Estimation of Road Load Parameters via On-road Vehicle Testing

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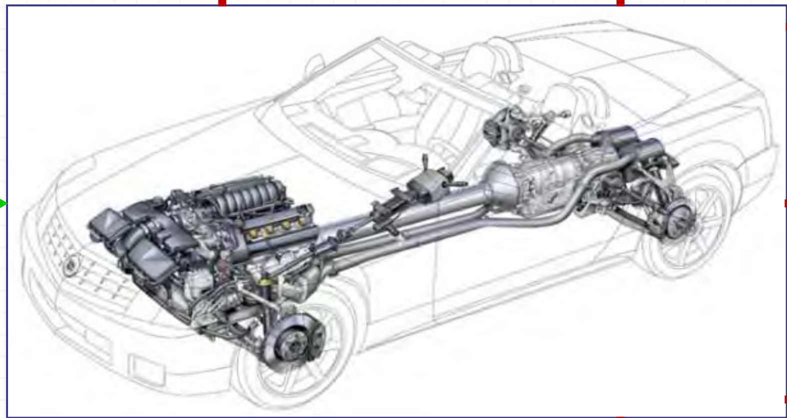
Energy Loss in Vehicles

Standby
17%(4%)

Accessories
2%(2%)

Fuel Tank
100%(100%)



Aerodynamic Drag
3%(11%)

Rolling Resistance
4%(7%)

Braking
6%(2%)

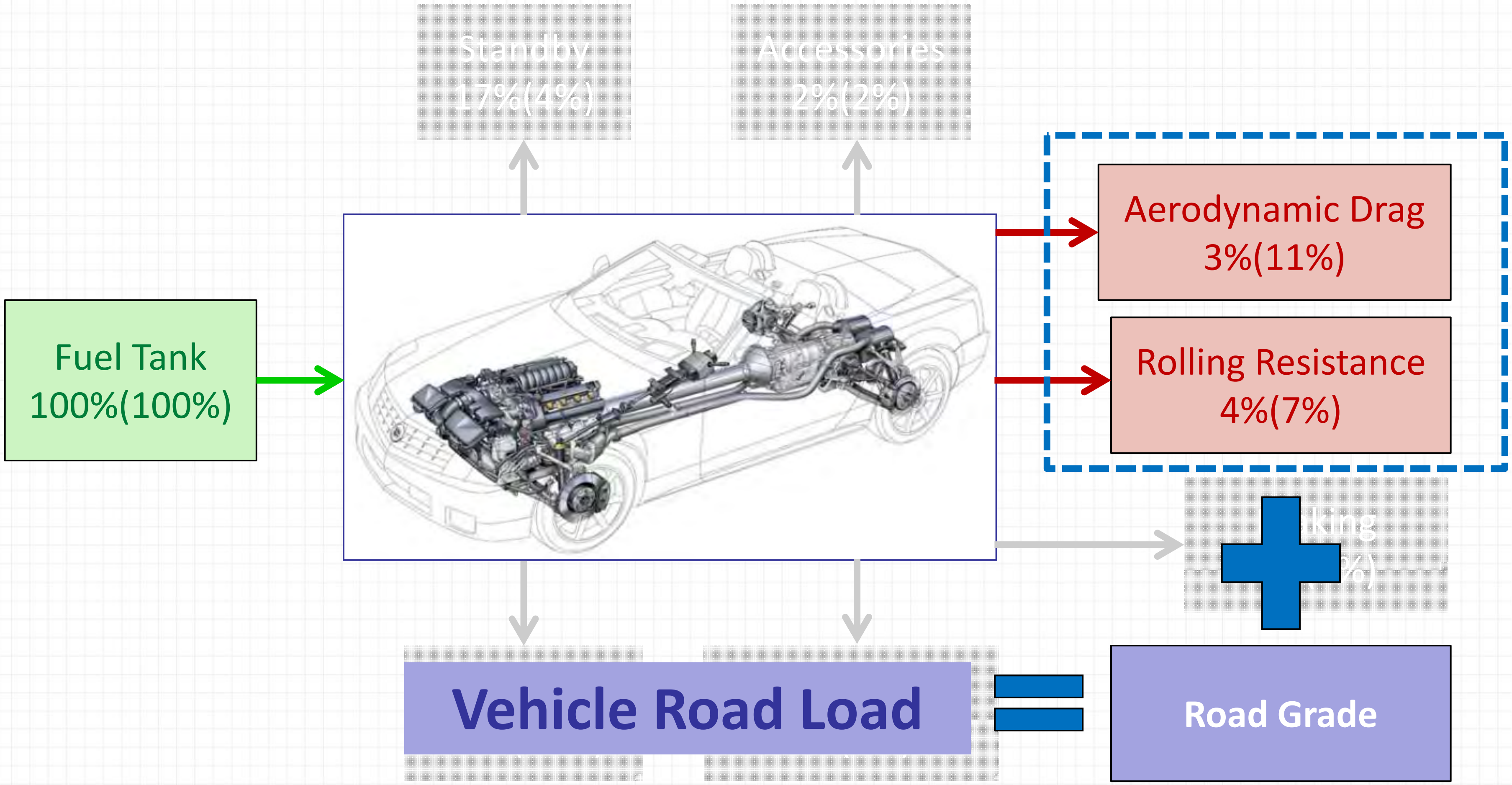
Engine Loss
62%(69%)

Drivetrain Loss
6%(5%)

Losses of fuel energy in a vehicle in city usage (highway usage)

[U.S. National Academy of Science, 2006]

Energy Loss in Vehicles



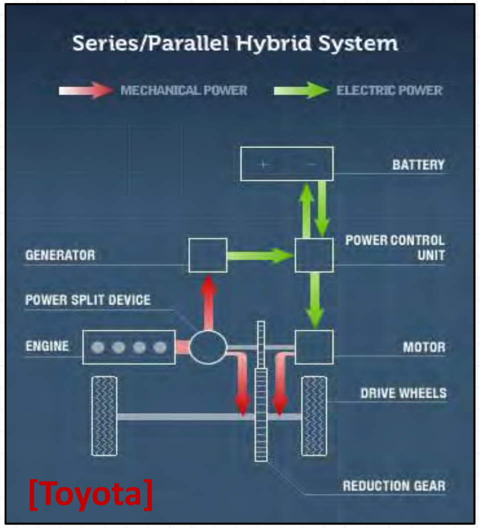
Road load is define as the "…force or torque which opposes the movement of a vehicle…"
[ISO 10521-1, 2006]

Significance of Road Load Determination

Vehicle platooning [1,2]

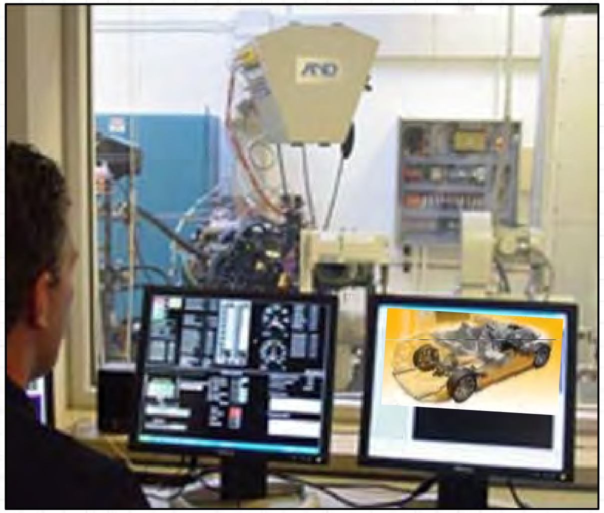
Roll-over prevention [3]

Energy management [4,5]



Offline modeling & control development [6]

Engine certification [7]



Objective

Estimate the road load parameters of a vehicle

- **Focus on rolling resistance & aerodynamic drag**
- **Use on-road testing of a production vehicle**
- **Use a novel force measurement method & compare results with traditional method(s)**

Outline

1. Introduction

2. Road load fundamentals

3. Instrumentation & sample data

4. Coast down method

5. Force measurement method

6. Summary

Rolling Resistance

For a free rolling tire under no slip:

Mg: Vertical load on the tire due to sprung & unsprung mass

v_x: Tire longitudinal velocity

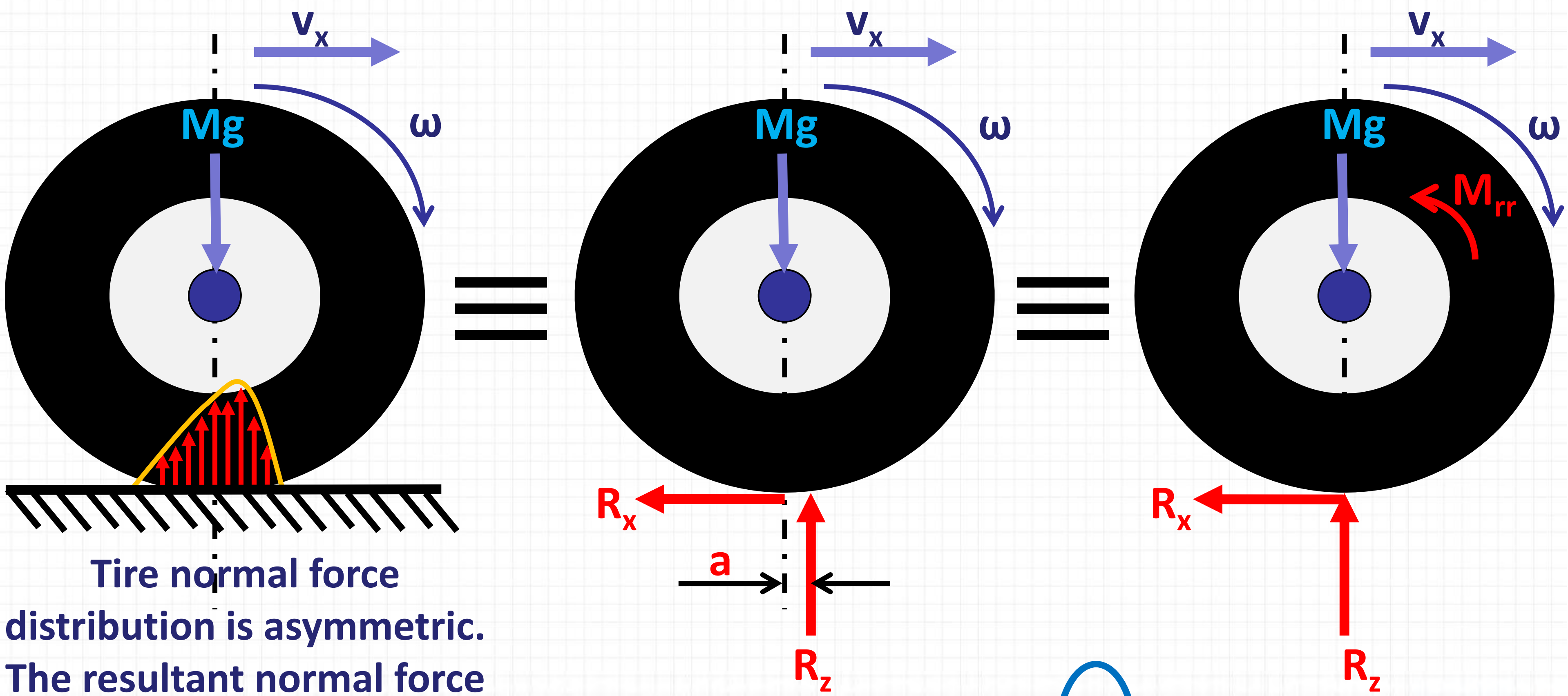
ω: Tire angular speed

R_z: Ground reaction force

R_x: Rolling resistance force

M_{rr}: Rolling resistance moment

r: Loaded tire radius

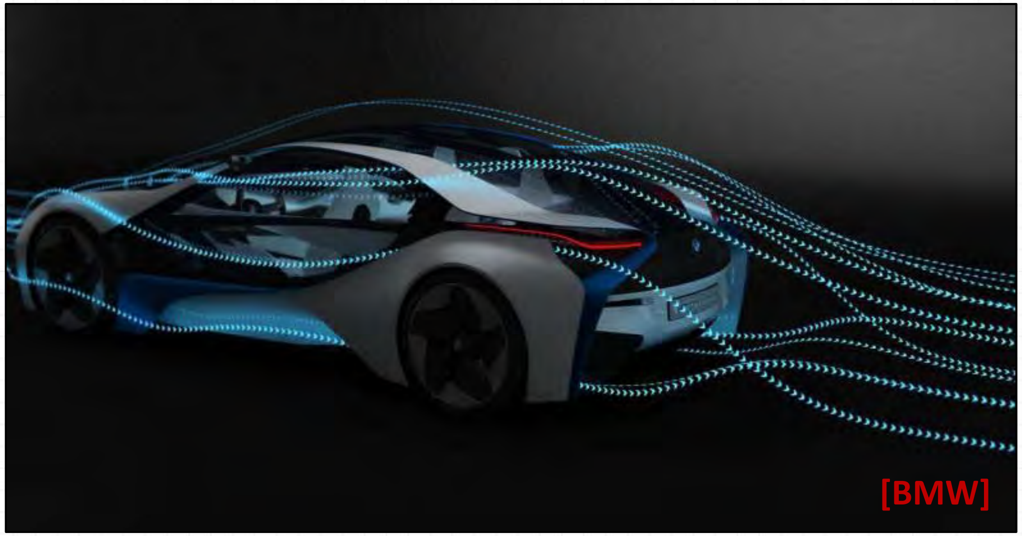


Tire normal force distribution is asymmetric. The resultant normal force acts towards the leading edge.

$$a \cdot R_z = M_{rr} = r \cdot R_x$$

Rolling resistance force

Aerodynamic Drag



$$F_{drag} = 0.5 \cdot \rho \cdot A \cdot C_d \cdot (v_{rel})^2$$

Density of air (ρ)

Frontal area of the vehicle (A)

Coefficient of aerodynamic drag (C_d)

Relative velocity of the vehicle wrt the wind (v_{rel})

Total Road Load

The most commonly used form of road load equation is:

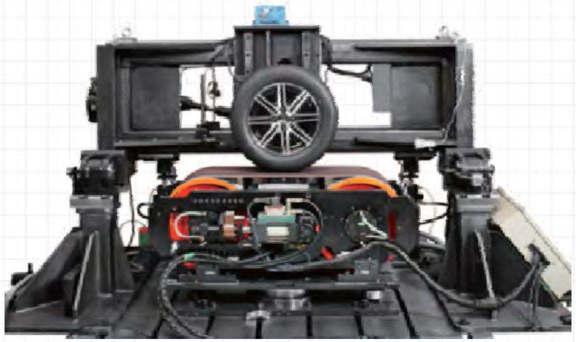
$$F_{road\ load} = \left(a + b \cdot v_x + c \cdot (v_{rel})^2\right) + M \cdot g \cdot \sin(\theta)$$

- a: **Predominantly includes the effect of rolling resistance**
- $b \cdot v_x$: **Includes dependence of rolling resistance on velocity & drivetrain losses**
- $c \cdot (v_{rel})^2$: **Includes aerodynamic drag**
- $M \cdot g \cdot \sin(\theta)$: **Includes influence of road grade**

- ‘b’ term is not always included
- A number of other formulations exist [8], including
  - Influence of rotational inertias
  - Correction factors
  - Additional dependencies

Road Load Measurement Methods

1. Individual component measurements



Rolling resistance: Tire testing

Aerodynamic drag: Wind tunnel testing

Grade: Road profiling

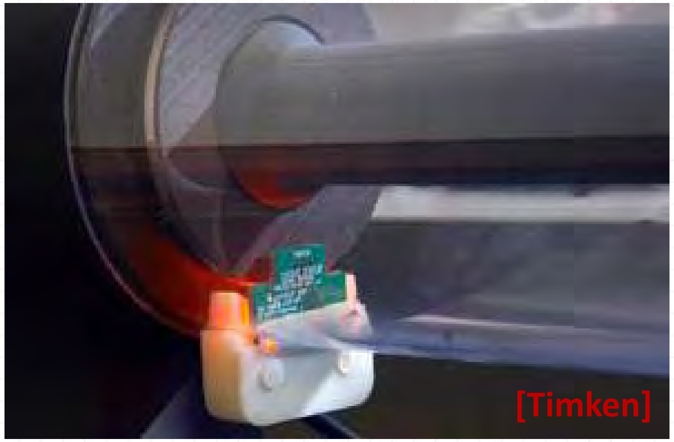
Pros: High repeatability, aids in parametric evaluation

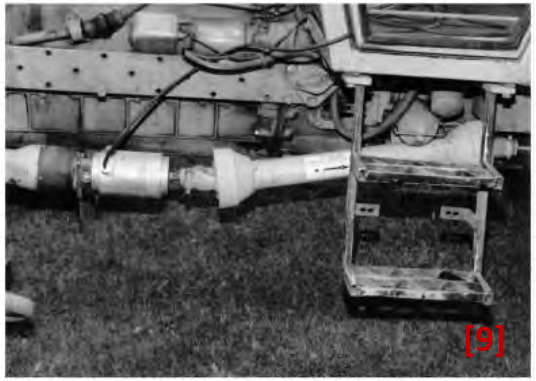
Cons: Higher cost, may not represent real driving conditions

Road Load Measurement Methods

2. Coast-down method [8,10]

3. Torque measurement [9]





Pros: Less instrumentation

Cons: Time consuming tests, include drivetrain losses

Pros: Drivetrain losses are excluded

Cons: Difficult to install on production vehicle

Road Load Measurement Methods

4. Complete vehicle measurement system

On-road Vehicle Testing

Test Vehicle: FWD Mini Cooper S

Test Track: Proving ground in Tochigi, Japan

Instrumentation

Anemometer

Measures wind velocity & direction

6-Component Wheel Force Transducer

(Fx, Fy, Fz, Mx, My, Mz)

- Distributed force bridges with model based decomposition to get orthogonal force components
- Very low cross sensitivity, interference & temperature sensitivity and high sampling rate
- 0.1% resolution (6N or 1.8Nm)

Instrumentation

Anemometer

Measures wind velocity & direction

6-Component Wheel Force Transducer

(Fx, Fy, Fz, Mx, My, Mz)

Influence of drivetrain losses is included in this measurement

Influence of a and b terms is included in this measurement (ignoring bearing friction and wheel well aerodynamic losses)

