percent. The potential for discrimination is an estimate of the ability of a test measure to classify the entire range of data for the tires of the study 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, the maximum number of groups that the 25 tire models could be divided into ranged from five to six.

Table 9. Variability and Discrimination of Tests for Rolling Resistance of Passenger Tires

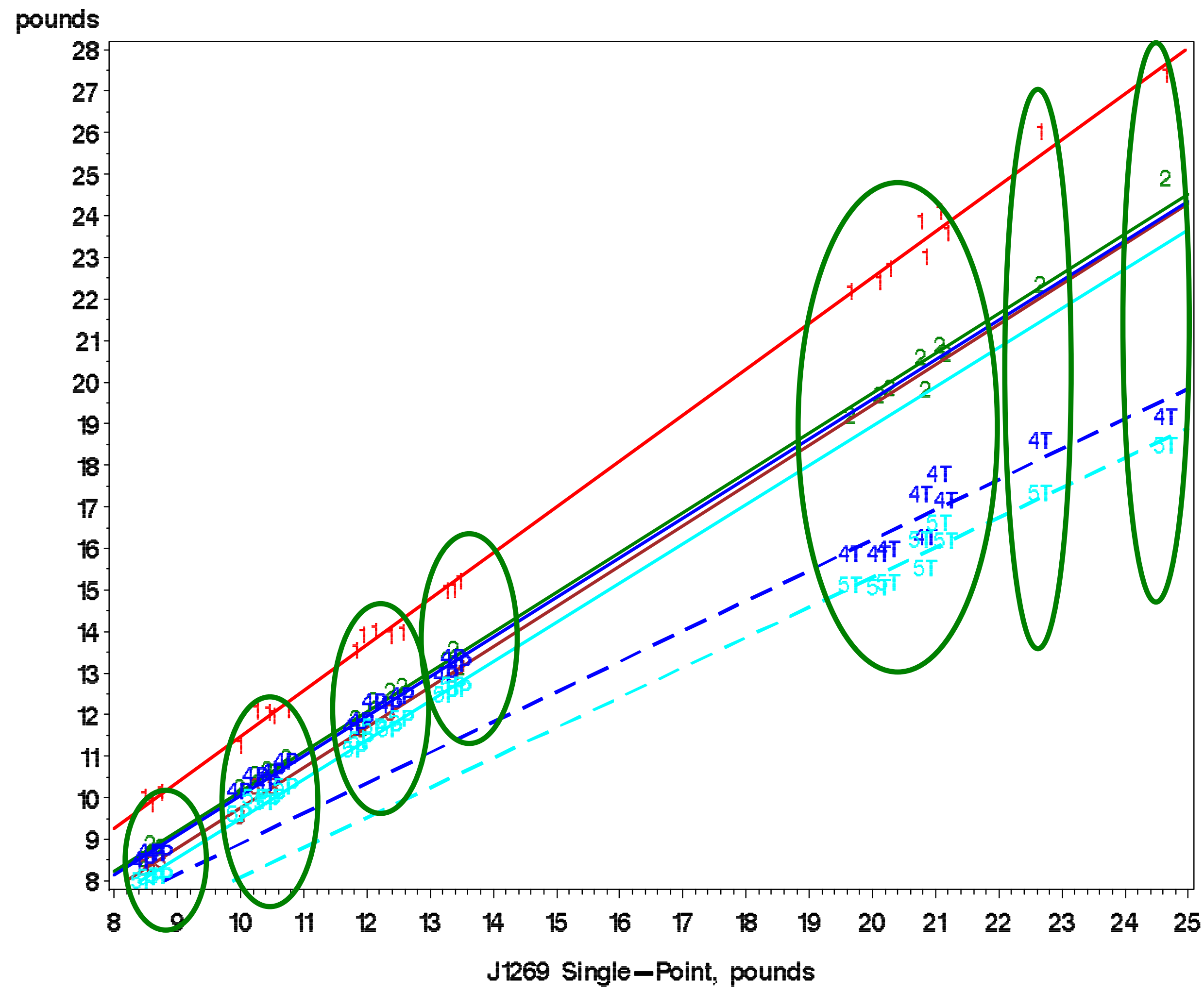
Test	C.V. (%)	Range of Data Means[4]	Potential for Discrimination (Passenger Tires)
SAE J1269 Single-Point	2.37%	4.99	5
ISO 28580 Single-Point	2.21%	5.38	5
SAE J1269 Multi-Point (calculated at SRC)	2.27%	5.06	5
ISO 18164 Multi-Point[5]	5.25%	4.87	3
SAE J2452 (calculated at SRC)	1.81%	4.89	6
SAE J2452 (SMERF)	1.87%	4.70	6

Based on the low C.V. of each test and the range of data, it appears that any of the tests could be selected to distinguish the rolling resistance values of the tires selected for the study. The test protocols involved different load, inflation, and speed conditions, and it is known that changes in any of these conditions produce different rolling resistance values. Additionally, some values are directly measured, while others are estimated from regression of the data. Thus, the next step in the analysis was to determine if the tests are measuring the same property of the tires, or if the reported rolling resistance is unique to the test conditions or calculations used to generate the response surface.

[4] Passenger tires only; (maximum mean value – minimum mean value) of tires in study.
[5] Only 10 passenger tires tested.

The values in Figure 14, showing the pounds force of rolling resistance for each test plotted versus the pounds force found on the SAE J1269 single-point test, appear to be divided in seven groups. It is clear that there is a linear relationship between each test and the SAE J1269 test. If each group contains the same tires tested by each of the different tests, it can be assumed that the tests are all measuring the same property of the tire. The population of the circled groups, numbers 1 through 7 from left to right (lowest to highest rolling resistance), are shown in Table 10. The tires are listed in order of rolling resistance force values for each test individually. All groups contain the same tires no matter which test was used to rank order the tires. However, the rank ordering of individual tires within a group can change from test to test and are within the expected variation of the tests. It should be noted that the rolling resistance values of tires are a continuous function. Therefore, the group divisions are shown to reinforce the consistency between the tests, and should not be construed as representing groupings of the entire population of tires.

Figure 14. Relationship between Rolling Resistance Values for All Tests



1 = ISO 28580 single-point value

2 = SAE J1269 multi-point value at SRC

3 = ISO 18164 value at SRC

4P = SAE J2452 value at SRC, Passenger Tires

4T = SAE J2452 value at SRC, Light Truck Tires

5P = SAE J2452 SMERF value, Passenger Tires

5T = SAE J2452 SMERF value, Light Truck Tires

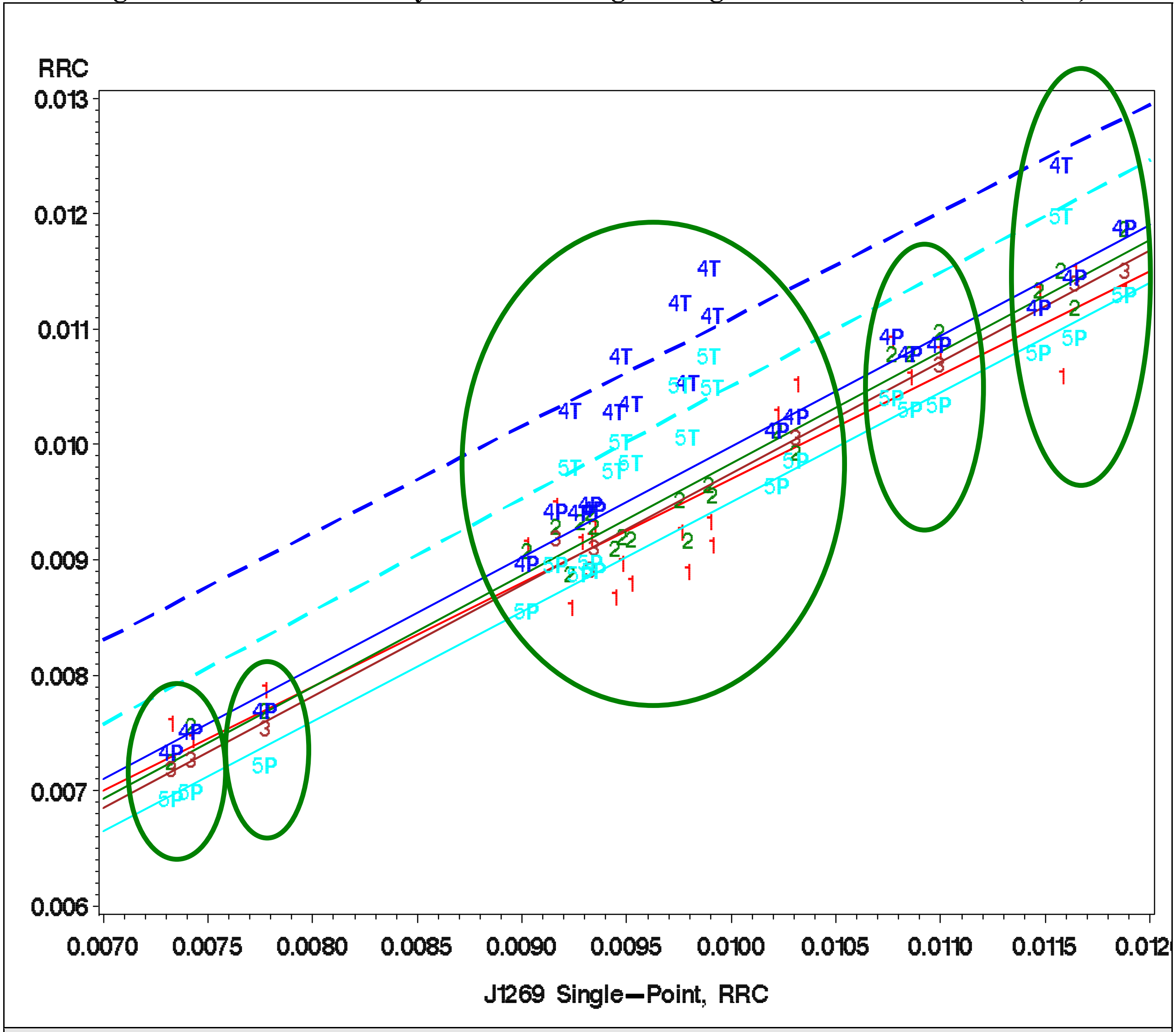
Table 10. Grouping of Tires by Rolling Resistance Force – Lowest to Highest

Group	Population					
	J1269 single-point	J1269 multi-point at SRC	ISO 28580	ISO 18164	J2452 at 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

Figure 15 shows the rolling resistance coefficient values plotted versus the RRc for the J1269 single-point test. These data can be divided into 5 groups. Again, each group contains the same tires no matter which test is used to rank the tires. We may conclude that the tests have nearly equal ability to discriminate between tires, and that all tests are measuring the same property of the tires in the study, within the error limit of the individual test. 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 rolling resistance force (RRf) as opposed to rolling resistance coefficient (RRc).

Figure 15. Tires Ranked by All Tests Using Rolling Resistance Coefficient (RRc)



1 = ISO 28580 single-point value
2 = SAE J1269 multi-point value at SRC
3 = ISO 18164 value at SRC
4P = SAE J2452 value at SRC, Passenger Tires
4T = SAE J2452 value at SRC, Light Truck Tires
5P = SAE J2452 SMERF value, Passenger Tires
5T = SAE J2452 SMERF value, Light Truck Tires

For any given test, there was a significant offset between the data generated by the two labs used in this study. This offset was not consistent between tests, or even between tire types within the same test in some cases. If a test is to be used to compare the rolling resistance of tires tested at different facilities and at different times, some method to account for this offset needs to be developed. One possible method is to develop a lab-to-lab correlation equation that converts the data obtained at an individual lab to the numbers expected to be attained by a reference laboratory. This method was used to correct the data to that expected from a single lab (Smithers, in this case). There is evidence that a single equation for all tire types may not be sufficient to correct data for all tires. Table 11 shows the equations developed from linear regression models to equate ARDL-STL pound force values to those values expected from Smithers. All models produced a good fit with R^2 values greater than 0.97. Thus, the models can be used to accurately correlate the values obtained in the two laboratories in this experiment. No data is available from this study to determine if a lab-to-lab correlation developed at a given time would remain constant over time, or if offsets and/or drifts will occur in a lab that will require additional standardization procedures to be employed. The intercepts range from nearly zero to ±10 percent of the average force value, and the slopes range from +0.9 to +1.17. Analyses of the residual values from the models showed no significant trends for test order. The residuals showed some correlation to rolling resistance values, and a slightly better fit was found for a second-order fit. Qualitatively, the data from Smithers was approximately 0.5 pounds higher than the data from ARDL-STL for three test procedures, and was approximately 0.5 pounds lower than the data from ARDL-STL for one test procedure.

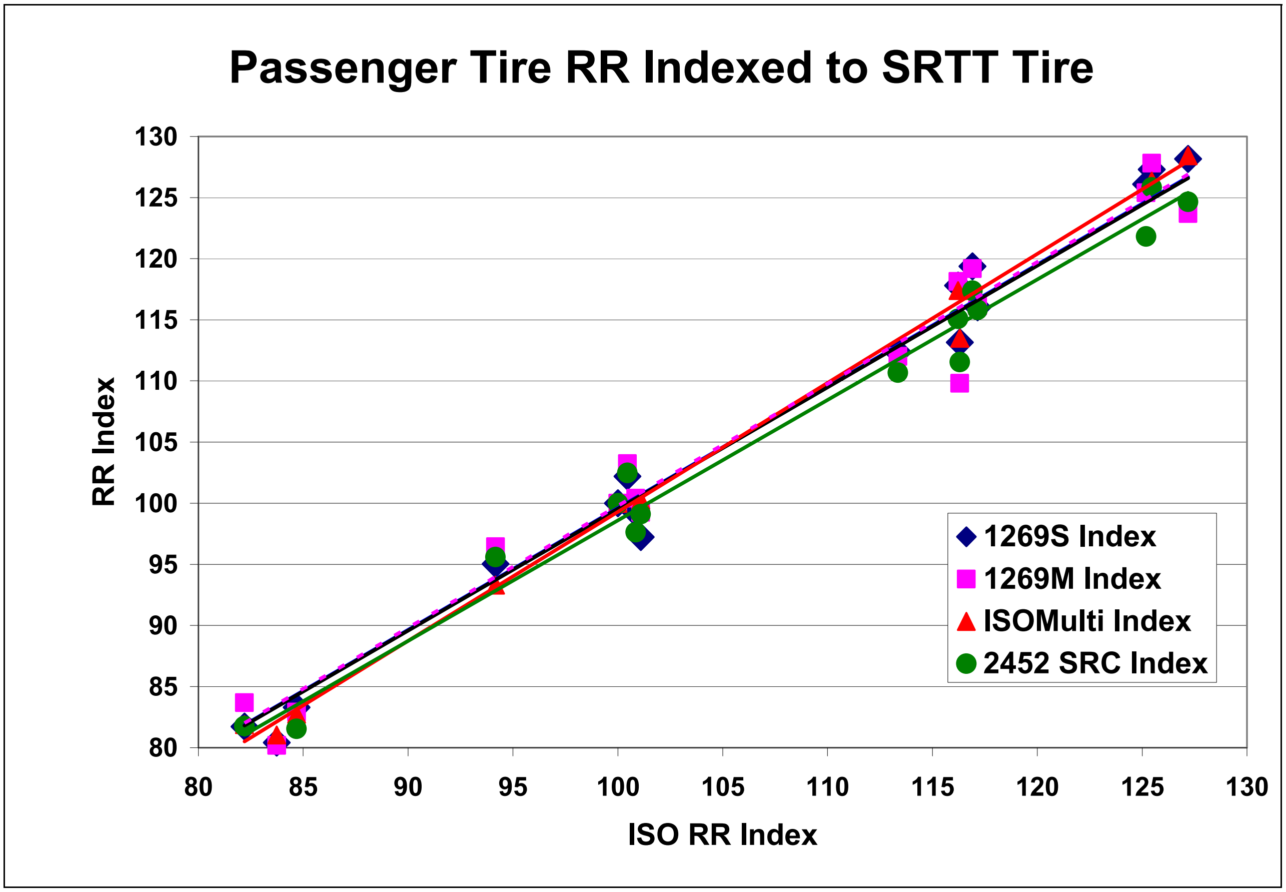
Table 11. Correlation Equations for Conversion of Pounds Force Values Obtained at ARDL-STL to Estimated Smithers Lab Data

Test	Tire Types	To Convert ARDL-STL Value (A) to "Smithers Value" (S)
SAE J1269 Single-point	All	S = 0.2568 + 1.0239*A
ISO 28580 Single-point	All	S = -0.0994 + 1.0120*A
SAE J1269 Multi-point at SRC	All	S = -1.7463 + 1.1732*A
ISO 18164 Multi-point at SRC	Passenger	[6]S = 0.7139 + 0.9076*A
SAE J2452, Calculated SRC Value	All	S= -0.02306 + 1.0769*A
SAE J2452, SMERF Value	All	S= -0.1425 + 1.0772*A

Tire M14, the Standard Reference Test Tire (SRTT) manufactured according to ASTM F2493-06, was included in all aspects of the study. The linear relationships between labs, and between all tests for passenger tires, indicates 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). Figure 16 shows the RRIndex from the three SAE tests versus the RRIndex for the ISO 28580 test. The correlations for the SAE tests are nearly identical, unlike those using pounds force or RRc. More importantly, both labs now have a linear one-to-one correlation for each test, with an average of 1.0022, and a standard deviation within the limits of the accuracy of the test. Normalization to the SRTT value is therefore 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. For passenger tires, normalization of RRc data to the RRc of the SRTT could also be completed. Since this data set contains nearly all the same size passenger tires, and were therefore tested at nearly the same load, no substantial conclusions could be drawn about any advantages or disadvantages for this calculation.

[6] Values may be confounded with order of test as a variable.

Figure 16. Passenger Tire Rolling Resistance by Various Tests Indexed to ASTM F2493 SRTT



4.1 Individual Tests

This section of the report will analyze each rolling resistance test individually. Later sections will compare the various methods.[7]

4.1.1 SAE J1269 Single-Point Method

The J1269 single-point method is run at the Standard Reference Condition (SRC), which began as a calculated value from the regression of the response for SAE J1269 multi-point test. The method was modified in 2006 to add single-point testing at the SRC conditions. The test is run on a 1.707-meter roadwheel with an 80-grit surface at the following conditions: 24° C reference temperature, 80 km/h (50 mph), 70 percent of tire sidewall load, and the pressure corresponding to the maximum rated load +20 kPa inflation. The pressure is regulated during the normal test to maintain constant pressure during the test. A subset of tires was run using capped inflation dur-

[7] All comparisons carried out at the default level of α=0.05 and β=0.15 unless otherwise indicated.

ing the test, during which the pressure is allowed to rise as the tire temperature increases due to the heat generated by the tire under dynamic rolling load.

The tests used for comparisons of tires are shown in Table 12. Six tires of each model were used for a minimum of eight tests and a maximum of ten tests for each model to compare lab-to-lab, regulated versus capped, and first versus subsequent test conditions. A SAS General Linear Model (GLM) analysis was carried out on the data set and the results are shown in Table 13. 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 above 0.950 are considered significant. The F Value of 15122 for the model and the R^2 of 0.996 indicate that the majority of the variation is accounted for by the model.

