Comparison of On-road & Laboratory-based Rolling Resistance Measurements

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• Objective
• On-Road Measurement
• On-Road Results
• In Door Testing
• In Door Results and Comparison
• Summary
Objectives

1. Comparison of on-road rolling resistance measurements with standardized indoor testing

2. Comparison of standardized testing on flat-belt and drum machines
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On-Road Rolling Resistance Measurements

Coast-down method
e.g. VTI, Sweden [9, 12]

Instrumented trailer
e.g. FKFS, Germany,
BASt, Germany,
HUT, Finland [6]

Instrumented vehicle
e.g. A&D, Japan
Test Vehicle:
• Instrumented Mini Cooper S
• Proving ground in Tochigi, Japan

Test Tires:
• Rear left (RL) & rear right (RR)
• Bridgestone Sneaker2 (205/55 R16 91V)
• 250 kPa (capped)

Test Procedure:
• Round course 6 repeats at different speeds
• Selection of straight, constant speed phase for data analysis
A&D Wheel force Sensor (WFS)

- Unique design
- Distributed force bridges with model based decomposition to get orthogonal force components
- Low cross sensitivity
- Low temperature sensitivity
- High sampling rate
- High Accuracy
  0.1% resolution
  (6N or 1.8Nm)
• Doppler Velocity Sensor
  – Vehicle velocity

• GPS Sensor & In-vehicle Network
  – vehicle longitude, latitude, altitude, and ECU CAN communication

• A&D Wheel Position Sensor
  – 6 degrees of freedom of the tire relative to chassis

• Inertial Sensor
  – vehicle roll, pitch and yaw

• Digital Signal Processing & Acquisition
  – 100Hz sampling of all signals
Rolling resistance is created in the Tire patch. Tire Patch shows an asymmetric Pressure distribution, which can be substituted by:
- a total contact force $F$ and
- a moment $M_R$

$M_R$ appears as resistance force $R$ on the wheel hub.
\[ M_R = R \cdot r \]
$r$: dynamic rolling radius
Mathematical Formulation

\[ M_R = R \cdot r \]  \hspace{1cm} \text{[1]}  

Torque equation:  \[ J \cdot \dot{\omega} = -My - MR + FA \cdot r \]  
with [1]:  \[ J \cdot \dot{\omega} = -My - R \cdot r + FA \cdot r \]  \hspace{1cm} \text{[2]}  

Force equation:  \[ m \cdot a = F_x - FA \]  
\[ \Rightarrow FA = F_x - m \cdot a \]  \hspace{1cm} \text{[3]}  

Kinematic condition:  \[ v = \omega \cdot r \]  
\[ \Rightarrow r = v / \omega \]  \hspace{1cm} \text{[4]}  

[3] in [2]:  \[ J \cdot \dot{\omega} = -My - R \cdot r + \left( F_x - m \cdot a \right) \cdot r \]  
\[ \Rightarrow R = F_x - m \cdot a - \left( \frac{1}{r} \right) \cdot (J \cdot \dot{\omega} + My) \]  

with [4]:  \[ R = F_x - m \cdot a - \left( \frac{\omega}{v} \right) \cdot (J \cdot \dot{\omega} + My) \]  

\[ \phi, \omega, \dot{\omega} \]  
\[ x, v, a \]  
\[ r \]  
\[ \text{Rolling radius} \]  
\[ \text{Angle, angular speed/acceleration of wheel} \]  
\[ \text{Distance, speed,acceleration of wheel} \]  
\[ \text{torque inertia/mass of wheel} \]  
\[ J, m \]  
\[ \text{Torque/force on wheel hub} \]  
\[ My, F_x \]  
\[ \text{Adhesive force} \]  