Vehicle Instrumentation II

Laser Doppler Sensor

Measures vehicle velocity & slip angle

GPS Sensor & In-vehicle Network

Measures vehicle longitude, latitude, altitude, and ECU CAN communication

Inertial Sensor

Measures vehicle roll, pitch and yaw

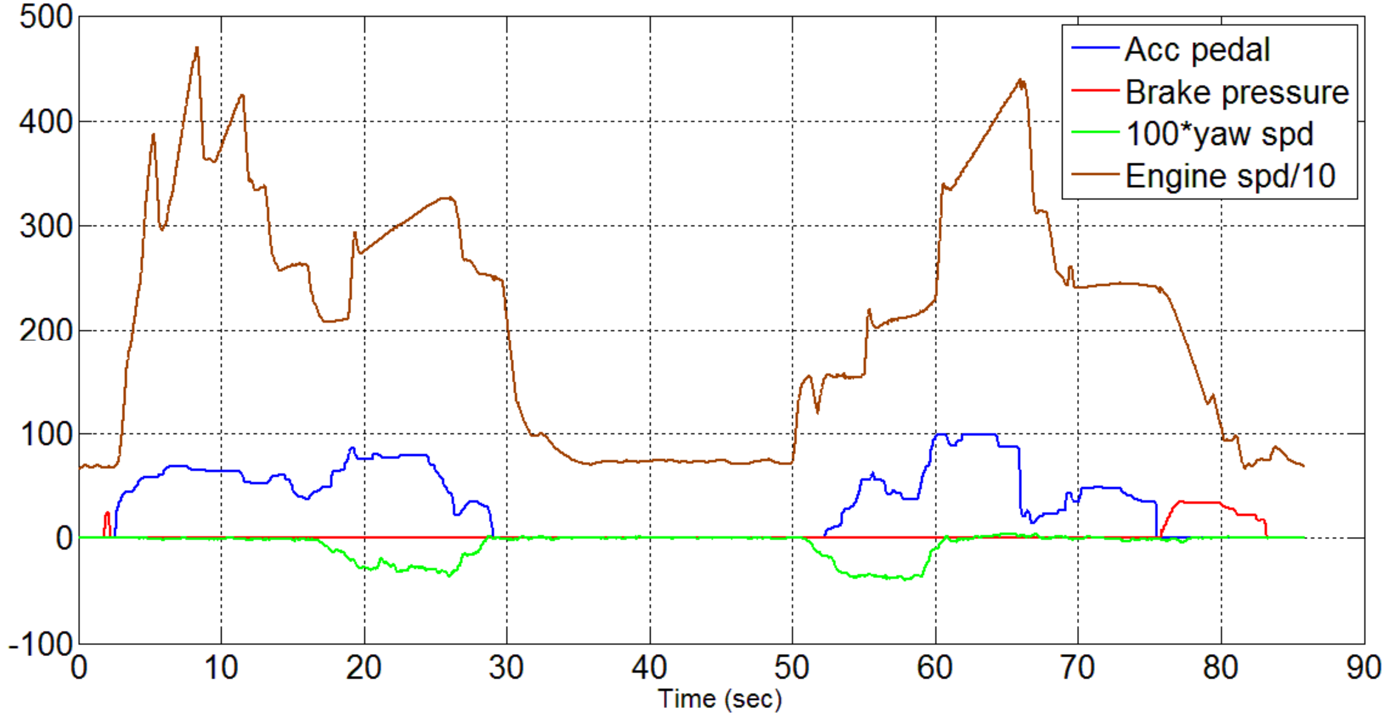
Wheel Position Sensor

Measures 6 degrees of freedom of the tire

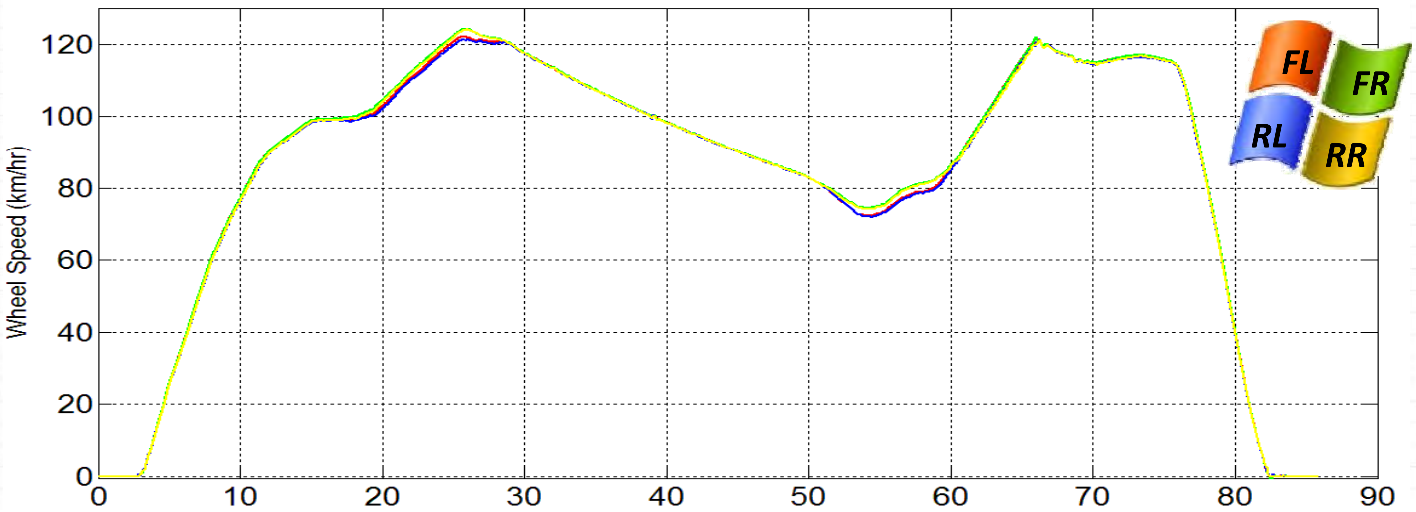
Digital Signal Processing & Acquisition

100Hz sampling (max 100kHz)

Sample Data

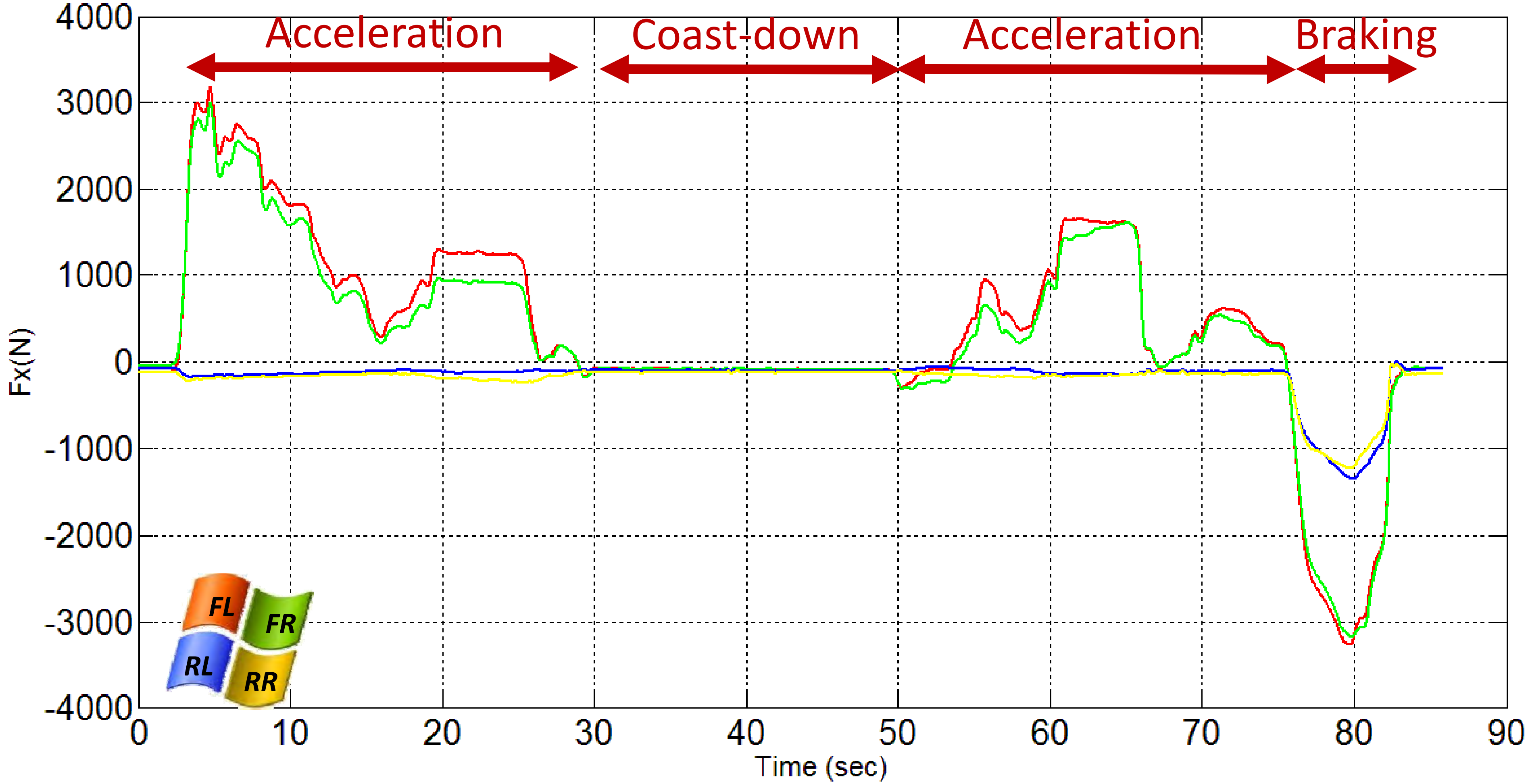


500
400
300
200
100
0
-100
0
10
20
30
40
50
60
70
80
90
Time (sec)
Acc pedal
Brake pressure
100*yaw spd
Engine spd/10