The influence of each factor is shown by the Sums of Squares for the individual terms, their significance is shown the Pr > F, where a Pr > F less than 0.050 is considered significant. The Sums of Squares for the individual terms indicate that Tire Type (Tire Model) is the major factor determining the rolling resistance followed by the significant terms of Laboratory and Procedure (capped versus regulated). Test sequence (whether tested first, second or third) is not a significant variable. Since all capped tires were run by ARDL-STL, the GLM model for these tires was run only comparing the capped tires to the tires run at ARDL-STL. 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 0.0002. 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.

The predicted mean value for the tires tested using the regulated procedure in the Smithers laboratory was 53.07 N (11.93 pounds) versus 51.02 N (11.47 pounds) for those tested by the ARDL-STL laboratory, with a Pr > F of 0.0001. The mean predicted values are 53.11 N (11.48 pounds) for the first test and 52.93 N (11.44 pounds) for subsequent tests. Again, the test order was not a significant variable in the model. The predicted Coefficient of Variation for the test method is 2.4 percent. Table 14 shows the rank order of the mean predicted rolling resistance in pounds for the 25 tire models studied. The Duncan multiple means comparison, produces five distinct groups for the Light Truck (LT) tires at forces from 87.2 N to 109.4 N (19.6 to 24.6 pounds) and four distinct groups for the passenger tires which range from 37.8 N to 60.0 N (8.5 to 13.5 pounds) force. The rolling resistance is often reported as the Rolling Resistance Coefficient (RRc) which is the rolling resistance divided by the normal load, in the same units. Table 15 shows the rank order for the RRc of the 25 tire models. The Duncan procedure produces seven distinct groups ranging from RRc values of 0.00733 to 0.01188. The values for the LT and passenger tires are interspersed. Significantly, a group of nine tires, group G-H-I-J-K, contains four light truck tires and five passenger tires with RRc values ranging from 0.00903 to 0.00952.

Table 12. Comparisons for 25 Models of Tires, SAE J1269 Single-Point Test

Comparison	Variables	Number of Tires	Notes:
Laboratory- Laboratory Standard Test	ARDL-STL Smithers	55 75	Tires used for second test
Inflation Pressure during Test	Regulated (standard) Capped	*130*[8] 20	Selected Passenger Tires Tested at ARDL-STL
Repeat Testing (Regulated Test)	First Test Subsequent Tests	*130* 70 (at same lab or opposite lab, regulated test)	Includes capped tires used for subsequent test
Laboratory- Laboratory All Tires	ARDL-STL Smithers	*120 (4 regulated + capped for selected models)* *100 (4 regulated per model)*	

Table 13. SAS GLM Analysis of SAE J1269 Single-Point Data

```
Dependent Variable: Rolling Resistance
                                          Sum of
       Source                   DF        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
```

[8] Numbers shown in italics are previously listed tests used for this comparison.

Table 14. Duncan's Multiple Range Test for Rolling Resistance in Pounds – SAE J1269 Single-Point Data

Alpha	0.05
Error Degrees of Freedom	195
Error Mean Square	0.127599
Harmonic Mean of Cell Sizes	8.72093

Number of Means	2	3	4	5	6	7	8	9	10	11	12	13
Critical Range	.3374	.3551	.3670	.3757	.3825	.3880	.3926	.3965	.3999	.4029	.4055	.4078

Number of Means	14	15	16	17	18	19	20	21	22	23	24	25
Critical Range	.4099	.4119	.4136	.4152	.4167	.4180	.4193	.4204	.4215	.4225	.4235	.4243

Means with the same letter are not significantly different.

Duncan Grouping		Mean, lbs-force	N	Type
	A	24.6555	8	C9
	B	22.6702	8	D9
	C	21.1789	8	P4
D	C	21.0732	8	D7
D	C	20.8553	8	K4
D		20.7798	8	D8
	E	20.2781	8	M11
	E	20.1117	8	M12
	F	19.6613	8	M10
	G	13.4712	10	B12
	G	13.3798	10	B13
	G	13.2730	9	R4
	H	12.5653	9	B15
I	H	12.3812	10	B14
I	J	12.1272	10	P5
	J	11.9331	8	U3
	J	11.8281	9	D10
	K	10.7414	10	B10
L	K	10.5261	9	M14
L	K	10.4436	9	M13
L	M	10.2535	8	G10
	M	10.0030	9	G9
	N	8.7548	10	B11
	N	8.5894	10	G8
	N	8.4801	8	G11

Table 15. Duncan's Multiple Range Test for Rolling Resistance Coefficient – SAE J1269 Single-Point Data

Alpha	0.05
Error Degrees of Freedom	195
Error Mean Square	4.518E-8
Harmonic Mean of Cell Sizes	8.72093

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.0002008	.0002113	.0002184	.0002236	.0002276	.0002309	.0002336	.0002360

Number of Means	10	11	12	13	14	15	16	17
Critical Range	.0002380	.0002397	.0002413	.0002427	.0002439	.0002451	.0002461	.0002471

Number of Means	18	19	20	21	22	23	24	25
Critical Range	.0002479	.0002487	.0002495	.0002502	.0002508	.0002514	.0002520	.0002525

Means with the same letter are not significantly different.

Duncan Grouping				Mean, lbs-force	N	Type
		A		0.0118829	10	B13
		B		0.0116432	10	B12
		B		0.0115799	8	C9
		B		0.0114719	9	R4
		C		0.0109960	10	B14
D		C		0.0108602	9	B15
D				0.0107705	10	P5
		E		0.0103137	8	U3
		E		0.0102231	9	D10
		F		0.0099128	8	P4
		F		0.0098976	8	D7
		F		0.0097953	8	K4
		F		0.0097598	8	D8
		G		0.0095239	8	M11
H		G		0.0094778	8	D9
H		G	I	0.0094461	8	M12
H	J	G	I	0.0093483	9	M14
H	J	G	I	0.0093312	9	G9
H	J		I	0.0092838	10	B10
	J	K	I	0.0092345	8	M10
	J	K		0.0091640	8	G10
		K		0.0090264	9	M13
		L		0.0077750	10	B11
		M		0.0074239	10	G8
		M		0.0073294	8	G11

4.2 ISO 28580 Single-Point Method (Draft International Standard)

The ISO 28580 is currently a draft method expected to be finalized by ISO in 2009. The test is run on a 1.707 meter, or a 2 m roadwheel, on a bare steel surface at the following conditions: 25^{o} C reference temperature, 80 km/h (50 mph), 80 percent of tire sidewall load, 220 kPa inflation pressure for passenger tires and 100 percent pressure at maximum rated load for LT tires. The inflation pressure is capped during the test. An option of the test is to use the 80-grit surface used for the SAE tests.

The tests used for tire comparisons are shown in Table 16. Four tires of each model were used for tests to compare lab-to-lab, and first versus subsequent test conditions. A SAS General Linear Model (GLM) analysis was carried out on the data set and the results are shown in Table 17. The F Value of 8320 for the model and the R^2 of 0.996 indicate that the majority of the variation is accounted for by the model. The Sums of Squares for the individual terms indicate that Type (Tire Model) is the only significant factor determining the rolling resistance. Test sequence (whether tested first or second) is not a significant variable. The predicted mean value for the tires tested in the Smithers laboratory was 62.00 N (13.94 pounds) versus 62.54 N (14.06 pounds) for those tested by the ARDL-STL laboratory, with a non-significant $Pr > F$ of 0.1476. A plot of the residual values showed differences between the passenger and LT tires. When only LT tires were considered the predicted values for tires tested at Smithers were significantly higher by 1.51 N (0.34 lbs) than the tires tested at ARDL-STL while passenger tires were within 0.18 N. The mean predicted values are 62.32 N (14.01 pounds) for the first test and 61.70 N (13.87 pounds) for subsequent tests. Again, the test order was not a significant variable in the model. The predicted Coefficient of Variation for the test method is 2.2 percent. Table 18 shows the rank order of the mean predicted rolling resistance in pounds for the 25 tire models studied. The Duncan multiple means comparison produces four distinct groups for the Light Truck (LT) tires at forces from 98.7 N to 121.8 N (22.2 to 27.4 pounds) and five distinct groups for the passenger tires which range from 43.6 N to 67.6 N (9.8 to 15.2 pounds) force. The rolling resistance is often reported as the Rolling Resistance Coefficient (RRc) which is the rolling resistance divided by the normal load, in the same units. Table 19 shows the rank order for the RRc of the 25 tire models. The Duncan procedure produces four distinct groups ranging from RRc values of 0.00744 to 0.01166. The values for the LT and passenger tires are interspersed. Significantly, a group of thirteen tires, group G-H-I-J-K-L-M, contains all but one of the light truck tires and five passenger tires with RRc values ranging from 0.00858 to 0.00946.

Table 16. Comparisons for 25 Models of Tires, ISO 28580 Single-Point Test

Comparison	Variables	Number of Tires	Notes:
Laboratory-Laboratory, First Test	ARDL-STL Smithers	50 39	
Repeat Testing (Regulated Test)	First Test Subsequent Tests	*39* 10 (tested at Smithers)	Tires for second test previously tested on other tests
Laboratory-Laboratory All Tires	ARDL-STL Smithers	*50* *49*	 10 tires second test

Table 17. SAS GLM Analysis of ISO 28580 Single-Point Data

```
Dependent Variable: Rolling Resistance

                                          Sum of
       Source                    DF      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 18. Duncan's Multiple Range Test for Rolling Resistance in Pounds – ISO 28580 Single-Point Data

Alpha	0.05
Error Degrees of Freedom	74
Error Mean Square	0.125134
Harmonic Mean of Cell Sizes	3.947368

Number of Means	2	3	4	5	6	7	8	9	10	11	12	13
Critical Range	.5017	.5279	.5452	.5578	.5676	.5755	.5820	.5874	.5921	.5961	.5997	.6028

Number of Means	14	15	16	17	18	19	20	21	22	23	24	25
Critical Range	.6056	.6081	.6103	.6123	.6141	.6158	.6173	.6187	.6200	.6211	.6222	.6232

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	27.3933	3	C9
	B	26.0325	4	D9
	C	24.1075	4	D7
	C	23.8725	4	D8
	C	23.5900	4	P4
	D	23.0125	4	K4
E	D	22.7325	4	M11
E	F	22.4225	4	M12
	F	22.1900	4	M10
	G	15.2150	4	B12
	G	15.0075	4	B13
	G	14.9750	4	R4
	H	14.0150	4	P5
	H	13.9850	4	B15
	H	13.9125	4	U3
	H	13.9025	4	B14
	H	13.5600	4	D10
	I	12.1075	4	B10
	I	12.0925	4	G10
	I	12.0650	4	M13
	I	11.9625	4	M14
	J	11.2650	4	G9
	K	10.1300	4	B11
	K	10.0175	4	G11
	K	9.8325	4	G8

Table 19. Duncan's Multiple Range Test for Rolling Resistance Coefficient – ISO 28580 Single-Point Data

Alpha	0.05
Error Degrees of Freedom	74
Error Mean Square	2.954E-8
Harmonic Mean of Cell Sizes	3.947368

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.0002438	.0002565	.0002649	.0002711	.0002758	.0002796	.0002828	.0002854

Number of Means	10	11	12	13	14	15	16	17
Critical Range	.0002877	.0002897	.0002914	.0002929	.0002943	.0002955	.0002965	.0002975

Number of Means	18	19	20	21	22	23	24	25
Critical Range	.0002984	.0002992	.0003000	.0003006	.0003012	.0003018	.0003023	.0003028

Duncan Grouping	Mean	N	Type

	A		0.0116613	4	B13
B	A		0.0115090	4	B12
B			0.0113274	4	R4
	C		0.0108901	4	P5
D	C		0.0108027	4	B14
D	E		0.0105929	3	C9
D	E		0.0105786	4	B15
	E		0.0105241	4	U3
	F		0.0102571	4	D10
	G		0.0094621	4	G10
H	G		0.0093223	4	D7
H	G		0.0092953	4	M14
H	G	I	0.0092314	4	D8
H		I	0.0091886	4	G9
H	J	I	0.0091584	4	B10
H	J	I	0.0091262	4	M13
H	J	I	0.0091222	4	P4
K	J	I	0.0089623	4	D9
K	J	L	0.0088988	4	K4
K	M	L	0.0087906	4	M11
	M	L	0.0086707	4	M12
	M		0.0085808	4	M10
	N		0.0078714	4	B11
	O		0.0075777	4	G11
	O		0.0074376	4	G8

4.2.1 SAE J1269 Multi-Point Method

The SAE J1269 test is run on a 1.707-meter roadwheel, on an 80-grit surface, at a 24^{o} C reference temperature, and at 80 km/h (50 mph). The test is run at four load/pressure combinations for passenger tires and six combinations for light truck tires, as shown in Table 1. The rolling resistance at the Standard Reference Condition (SRC), which is defined at the same conditions as the J1269 single-point test (70 percent of maximum load, and at +20 kPa (3 psi) inflation pressure), is calculated from the regression equations included in the method. For passenger tires, the regression is modeled by:

Equation 1. $$F_R = F_Z(A_0 + A_1F_Z + A_2/p)$$

For Light Truck tires, the regression is modeled by:

Equation 2. $$F_R = A_0 + A_1F_Z + A_2/p + A_3F_Z/p + A_4F_Z/p^2$$

Where F_R is the force of rolling resistance at a test point, F_Z is the normal load on the tire at a test point, p is the tire inflation pressure at a test point, and $A_{1..n}$ are the coefficients of the least squares regression model.

The tests used for comparisons of tires are shown in Table 20. Four tires of each model were used for tests to compare lab-to-lab, and first versus subsequent test conditions. A SAS General Linear Model (GLM) analysis was carried out on the data set for values calculated at the Standard Reference Conditions (SRC), and the results are shown in Table 21. The F Value of 15929 for the model and the R^2 of 0.996 indicate that the majority of the variation is accounted for by the model. The Sums of Squares for the individual terms indicate that Type (Tire Model) is the most significant factor determining the rolling resistance. Test sequence (whether tested first or second) is not a significant variable. The predicted mean value for the tires tested in the Smithers laboratory was significantly higher at 52.18 N (11.73 pounds) versus 50.04 N (11.25 pounds) for those tested by the ARDL-STL laboratory. The mean predicted values are 51.82 N (11.65 pounds) for the first test and 52.18 N (11.72 pounds) for subsequent tests. Again, the test order was not a significant variable in the model. The predicted Coefficient of Variation for the test method is 2.3 percent. Table 22 shows the rank order of the mean predicted rolling resistance in pounds for the 25 tire models studied. The Duncan multiple means comparison produces five distinct groups for the Light Truck (LT) tires at forces from 85.4 N to 110.8 N (19.2 to 24.9 pounds) and five distinct groups for the passenger tires which range from 36.4 N to 60.5 N (8.2 to 13.6 pounds) force. The rolling resistance is often reported as the Rolling Resistance Coefficient (RRc) which is the rolling resistance divided by the normal load, in the same units. Table 23 shows the rank order for the RRc of the 25 tire models. The Duncan procedure produces seven distinct groups ranging from RRc values of 0.00725 to 0.01187. The values for the LT and passenger tires are interspersed. Significantly, a single group of thirteen tire types has RRc values ranging from 0.00907 to 0.00965.

Table 20. Comparisons for 25 Models of Tires, SAE J1269 Multi-Point Test

Comparison	Variables	Number of Tires	Notes:
Laboratory-Laboratory, First Test	ARDL-STL Smithers	75 75	
Repeat Testing (Regulated Test)	First Test Second Tests	*150* 50 (1 per model tested at each lab)	Tires for second test previously tested on other tests
Laboratory-Laboratory All Tires	ARDL-STL Smithers	*100* *100*	25 tires second test 25 tires second test

Table 21. SAS GLM Analysis of SAE J1269 Multi-Point Data at 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 22. Duncan's Multiple Range Test for Rolling Resistance in Pounds – J1269 Multi-Point at SRC

Alpha	0.05
Error Degrees of Freedom	175
Error Mean Square	0.119057

Number of Means	2	3	4	5	6	7	8	9	10	11	12	13
Critical Range	.3405	.3584	.3703	.3791	.3860	.3915	.3961	.4001	.4035	.4065	.4091	.4114

Number of Means	14	15	16	17	18	19	20	21	22	23	24	25
Critical Range	.4135	.4155	.4172	.4188	.4203	.4216	.4228	.4240	.4251	.4261	.4270	.4279

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	24.8924	8	C9
	B	22.3534	8	D9
	C	20.8760	8	D7
	C	20.6751	8	P4
	C	20.5886	8	D8
	D	19.8471	8	M11
	D	19.8357	8	K4
	D	19.6673	8	M12
	E	19.2011	8	M10
	F	13.5840	8	B13
G	F	13.3251	8	R4
G		13.1444	8	B12
	H	12.6760	8	B15
	H	12.5542	8	B14
	H	12.3423	8	P5
	I	11.9024	8	D10
	I	11.6686	8	U3
	J	10.9700	8	B10
K	J	10.6695	8	M13
K	J	10.6274	8	M14
K	L	10.5483	8	G10
	L	10.2485	8	G9
	M	8.8926	8	G8
N	M	8.8111	8	B11
N		8.5221	8	G11

Table 23. Duncan's Multiple Range Test for Rolling Resistance Coefficient – SAE J1269 Multi-Point Test at SRC

Alpha	0.05
Error Degrees of Freedom	175
Error Mean Square	5.494E-8

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.0002313	.0002435	.0002516	.0002575	.0002622	.0002660	.0002691	.0002718

Number of Means	10	11	12	13	14	15	16	17
Critical Range	.0002741	.0002761	.0002779	.0002795	.0002809	.0002822	.0002834	.0002845

Number of Means	18	19	20	21	22	23	24	25
Critical Range	.0002855	.0002864	.0002872	.0002880	.0002888	.0002894	.0002901	.0002907

Duncan Grouping				Mean	N	Type
		A		0.0118705	8	B13
		B		0.0115067	8	C9
C		B		0.0113336	8	R4
C		D		0.0111799	8	B12
E		D		0.0109705	8	B14
E				0.0107853	8	P5
E				0.0107815	8	B15
		F		0.0101236	8	D10
		F		0.0099247	8	U3
		G		0.0096501	8	D7
H		G		0.0095572	8	P4
H		G	I	0.0095172	8	D8
H	J	G	I	0.0094066	8	G9
H	J	K	I	0.0093305	8	B10
	J	K	I	0.0092868	8	M14
	J	K	I	0.0092812	8	G10
	J	K		0.0091997	8	D9
	J	K		0.0091745	8	M11
	J	K		0.0091691	8	K4
L		K		0.0090913	8	M12
L		K		0.0090749	8	M13
L				0.0088758	8	M10
		M		0.0076931	8	B11
		M		0.0075637	8	G8
		N		0.0072485	8	G11

4.2.2 ISO 18164 Multi-Point Method

The ISO 18164 test is run on a 1.707 or a 2-meter roadwheel, on bare steel surface at 25^{o} C reference temperature, and at 80 km/h (50 mph). The test is run at four load/pressure combinations for passenger tires as shown in Figure 7. The rolling resistance at the Standard Reference Condition (SRC) of the J1269 test (70 percent of maximum load, and at +20 kPa (3 psi) inflation pressure) was calculated from the regression Equation 1 for comparison to the other tests.

Ten models of passenger tires were tested using the ISO multi-point test. The tests used for comparisons tires are shown in Table 24. One tire of each model was tested in each lab. All of the tires were tested at Smithers as a first test and as a second test at ARDL-STL; therefore the variables of lab and test are confounded. Since the test order was not a significant variable in the other tests, and lab-to-lab variation was a significant variable, all of the variability was arbitrarily assigned to lab variation. A SAS General Linear Model (GLM) analysis was carried out on the data set, and the results are shown in Table 25. The F Value of 2432 for the model and the R^2 of 0.989 indicate that the majority of the variation is accounted for by the model. The Sums of Squares for the individual terms indicate that tire type is the most significant factor determining the rolling resistance. The predicted mean value for the tires tested in the Smithers laboratory (confounded with test sequence) was significantly higher at 53.69 N (12.07 pounds) versus 51.95 N (11.68 pounds) for those tested by the ARDL-STL laboratory. The predicted Coefficient of Variation for the test method is 5.5 percent. Table 26 shows the rank order of the mean predicted rolling resistance in pounds for the ten tire models studied. The Duncan multiple means comparison produces two distinct groups of tires that range from 36.9 N to 58.3 N (8.3 to 13.1 pounds) force. The rolling resistance is often reported as the Rolling Resistance Coefficient (RRc) which is the rolling resistance divided by the normal load, in the same units. Table 27 shows the rank order for the RRc of the 10 tire models. The Duncan procedure produces two distinct groups ranging from RRc values of 0.00718 to 0.01151.

Table 24. Comparisons for 10 Models of Passenger Tires, ISO 18164 Multi-Point Test

Comparison	Variables	Number of Tires	Notes:
Laboratory- Laboratory	ARDL-STL	10	All tested as a second test
	Smithers	10	All tested as a first test
Measurement Condition	1, 2, 3, 4, S (SRC calculated)	*20*	
Confounded Variables	Lab and Test Sequence		

Table 25. SAS GLM Analysis of ISO 18164 Multi-Point Data at SRC

