Rolling resistance measurement on the road: A dream?

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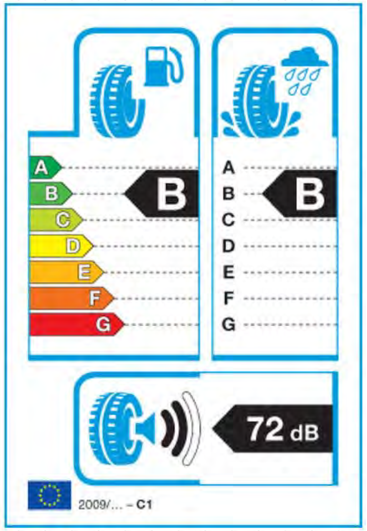
- Motivation
- Introduction of the used Measurement Equipment
- Introduction of the theoretical approach
- Description of the Test procedure
- Results
- Summary / Conclusions

Motivation

- The demand to higher efficiency concerns each component of future vehicles
- Tire resistance is identified as one of the areas for efficiency improvements independent of vehicle drive concepts
- Understanding the behavior in real road conditions will become more important
- Standard testing methods (drum based) do not deliver road condition related information
- Real road conditions measurement was suffering from:
  - Accurate measurement equipment for the forces as Tire resistance value is relative low
  - Low repeatability
  - Ability to separate different influence sources



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Measurement Equipment on Road

- Vehicle measurement System (VMS)
  - Wheel Force Sensor(WFS)
  - Wheel Position Sensor (WPS)
  - Other sensors such as GPS
  - Vehicle ECU Information

Rig Measurement Equipment

- Flat belt tire testing rig (steel belt)
  - Best simulation of the road
- Test is performed with the same sensor used for the vehicle testing

Rig Specification	
Velocity	0~200km/h
Slip Angle	±20deg（0~3Hz）
Camber Angle	±15deg（0~1Hz）
Up & Down	0~50mm（0~25Hz）
Load	Fx: ±10 kN Fy: ± 10 kN Fz: 12 kN
Flatness of the steel belt (under load condition)	Less than 10 µm
Bearing under the belt	Air bearing

Wheel Force Sensor (WFS)

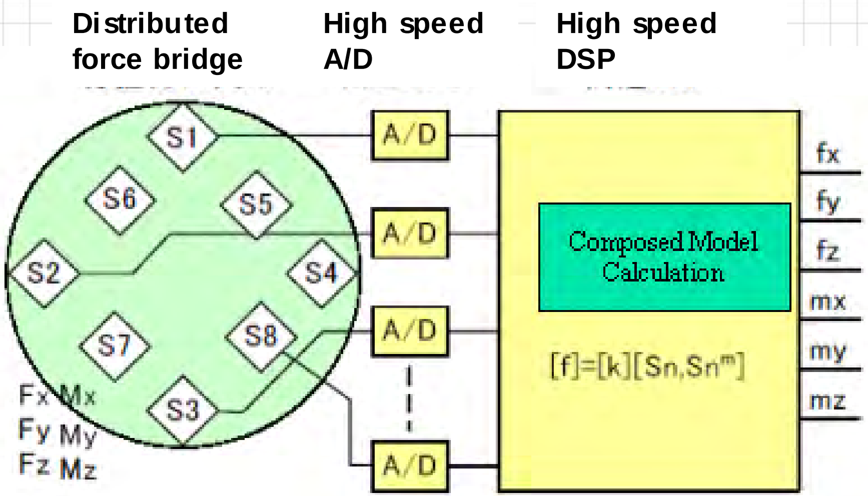
6 component in wheel force sensor main properties

- 3 axis of force and 3 axis of moment

- Total error 0.1%
- Capacity:
  - Fx = 24KN, Fy = 15KN, Fz = 24KN
  - Mx= 4.5 KNm, My =4 KNm,
    Mz = 4.5KNm
- Resolution 1/4000
  - 6N or 1.8Nm
- Data acquisition up to 1kHz
- Lightweight 3.2 Kg

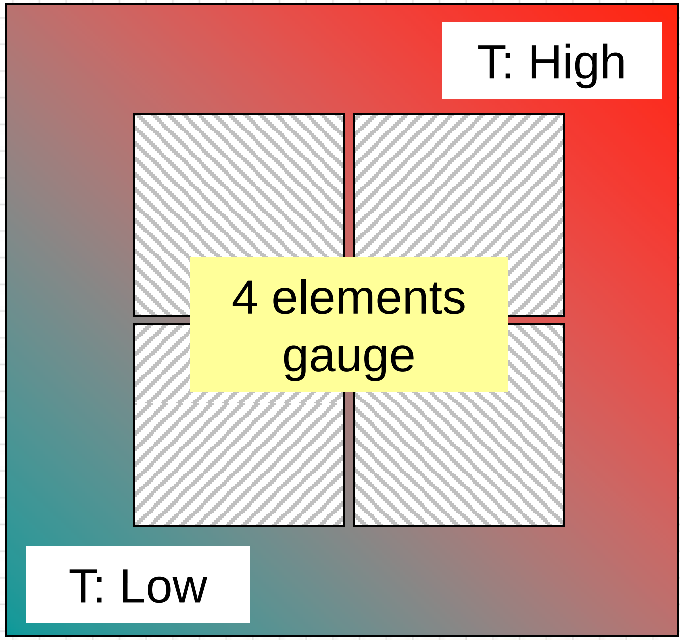
Unique Force Detection Method

- Model Based Sensor concept
  - Shared force detection method
    - Eight bridges are applied to the spring element
    - No direct detection of each component
    - Components are re-composed by model based calculation using real time calculation DSP platform
    - Digital conversion of all signals and electronically re-composing overcomes disadvantages of analogue approach
    - Cross talk error can be canceled out