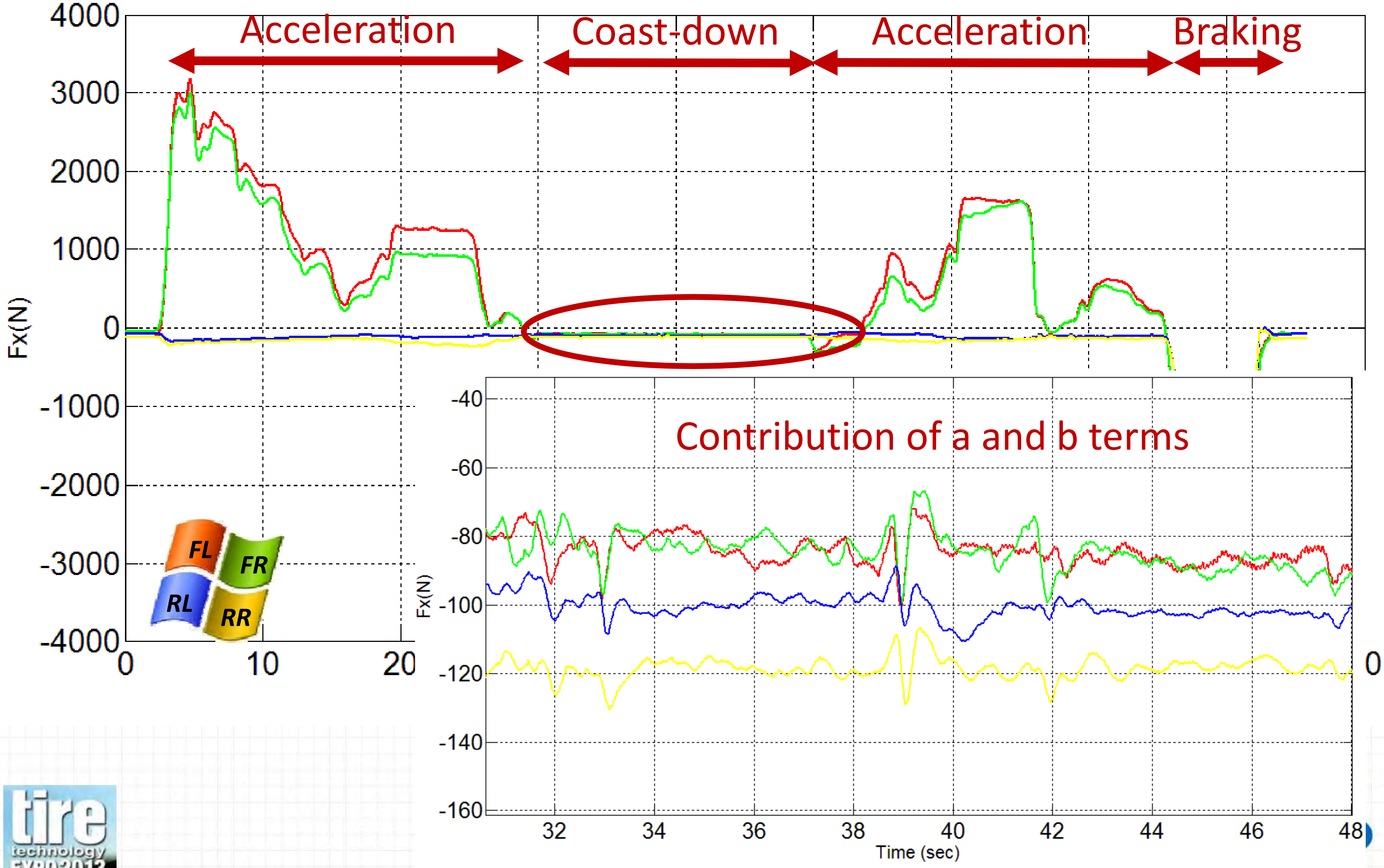
Wheel Speed (km/hr)
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
FL
FR
RL
RR

Sample Data



Acceleration
Coast-down
Acceleration
Braking
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
Fx(N)
0
10
20
30
40
50
60
70
80
90
Time (sec)
FL
FR
RL
RR

Sample Data



Acceleration
Coast-down
Acceleration
Braking
Fx(N)
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
0
10
20
FL
FR
RL
RR
Contribution of a and b terms
-40
-60
-80
-100
-120
-140
-160
32
34
36
38
40
42
44
46
48
Time (sec)

Outline

1. Introduction
2. Road load fundamentals
3. Instrumentation & sample data
4. Coast down method
5. Force measurement method
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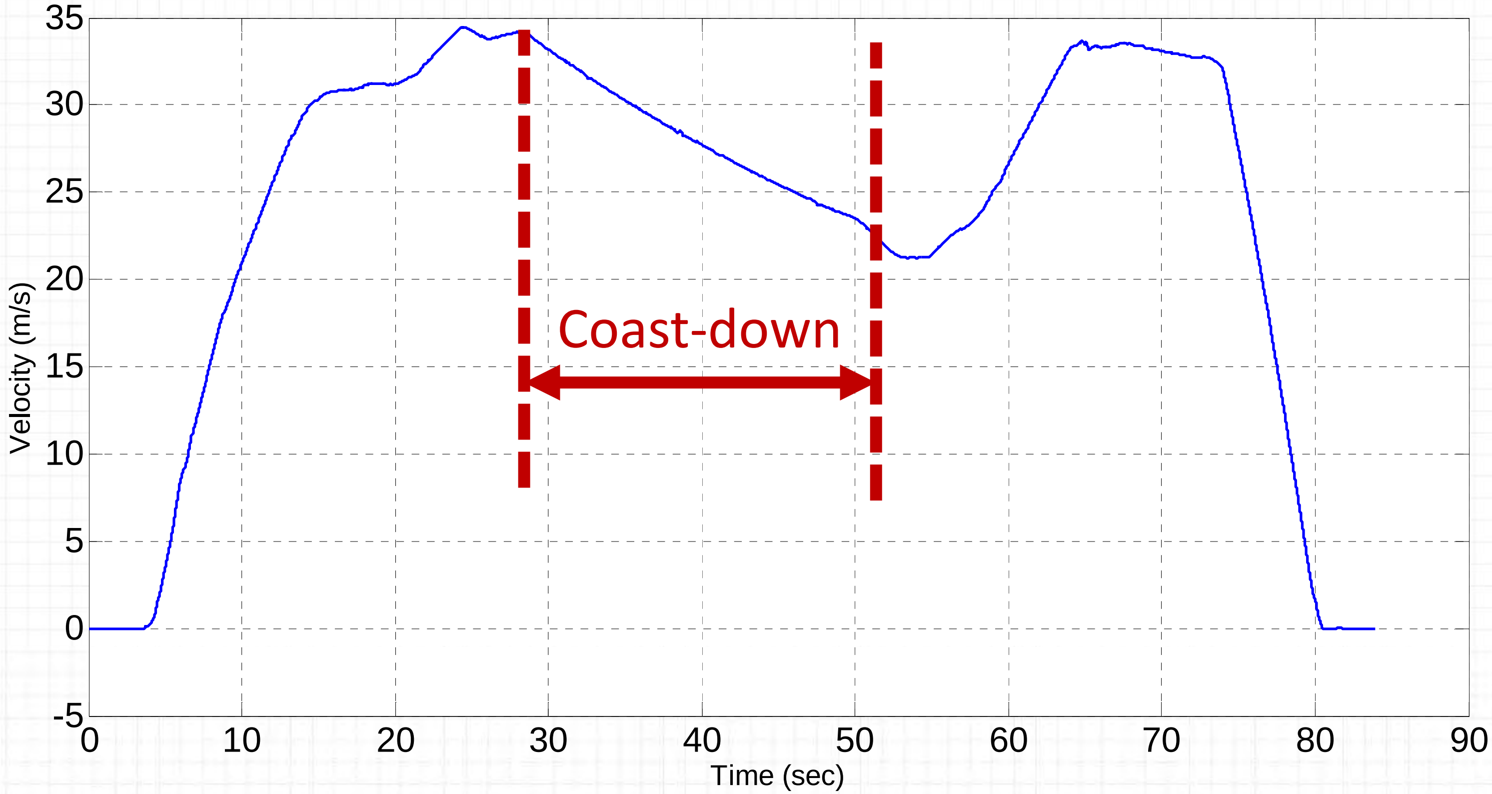
Coast-down Tests

Procedure:

- Conduct tests on a flat road with low wind conditions
- Accelerate the vehicle and put the transmission in N
- Begin coast down in a straight line
- Record vehicle velocity and vehicle velocity relative to wind as a function of time



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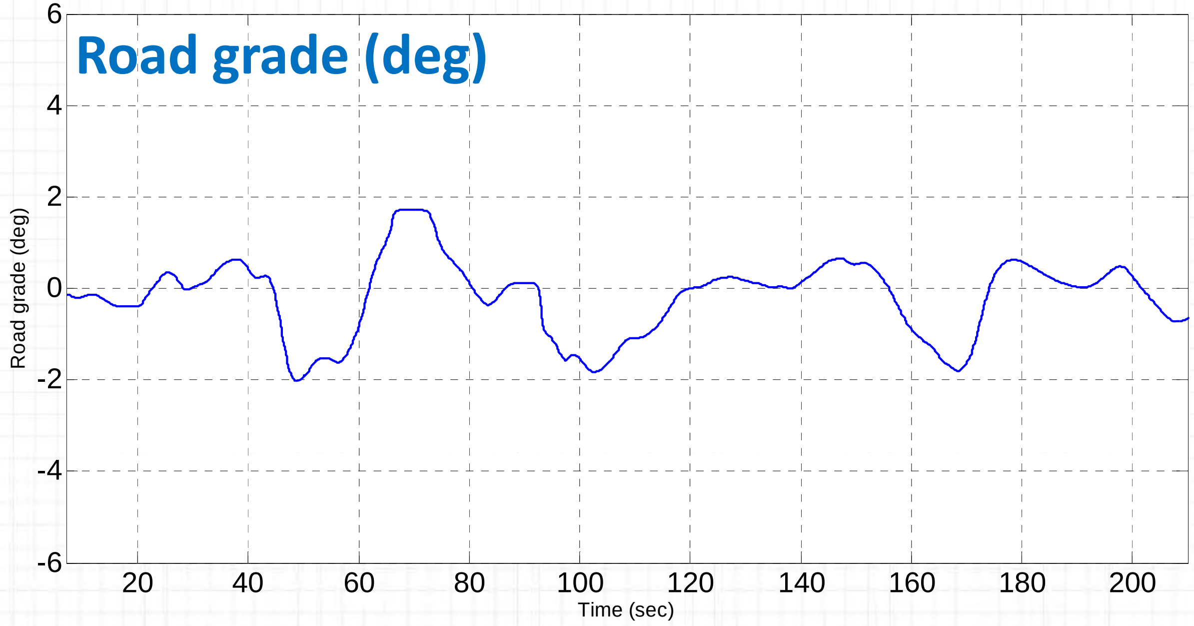
$$F_{road\ load} = \left(a + b \cdot v_x + c \cdot (v_{rel})^2\right) + \cancel{M \cdot g \cdot \sin(\theta)}$$