```
Dependent Variable: Rolling Resistance

                                        Sum of
      Source                   DF      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 26. Duncan's Multiple Range Test for Rolling Resistance – ISO 18164 Multi-Point Values in Pounds

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	0.261272

Number of Means	2	3	4	5	6	7	8	9	10
Critical Range	1.139	1.190	1.220	1.240	1.252	1.261	1.267	1.271	1.273

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	13.1771	2	B12
	A	12.9601	2	B13
B	A	12.0440	2	B14
B		11.6427	2	U3
	C	10.2737	2	G10
	C	10.2564	2	M14
D	C	9.5599	2	G9
D	E	8.4889	2	B11
D	E	8.4038	2	G8
	E	8.3096	2	G11

Table 27. Duncan's Multiple Range Test for Rolling Resistance Coefficient – ISO 18164 Multi-Point

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	2.003E-7

Number of Means	2	3	4	5	6	7	8	9	10
Critical Range	.000997	.001042	.001068	.001085	.001097	.001104	.001109	.001113	.001115

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	0.0115068	2	B13
	A	0.0113880	2	B12
B	A	0.0106934	2	B14
B	C	0.0100620	2	U3
D	C	0.0091844	2	G10
D	C	0.0091063	2	M14
D		0.0089145	2	G9
	E	0.0075369	2	B11
	E	0.0072628	2	G8
	E	0.0071814	2	G11

4.2.3 SAE J2452 Coastdown Method

The test is run at four load/pressure combinations for passenger tires and five combinations for LT tires as shown in Figure 5 and Figure 6. Rolling resistance is reported as the Standard Mean Equivalent Rolling Force (SMERF). The rolling resistance at the Standard Reference Condition

(SRC) of the J1269 test (70 percent of maximum load, and at +20 kPa (3 psi) inflation pressure) was also calculated from the regression Equation 1 for comparison to the other tests.

The tests used for comparisons are shown in Table 28. A SAS General Linear Model (GLM) analysis was carried out on the data set, excluding tire model D10 that was only tested in the Smithers laboratory. The results are shown in Table 29. The F Value of 23535 and the R^2 of 0.995 for the model of the values at the SRC, and F Value of 22051 and R^2 of 0.995 for the model of SMERF values indicate that the majority of the variation is accounted for by the model. The Sums of Squares for the individual terms indicate that the tire model is the most significant factor determining the rolling resistance. The predicted mean value for force at SRC of the tires tested in the Smithers laboratory was significantly higher at 53.60 N (12.05 pounds) versus 49.42 N (11.11 pounds) for those tested by the ARDL-STL laboratory. The predicted mean value for the SMERF for the tires tested in the Smithers laboratory was significantly higher at 51.64 N (11.61 pounds) versus 48.18 N (10.83 pounds) for those tested by the ARDL-STL laboratory. The test order is a significant term, although the effect is less than the variation in the test, which is approximately 1 N for both measures. The predicted mean value for force at SRC for the first test of the tires was 52.04 N (11.70 pounds) versus 53.11 N (11.94 pounds) for those tested as a third test. The predicted mean value for the SMERF for the tires tested as a first test was 50.71 N (11.24 pounds) versus 51.06 N (11.48 pounds) for those tested as a third test. The predicted Co-efficient of Variation for the test method is 1.8 – 1.9 percent. Table 30 shows the rank order of the mean predicted rolling resistance in pounds for the 25 tire models using the SRC values.

Table 31 shows the rank order of the mean predicted rolling resistance in pounds for the SMERF values. Both measures divide the passenger tires into 8 groups and the light truck tires into 5 groups. The rolling resistance is often reported as the Rolling Resistance Coefficient (RRc) which is the rolling resistance divided by the normal load, in the same units. Table 32 shows the rank order for the RRc of the 25 tire models using the SRC value. This measure produces 12 Duncan groupings with the light truck and passenger tires interspersed. There were no large in-distinguishable groups produced using this measure. Table 33 shows the rank order for RRc us-ing the SMERF values. The Duncan procedure produces 10 groupings with one group of twelve passenger and light truck tires RRc values ranging from 0.0096 to 0.0105

Table 28. Comparisons for 25 Models of Passenger Tires, SAE J2452 Test

Comparison	Variables	Number of Tires	Notes:
Laboratory- Laboratory, First Test	ARDL-STL Smithers	70 75	Model D10 not tested, 2 each of model B10 & U3, all others used 3 of each model
Test Sequence	First Test Third Test	*145* 51	26 tires ARDL-STL/25 tires Smithers (Includes model D10)
Laboratory/Laboratory – All tires	ARDL-STL Smithers	*96* *100*	26 tires third test 25 tires second test (Includes model D10)

Table 29. 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 30. Duncan's Multiple Range Test for Rolling Resistance – SAE J2452 Procedure/SRC Value in Pounds

```
                         Alpha                            0.05
                         Error Degrees of Freedom          171
                         Error Mean Square            0.044483
                         Harmonic Mean of Cell Sizes  7.806691

Number of Means      2     3     4     5     6     7     8     9    10    11    12    13
Critical Range   .2107 .2218 .2292 .2346 .2389 .2423 .2452 .2476 .2497 .2515 .2532 .2546

Number of Means     14    15    16    17    18    19    20    21    22    23    24    25
Critical Range   .2559 .2571 .2582 .2591 .2600 .2609 .2616 .2624 .2630 .2636 .2642 .2648

              Means with the same letter are not significantly different.

                 Duncan Grouping          Mean      N    Type

                               A       19.1729      8    C9
                               B       18.6106      8    D9
                               C       17.7846      8    D7
                               D       17.3166      8    D8
                               D       17.1521      8    P4
                               E       16.2616      8    K4
                               F       15.9826      8    M11
                               F       15.8877      8    M10
                               F       15.8634      8    M12
                               G       13.3765      8    B13
                               G       13.2496      8    B12
                               H       12.9499      8    R4
                               I       12.4753      8    B15
                          J    I       12.3114      8    P5
                          J            12.2327      8    B14
                               K       11.8490      7    U3
                               K       11.7070      6    D10
                               L       10.8842      7    B10
                               M       10.6298      8    M14
                          N    M       10.5345      8    G10
                          N            10.3776      8    M13
                               O       10.1602      8    G9
                               P        8.6899      8    G8
                               P        8.6666      8    B11
                               P        8.4819      8    G11
```

Table 31. Duncan's Multiple Range Test for Rolling Resistance – SAE J2452 Procedure/SMERF Value in Pounds

Alpha	0.05
Error Degrees of Freedom	171
Error Mean Square	0.040717
Harmonic Mean of Cell Sizes	7.806691

Number of Means	2	3	4	5	6	7	8	9	10	11	12	13
Critical Range	.2016	.2122	.2193	.2245	.2285	.2318	.2345	.2369	.2389	.2406	.2422	.2436

Number of Means	14	15	16	17	18	19	20	21	22	23	24	25
Critical Range	.2448	.2460	.2470	.2479	.2488	.2496	.2503	.2510	.2516	.2522	.2528	.2533

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	18.4900	8	C9
	B	17.3241	8	D9
	C	16.6153	8	D7
	D	16.2292	8	D8
	D	16.1950	8	P4
	E	15.5242	8	K4
	F	15.1923	8	M11
	F	15.1213	8	M10
	F	15.0797	8	M12
	G	12.7252	8	B13
H	G	12.6391	8	B12
H		12.4950	8	R4
	I	11.9192	8	B15
J	I	11.7189	8	P5
J		11.6487	8	B14
	K	11.4121	7	U3
	L	11.1589	6	D10
	M	10.2726	7	B10
	N	10.0327	8	M14
	N	10.0184	8	G10
	N	9.9016	8	M13
	O	9.6294	8	G9
	P	8.1280	8	B11
	P	8.0893	8	G8
	P	8.0238	8	G11

Table 32. Duncan's Multiple Range Test for Rolling Resistance Coefficient – SAE J2452 Procedure/SRC Value

Alpha	0.05
Error Degrees of Freedom	171
Error Mean Square	2.576E-8
Harmonic Mean of Cell Sizes	7.806691

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.0001603	.0001688	.0001744	.0001785	.0001818	.0001844	.0001865	.0001884

Number of Means	10	11	12	13	14	15	16	17
Critical Range	.0001900	.0001914	.0001926	.0001937	.0001947	.0001956	.0001964	.0001972

Number of Means	18	19	20	21	22	23	24	25
Critical Range	.0001979	.0001985	.0001991	.0001996	.0002001	.0002006	.0002011	.0002015

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	Type
	A	0.01242397	8	C9
	B	0.01187542	8	B13
	C	0.01152439	8	D7
	C	0.01144920	8	B12
	D	0.01122110	8	D8
	D	0.01119020	8	R4
	D	0.01111452	8	P4
	E	0.01092989	8	P5
	E	0.01086001	8	B14
	E	0.01078012	8	B15
	E	0.01076745	8	D9
	F	0.01053746	8	K4
	G	0.01035667	8	M11
	G	0.01029519	8	M10
H	G	0.01027940	8	M12
H	G	0.01023909	7	U3
H		0.01011756	6	D10
	I	0.00947385	8	G9
	I	0.00943693	8	M14
	I	0.00941674	8	G10
	I	0.00940539	7	B10
	J	0.00896744	8	M13
	K	0.00769403	8	B11
	L	0.00750911	8	G8
	M	0.00732935	8	G11

Table 33. Duncan's Multiple Range Test for Rolling Resistance Coefficient – SAE J2452 Procedure/SMERF Value

Alpha	0.05
Error Degrees of Freedom	171
Error Mean Square	2.406E-8
Harmonic Mean of Cell Sizes	7.806691

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.0001550	.0001631	.0001686	.0001726	.0001757	.0001782	.0001803	.0001821

Number of Means	10	11	12	13	14	15	16	17
Critical Range	.0001836	.0001850	.0001862	.0001872	.0001882	.0001891	.0001899	.0001906

Number of Means	18	19	20	21	22	23	24	25
Critical Range	.0001913	.0001919	.0001924	.0001930	.0001934	.0001939	.0001943	.0001947

Means with the same letter are not significantly different.

Duncan Grouping			Mean	N	Type
	A		0.01198145	8	C9
	B		0.01129724	8	B13
	C		0.01092168	8	B12
	C		0.01079718	8	R4
	C		0.01076664	8	D7
	D		0.01051648	8	D8
E	D		0.01049429	8	P4
E	D	F	0.01040384	8	P5
E		F	0.01034151	8	B14
		F	0.01029958	8	B15
	G		0.01005965	8	K4
	G		0.01002310	8	D9
	H		0.00986152	7	U3
	H		0.00984453	8	M11
I	H		0.00979852	8	M10
I	H		0.00977156	8	M12
I			0.00964300	6	D10
	J		0.00897893	8	G9
	J		0.00895536	8	G10
	J		0.00890682	8	M14
	J		0.00887686	7	B10
	K		0.00855616	8	M13
	L		0.00721588	8	B11
	M		0.00699010	8	G8
	M		0.00693354	8	G11

4.3 <u>Comparison of Tests</u>

For the purpose of comparing the values between tests, it is necessary to correlate the values to those expected to be obtained from one laboratory. The coefficients from the SAS GLM procedure were used to correct all values to the predicted value from the Smithers laboratory using the correction factors listed in Table 34. Note that the values are essentially identical to those produced by the SAS using the GLM model in the previous section. In practice, it would be necessary to correlate each lab, or even each machine within a lab, to some accepted standard. It would then be necessary to periodically validate the comparison to account for possible shifts in the average level of rolling resistance produced by the lab due to mechanical, environmental, and electronic changes over time. This procedure would be necessary in addition to the normal calibration procedures within the lab. The testing for this project was carried out in a single block of time in each lab. Thus, no information can be gleaned about the magnitude or significance of shifts of the average data produced by a single machine. The correlation of test results between labs will be discussed in more detail in a later section. After the values were "corrected", the mean values were then compared for all test procedures. Table 35 lists the mean rolling resistance for the various tests in pounds and Table 36 lists the values for the rolling resistance coefficients for each test.

Table 34. Correction Factor to Correlate Rolling Resistance to Estimated Smithers Value

Test	Tire Types	To Convert ARDL-STL Value (A) to "Smithers Value" (S)
SAE J1269 single-point	All	S = 0.2568 + 1.0239*A
ISO 28580 single-point	All	S = -0.0994 + 1.0120*A
SAE J1269 multi-point at SRC	All	S = -1.7463 + 1.1732*A
ISO 18164 multi-point at SRC	Passenger	[9]S = 0.7139 + 0.9076*A
SAE J2452, Calculated SRC Value	All	S= -0.02306 + 1.0769*A
SAE J2452, SMERF Value	All	S= -0.1425 + 1.0772*A

[9] Values may be confounded with order of test as a variable.

Table 35. Pounds Force - Mean Values for All Tests. Corrected to Smithers Lab Values

Test	SAE J1269 single-point	ISO 28580 single-point	SAE J1269 multi-point, SRC Value	ISO 18164 multi-point	SAE J2452, SRC Value	SAE J2452, SMERF Value
Tire						
C9	24.66	27.39	24.89		19.18	18.49
D9	22.67	26.03	23.35		18.61	17.32
P4	21.18	23.59	20.68		17.15	16.20
D7	21.07	24.11	20.88		17.78	16.62
K4	20.86	23.01	19.84		16.26	15.52
D8	20.78	23.87	20.59		16.26	16.23
M11	20.28	22.73	19.85		15.98	15.19
M12	20.11	22.42	19.67		15.86	15.08
M10	19.66	22.19	19.20		15.89	15.12
↑ Light Truck ------------- Passenger ↓						
B12	13.47	15.22	13.14	13.18	13.38	12.64
B13	13.38	15.01	13.58	12.96	13.38	12.73
R4	13.27	14.98	13.33		12.95	12.50
B15*	12.57	13.99	12.68		12.48	11.92
B14	12.38	13.90	12.55	12.04	12.23	11.65
P5	12.13	14.02	12.34		12.31	11.72
U3	11.93	13.91	11.67	11.65	11.85	11.41
D10	11.83	13.56	11.90		11.71	11.16
B10*	10.74	12.11	10.97		10.88	10.27
M14	10.53	11.96	10.63	10.26	10.63	10.03
M13	10.44	12.07	10.67		10.38	9.902
G10	10.25	12.09	10.55	10.27	10.53	10.02
G9	10.00	11.27	10.25	9.560	10.16	9.630
B11	8.755	10.13	8.811	8.489	8.667	8.128
G8	8.589	9.833	8.893	8.404	8.690	8.089
G11	8.480	10.02	8.522	8.310	8.482	8.024

*Snow tire models

Table 36. Rolling Resistance Coefficient - Mean Values for All Tests. Corrected to Smithers Lab Values

Test	SAE J1269 single-point	ISO 28580 single-point	SAE J1269 multi-point, SRC Value	ISO 18164 multi-point	SAE J2452, SRC Value	SAE J2452, SMERF Value
			Passenger Tires			
B13	0.01188	0.01166	0.01187	0.01151	0.01188	0.01130
B12	0.01164	0.01151	0.01118	0.01139	0.01145	0.01092
R4	0.01147	0.01133	0.01133		0.01119	0.01080
B14	0.01100	0.01080	0.00965	0.01069	0.01086	0.01034

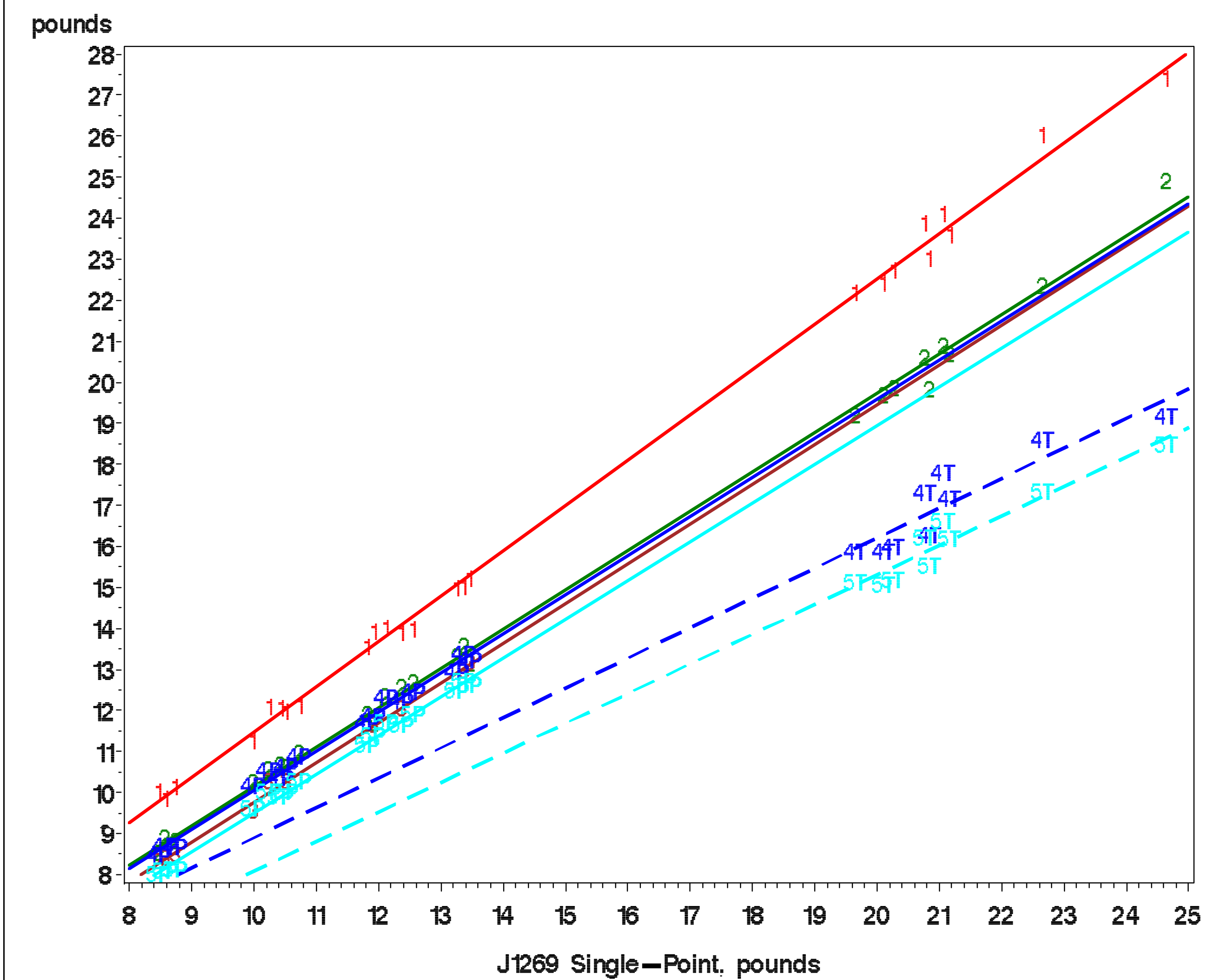
Test	SAE J1269 single-point	ISO 28580 single-point	SAE J1269 multi-point, SRC Value	ISO 18164 multi-point	SAE J2452, SRC Value	SAE J2452, SMERF Value
B15*	0.01086	0.01058	0.01078		0.01078	0.01030
P5	0.01077	0.01089	0.01078		0.01093	0.01040
U3	0.01031	0.01052	0.00992	0.01006	0.01024	0.00986
D10	0.01022	0.01026	0.01012		0.01012	0.00964
M14	0.00935	0.00930	0.00929	0.00911	0.00944	0.00891
G9	0.00933	0.00919	0.00940	0.00891	0.00947	0.00899
B10*	0.00928	0.00916	0.00933		0.00941	0.00888
G10	0.00916	0.00946	0.00928	0.00918	0.00942	0.00896
M13	0.00903	0.00913	0.00907		0.00897	0.00856
B11	0.00778	0.00787	0.00770	0.00754	0.00769	0.00722
G8	0.00742	0.00744	0.00756	0.00726	0.00751	0.00699
G11	0.00733	0.00758	0.00725	0.00718	0.00733	0.00693
			Light Truck Tires			
C9	0.01158	0.01060	0.01151		0.01243	0.01198
P4	0.00991	0.00912	0.00956		0.01111	0.01049
D7	0.00990	0.00932	0.01094		0.01152	0.01077
K4	0.00980	0.00890	0.00917		0.01054	0.01006
D8	0.00976	0.00923	0.00952		0.01122	0.01052
M11	0.00952	0.00879	0.00918		0.01036	0.00984
D9	0.00948	0.00896	0.00920		0.01077	0.01002
M12	0.00945	0.00867	0.00909		0.01028	0.00978
M10	0.00923	0.00858	0.00888		0.01030	0.00980