Minimized Temperature effects

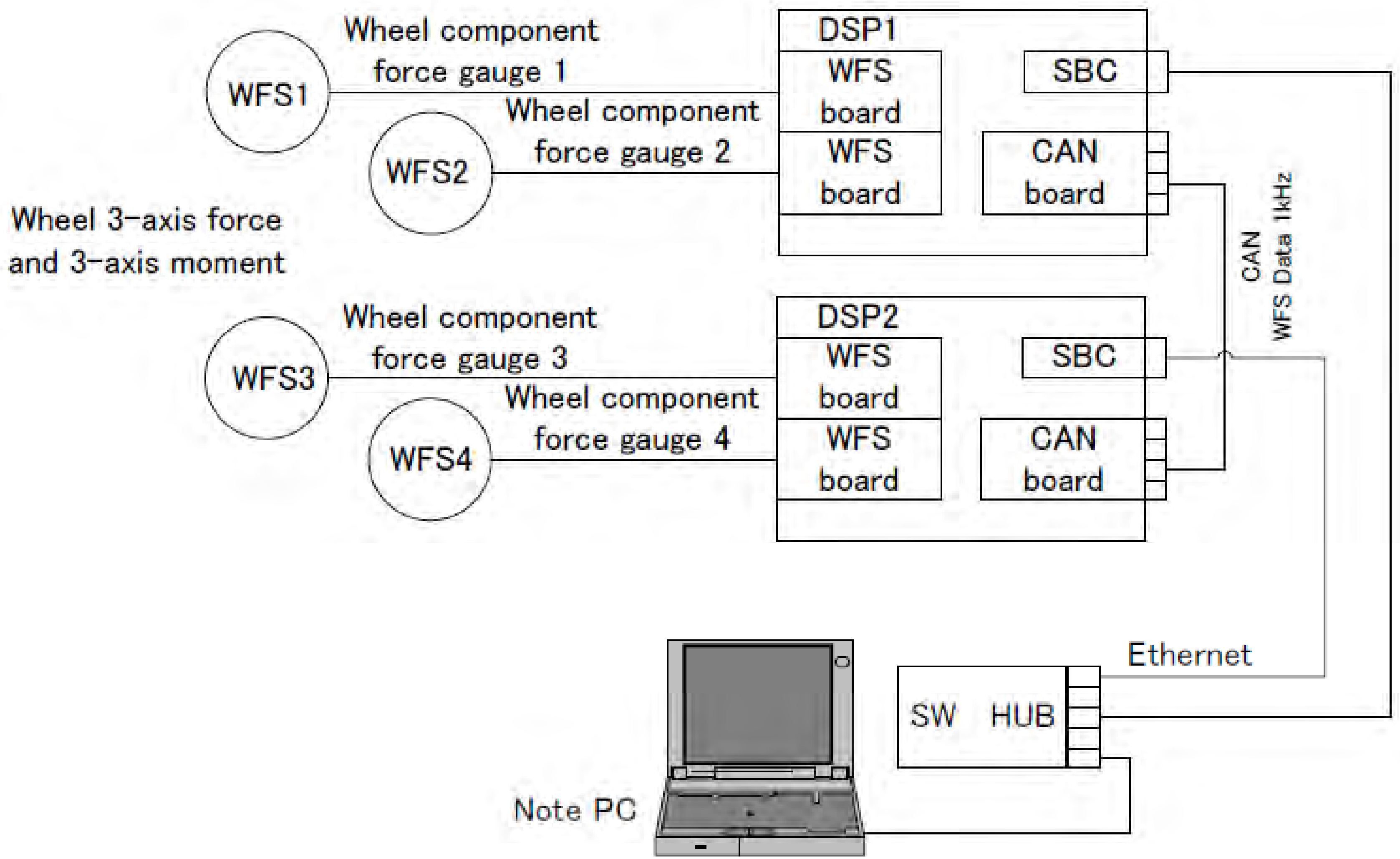
- Vehicle measurement is a challenge for the temperature influence
  - Temperature gradient e.g. break side outside
  - Quick change of temperature depending on driving maneuver
- Need for robust design against Temperature effects
  - Share Force method allows to place the strain gauges very close to each other
  - Total gradient on each gauge is very small
  - Small temperature effect on the measurement
  - At the same time robustness against dynamic temperature changes



Mechanical and Electrical sensitivity

- Application needs stiff sensor and high accuracy
- Sensor sensitivity:
  - Mechanical sensitivity x electrical sensitivity
- Stiff Spring element design results in:
  - Increase of robustness
  - Increase of eigenfrequency
  - Reduction of mechanical sensitivity
- Increase electrical sensitivity by utilizing:
  - High precision A/D converting of nV order
  - Low noise design from less analog circuit
  - Optimized temperature compensation from gauge layout
- The combination of all technology results in a high accurate sensor with 1/4000 resolution

Wheel Force Sensor Configuration



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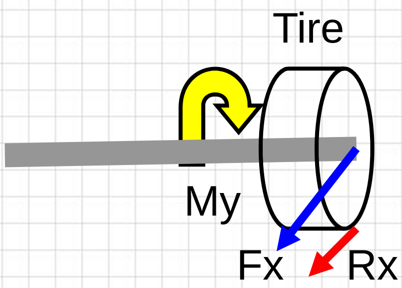
Tire Loss Theory

- Tire loss can be calculated from measured parameters on the wheel
- Measurement parameters
  - Tire rolling inertia J_t in kg·m^2
  - Tire effective radius r_t in m
  - Wheel torque My in Nm
  - Tire longitudinal force Fx in N
  - Tire Angular speed ω in rad/s
  - Tire Angular acceleration $\dot{\omega}$ rad/s^2
- Calculated parameter
  - Tire loss (rolling resistance) Rx in N

$$Rx = \frac{My + J_t * \dot{\omega}}{r_t} - Fx$$

Driven Wheel



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Testing procedure on the test track

- Target: Determine "Tire Loss" from real driving condition
- Test car: BMW Mini Cooper S
- Test Track:
  - Total length: 1,792m
  - East straight line: 550m
  - West straight line: 554m
- Driving Maneuver:
  – Acceleration at west straight line
  – Cost down at East straight line
  – Test laps: 10 laps
- 100Hz data acquisition

