ROLLING RESISTANCE OF TIRES FOR LIGHT VEHICLES II: COMPARISON OF ROLLING RESISTANCE VALUES OBTAINED FROM DIFFERENT TEST METHODS AND IN DIFFERENT LABORATORIES

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Rolling Resistance of Tires for Light Vehicles, II: Comparison of Rolling Resistance Values Obtained from Different Test Methods and in Different Laboratories

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Objective

- Select a Method to Measure Tire Rolling Resistance in Order to Compare Tires
  - SAE J2452 values at various speed, load, and inflations used to relate tire properties to vehicle
    - SMERF (Standard Mean Equivalent Rolling Force)
  - SAE J1269 and ISO 18164 describe the tire response at various load and inflation conditions
    - SRC (Standard Reference Condition)
  - SAE J1269 and ISO 28580 test a tire at standard conditions of speed, load, and inflation
Measuring Rolling Resistance

- Evaluate Sources of Variability in Testing
  - Tire
    - Different Tire Types
    - Different Tires of Same Type
    - Same Tire - Repeat Testing
  - Lab
  - Test
Test Matrix

- Five Test Protocols
- 25 Tire Types
- Capped or Regulated Pressure (J1269)
- First, Second and Third Tests on Individual Tires
- Different Inflation Gas
- 641 Tests

Only one tire was an outlier from other tires of the same model.
ANOVA

- Analysis of Variance was conducted on results from each test
  - SAE J1269 Single-Point
  - SAE J1269 Multi-Point
    - Calculated value at SRC using regression specified
  - ISO DIS28580 Single-Point
  - ISO 18164 Multi-Point
    - Calculated at SRC using J1269 regression method
  - SAE J2452
    - SMERF
    - Calculated value at SRC using J2452 regression
### SAE J1269 Single-Point

#### Dependent Variable: Rolling Resistance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>29</td>
<td>49358.7</td>
<td>1702.0</td>
<td>15122.2</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>191</td>
<td>21.5</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncorrected Total</td>
<td>220</td>
<td>49380.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R-Square</th>
<th>Coeff Var</th>
<th>Root MSE</th>
<th>RR Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.995985</td>
<td>2.371565</td>
<td>0.335487</td>
<td>14.14623</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Type III SS</th>
<th>Mean Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Where Tested</td>
<td>1</td>
<td>9.45</td>
<td>9.45</td>
<td>83.99</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Procedure for Inflation</td>
<td>1</td>
<td>2.99</td>
<td>2.99</td>
<td>26.62</td>
<td>&lt;.0001</td>
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<tr>
<td>Test Order</td>
<td>2</td>
<td>0.07</td>
<td>0.036</td>
<td>0.32</td>
<td>0.7265</td>
</tr>
<tr>
<td>Type (Tire Model)</td>
<td>24</td>
<td>4871.64</td>
<td>202.98</td>
<td>1803.49</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Test</td>
<td>F Value</td>
<td>R²</td>
<td>F Value - Lab</td>
<td>F Value - Capped / Regulated</td>
<td>F Value - Test Order</td>
</tr>
<tr>
<td>----------------------------</td>
<td>---------</td>
<td>--------</td>
<td>---------------</td>
<td>-----------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>J2452 SMERP</td>
<td>23,535</td>
<td>0.9953</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISO 18164 (10 Tires)</td>
<td>2,687.6</td>
<td>0.9891</td>
<td></td>
<td></td>
<td>4.30*</td>
</tr>
<tr>
<td>ISO DIS28580</td>
<td>8,320.9</td>
<td>0.9967</td>
<td></td>
<td></td>
<td>2.14</td>
</tr>
<tr>
<td>J1269 Multi-Point</td>
<td>15,929.5</td>
<td>0.9960</td>
<td></td>
<td></td>
<td>11.24</td>
</tr>
<tr>
<td>J1269 Single-Point</td>
<td>15,122.2</td>
<td>0.9960</td>
<td></td>
<td></td>
<td>83.99</td>
</tr>
</tbody>
</table>

*Variables were confounded
ANOVA Conclusions

- F and R² values indicate that the sources of variation are accounted for in model.
  - Tire type is the most significant variable.
  - The two labs studied produced significantly different values.
  - Capped vs. regulated inflation pressure during the test was significant.
  - First, second, or third test on the same tire was not a significant variable.
Lab Variation

- Test order (1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}) ignored
- Coefficient of Variation within a lab for a tire type on a test was $\leq 2.5\%$
- Values were normally distributed within each lab
- There was a significant variation between labs for all tests
Rolling Resistance @ Lab B = 0.257 + 1.024*(Lab A)
<table>
<thead>
<tr>
<th>Test</th>
<th>J1269 Single-Point</th>
<th>J1269 Multi-Point</th>
<th>ISO 28580 Single-Point</th>
<th>ISO 18164</th>
<th>J2452 SMERF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation of Lab B to Lab A</td>
<td>$B = 0.257 + 1.024A$</td>
<td>$B = -1.746 + 1.012A$</td>
<td>$B = -0.099 + 1.012A$</td>
<td>$B = 0.714 + 0.908A$</td>
<td>$B = -0.143 + 1.077A$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9975</td>
<td>0.9659</td>
<td>0.9623</td>
<td>0.9623</td>
<td>0.9915</td>
</tr>
</tbody>
</table>
Lab to Lab Correlation

- Statistically significant offset between labs.
  - Lab B had higher values than Lab A for 3 of the tests
  - Lab B had lower values than Lab A for 1 test
  - Equal on average for 1 test