Determined before the Experiment
Parameter Determination

- Tire mass can be determined by lifting the wheel. WFS will show the mass.
- Tire rolling inertia is determined using free load rotating wheel in acceleration and deceleration condition.
- Measurement items:
  - Tire angular speed $\omega$ [rad/s]
  - Angular acceleration $\dot{\omega}$ [rad/s$^2$]
  - Wheel torque $M_{y\text{free}}$ [Nm]
- Rolling inertia formula:
  $$J_t = \frac{M_{y\text{free}}}{\dot{\omega}}$$
Data selection

- Data is filtered at 5Hz
- Various signals are analyzed to find a time period having constant speed, straight line vehicle motion
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- Three speeds
- 6 tests for each speed
- Calculation applied to time data of Fx and My according to introduced formula
Mean Rolling Resistance Forces (RRF)

- Averaging the time record data for individual speeds
- Rolling resistance force does not vary significantly with speed
- It is possible to have good repeatability for on-road measurements

![Graph showing mean RRF values and standard deviations](image)

Mean RRF = 85.4 N
\( \sigma_{RRF} = 1.8 \) N
\( \sigma_{RRC} = 0.65 \) N/kN

Mean RRF = 84.9 N
\( \sigma_{RRF} = 2.3 \) N
\( \sigma_{RRC} = 0.84 \) N/kN

Mean RRF = 84.6 N
\( \sigma_{RRF} = 1.9 \) N
\( \sigma_{RRC} = 0.70 \) N/kN
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Indoor Testing Equipment

- A&D Standard Rolling resistance test rig
  - 2m Drum, Steel covered

- A&D Dynamic Flat Belt Test Rig
  - Steel Belt

- Force Measurement utilizing A&D Hub Sensor
  - MBS Sensor approach
  - Fx: 300N ±0.3N
  - Fz: 15kN ±20N
  - Machines Meet Reference Lab repeatability criteria
Test Procedure for Indoor Testing

Follow ISO28580 Test Procedure

- 3h thermal conditioning
- 30 min warm up
- Test conditions: Speed 80 km/h, 210kPa (capped), 80% max Load
- Skim Test at 150N

Measurements:

- Spindel Force
- Loaded Tire radius

Calculation of:

- Surface Force
- Parasitic Force
- Rolling resistance Force
- Temperature correction
- Rolling resistance Coefficient
- Curvature correction [3], [5]
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Comparison of Results

Comparison of On-road and Indoor Measurements

On-Road \( (F_z=2.73\,\text{kN}) \)

Indoor \( (F_z=4.82\,\text{kN}) \)

Drum Machine

Clark’s Curvature Correction

Flat-belt Machine
Potential Reasons for Differences

- Tire alignment (camber, toe) on the road [4]
- Roughness of road surface (unevenness, macrotexture) [7, 10-12]
  - Energy dissipation in the suspension
  - Dynamic vertical deflection of the tire leading to additional hysteresis
  - Additional friction losses due to microslip
- Uncontrolled environmental factors such as temperature and inflation pressure
- Measurement errors such as loaded tire radius
Indoor Testing Results

Comparison of ISO28580 Rolling Resistance Test Results

Rolling Resistance Force (N)

Drum Machine  |  Curv. Correction  |  Flat-belt Machine

Bridgestone Sneaker2 205/55 R16 91V
• Excellent repeatability is achieved for both drum & flat-belt machines
• Tire ranking is preserved during iterative testing
• Drum and Flat-Belt machines rank tires differently
• Flat-Belt results are lower than drum and curvature corrected [3, 5] drum machine results
Temperature Differences

Drum acts as a heat sink whereas belt gets heated up

Temperature Comparison for ISO28580 Rolling Resistance Tests

Flat-belt machine

Drum machine
- Relative ranking is not preserved for both RRF and RRC
- Ranking based on RRC and RRF will be different as they represent different things
Summary

• Repeatable on-road measurements are possible
• Indoor measurements offer superior control of test parameters and very high repeatability
• Measured losses are significantly less than what we see on the real road
• In door testing should include more test variables (such as camber, toe, slip, etc.) to get a closer approximation of in-vehicle & on-road tire performance
• Relative tire rankings from drum and flat-belt measurements are not necessarily equivalent
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