*Snow tire models

4.3.1 SAE J1269 Single-Point Value in Pounds; Comparison to All Other Tests

Figure 17 shows values, in pounds, for all other tests versus the SAE J1269 single-point value in pounds. It is apparent that the values all have a linear relationship with the J1269 single-point values. The passenger tires measured or calculated values all show parallel lines with little difference in the intercept. The LT tires measured using the SAE J2452 method show a different correlation than the passenger tires whether calculated at the SRC value or using the SMERF. The ISO 28580 values are offset due to the different load and pressure conditions of the test. Table 37 details the equations for a linear fit for each test. For the ISO tests, the SAE J1269 multi-point test, and the SAE J2452 test of passenger tires only, the R^2 for the correlations are all greater than 0.989 and the intercepts are between 0.06 and 0.55 pounds. As seen previously, the J2452 test has a different correlation for light truck tires than for passenger tires. With only nine models and more scatter in the correlation, the confidence is reduced. However, the correlations are still good, with R^2 values of 0.83 for the SRC value and 0.92 for the SMERF value and intercepts below 1.6 pounds.

Figure 17. Rolling Resistance Values in Pounds – Comparison of Values for Each Test to Value of J1269 Single-Point



1 = ISO 28580 single-point value
2 = SAE J1269 multi-point value at SRC
3 = ISO 18164 value at SRC
4P = SAE J2452 value at SRC, Passenger Tires
4T = SAE J2452 value at SRC, Light Truck Tires
5P = SAE J2452 SMERF value, Passenger Tires
5T = SAE J2452 SMERF value, Light Truck Tires

Table 37. Linear Correlation of Test Values to SAE J1269 Single-Point Values in Pounds

Test	Tire Type	R^2	Intercept	Coefficient
ISO 28580 single-point	All	0.9978	0.4075	1.1059
SAE J1269 multi-point at SRC	All	0.9974	0.5512	0.9587
ISO 18164 multi-point at SRC	Passenger	0.9959	0.0690	0.9690
SAE J2452, Calculated SRC Value	Passenger	0.9924	0.5194	0.9525
SAE J2452, Calculated SRC Value	Light Truck	0.8326	1.5894	0.7305
SAE J2452, SMERF Value	Passenger	0.9937	0.0655	0.9441
SAE J2452, SMERF Value	Light Truck	0.9233	0.8807	0.7207

4.3.2 J1269 Single-Point Rolling Resistance Coefficient; Comparison to All Other Tests

The division of the linear function of the rolling resistance in pounds by the normal force in pounds will produce a linear function. Since the passenger and light truck tires are tested at different loads, and thus the values divided by different normal forces, it is not surprising that the passenger and light truck tires are related by different linear functions, even when they were represented by the same function for the rolling resistance in pounds. For example, Figure 18 shows a graph for the RRc of the SRC value of the J1269 multi-point test versus the value of the J1269 single-point test showing this obvious difference.

Figure 19 shows the value of RRc for all other tests versus the SAE J1269 single-point RRc value for the passenger tires in the study. It is apparent that the values all have a linear relationship with the J1269 single-point value, showing parallel lines with little difference in the intercept. The relationship of the LT tires is shown in Figure 20. The correlation is generally linear, but the scatter is much greater than for the passenger tires and the slopes differ significantly. Table 38 details the equations for a linear fit for each test. For the passenger tires the R^2 for the correlations are all greater than 0.99 and the intercepts are between 0.0000 and 0.0007. For light truck tires, the correlations are still good, with R^2 values of 0.81 to 0.96. It should be noted that these R^2 values might be artificially high, particularly for the J2452 values, due to the influence of the tire type C9 with very high RRc values. Removing this tire reduces the R^2 values to approximately 0.7 and changes the slope by more than 50 percent in some cases. Removing this tire does however produce a more nearly 1:1 correlation between the measured and calculated values of the J1269 test at the SRC, with an intercept of 0.0007 and a slope of 1.03 with the tire excluded, instead of a slope of 1.12 when tire type C9 is included. However, the R^2 value is only 0.69. There were no discernible trends in the residual values that would indicate a systematic bias based on RRc or rolling resistance values.

Figure 18. Rolling Resistance Coefficient for SAE J1269 Multi-Point Test Versus J1269 Single-Point Value: P = Passenger Tire Data, LT = Light Truck Tire Data

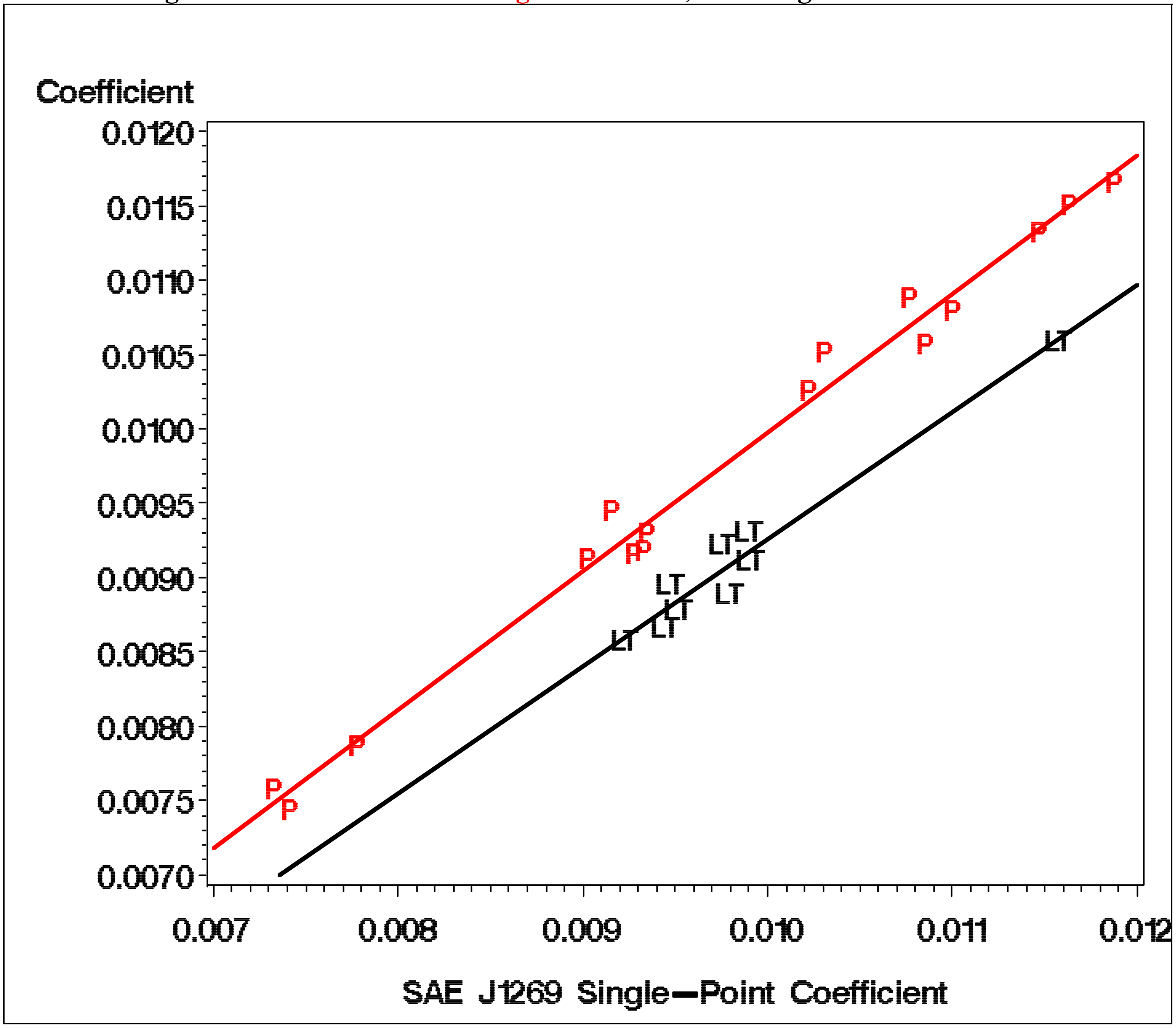


Figure 19. Passenger Tires, RRc for Other Tests Versus RRc for SAE J1269 Single-Point Test

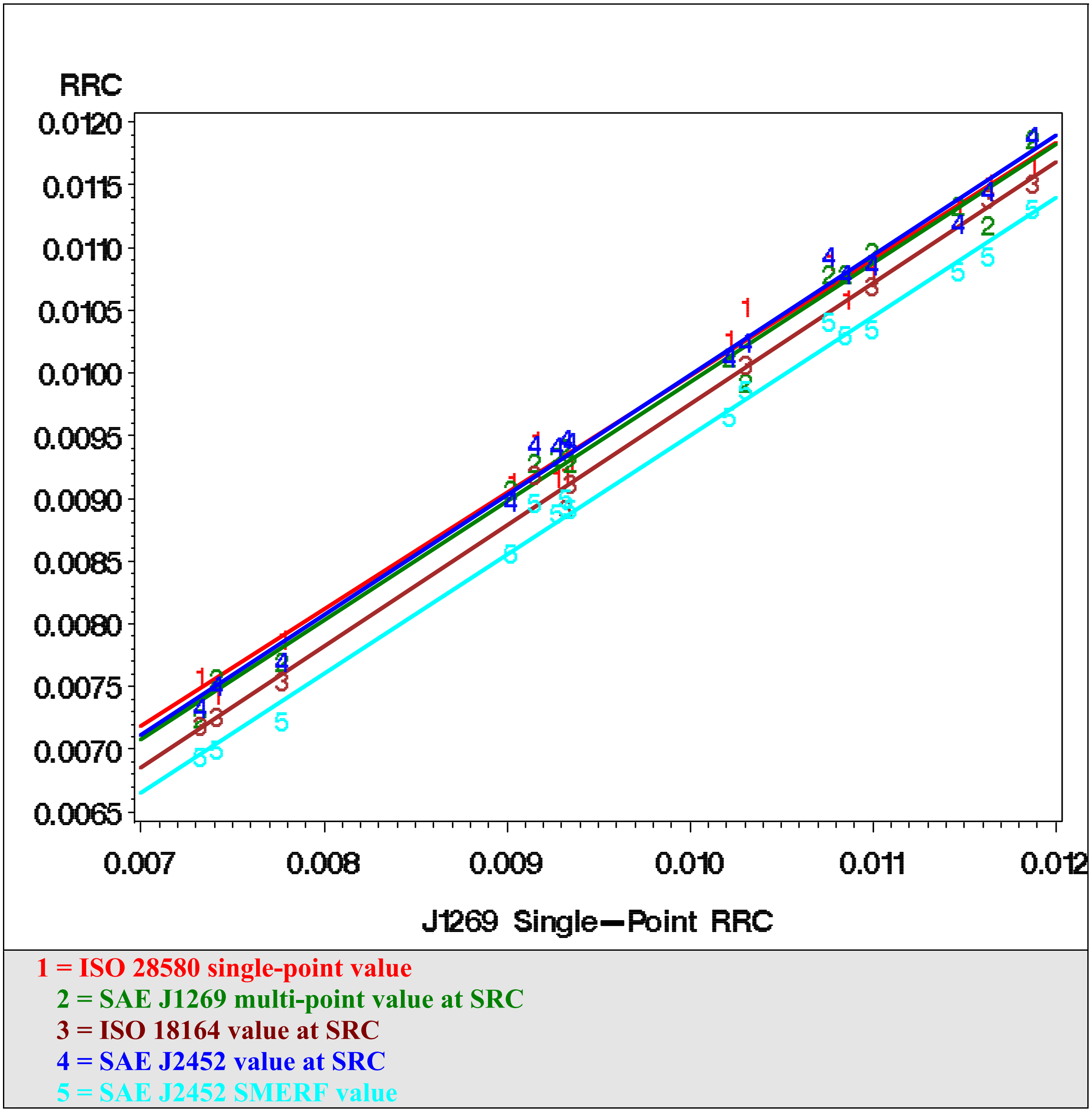
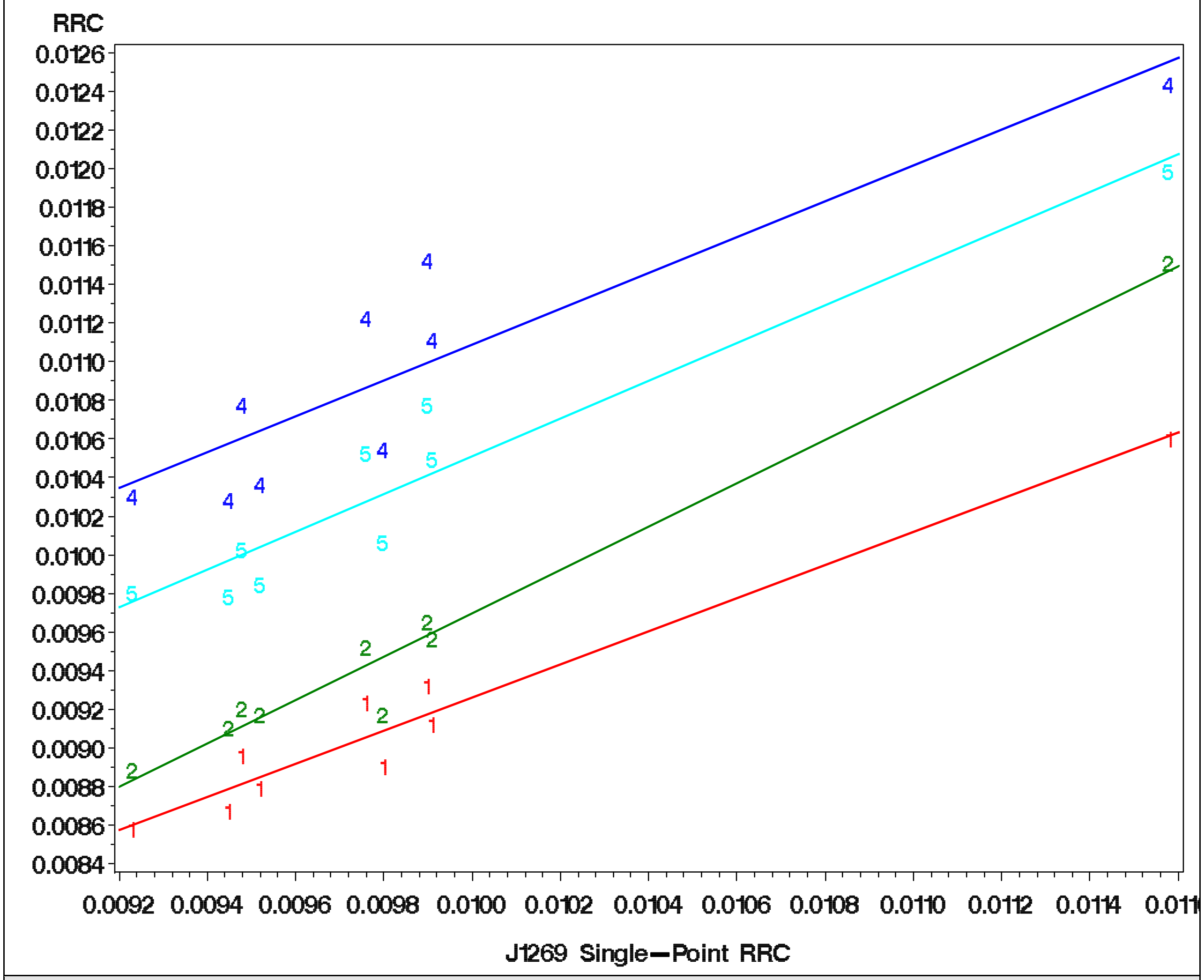


Figure 20. Light Truck Tires, RRc for Other Tests Versus RRc for SAE J1269 Single-Point Test



1 = ISO 28580 single-point value
2 = SAE J1269 multi-point value at SRC
4 = SAE J2452 value at SRC
5 = SAE J2452 SMERF value