- A slightly better prediction of lab offset could be obtained with a non-linear equation, especially for multi-point tests
Lab-to-Lab Offset

Correlation of Lab B to Lab A for all conditions of the J1269 Multi-Point test. Test Point 1 [Capped Inflation] is significantly offset.
## Variability of Test

<table>
<thead>
<tr>
<th>Test</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1269 Single-Point</td>
<td>2.4%</td>
</tr>
<tr>
<td>J1269 Multi-Point</td>
<td>2.4%</td>
</tr>
<tr>
<td>ISO DIS28580</td>
<td>2.2%</td>
</tr>
<tr>
<td>ISO 18164 (10 Tires)</td>
<td>5.2%</td>
</tr>
<tr>
<td>J2452 SMERF</td>
<td>1.9%</td>
</tr>
</tbody>
</table>
Sources of Variability in Testing

- Different Tires of Same Type
  - Only 1 Tire significantly different
- Same Tire – Repeat Testing
  - No significant effect
- Lab
  - Significant differences
    - Varies by test and conditions
- Test
  - All tests have low Coefficient of Variation (C.V.)
Ranking Tire Rolling Resistance

- Data for values from Lab A corrected to Lab B values using correlation equations
- Do tests rank-order tires differently?
- Rolling resistance of tires was grouped using least significant differences at 95% confidence level for data from each test
Correlation of Test Data

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

<table>
<thead>
<tr>
<th>Group</th>
<th>J1269 Single-Point</th>
<th>J2452, SMERF</th>
<th>J2452 @ SRC</th>
<th>ISO 18164</th>
<th>ISO 28580</th>
<th>J1269 Multi-point @ SRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L0</td>
<td>L0</td>
<td>L0</td>
</tr>
<tr>
<td>1</td>
<td>B11</td>
<td>G11</td>
<td>G11</td>
<td>B12</td>
<td>B12</td>
<td>R4</td>
</tr>
<tr>
<td>2</td>
<td>G11</td>
<td>G11</td>
<td>G11</td>
<td>B12</td>
<td>B12</td>
<td>R4</td>
</tr>
<tr>
<td>3</td>
<td>U3</td>
<td>U3</td>
<td>U3</td>
<td>B15</td>
<td>B15</td>
<td>R4</td>
</tr>
<tr>
<td>4</td>
<td>R4</td>
<td>R4</td>
<td>R4</td>
<td>B15</td>
<td>B15</td>
<td>R4</td>
</tr>
</tbody>
</table>

**(ISO 18164)**
- L0: Group 1 (Lowest)
- L4: Group 4 (Highest)

**(ISO 28580)**
- L0: Group 1 (Lowest)
- L4: Group 4 (Highest)

**(J1269 Multi-point @ SRC)**
- L0: Group 1 (Lowest)
- L4: Group 4 (Highest)

**(J1269 Single-Point)**
- L0: Group 1 (Lowest)
- L4: Group 4 (Highest)

**(J2452, SMERF)**
- L0: Group 1 (Lowest)
- L4: Group 4 (Highest)
<table>
<thead>
<tr>
<th>Group</th>
<th>J1269 Single-Point</th>
<th>J1269 multi-point @ SRC</th>
<th>ISO 28580</th>
<th>J2452 @ SRC</th>
<th>J2452, SMERF</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>D9</td>
<td>D9</td>
<td>D9</td>
<td>D9</td>
<td>C9</td>
</tr>
<tr>
<td>6 (Highest)</td>
<td>C9</td>
<td>C9</td>
<td>C9</td>
<td>C9</td>
<td>C9</td>
</tr>
</tbody>
</table>

Light Truck Tire Groups

J1269, ISO 28580, J2452, SMERF.
Selection of Method

- All methods produce data with low variation
- All methods rank tires into the same groups
- Data from any method can be correlated to data from any other method
- Single-point method is most efficient
- Any method selected will need a procedure to account for lab-to-lab differences
Rolling Resistance Coefficient (RRC) is often used to report the rolling resistance of tires.

- RRC is Rolling Resistance Force / Normal Force
  - Using same units removes the dimension

When comparing tires tested at the same load, there is no change in comparisons.

Can RRC be used to compare tires of different load ratings?
Correlation of Test Data

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

- While RRC is dimensionless, it is not independent of conditions of testing.
- For passenger tires using J1269 RR:
  \[ RR_{\text{Force}} = \text{Load} \times (A_1 + A_2 \times \text{Load} + A_3 \div \text{Pressure}) \]
  - Dividing both sides by load
  \[ \text{RRC} = A_1 + A_2 \times \text{Load} + A_3 \div \text{Pressure} \]
  - At constant pressure
  \[ \text{RRC} = A_2 \times \text{Load} + A_1 + A_3 \div k \]

RRC is still a function of load.

J2452 and LT tires are even more complex.
RRC is between 0.0093 and 0.0161, depending on test condition. It is not an intrinsic property of the tire.
Conclusions (I)

- Up to 3 repeat tests of the same tire has no significant effect on rolling resistance values.
- As expected, testing with capped inflation pressure produces a lower value, due to increased pressure.
- Tires of the same model and size produce equivalent rolling resistance values, ± ~6%.
- Data is normally distributed.
- 1 outlier tire discovered.
Conclusions (II)

- Lab-to-Lab variation is significant
  - Dependent on test conditions and protocol
- All tests produce reliable data with low variation
- All tests rank order tires into the same groupings
- Values for all tests are approximately linear functions of the values of any other test
- Rolling Resistance or RR Coefficient describe a tire’s response at the conditions of test only