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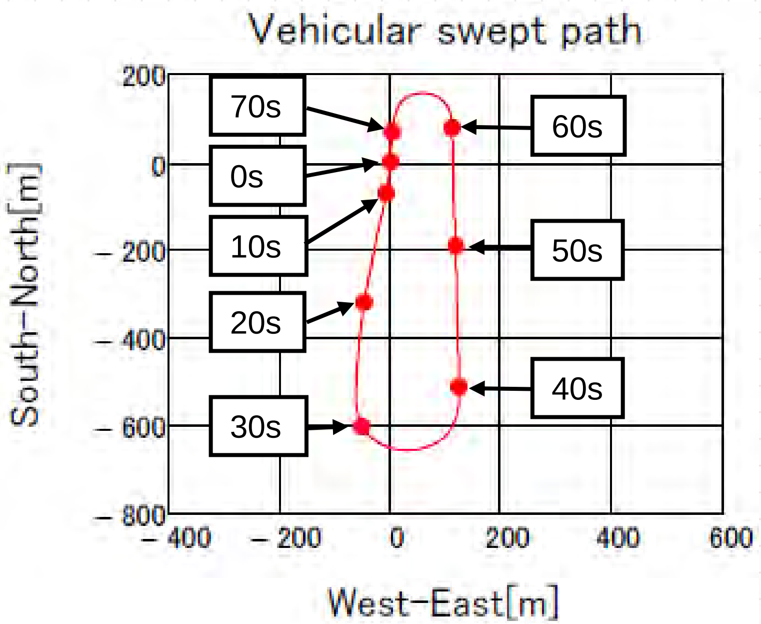
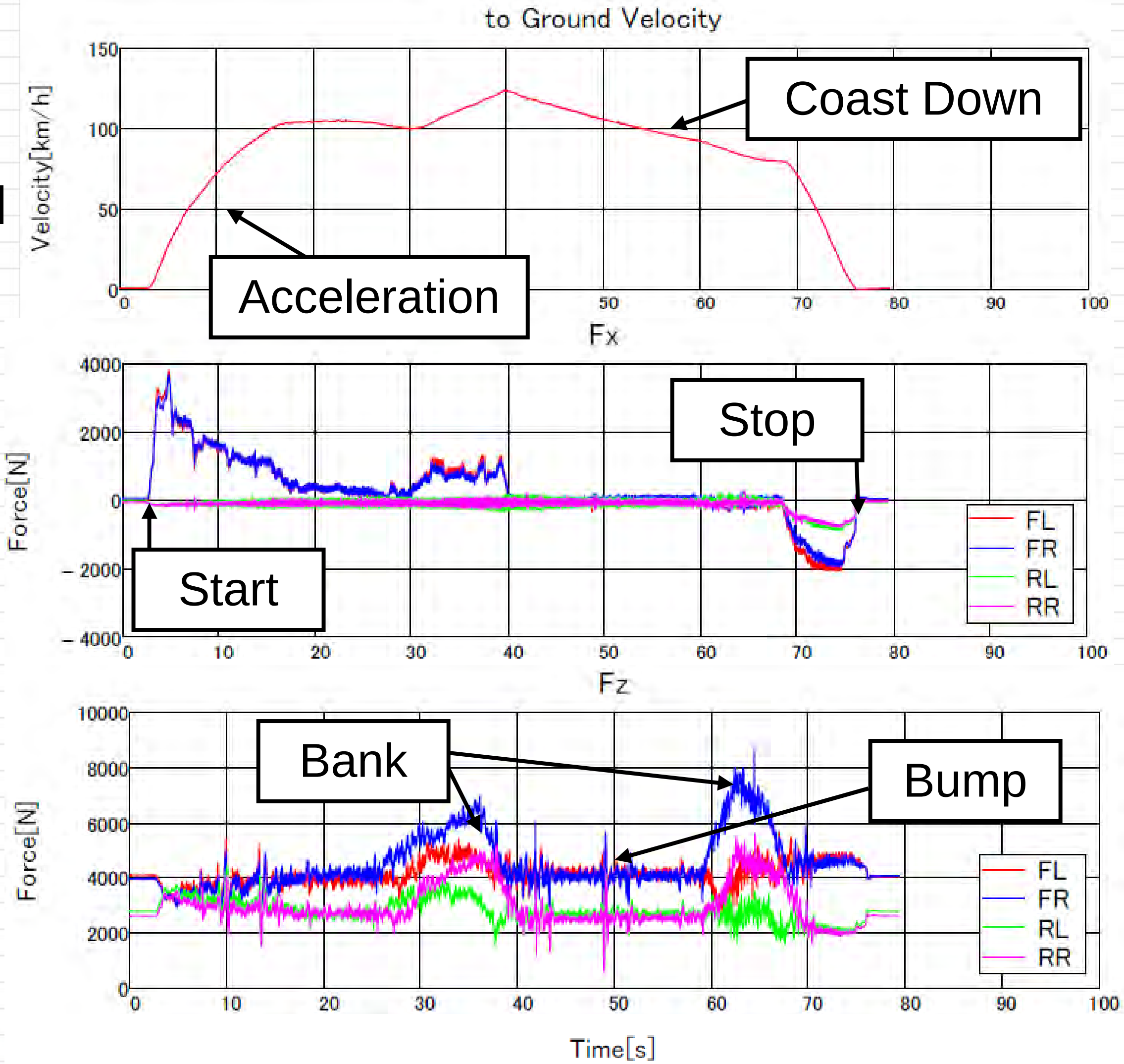
Test Track Measurement Results

- Example plot of one round
- Fx shows mainly difference between front and rear wheel
- Fz shows change between left and right





Parameter Determination

Direct Measures from the sensor:

- Wheel torque My in Nm
- Tire longitudinal force Fx in N

Indirect Measures:

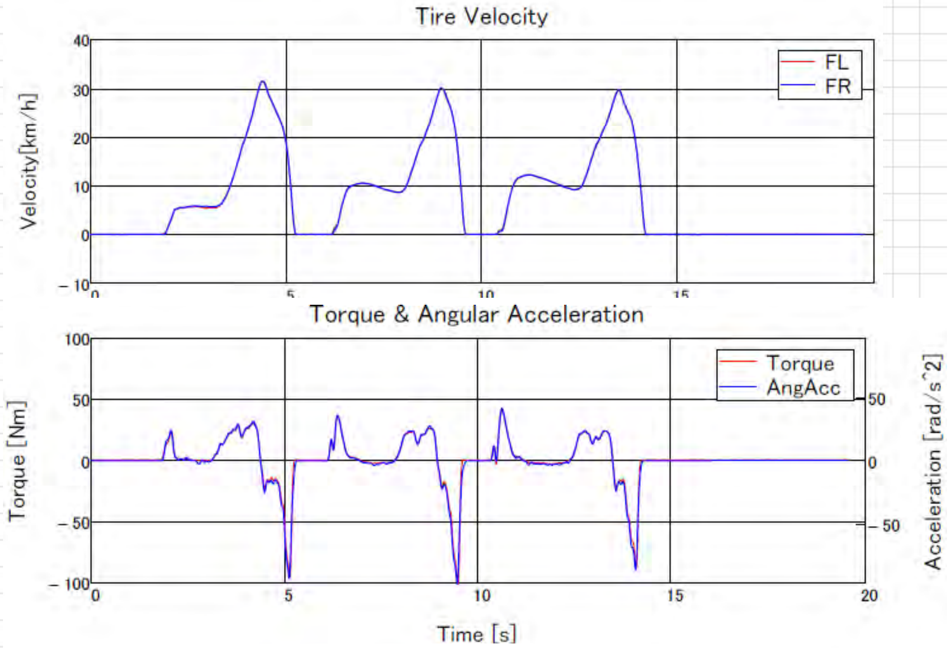
- Tire rolling inertia J_t in kg▪m²
- Tire effective radius r_t in m
- Tire Angular acceleration $\dot{\omega}$ rad/s²

$$Rx = \frac{My + J_t * \dot{\omega}}{r_t} - Fx$$

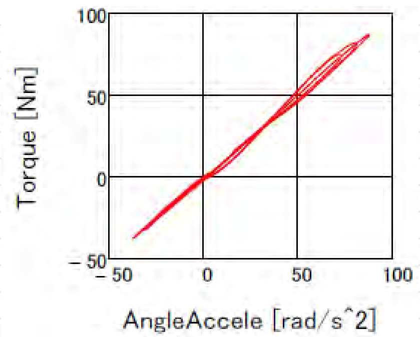
Wheel inertia

- Tire rolling inertia is premeasured using free load rotating wheel in acceleration and deceleration condition
- Measurement items
  - Tire angular speed ω [rad/s]
  - Angular acceleration $\dot{\omega}$ [rad/s^2]
  - Wheel torque My_{free} [Nm]
- Rolling inertia formula:

$$J_t = \frac{My_{free}}{\dot{\omega}}$$



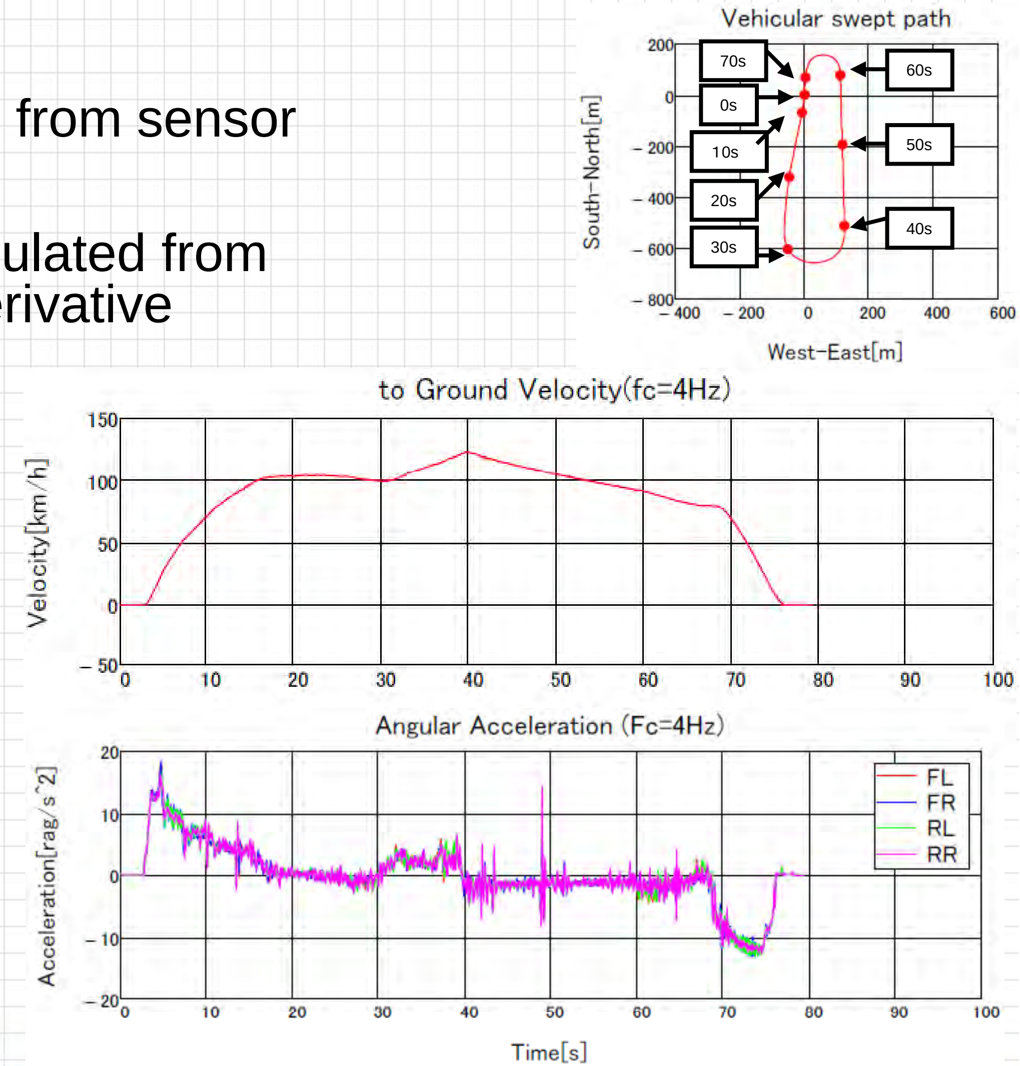
Torque Vs. Angular acceleration



Angular acceleration determination

- Tire angular speed is measured from sensor angle encoder.
- Tire angular acceleration is calculated from angular speed signal by time derivative
- Measurement item:
  - Tire angular speed ω [rad/s]
  - Tire angular acceleration