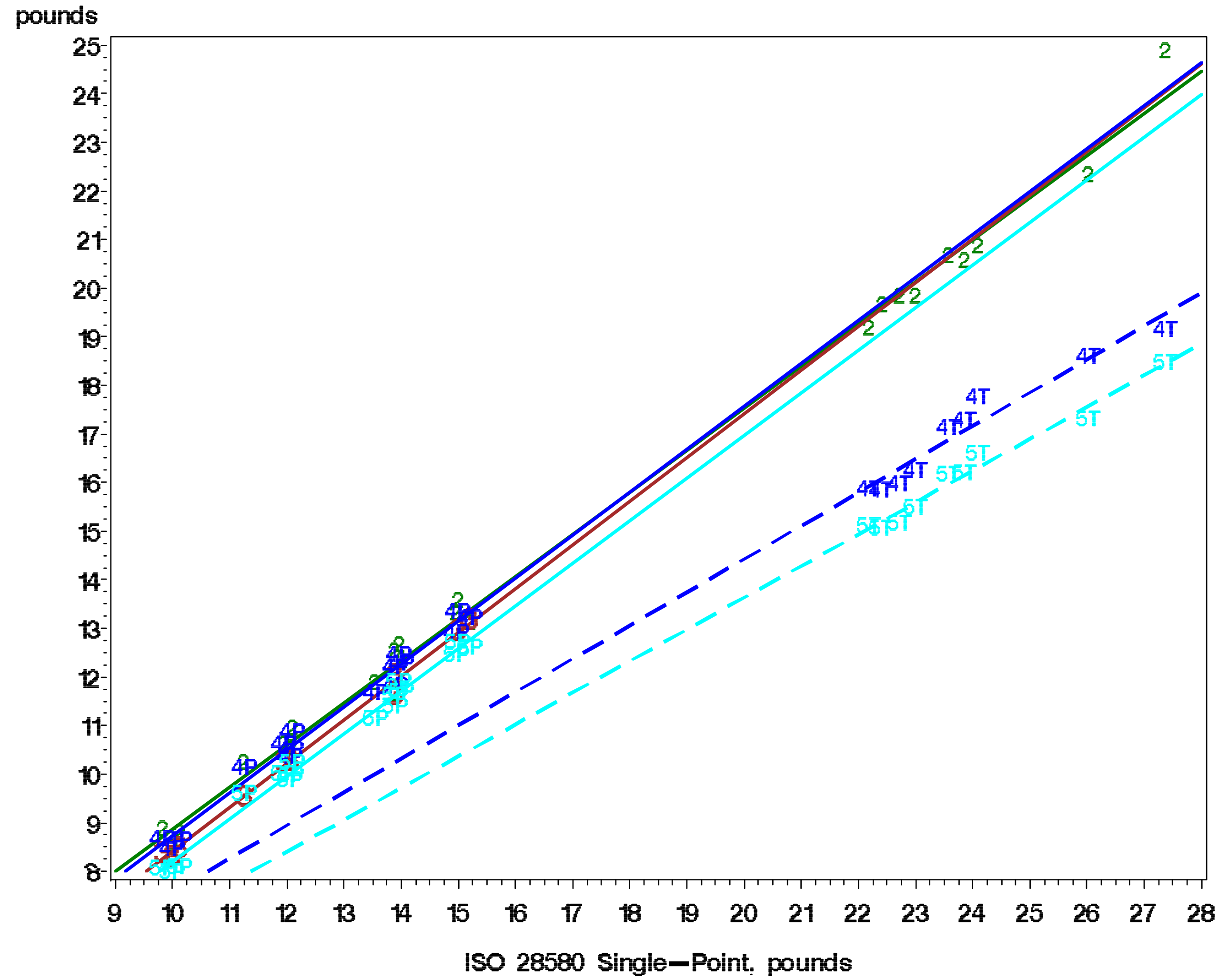
Table 38. Linear Fit Equations for RRc – Other Tests Predicted from SAE J1269 Single-Point RRc Value

Test	Tire Type	R^2	Intercept	Coefficient
ISO 28580 single-point	Passenger	0.9889	0.0007	0.9315
SAE J1269 multi-point at SRC	Passenger	0.9891	0.0006	0.9502
ISO 18164 multi-point at SRC	Passenger	0.9955	0.0001	0.9659
SAE J2452, Calculated SRC	Passenger	0.9913	0.0004	0.9588
SAE J2452, SMERF	Passenger	0.9931	0.0000	0.9483
ISO 28580 single-point	Light Truck	0.9551	0.0007	0.8565
SAE J1269 multi-point at SRC	Light Truck	0.9626	-0.0152	1.1232
SAE J2452, Calculated SRC	Light Truck	0.8116	0.0018	0.9282
SAE J2452, SMERF	Light Truck	0.9136	0.0008	0.9759

4.3.3 ***ISO 28580 (Draft Method) Single-Point Value in Pounds; Comparison to Other Tests***

The previous section detailed the linear correlation of the ISO 28580 test to the SAE J1269 single-point test. The linear correlations of all tests to the SAE J1269 would lead us to expect that the ISO single-point test would therefore have a linear correlation to the other tests. However, it is important to verify the strength of this conclusion, and to quantify these relationships. Figure 21 shows the values, in pounds, for all other tests versus the ISO 28580 single-point value in pounds. It is apparent that the values all have a linear relationship with the ISO 28580 single-point value. The passenger tires measured or calculated values all show parallel lines with little difference in the intercept. The LT tires measured using the SAE J2452 method show a different correlation than the passenger tires whether calculated at the SRC value or using the SMERF. Table 39 details the equations for a linear fit for each test. For the ISO and SAE J1269 multi-point tests and the SAE J2452 test of passenger tires only, the R^2 for the correlations are all greater than 0.983 and the intercepts are between -0.60 and 0.23 pounds. As seen previously, the J2452 test has a different correlation for light truck tires than for passenger tires. With only nine models and more scatter in the correlation, the confidence is reduced. However, the correlations are still very good, with R^2 values of 0.94 for the SRC value and 0.97 for the SMERF value and intercepts of 0.5 to 0.8 pounds.

Figure 21. Rolling Resistance Values in Pounds – Comparison of Values for Each Test to ISO 28580 Single-Point Value



2 = SAE J1269 multi-point value at SRC
3 = ISO 18164 value at SRC
4P = SAE J2452 value at SRC, Passenger Tires
4T = SAE J2452 value at SRC, Light Truck Tires
5P = SAE J2452 SMERF value, Passenger Tires
5T = SAE J2452 SMERF value, Light Truck Tires

Table 39. Linear Correlation of Test Values to ISO 28580 Single-Point Values in Pounds

Test	Tire Type	R^2	Intercept	Coefficient
SAE J1269 multi-point at SRC	All	0.9958	0.2253	0.8652
ISO 18164 multi-point at SRC	Passenger	0.9952	-0.5944	0.9005
SAE J2452, Calculated SRC Value	Passenger	0.9837	-0.1037	0.8833
SAE J2452, Calculated SRC Value	Light Truck	0.9394	0.7330	0.6846
SAE J2452, SMERF Value	Passenger	0.9892	-0.5761	0.8774
SAE J2452, SMERF Value	Light Truck	0.9733	0.5733	0.6528

4.3.4 ISO 28580 Single-Point Rolling Resistance Coefficient; Comparison to Other Tests

Figure 22 shows the value of RRc for other tests versus the ISO 28580 single-point RRc value for the passenger tires in the study. It is apparent that the values all have a linear relationship with the ISO 28580 single-point value, showing parallel lines with little difference in the intercept. The relationship of the LT tires is shown in Figure 23. The correlation is generally linear, but the scatter is greater than for the passenger tires and the slopes differ significantly. Table 40 details the equations for a linear fit for each test. For the passenger tires the R^2 for the correlations are all greater than 0.97 and the intercepts are near zero and the slopes nearly equal to 1.0. For light truck tires, the correlations are very good, with R^2 values of 0.93 to 0.98. There were no discernible trends in the residual values that would indicate a systematic bias based on RRc or rolling resistance values.

Figure 22. Passenger Tires, RRc for Other Tests Versus RRc for ISO 28580 Single-Point

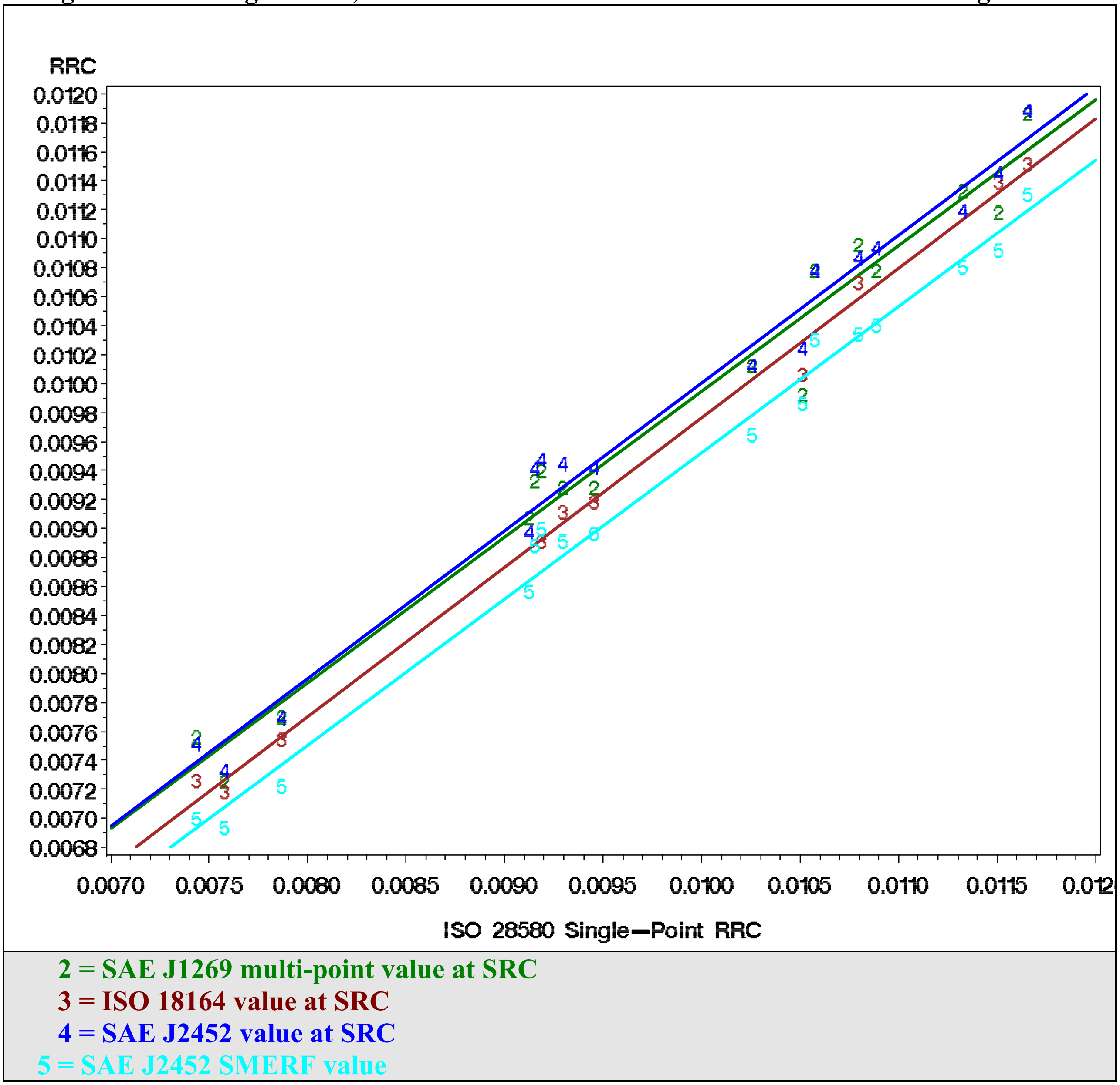
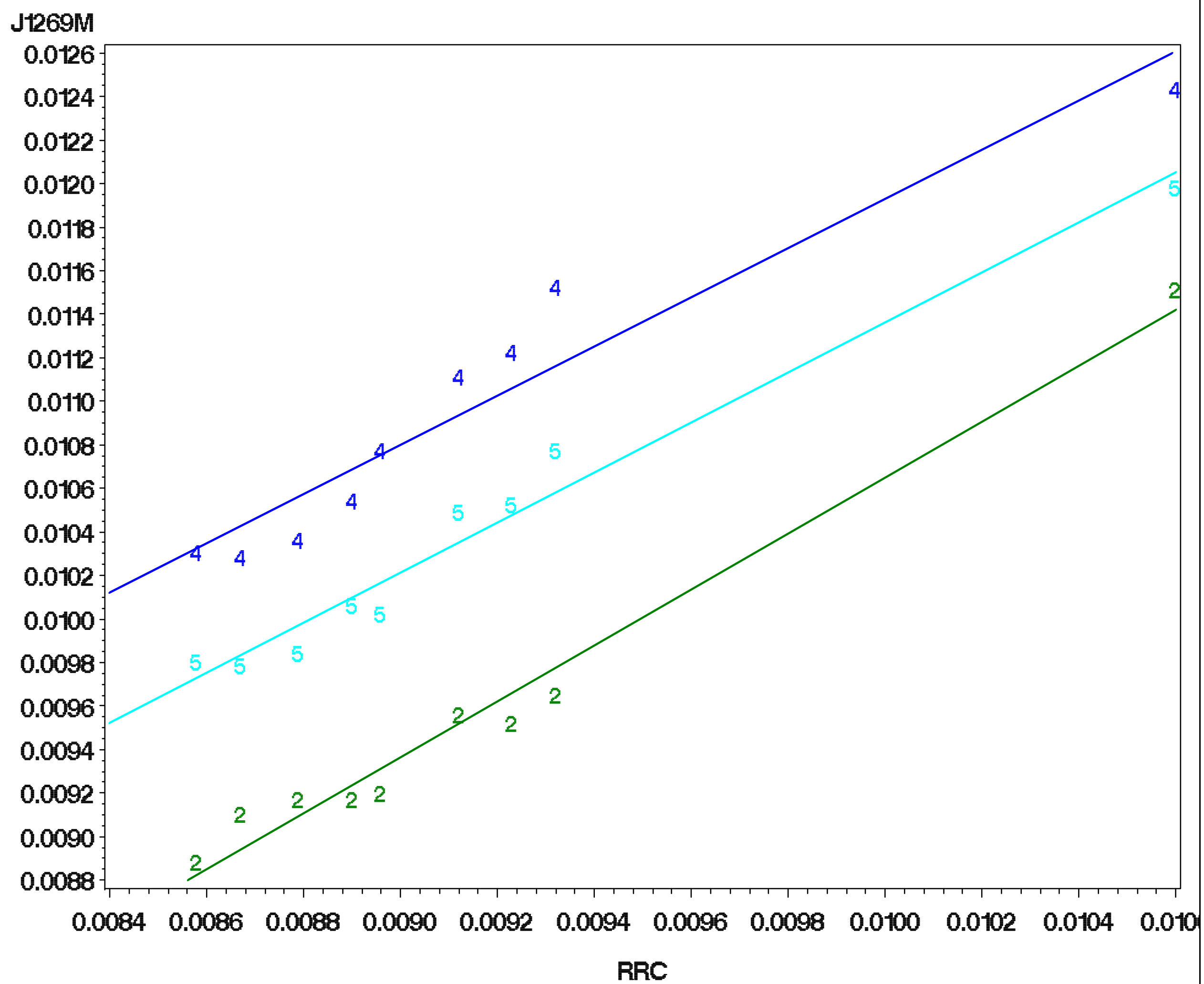


Figure 23. Light Truck Tires, RRc for Other Tests Versus RRc for ISO 28580 Single-Point



2 = SAE J1269 multi-point value at SRC
4 = SAE J2452 value at SRC
5 = SAE J2452 SMERF value

Table 40. Linear Fit Equations for RRc – Other Tests Predicted from ISO 28580 Single-Point RRc Value

Test	Tire Type	R^2	Intercept	Coefficient
SAE J1269 multi-point at SRC	Passenger	0.9720	-0.0001	1.0054
ISO 18164 multi-point at SRC	Passenger	0.9955	-0.0006	1.0324
SAE J2452, Calculated SRC	Passenger	0.9834	-0.0002	1.0194
SAE J2452, SMERF	Passenger	0.9892	-0.0006	1.0102
SAE J1269 multi-point at SRC	Light Truck	0.9253	-0.0022	1.2844
SAE J2452, Calculated SRC	Light Truck	0.9253	0.0006	1.1309
SAE J2452, SMERF	Light Truck	0.9722	-0.0001	1.1486

5.0 LAB-TO-LAB CORRELATION PROCEDURES

As previously discussed, for any given test there was a significant offset between the data generated by the two labs used in this study. This offset was not consistent between tests, or even between tire types within the same test in some cases. If a test is to be used to compare the rolling resistance of tires tested at different facilities and at different times some method to account for this offset needs to be developed. Two possible methods were investigated in this study: (1) development of a lab-to-lab correlation equation; and (2) use of the ASTM F2493 Standard Reference Test Tire (SRTT) to normalize data across labs.

The former method was used in the previous section to correct the data to that expected from a single lab (Smithers, in this case). It is also currently under investigation as part of the ISO 28580 standard. In addition to the normal lab calibration procedures within each lab, this correlation would have to be developed across the entire range of rolling resistance values. There is evidence that a single equation for all tire types may not be sufficient to correct data for all tires. No data is available from this study to determine if a lab-to-lab correlation developed at a given time would remain constant over time, or if offsets and/or drifts will occur in a lab that will require a standardization procedure to be employed.

The ASTM F2493 SRTT was used as in internal standard for each lab and all data within the lab for a test was normalized to the SRTT value. This strategy was very successful for lab-to-lab correlation. It has the added benefit of showing good test method-to test method correlation for passenger tires. The advantages to this method are that it would automatically correct for any systematic drift within a laboratory and that it would fit well into any existing SPC/SQC procedures in place in a lab. It could be further refined by providing a "certified" rolling resistance value to each individual SRTT. Additional work would be needed to investigate whether the rolling resistance value of the SRTT is constant over time before this strategy could be employed.

5.1 Use of Correction Factors for Lab-to-Lab Correlation

Values are compared in pounds rolling resistance, as reported by the laboratories. The conversion to RRc is a scalar that will not affect the correlation between labs so a separate analysis is not required. Where possible the correlation between the identical tire, measured at each lab, is compared. Otherwise, the means of values for each tire type are used for the comparisons. A linear correlation between labs generally provided an excellent fit for correlation. Since the physical lab calibration procedure provides a zero value for the test it is appropriate to model the values with a zero intercept for each lab. A second order fit with a zero intercept provides a slightly better correlation between labs.