Flat road assumption



Coast-down Tests

<u>Procedure:</u>

- Conduct tests on a flat road with low wind conditions
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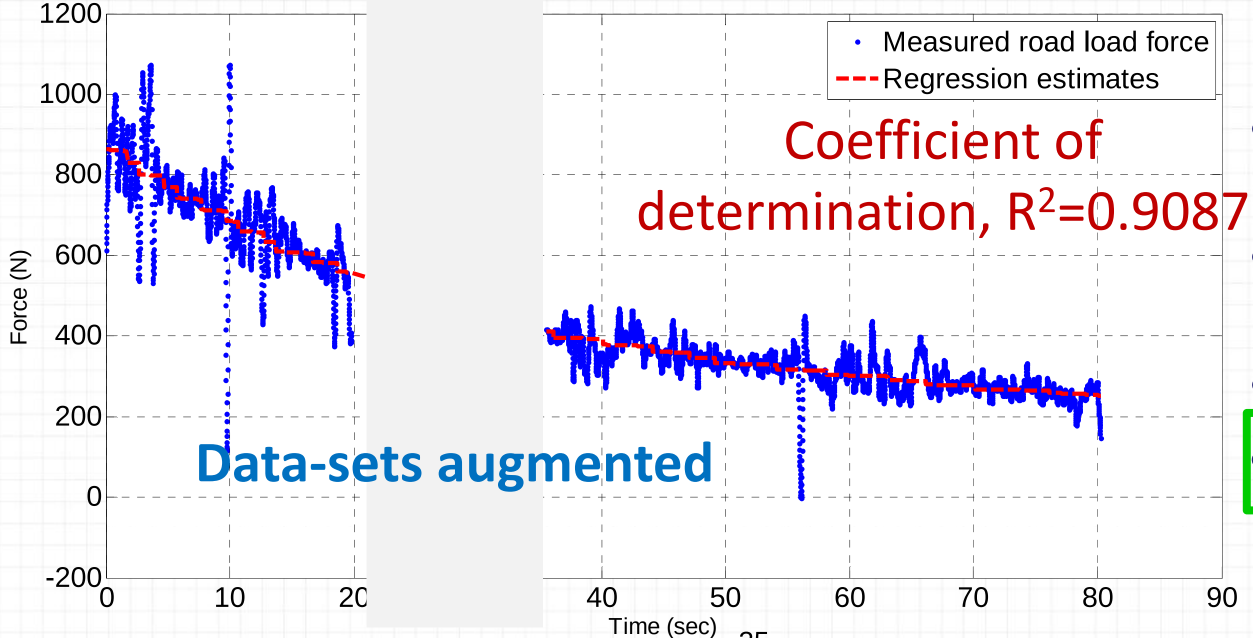
$$F_{road\ load} = \left(a + b \cdot v_x + c \cdot (v_{rel})^2\right) + \cancel{M \cdot g \cdot \sin(\theta)}$$

$$-F_{road\ load} = M \frac{dv_x}{dt}$$

- Use linear regression to obtain coefficients a, b & c
  - Use minimization of $\| L \|_2$
  - Verify by Simulated Annealing
- SAE J1263, J2263 and ISO 10521-1 contain more detailed procedures

Coast-down Test Results



- Front tires: Bridgestone Sneaker
- Rear tires: Bridgestone Sneaker
- Estimated Values:

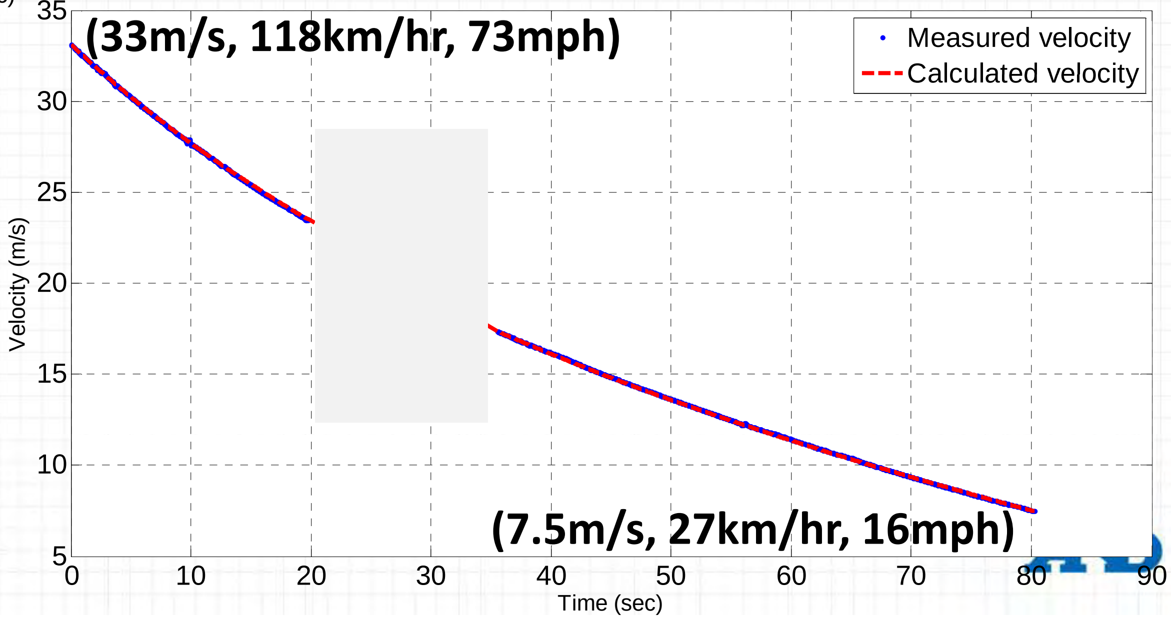
a = 194.87, b = 3.87, c = 0.37

<u>95% Confidence bounds:</u>

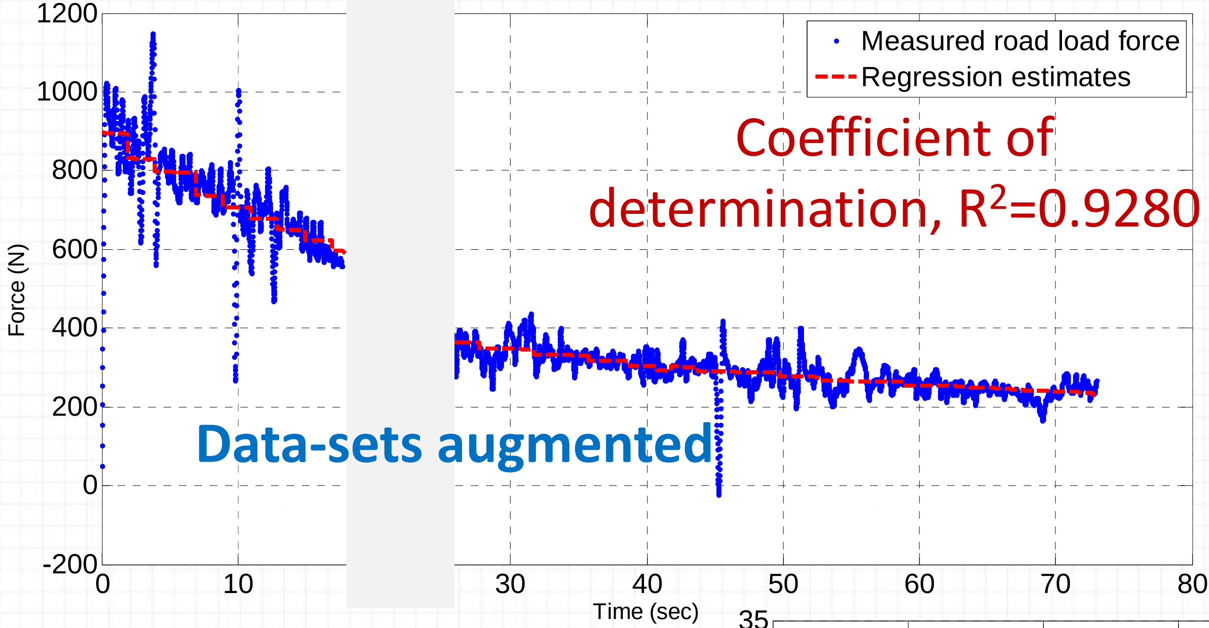
a: 184 – 204

b: 2.7 – 5

c: 0.35 – 0.39



Coast-down Test Results



- Front tires: Bridgestone Blizzak
- Rear tires: Bridgestone Sneaker
- Estimated Values:

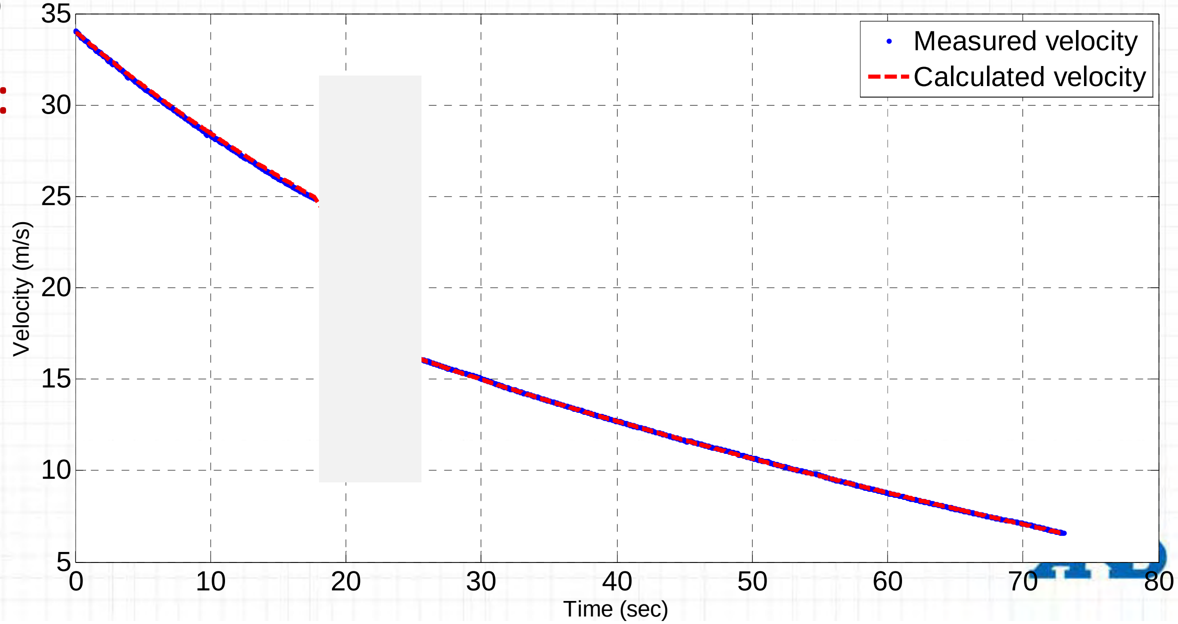
a = 191.69, b = 2.54, c = 0.41

<u>95% Confidence bounds:</u>

a: 183 – 200

b: 1.5 – 3.5

c: 0.39 – 0.43



Validation Procedure

$$F_{road\ load} = \left(a + b \cdot v_x + c \cdot (v_{rel})^2\right)$$

During coast-down:

$$-F_{road\ load} = M\frac{dv_x}{dt}$$

Generalized equation under all conditions (including coast-down):

Tire traction/braking force

$$\Sigma F_{tb} - F_{road\ load} = M\frac{dv_x}{dt}$$

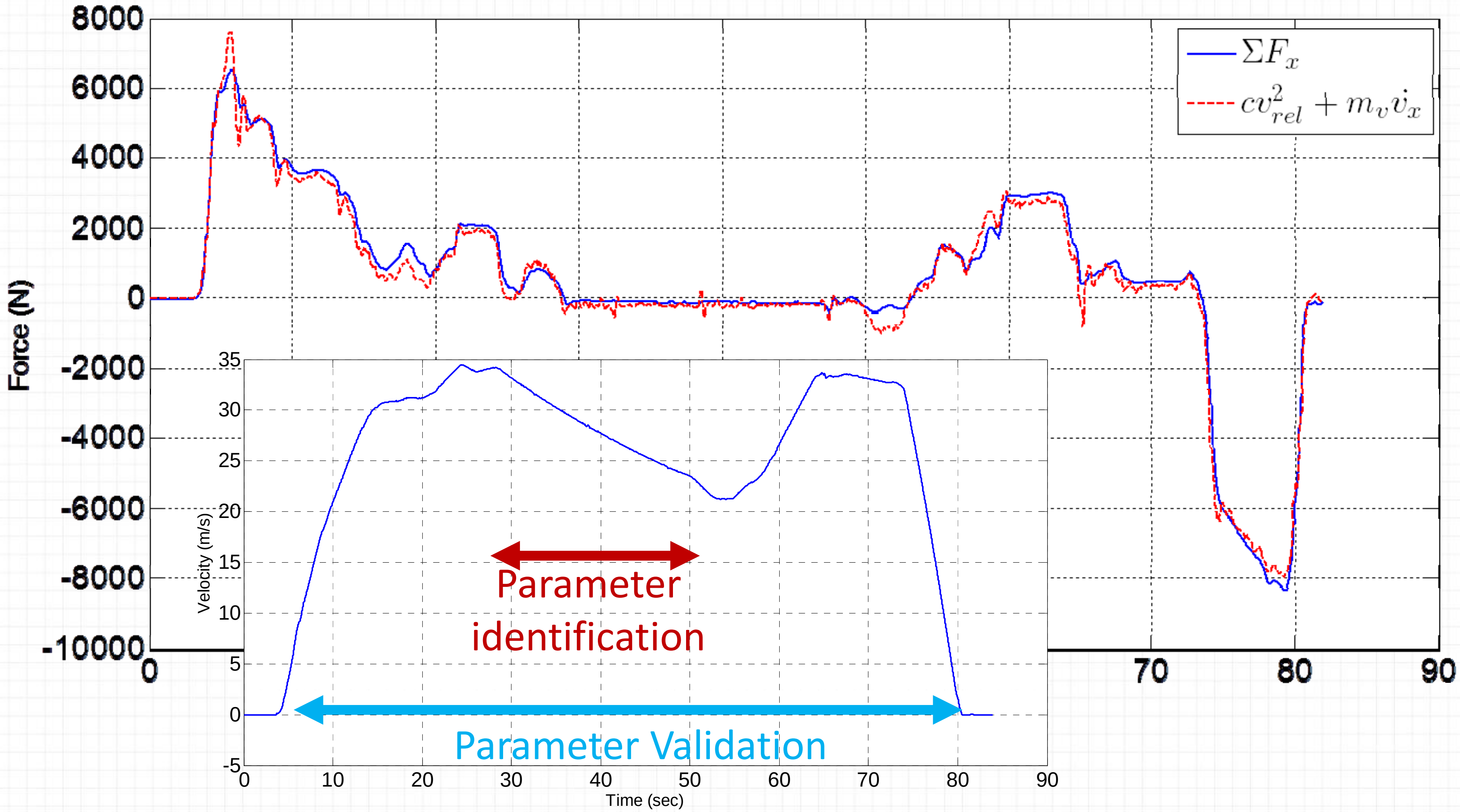
$$\Sigma F_{tb} - \left(a + b \cdot v_x + c \cdot (v_{rel})^2\right) = M\frac{dv_x}{dt}$$

$$(\Sigma F_{tb} - a - b \cdot v_x) - c \cdot (v_{rel})^2 = M\frac{dv_x}{dt}$$

Wheel force sensor measurements

$$\Sigma F_x = c \cdot (v_{rel})^2 + M\frac{dv_x}{dt}$$

Validation Procedure



Estimates are poor outside the coast-down region

Residual Analysis

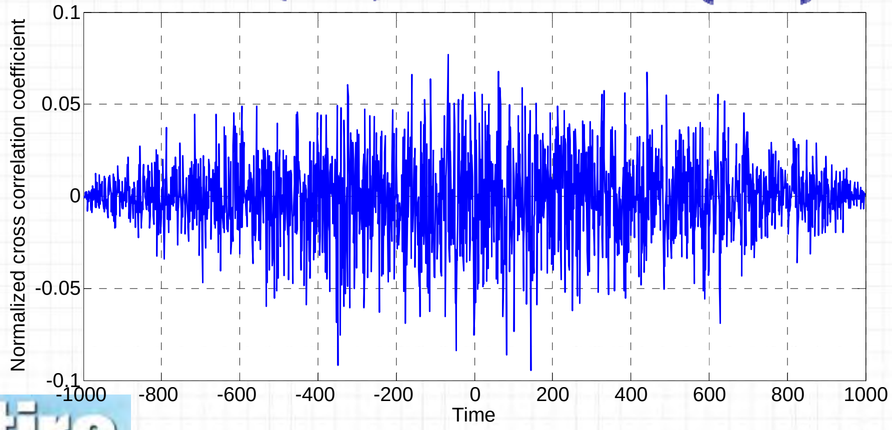
$$\Sigma F_x = c \cdot (v_{rel})^2 + M\frac{dv_x}{dt}$$

$$Res = \Sigma F_x - [c \cdot (v_{rel})^2 + M\frac{dv_x}{dt}]$$

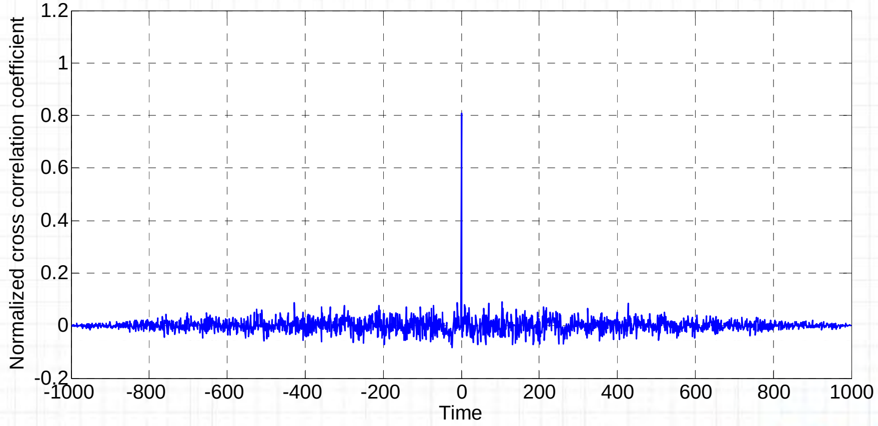
Analyze cross-correlation coefficient of residuals:

An example:

$x1 \in \mathcal{N}(0,1) \quad x2 \in \mathcal{N}(0,1)$



$x1 \in \mathcal{N}(0,1) \quad x2 = x1^3$

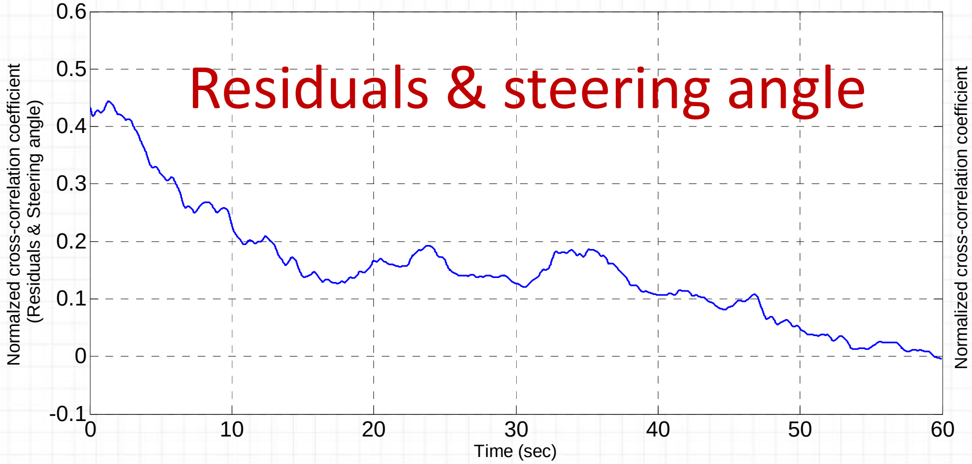


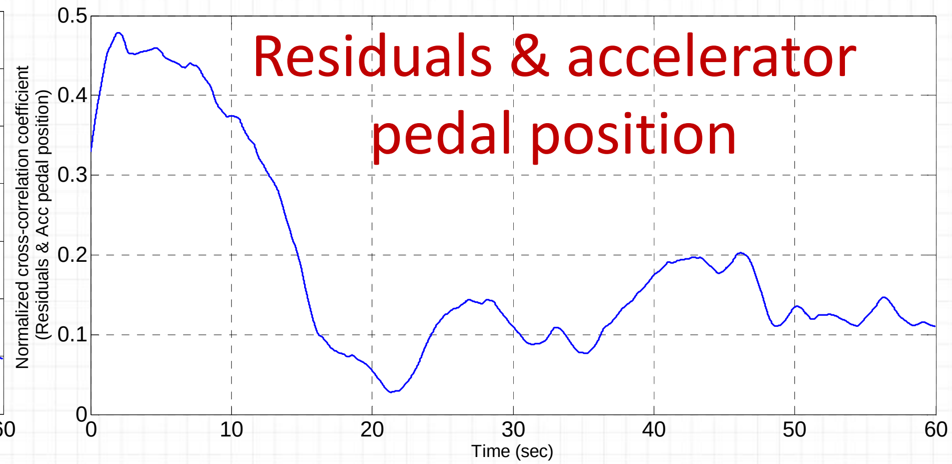
Residual Analysis

$$\Sigma F_x = c \cdot (v_{rel})^2 + M\frac{dv_x}{dt}$$

$$Res = \Sigma F_x - [c \cdot (v_{rel})^2 + M\frac{dv_x}{dt}]$$

Analyze cross-correlation coefficient of residuals:





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Limitations of Coast-down Tests

Procedure:

1. A long straight flat track is needed
   - SAE procedures requires a minimum speed band of 70 to 15 mph
2. Results include drivetrain losses and may not be suitable for some applications
3. Results are not consistent for all driving conditions, especially outside the coast-down region
   - Residuals are correlated with accelerator pedal position, steering angle,…
4. Predictor basis is not orthogonal giving rise to the mathematical complications due to multicollinearity
   - Estimates of a, b, c might be biased or have high variance

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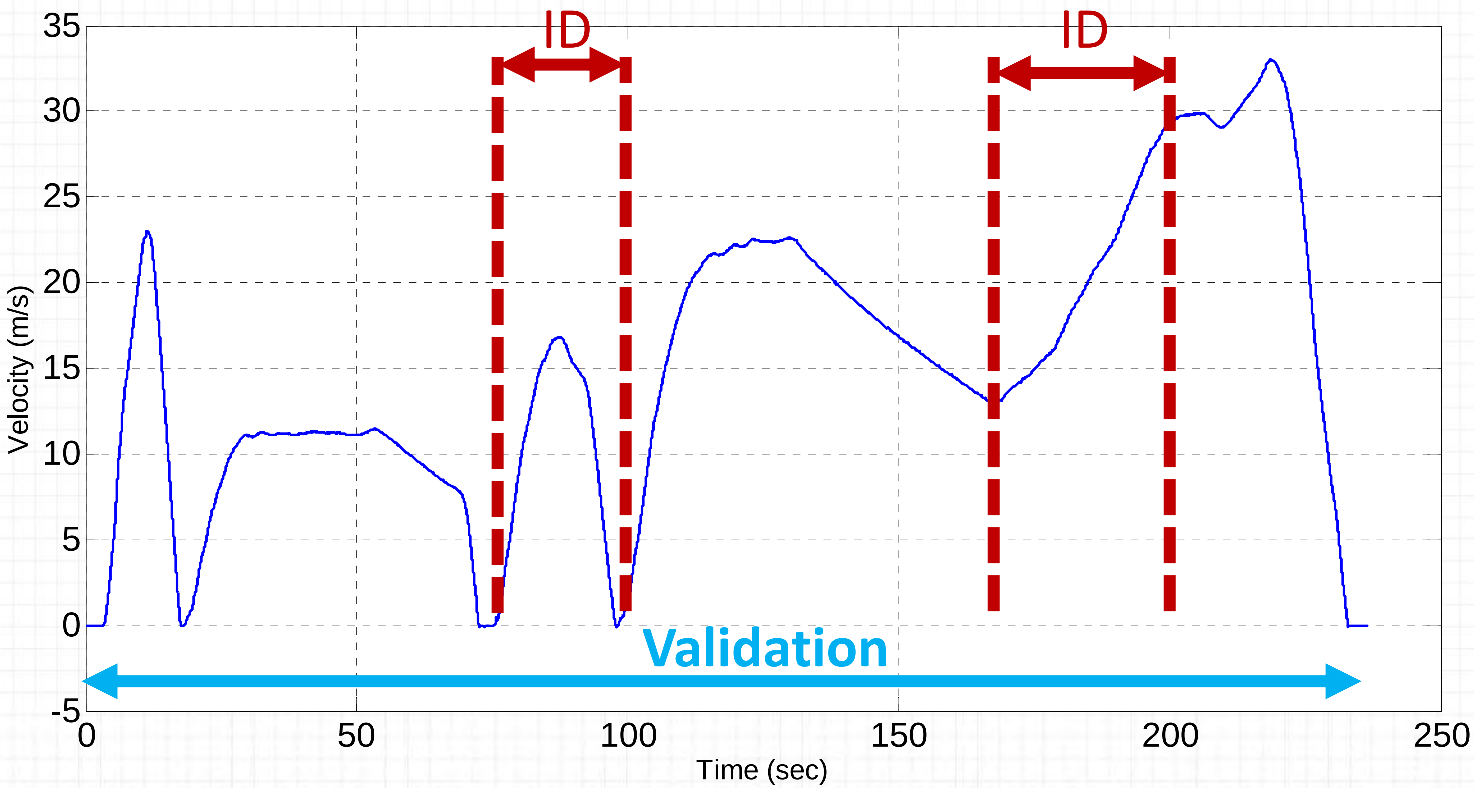
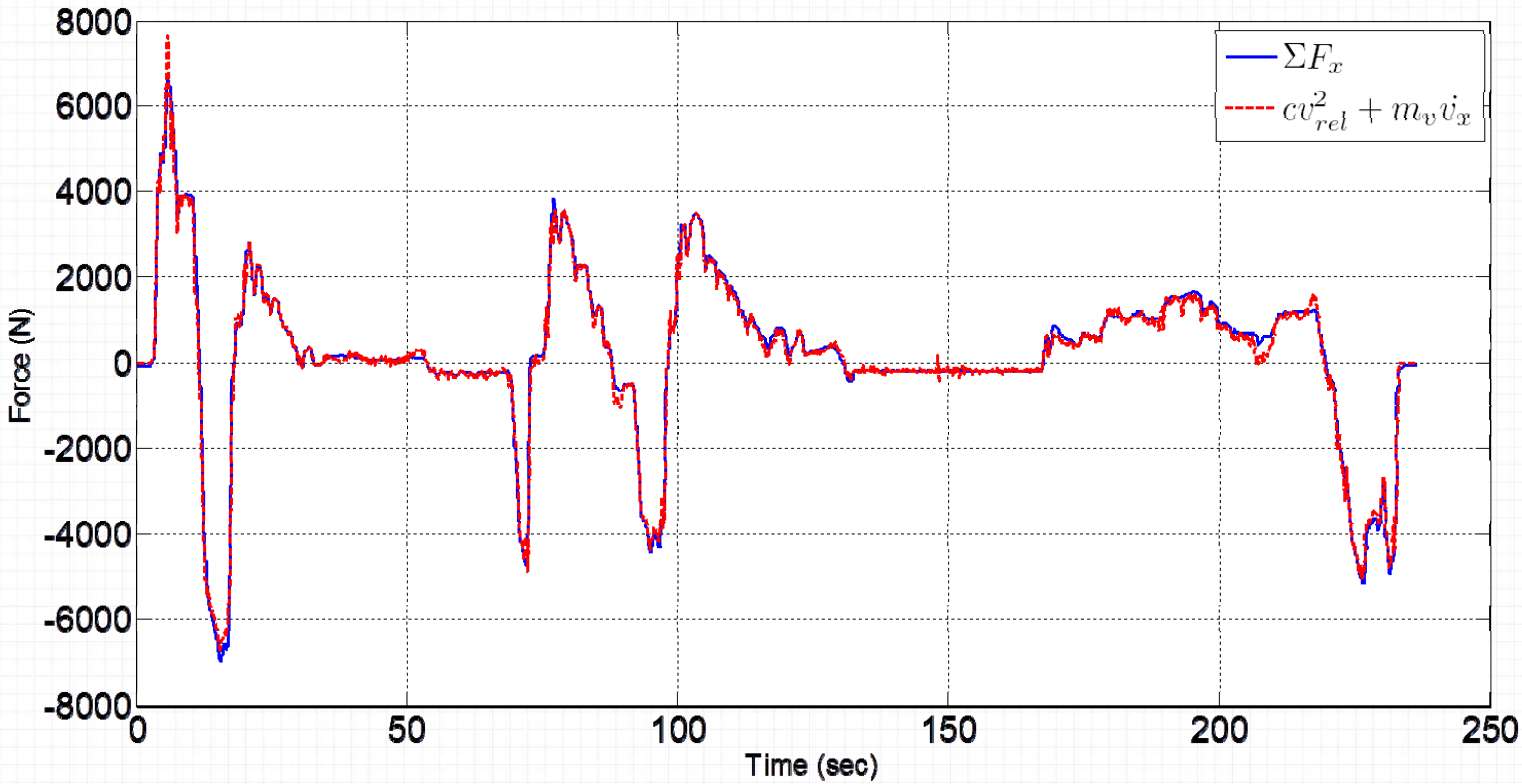
Identification using Force Method