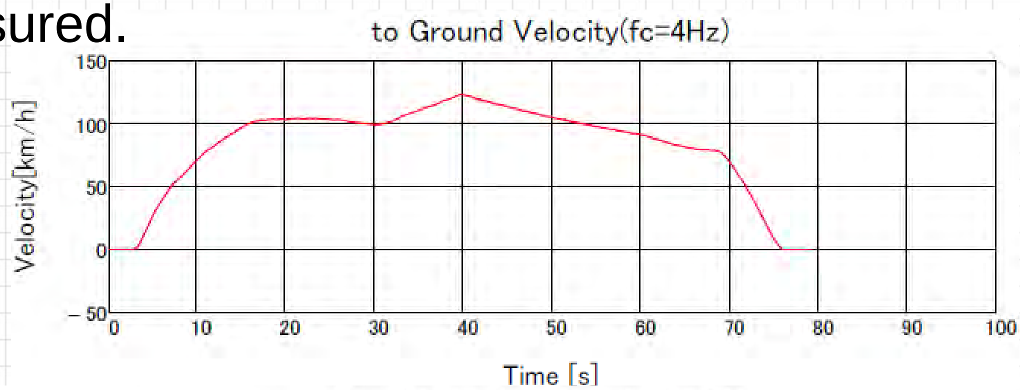
$$\dot{\omega} = \frac{d\omega}{dt}$$

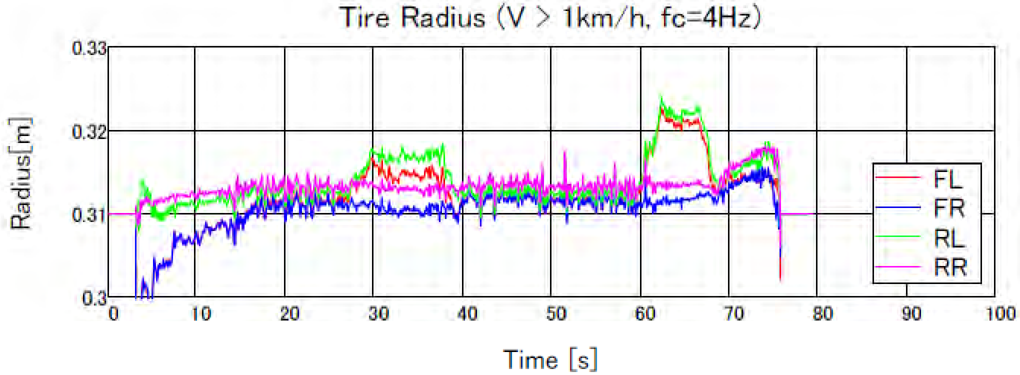


Tire radius determination

- Tire mean radius is calculated from vehicle velocity and tire angular speed.
- Vehicle velocity is measured from optical Doppler sensor
- Instant tire mean radius is measured.
- Measurement items
  - Vehicle velocity against road Vph [m/s]
  - Tire angular speed ω [rad/s]
- Tire radius formula (Not considering tire slip)

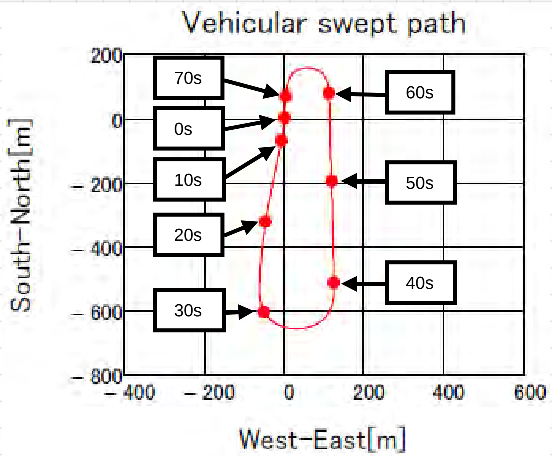
$$r_t = \frac{Vph}{\omega} \quad [\mathrm{m}]$$