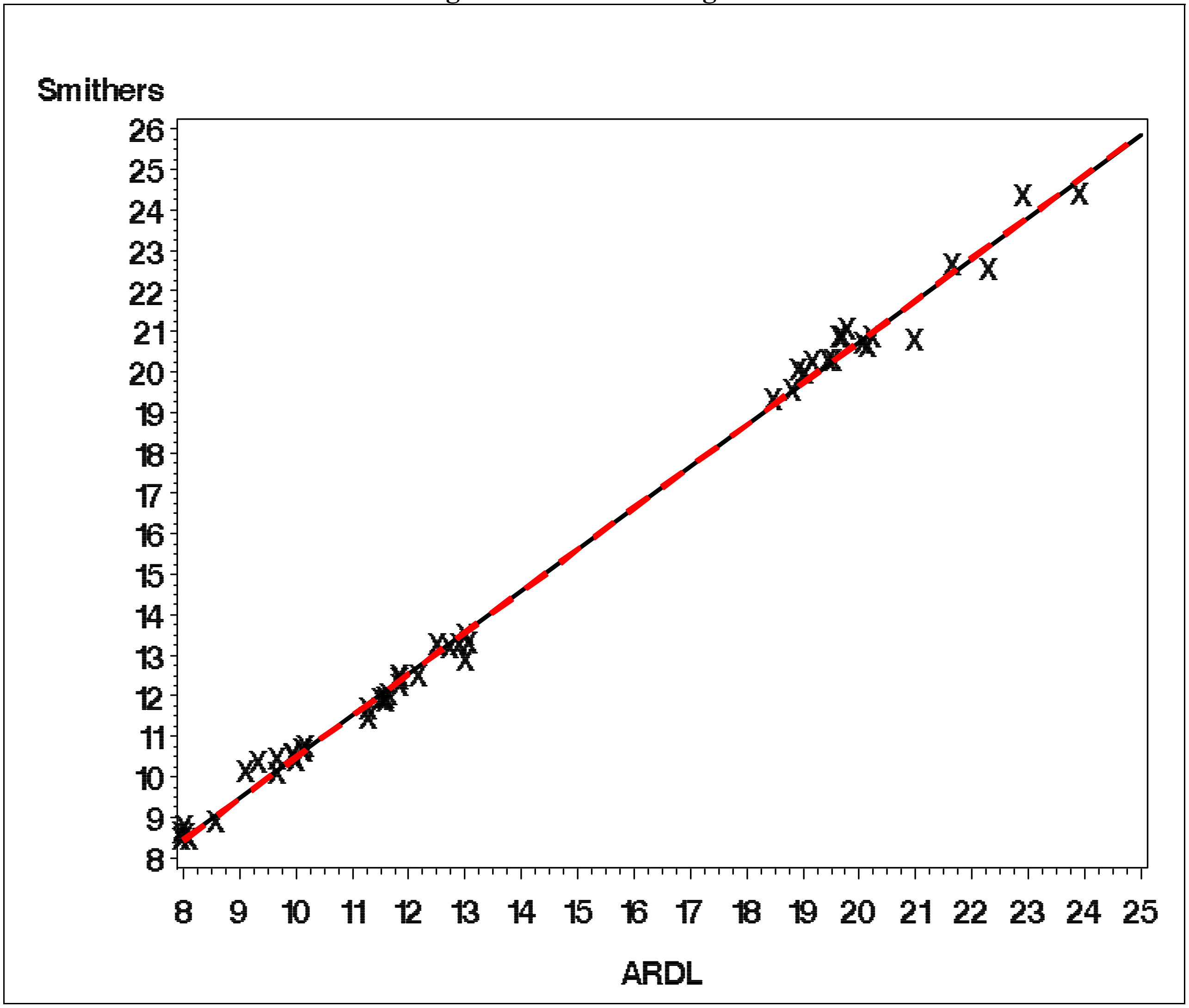
5.1.1 Lab-to-Lab Correlation of SAE J1269 Single-Point Method

Figure 24 shows the relationship for rolling resistance values of the same tire tested at ARDL-STL and at Smithers. The relationship between the labs is linear and fits Equation 3 below, with an R^2 of 0.9961. This calculation is shown as the solid black line in Figure 24. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 4 and as the dashed red line in Figure 24 below. Analysis of the residual values indicates that Equation 4 is a slightly better fit. Compared to the slope of zero for the residuals using Equation 4, Equation 3 predicts values approximately 0.02 pounds (0.25 percent) higher for the lowest passenger tire and approximately 0.02 pounds (0.08 percent) lower for the highest light truck tire. In practical terms, within this range of rolling resistance values and with a standard deviation for the test of approximately 2 percent for these tires, the equations are indistinguishable. Thus, the linear fit (Equation 3) was used for calculations. Since conversion to RRc is simply division of each lab's data by the same factor, the basic relationships for the offset between the labs will be unchanged. The coefficients for the equations will change depending on the load used as the divisor.

Equation 3. (Expected Value at Smithers) = 0.256809515 + 1.023893683*(Value at ARDL-STL)

Equation 4. (Expected Value at Smithers) = 1.057953360*(Value at ARDL-STL) - 0.001025147*(Value at ARDL-STL)^2

Figure 24. Rolling Resistance Values for Identical Barcode Tires Tested at ARDL-STL and Smithers Using the SAE J1269 Single-Point Method



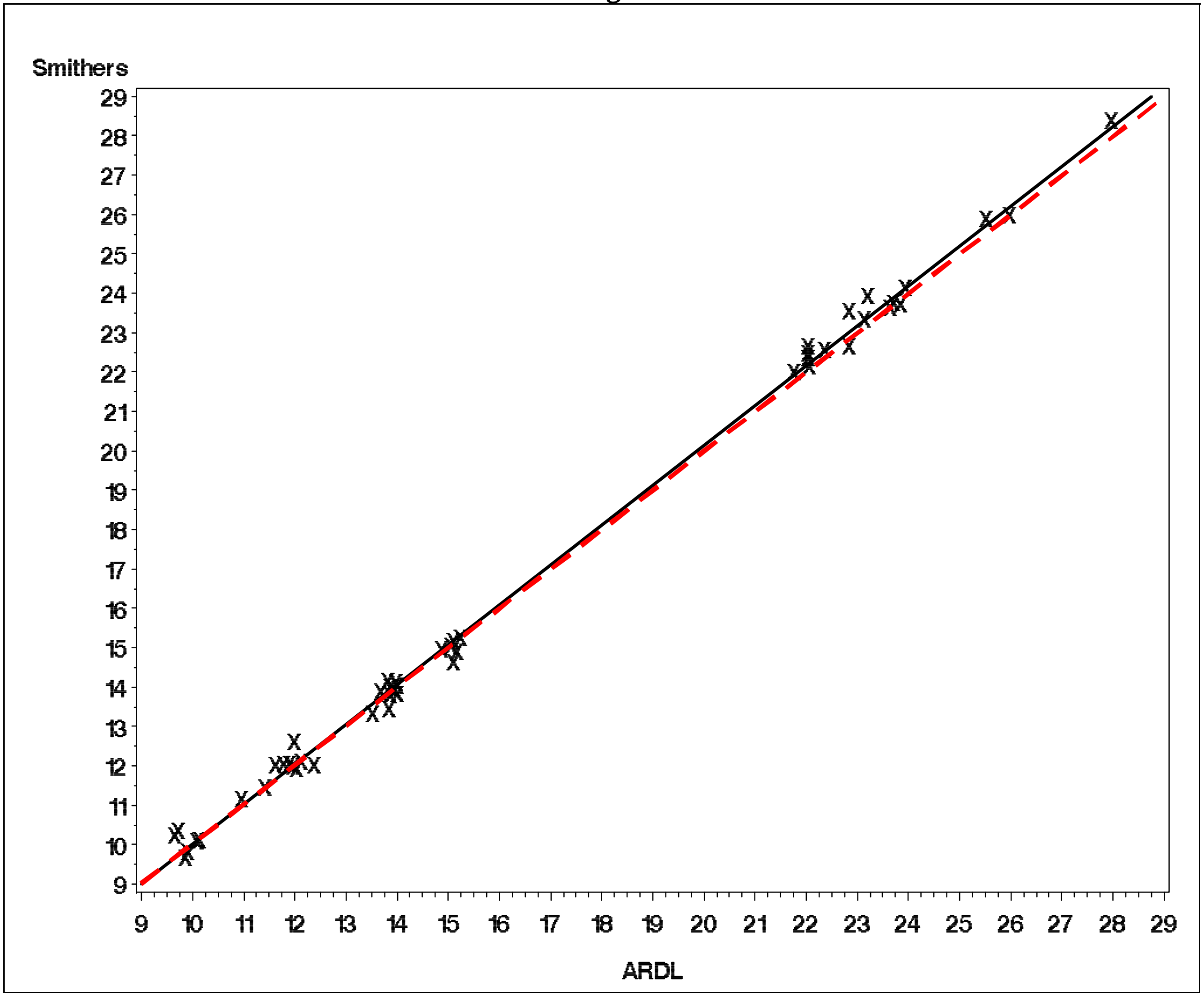
5.1.2 Lab-to-Lab Correlation of ISO 28580 Single-Point Method

Figure 25 shows the relationship for rolling resistance values for tires tested at ARDL-STL and at Smithers. Unlike the J1269, tires of the identical barcode were not tested at each lab and the relationship is based on the mean values by tire type in each lab. The relationship between the labs is linear and fits Equation 5 below, with an R^2 of 0.9975. This calculation is shown as the solid black line in Figure 25. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 6 and as the dashed red line in Figure 25 below. Analysis of the residual values indicates that Equation 6 is a slightly better fit. Compared to the slope of zero for the residuals using Equation 6, Equation 5 predicts values approximately 0.02 pounds (0.08 percent) lower for the highest rolling resistance light truck tire. In practical terms, within this range of rolling resistance values and with a standard deviation for the test of approximately 2 percent for these tires, the equations are indistinguishable. Thus, the linear fit (Equation 5) was used for calculations.

Equation 5. (Expected Value at Smithers) = -0.099369974 + 1.012042485*(Value at ARDL-STL)

Equation 6. (Expected Value at Smithers) = 0.9967824134*(Value at ARDL-STL) + 0.0004918546*(Value at ARDL-STL)^2

Figure 25. Rolling Resistance Values for Tires Tested at ARDL-STL and Smithers Using the ISO 28580 Single-Point Method



5.1.3 Lab-to-Lab Correlation of SAE J1269 Multi-Point Method

Figure 26 shows the relationship for rolling resistance values at SRC for tires tested at ARDL-STL and at Smithers. Unlike the J1269, tires of the identical barcode were not tested at each lab and the relationship is based on the mean values by tire type in each lab. The relationship between the labs is linear and fits Equation 7 below, with an R^2 of 0.9659. This calculation is shown as the solid black line in Figure 26. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 8 and as the dashed red line in Figure 26 below. Analysis of the residual values indicates that Equation 8 is a slightly better fit. Compared to the slope near zero for the residuals using Equation 8, Equation 7 predicts values approximately 0.03 pounds (0.4 percent) higher for the lowest rolling resistance tire. In practical terms, within this range of rolling resistance values and with a standard deviation for the test of approximately 2 percent for these tires, the equations are indistinguishable. Thus, the linear fit (Equation 7) was used for calculations.

Equation 7. (Expected SRC Value at Smithers) = -1.7462527084 + 1.173228733*(SRC Value at ARDL-STL)

Equation 8. (Expected SRC Value at Smithers) = 0.8963571896*(SRC Value at ARDL-STL) + 0.0108940029*(SRC Value at ARDL-STL)^2

Figure 27 shows the correlation between the labs for each of the measured values. It is apparent that the correlation between the labs is consistent for the entire range of rolling resistance values for passenger and light truck tires measured at a wide variety of normal load conditions and inflation pressures. The greatest difference between the labs is for the condition 1 for both passenger and light truck tires where the data from Smithers is significantly higher than expected. This is the first measurement obtained and is obtained with capped inflation, in which the inflation pressure is allowed to rise as the tire heats up during the test. This systematic offset would generate a bias into the calculated value at the SRC for this lab since it would affect the coefficients of the regression equation.

Figure 26. Rolling Resistance Values at SRC for Tires Tested at ARDL-STL and Smithers Using the SAE J1269 Multi-Point Method

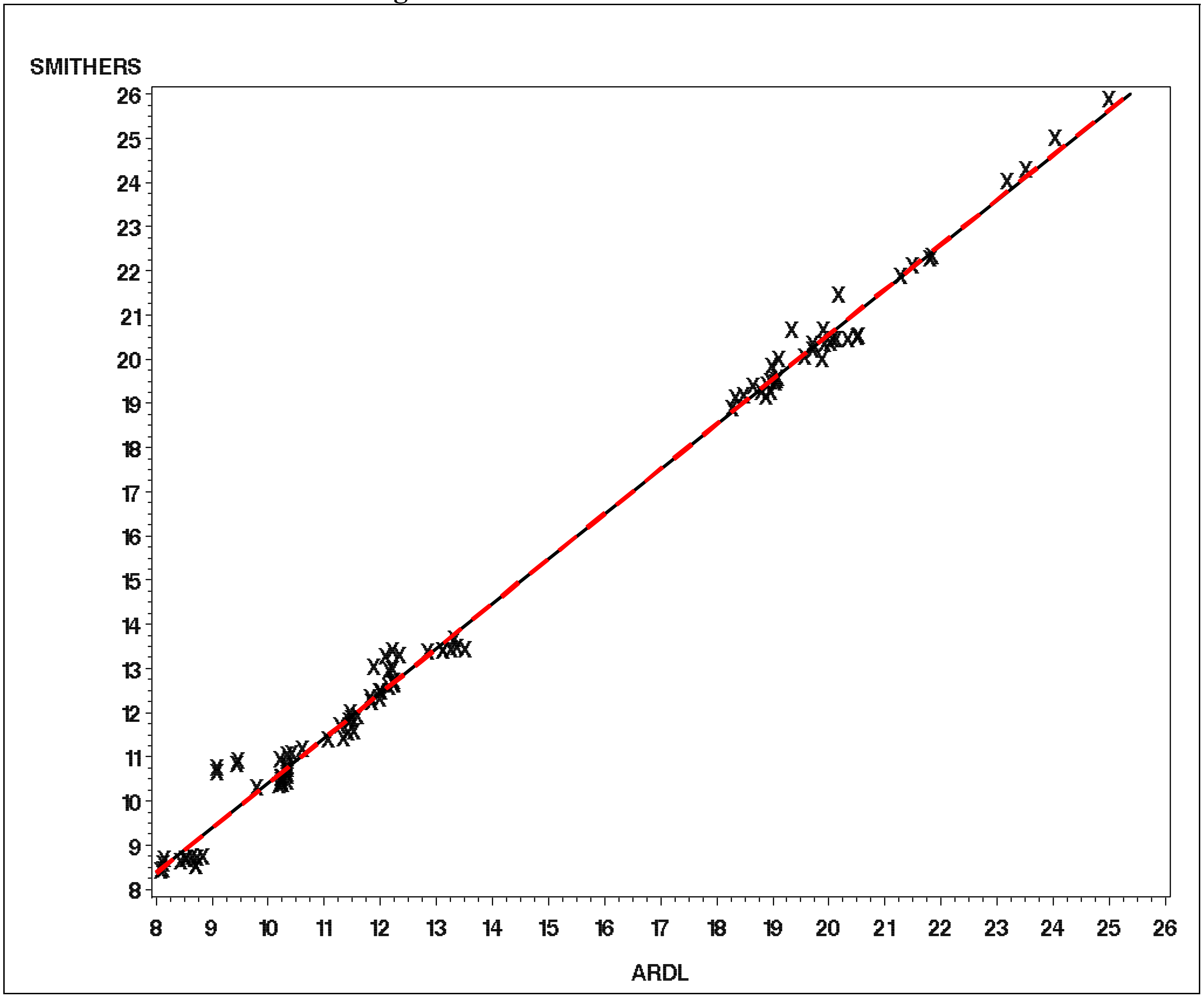
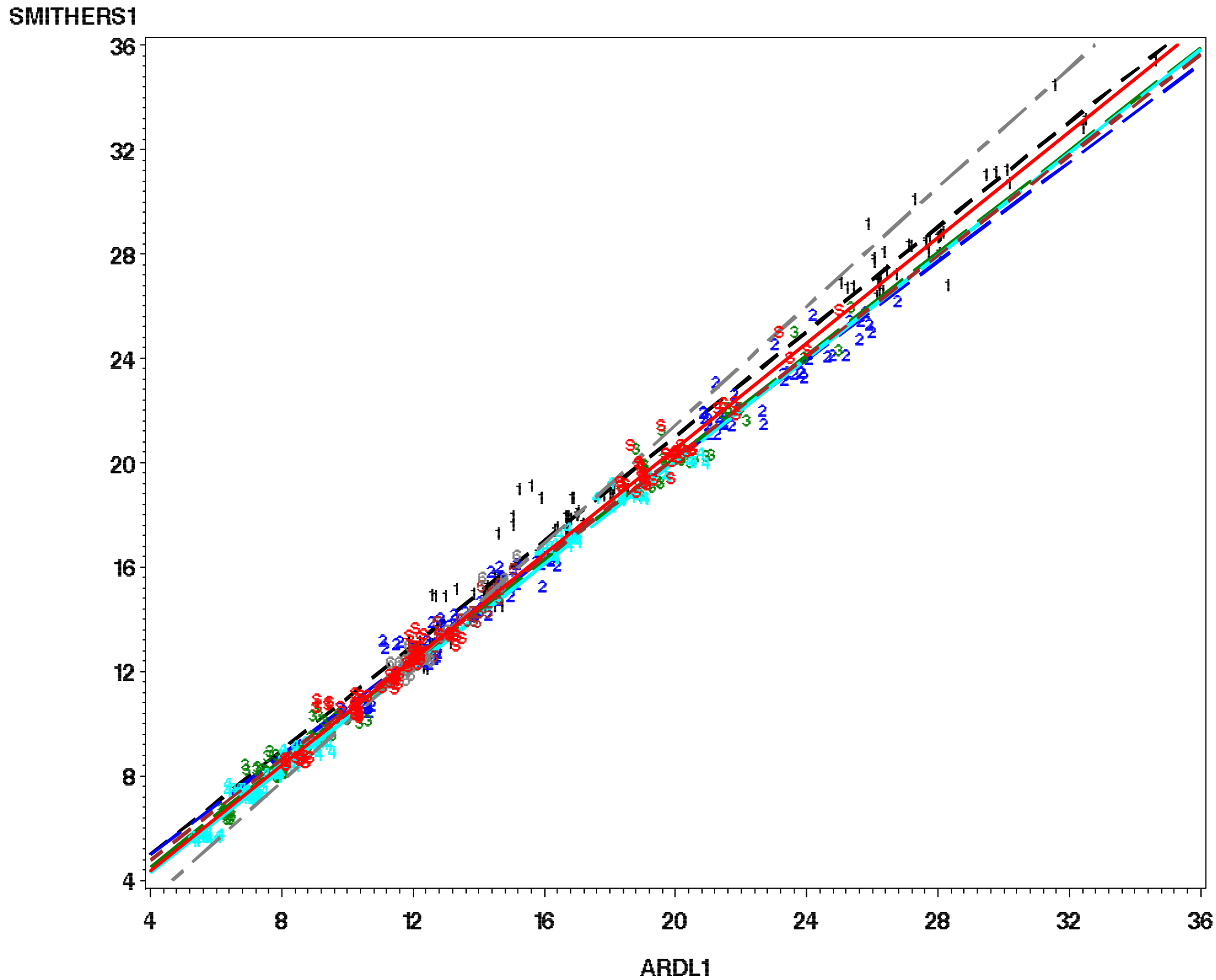


Figure 27. Rolling Resistance Values in Pounds at Smithers and ARDL-STL for Each Condition of the SAE J1269 Multi-Point Method



Passenger Tires	Light Truck Tires
1 = Condition 1 [90% Sidewall Load, -50 kPa Inflation, Capped] 2 = Condition 2 [90% Sidewall Load, +70 kPa Inflation, Regulated] 3 = Condition 3 [50% Sidewall Load, -30 kPa Inflation, Regulated] 4 = Condition 4 [50% Sidewall Load, +70kPa Inflation, Regulated] S = Standard Reference Condition [70% Sidewall Load, +20kPa Inflation]	1 = Condition 1 [100% Sidewall Load, 100% Inflation, Capped] 2 = Condition 2 [70% Sidewall Load, 60% Inflation, Regulated] 3 = Condition 3 [70% Sidewall Load, 110% Inflation, Regulated] 4 = Condition 4 [40% Sidewall Load, 30% Inflation, Regulated] 5 = Condition 5 [40% Sidewall Load, 60% Inflation, Regulated] 6 = Condition 6 [40% Sidewall Load, 110% Inflation, Regulated] S = Standard Reference Condition [70% Sidewall Load, +20kPa Inflation]

5.1.4 *Lab-to-Lab Correlation of ISO 18164 Multi-Point Method*

Figure 28 shows the relationship for rolling resistance values at SRC for tires tested at ARDL-STL and at Smithers. The relationship between the labs is linear and fits Equation 9 below, with an R^2 of 0.9623. This calculation is shown as the solid black line in Figure 26. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 10 and as the dashed red line in Figure 28 below. There is no difference in slope for the analysis of the residual values between Equations 9 and 10. Thus, the linear fit (Equation 9) was used for calculations.