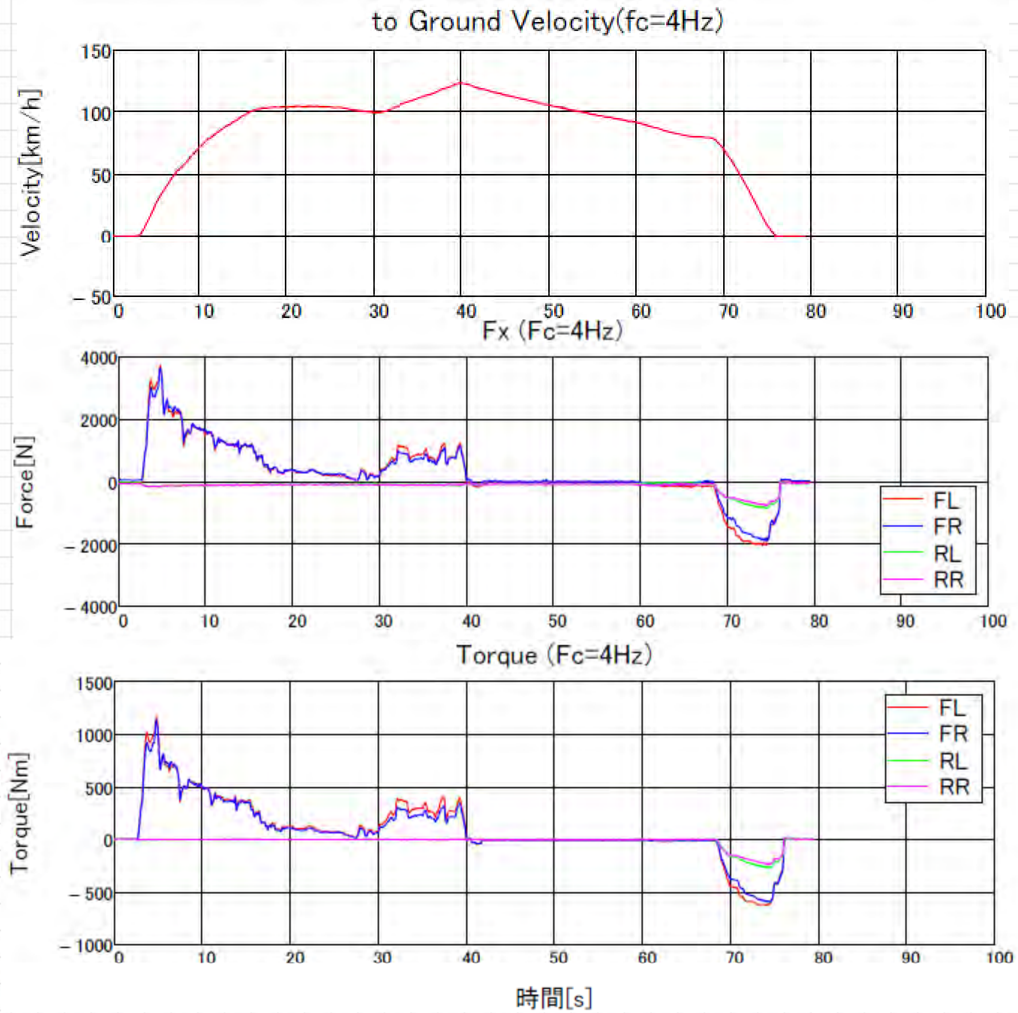




Measurement parameter: Wheel torque and longitudinal force

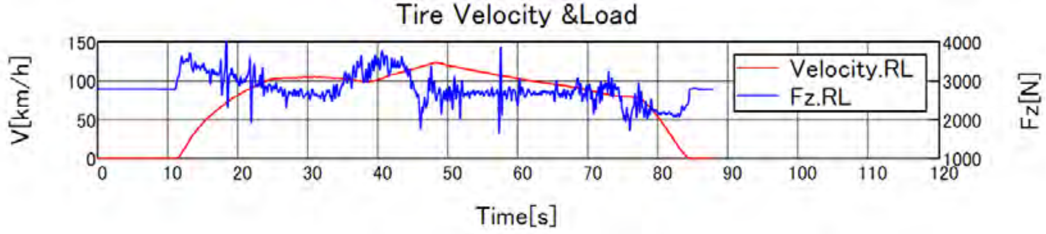
- Wheel torque My and longitudinal force Fx are measured from 6 components of the Wheel Force Sensor (WFS)

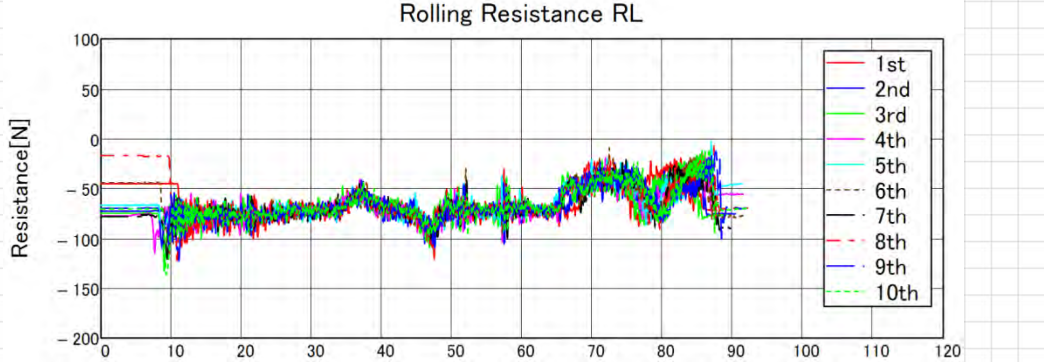


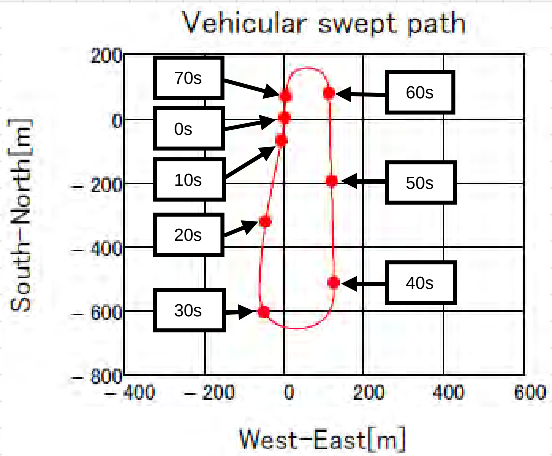


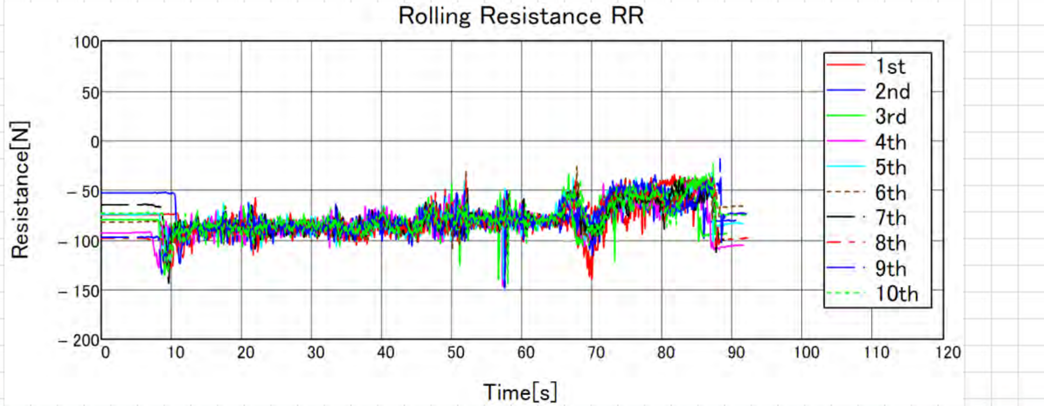
Rolling Resistance Results

- To avoid tire slip error, driven wheel data is evaluated
- 10 laps of data
- To avoid some high frequency noise a low pass filter (4 Hz) is applied to the measurement data
- Very good repeatability for 10 laps