Equation 9. (Expected SRC Value at Smithers) = 0.7139201541 + 0.9076069631*(SRC Value at ARDL-STL)

Equation 10. (Expected SRC Value at Smithers) = 1.052822184*(SRC Value at ARDL-STL) - 0.007123590*(SRC Value at ARDL-STL)^2

Figure 29 shows the correlation between the labs for each of the measured values. It is apparent that the correlation between the labs is consistent for the entire range of rolling resistance values. Unlike the other tests, the measured values at ARDL-STL are significantly higher than those obtained at Smithers for all test conditions. There is no apparent reason for this reversal of the relationship between the labs since many of the test conditions are identical for the ISO 18164 and SAE J1269 test. To investigate the potential source of the difference, the rolling resistance values for the load and inflation conditions that are identical for the two tests (see Table 41) were compared for each lab. The data is shown in Figure 29. The data can be readily fitted to linear equations with near-zero intercept terms, see Figure 30. For the ARDL-STL lab, the ISO test results are approximately 5 percent higher than those obtained with the SAE test. For the Smithers lab, the ISO test results are approximately 3 percent lower than those obtained with the SAE test. Thus, no single shift in data seems to account for the difference in lab-to-lab correlation for the ISO 18164 test compared to the other tests.

Table 41. Common Test Conditions for SAE J1269 and ISO 18164 Tests

Test Condition	Measurement, SAE J1269 Test	Measurement, ISO 18164 Test
90% Load, +70 kPa Inflation, Regulated	2	3
50% Load, -30 kPa Inflation, Regulated	3	2
50% Load, +70 kPa Inflation, Regulated	4	1

Figure 28. Rolling Resistance Values in Pounds, Calculated at SRC, for Passenger Tires Tested at ARDL-STL and Smithers Using the ISO 18164 Multi-Point Method.

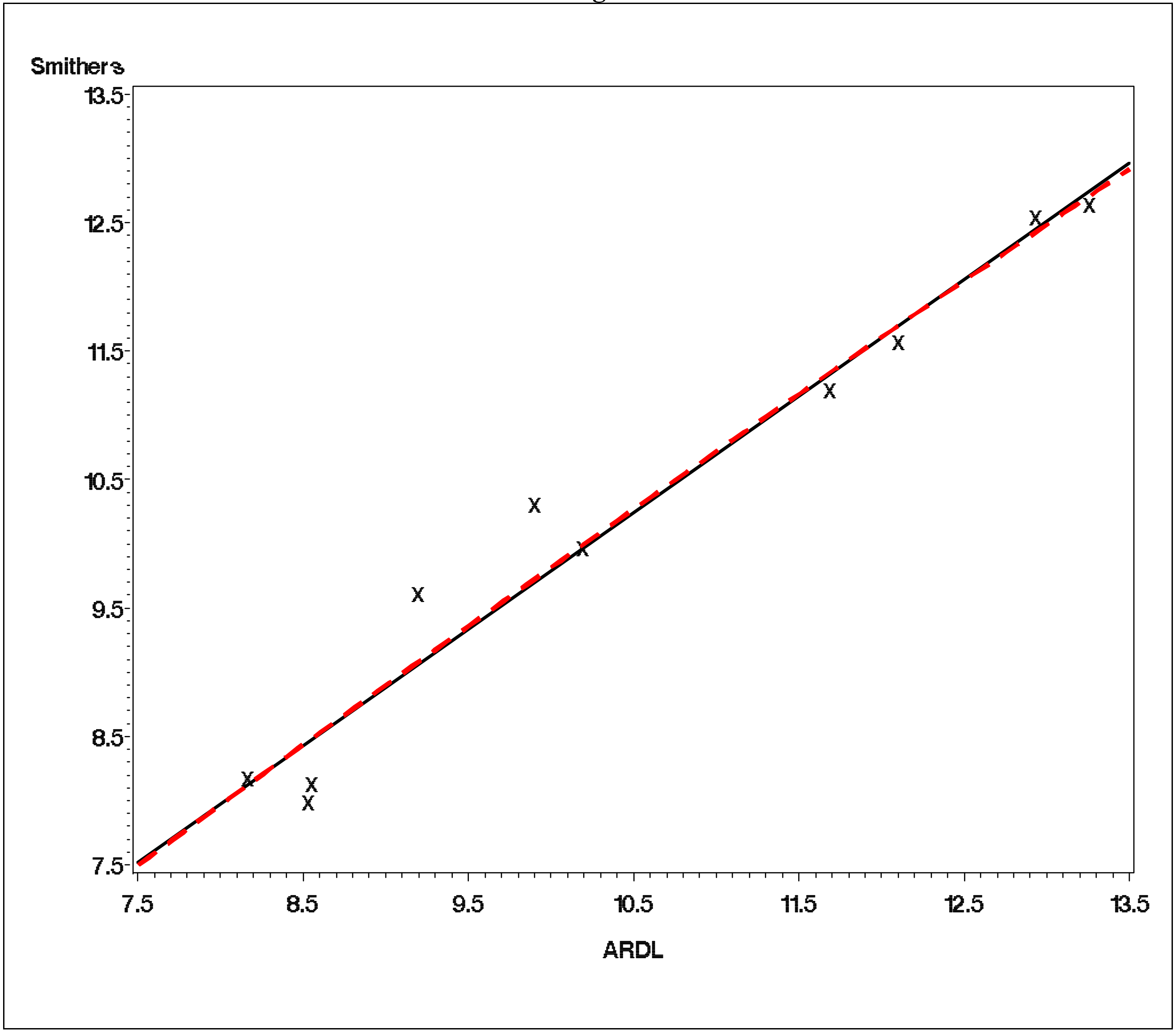
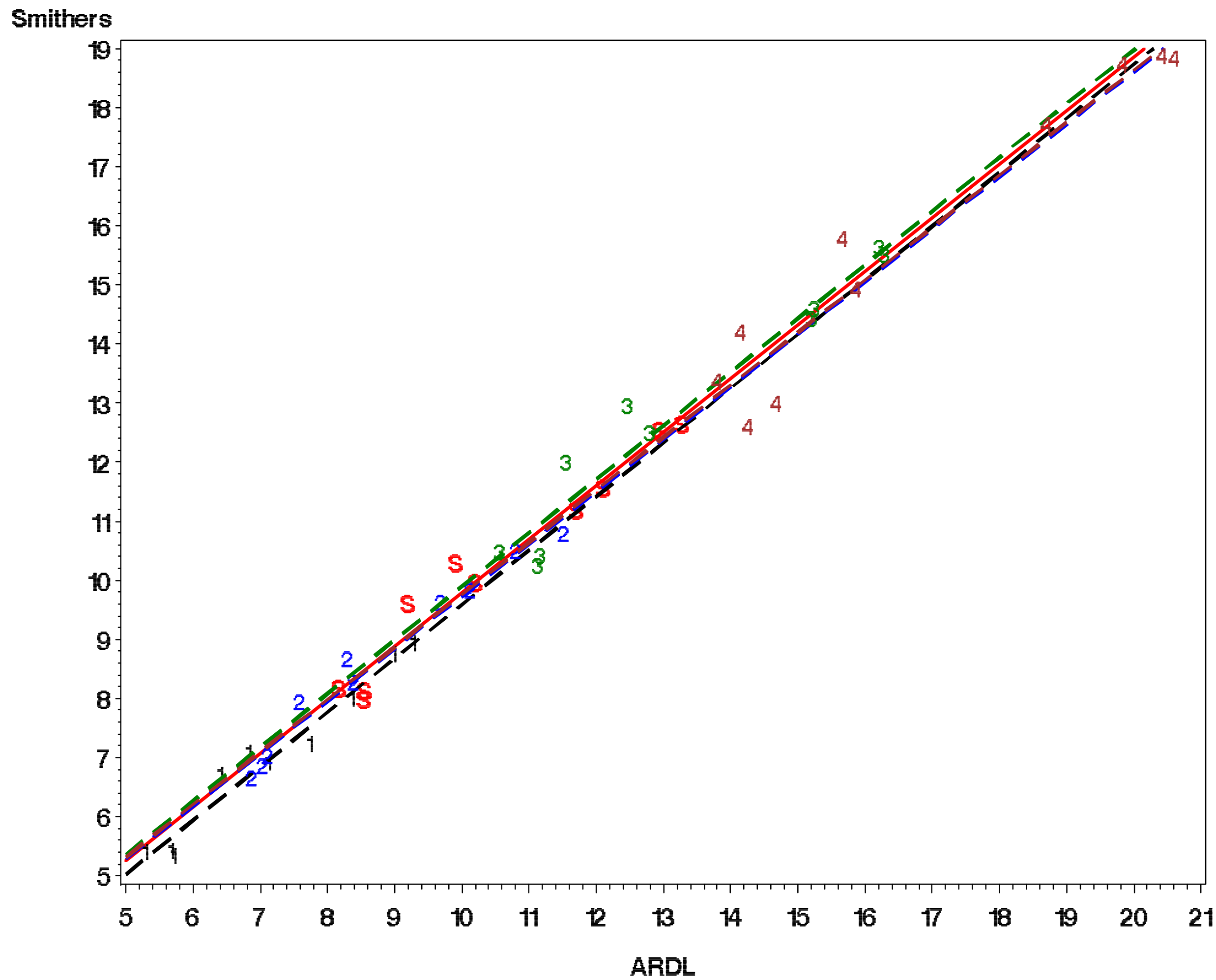
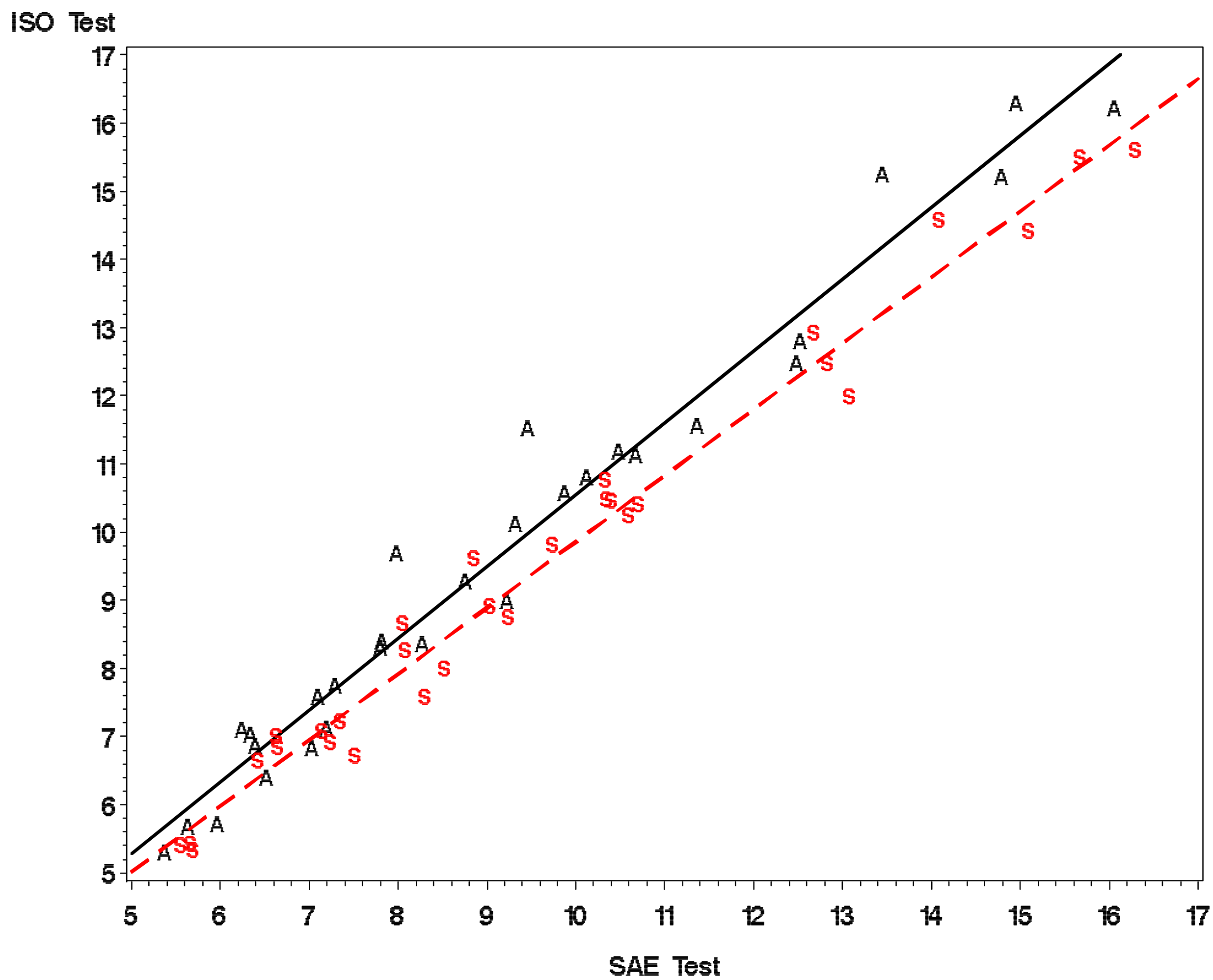


Figure 29. Rolling Resistance Values in Pounds at Smithers and ARDL-STL for Each Condition of the ISO 18164 Multi-Point Method



1 = Condition 1 [50% Sidewall Load, +70 kPa Inflation, Regulated]
2 = Condition 2 [50% Sidewall Load, -30 kPa Inflation, Regulated]
3 = Condition 3 [90% Sidewall Load, +70 kPa Inflation, Regulated]
4 = Condition 4 [90% Sidewall Load, -30 kPa Inflation, Regulated]
S = Standard Reference Condition [70% Max Load, +20kPa Inflation]

Figure 30. Rolling Resistance (lbs.), Value Measured on ISO 18164 Test Versus Measured on SAE J1269 Test at Identical Load and Pressure Conditions by Smithers (S) and ARDL-STL (A)



ARDL-STL Lab. (Value for ISO Test) = 0.0166 + 1.0529*(Value on SAE Test)
Smithers Lab: (Value for ISO Test) = 0.1536 + 0.9706*(Value on SAE Test)

5.1.5 Lab-to-Lab Correlation of SAE J2452 Coastdown Method at SRC and SMERF

Figure 31 shows the relationship for rolling resistance values at SRC for tires tested at ARDL-STL and at Smithers. The relationship between the labs is linear and fits Equation 11 below, with an R^2 of 0.9926. This calculation is shown as the solid black line in Figure 31. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 12 and as the dashed red line in Figure 31 below. There is no difference in slope for the analysis of the residual values between Equations 11 and 12. Thus, the linear fit (Equation 11) was used for calculations.

Equation 11. (Expected SRC Value at Smithers) = -0.023059341 + 1.076906535*(SRC Value at ARDL-STL)

Equation 12. (Expected SRC Value at Smithers) = 1.069845896*(SRC Value at ARDL-STL) - 0.000384701 *(SRC Value at ARDL-STL)^2

Figure 31. Rolling Resistance Values in Pounds, Calculated at SRC, for Passenger Tires Tested at ARDL-STL and Smithers Using the SAE J2452 Coastdown Method

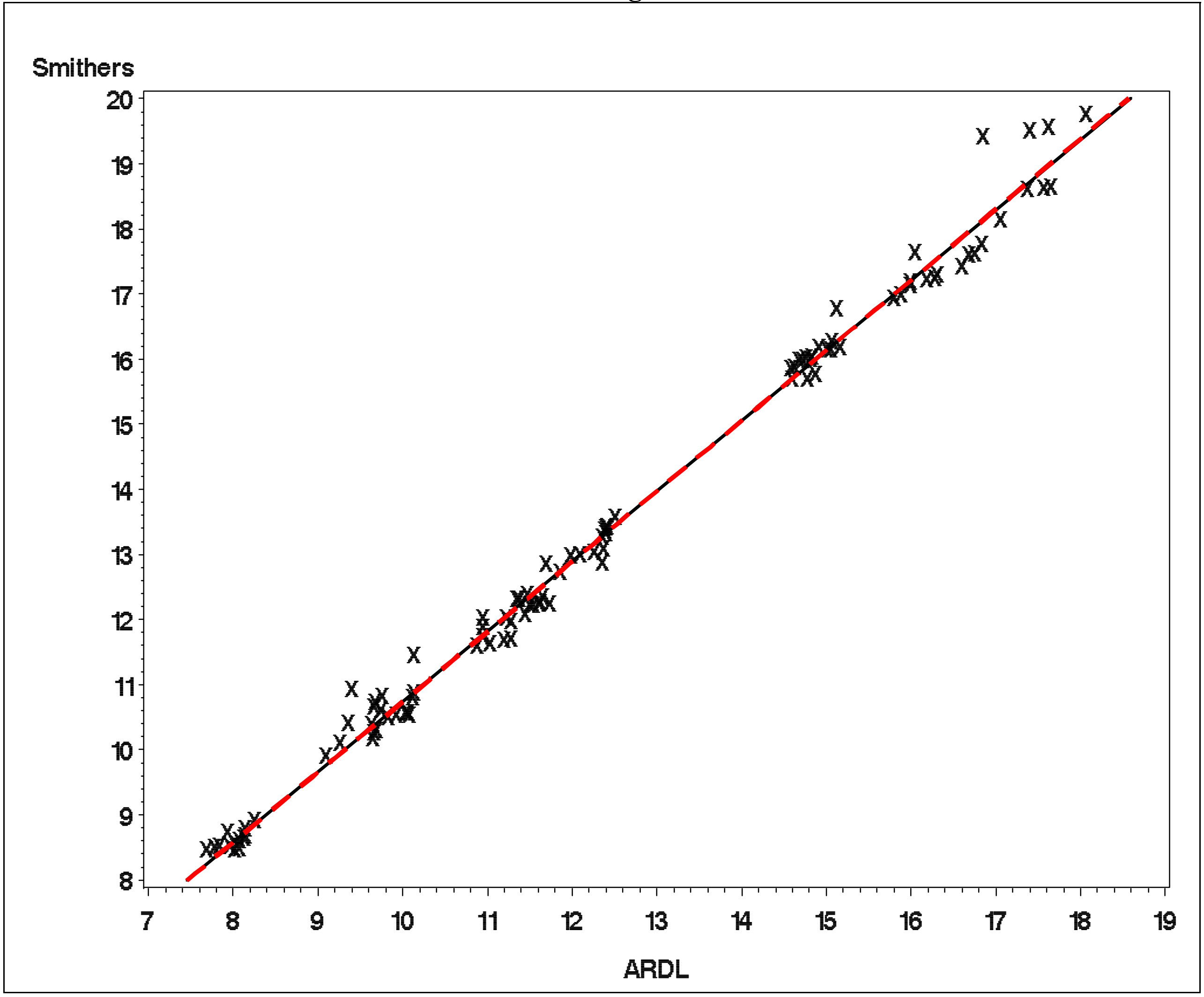
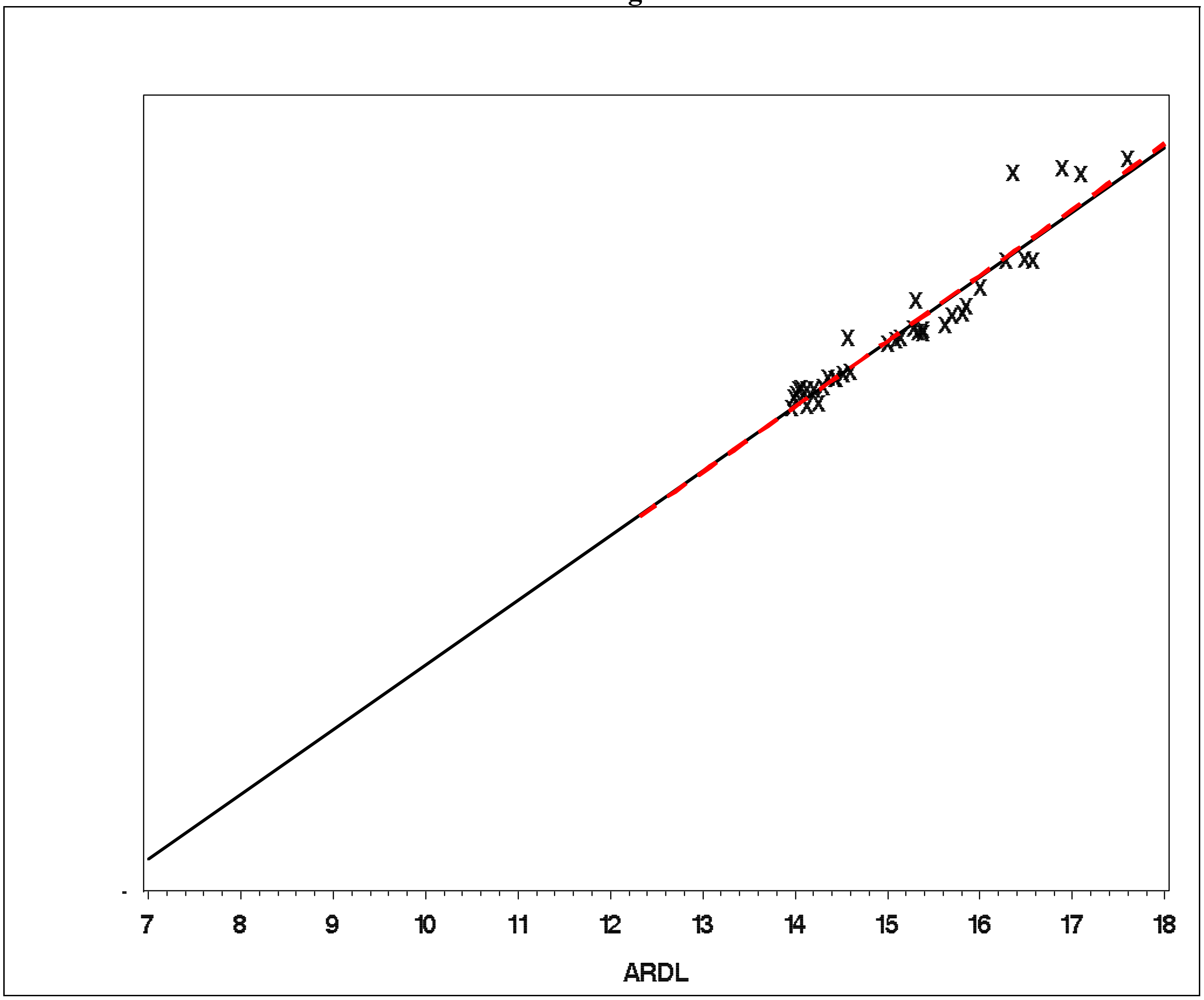