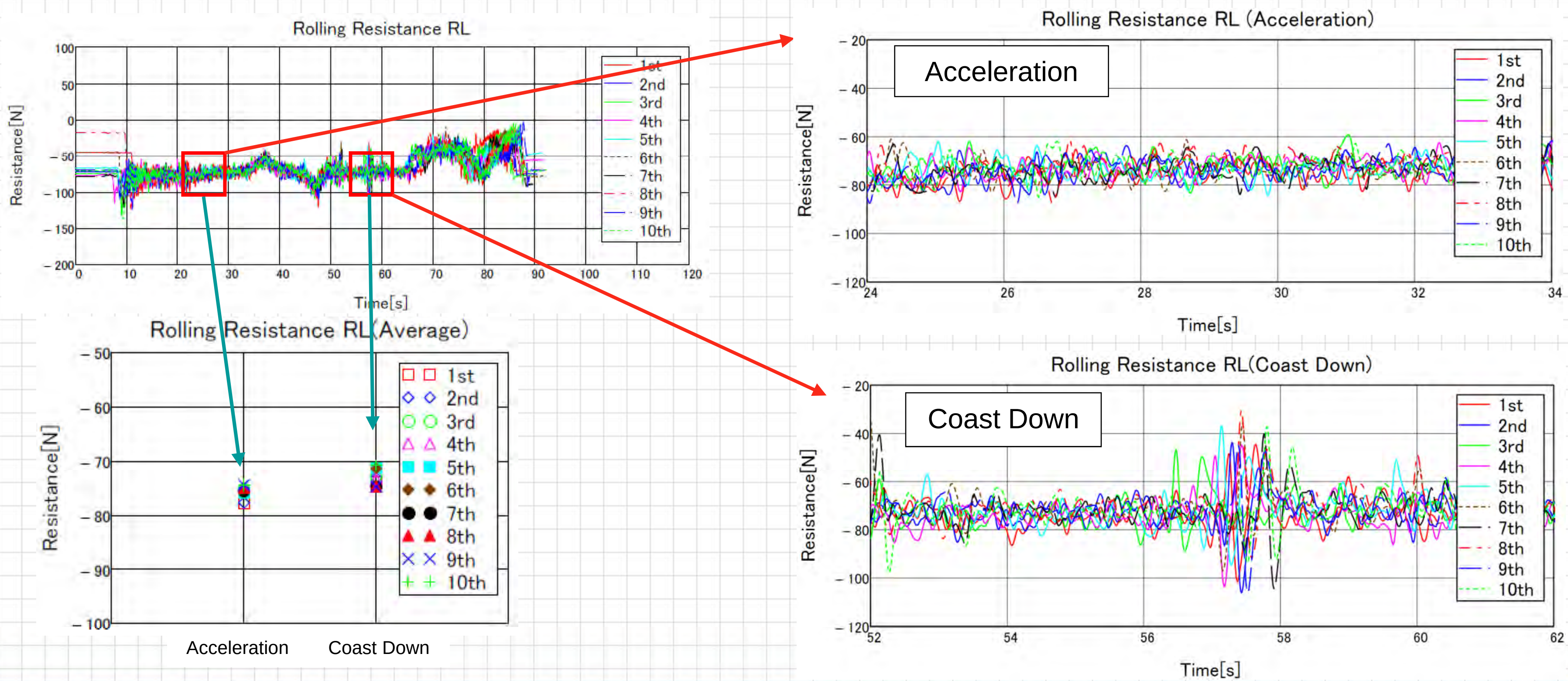






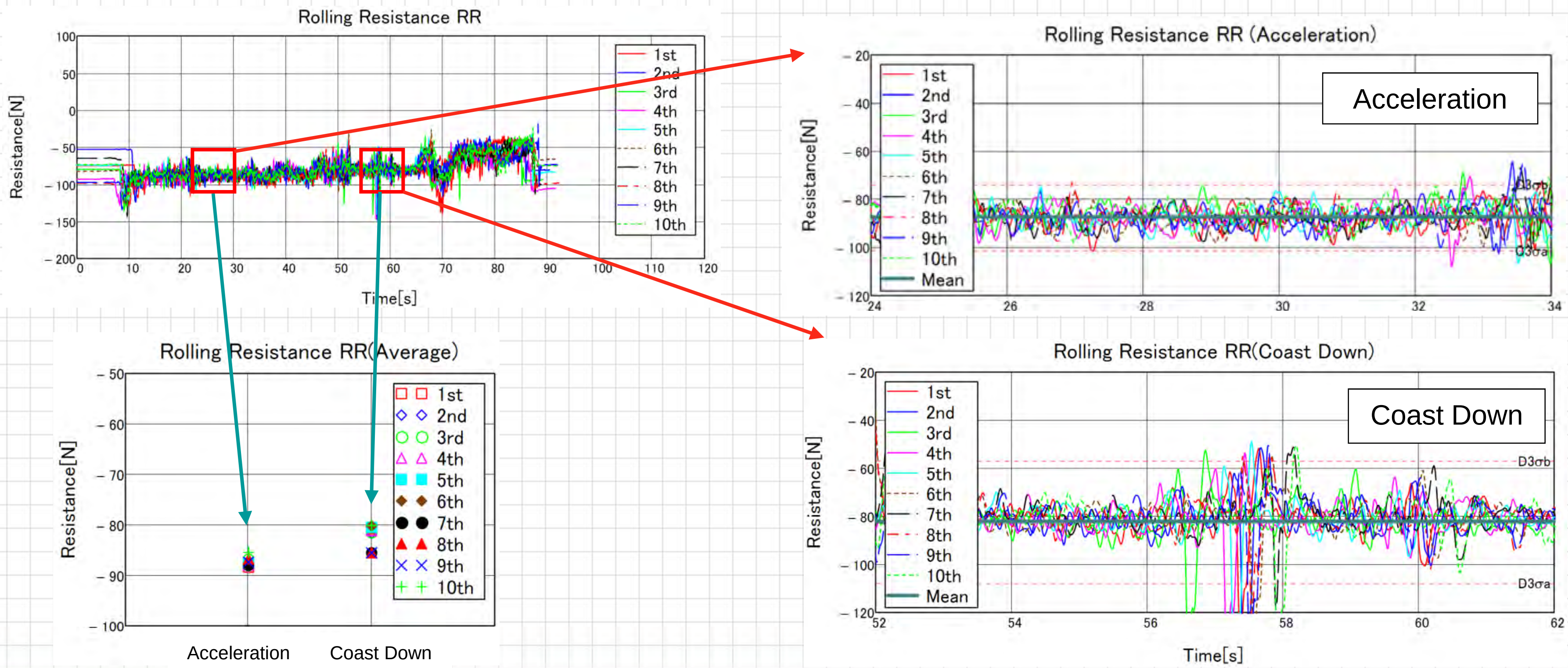
Rear Left Wheel results

- Average Rx: Rx = -76.1N (Acceleration), Rx = -72.8N (Cost down)
- 10 laps data variation 3σ : 2.8N (Acceleration), 3.6N (Cost down)
- Rx for Acceleration and Rx for Cost down data are very close to each other: 3.3N



Rear Right Wheel results

- Average Rx: Rx = -87.6N (Acceleration). Rx = -82.6N (Cost down)
- 10 laps data variation 3σ: 2.5N (Acceleration)., 6.6N (Cost down)
- Rx for Acceleration and Rx for Cost down data are very close to each other: 5.0N



Measurement result :Test rig

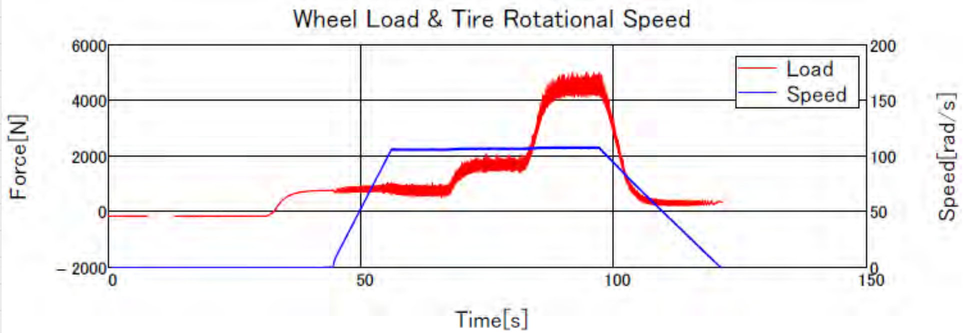
Test condition:

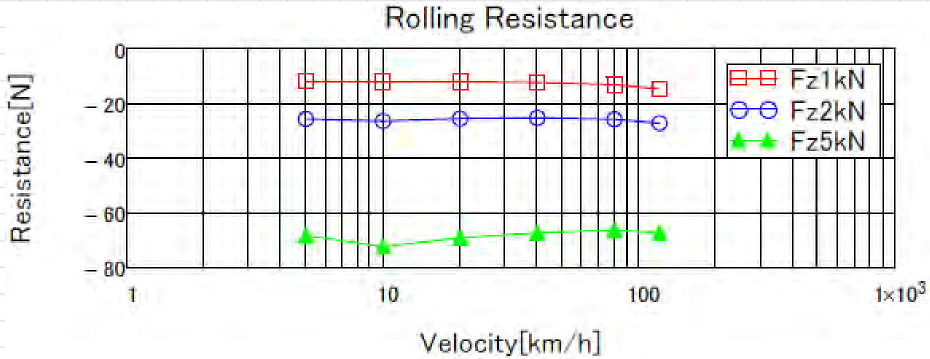
- Slip angle :0 [deg]
- Camber angle: 0 [deg]
- Wheel driven by steel belt
- Vertical load Fz: 1kN, 2kN, 5kN
- Static velocity: 5km/h, 10km/h, 20km/h, 60km/h, 80km/h, 120km/h

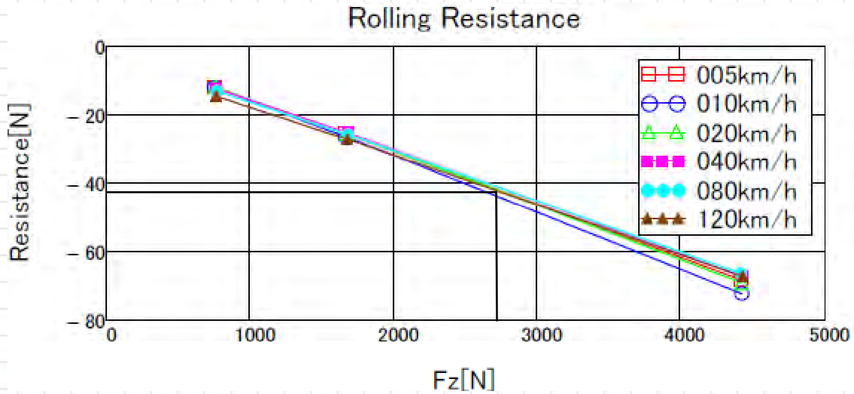
- Rolling resistance is directly measured from Fx using same sensor as on the road

Results:

- Rolling resistance is proportional to the vertical load and is not a function of velocity
- Rolling resistance at 2.7kN is 42N







Comparison: Real road vs Test rig

Real road rolling resistance :

- Rx(Left) = 74 N
- Rx(Right) = 82 N

Test rig:

- Rx = 42 N

Reasons for the difference:

- Tire alignment on Road and rig is different
- Road surface condition
- Environment conditions
  - Wind force to tire
  - Temperature
- Measurement errors
  - Tire effective radius measurement

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Summary and Conclusion

Summary:

- A&D Sensor delivers high quality data
    - Repeatability of 10 lab data did show good match
- It was possible to measure the tire loss (rolling resistance) during real driving condition
- Great match on the results though 10 laps of data
- Rolling resistance measurement result is depending on driving conditions
    - We did observer difference between acceleration and coast down conditions
- There are differences between road and test rig results

Conclusion:

- WFS is a useful tool for analyzing energy loss at real driving condition
- We are very close to the dream and will continue this investigation

Thank you for your attention!

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