Figure 32 shows the relationship for calculated SMERF rolling resistance values for tires tested at ARDL-STL and at Smithers. The relationship between the labs is linear and fits Equation 13 below, with an R2 of 0.9915. This calculation is shown as the solid black line in Figure 32. Since the calibration procedure at both labs requires a calibration at zero, it may be argued that the intercept should also be forced to zero. This relationship is shown in Equation 14 and as the dashed red line in Figure 32 below. There was no difference in slope for the analysis of the residual values between Equations 13 and 14. Thus, the linear fit (Equation 13) was used for calculations.

Equation 13. (Expected SMERF Value at Smithers) = -0.142480129 + 1.077194028*(SMERF Value at ARDL-STL)

Equation 14. (Expected SMERF Value at Smithers) = 1.046508919*(SMERF Value at ARDL-STL) - 0.001467508*(SMERF Value at ARDL-STL)^2

Figure 32. Rolling Resistance Values in Pounds, SMERF Calculation, for Passenger Tires Tested at ARDL-STL and Smithers Using the SAE J2452 Coastdown Method



5.2 Normalization to the ASTM F2493-06 Standard Reference Test Tire (SRTT)

Tire M14, the SRTT manufactured according to ASTM F2493-06, was included in all aspects of the study. The fact that there were linear relationships between labs and between all tests for passenger tires indicates 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).

Figure 33 shows the correlation between labs for each test using the RRIndex values. Comparing these to the correlations from the previous section, (Figure 25 to Figure 32) shows that the correlations continue to be linear between labs. Figure 34 shows that using RRIndex the correlation between labs for the SAE and J1269 single-point tests are nearly identical, unlike those using pounds force or RRc, as previously shown by Figure 30. More importantly, all correlations between labs are now very nearly one-to-one for each test, with an average of 1.0022 as shown in Table 42. The standard deviation of 0.0112 is within the normal range of test repeatability found. Thus, normalization to the SRTT value is a valid method of maintaining correlation between labs. Finally Figure 35 shows that not only are the correlations nearly identical between tests, but the actual values obtained for RRIndex are equivalent for passenger tires, no matter which test is employed to measure the rolling resistance. The use of the SRTT as a reference and statistical process control techniques within each lab will give results that can be directly compared. For passenger tires, normalization of RRc data to the RRc of the Standard Tire could also be used as a measure of rolling resistance. Since this data set contains nearly all the same size passenger tires, and were therefore tested at the same load, no substantial conclusions could be drawn about any advantages or disadvantages for this calculation.

Figure 33. Lab-to-Lab Correlation Using RRIndex (Normalized to SRTT)

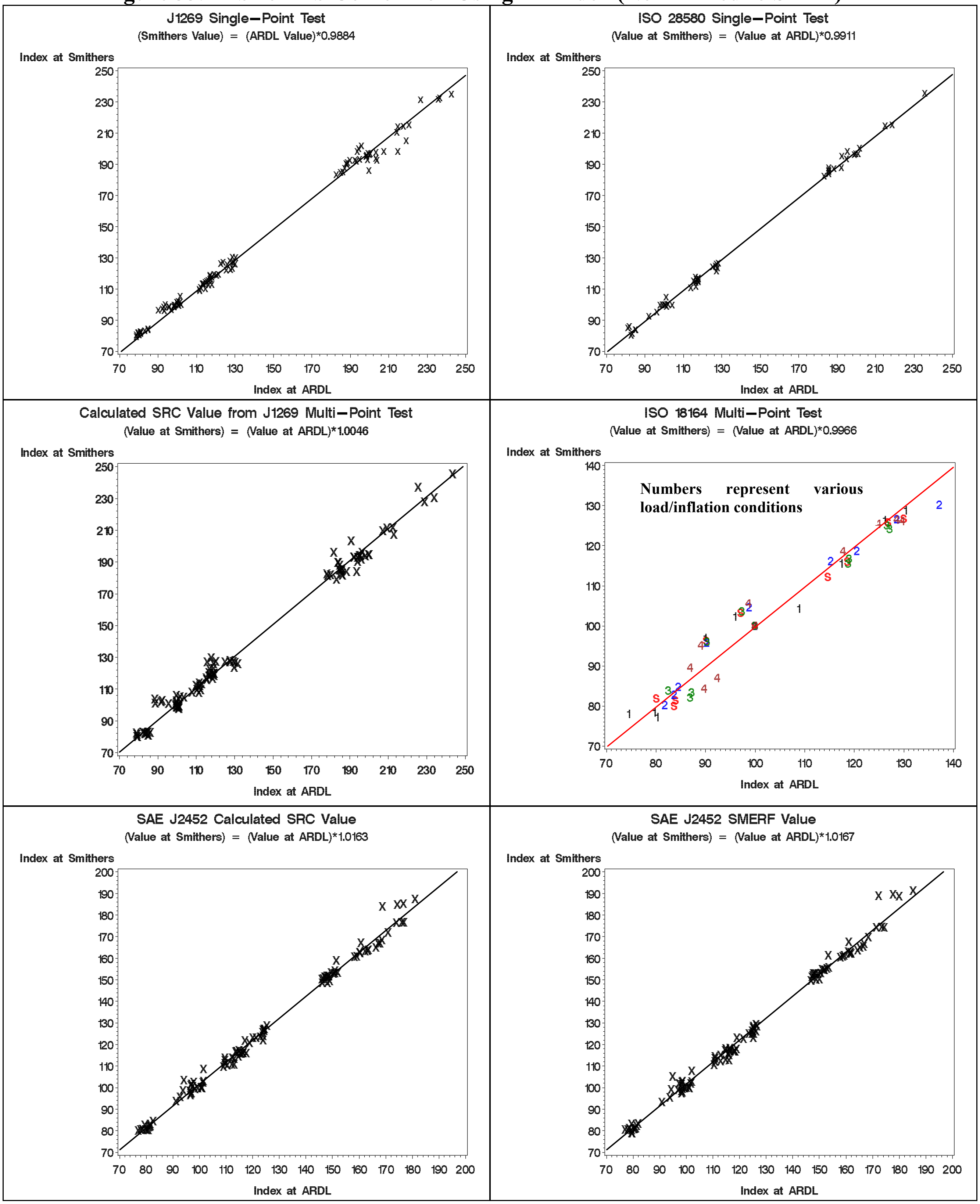


Figure 34. Correlation of ISO and SAE Test Values for ARDL-STL (-A-) and Smithers (-S-) Normalized to SRTT Value

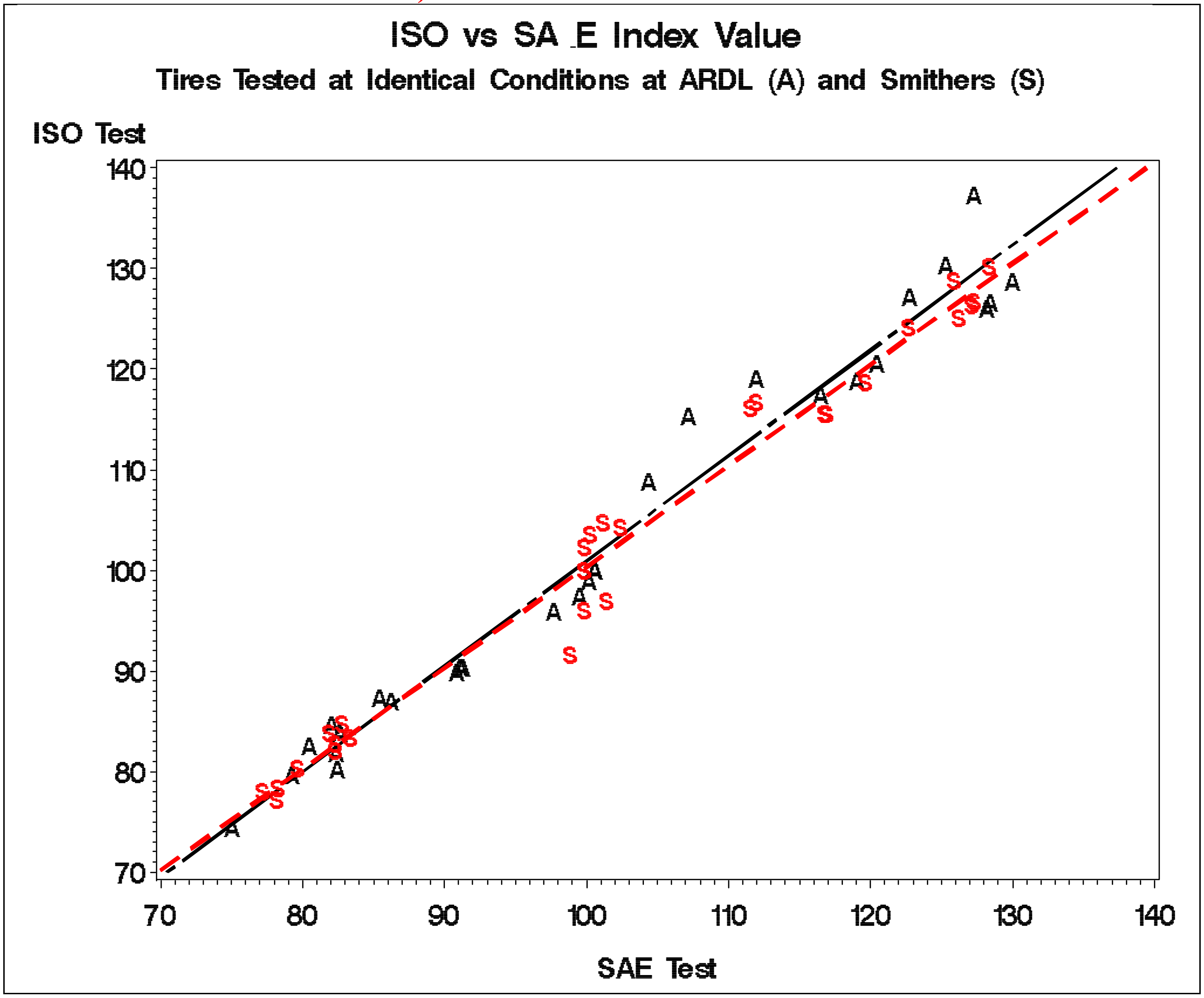
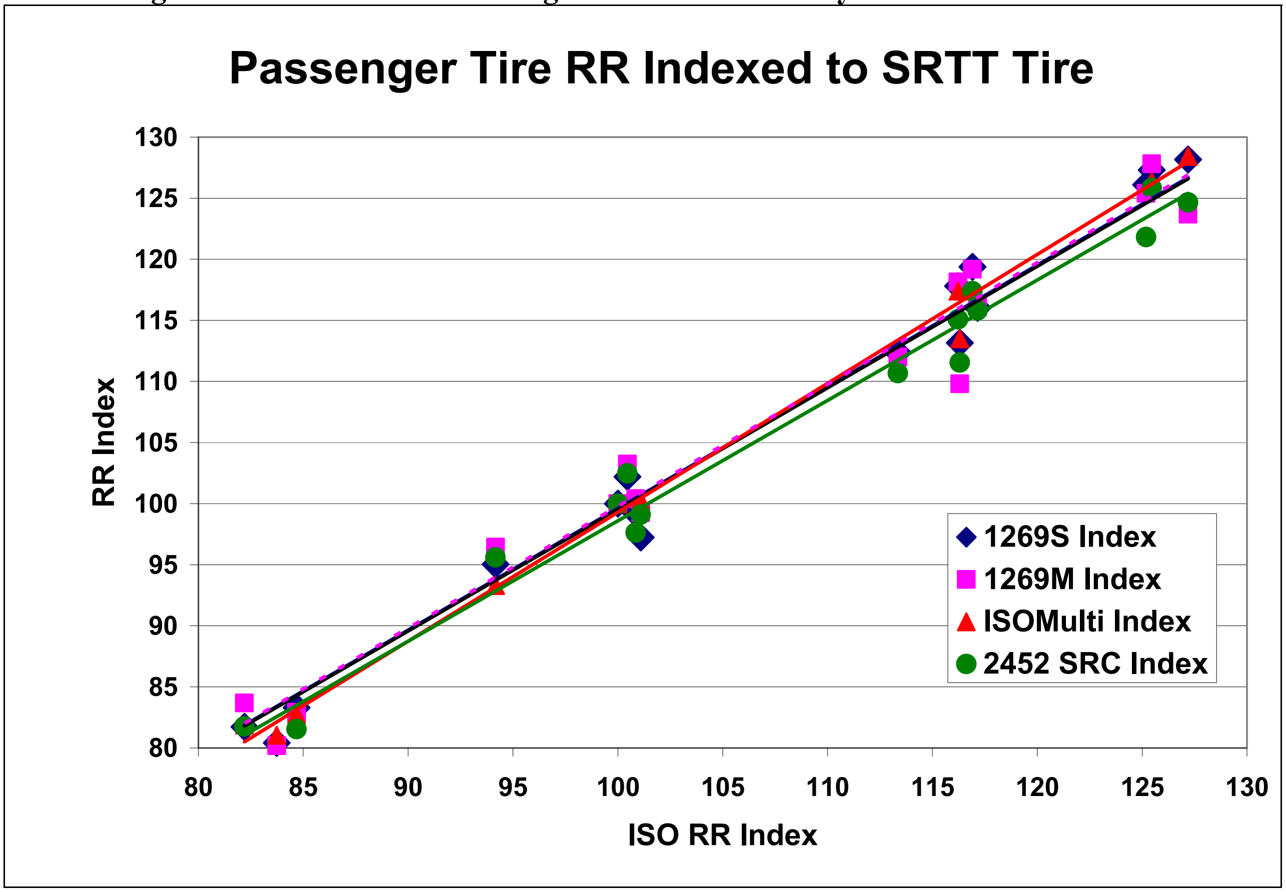


Table 42. Correlation between Labs Using RRIndex, Normalized to SRTT

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

Figure 35. RRIndex for Passenger Tires Measured by Various Test Methods



6.0 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. Furthermore, all tests rank ordered the tires equivalently. However, the relative rankings of the tires within the population of the 25 models tested shifted considerably when tires were ranked by rolling resistance force (RRf) as opposed to rolling resistance coefficient (RRc). Equations were derived that allow accurate conversion of data from any one test to the expected data from any other test. 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.

Within each group of tires, the individual tire model was the most significant variable determining the rolling resistance. Of the 600 tires measured in the study, only one individual tire was significantly different than the other tires of the same model, indicating that the rolling resistance of tires with the same model and construction can be expected to be relatively uniform. There was a significant offset between the data generated by each laboratory testing tires in this study. This could be compensated for by correcting the data to a reference laboratory using the results of regression equations or by the use of a standard reference test tire (SRTT) to align the data. There was little or no significant effect of repeat rolling resistance testing on the same tire. Therefore, repeat testing of the same calibration tire appears to be viable. The pressure rise in the tire during testing using a capped inflation procedure reduced the rolling resistance compared to maintaining the pressure at a constant pressure during the test. Therefore, the choice of a test that uses capped inflation pressure for some or all of the test points should provide a more accurate representation of in-service behavior.

To minimize variability when evaluating the five test methods, tires of each model were purchased with identical or similar build dates. Therefore, the variability of an individual tire model's rolling resistance over a long duration of build dates, or for a single model built at different plants, has not been evaluated. 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 ARDL-STL, 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.

The next phase of the project will examine possible correlations between tire rolling resistance levels and wet and dry traction, indoor and outdoor treadwear, and vehicle fuel economy as measured on a dynamometer.

7.0 RECOMMENDATIONS

It is recommended that the agency adopt the ISO 28580 single-point test procedure, when issued in its final version, as the standard test for rolling resistance of light vehicle tires.

Since all procedures provided reliable and equivalent information about the rank-order of rolling resistance for the tires studied, a single-point test is the most cost effective option. The increased information about the response of an individual tire's rolling resistance due to changes in pressure, load, or speed inherent in the multi-point test procedures do not warrant the increased cost of the testing.

The most significant provision of the ISO 28580 method is the use of defined reference tires to allow comparison of data between labs on a standardized basis. The use of any other procedure 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.

Finally, the Commission of the European Communities (EU) has selected ISO 28580 international standard as the basis of their rolling resistance rating system. Use of ISO 28580 would allow international harmonization of U.S. and European test practices.

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