$$\Sigma F_x - M\frac{dv_x}{dt} = c \cdot (v_{rel})^2$$

Use regression to identify c → c = 0.5371



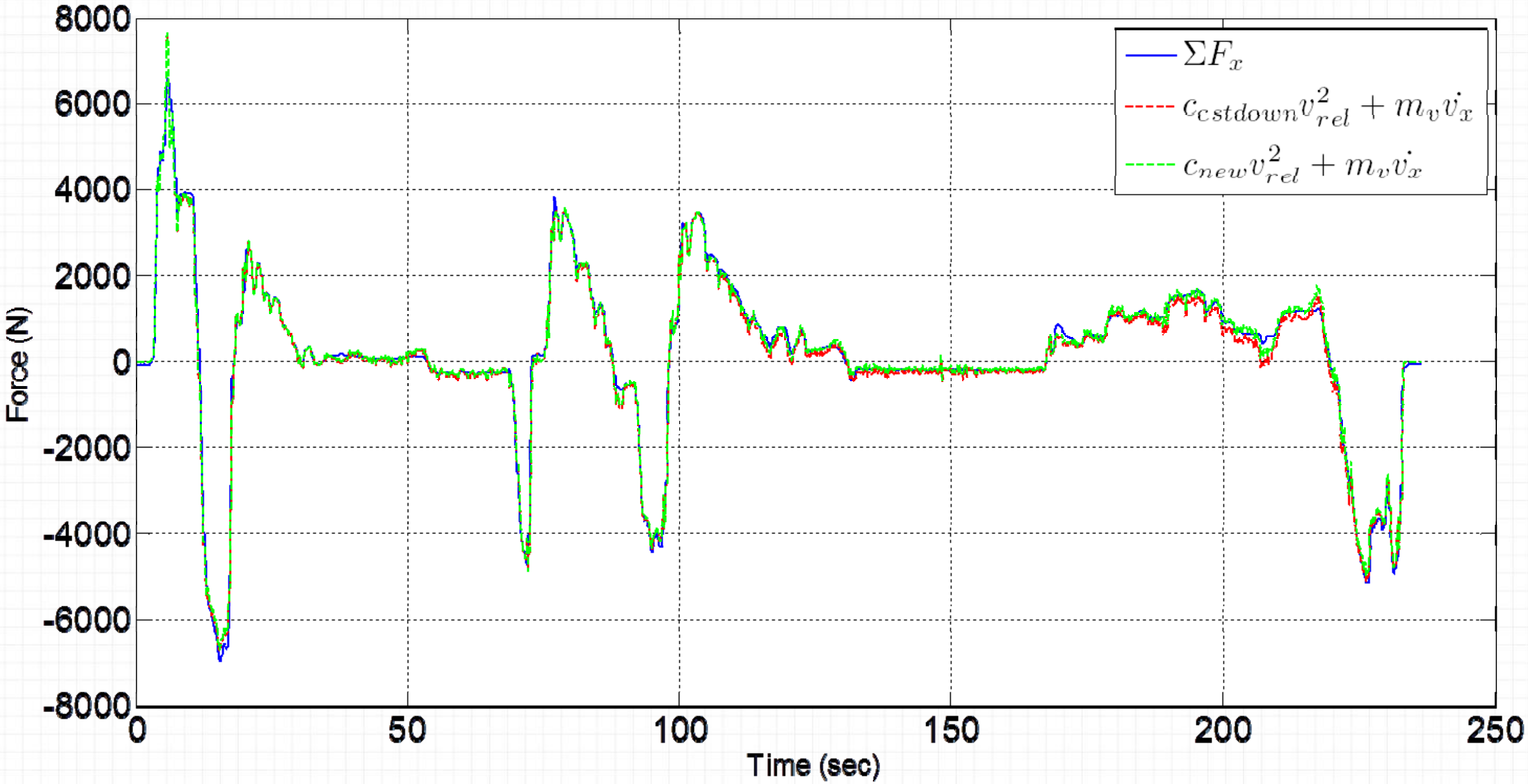
Validation Test



$R^2 = 0.9926$

95% confidence limit for c: 0.53- 0.55

Comparison of Coast-down & Force Method



- Front tires: Bridgestone Blizzak
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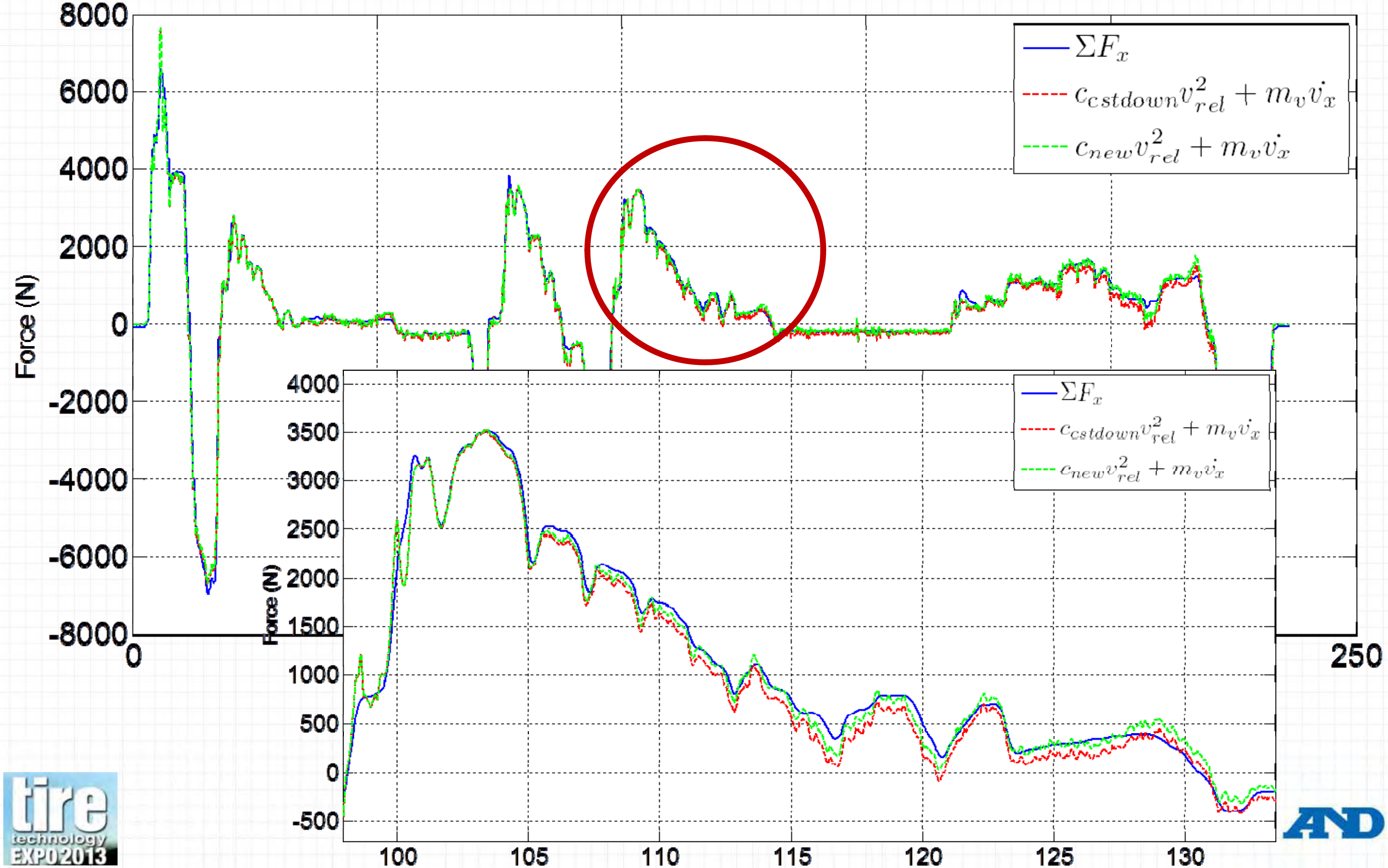

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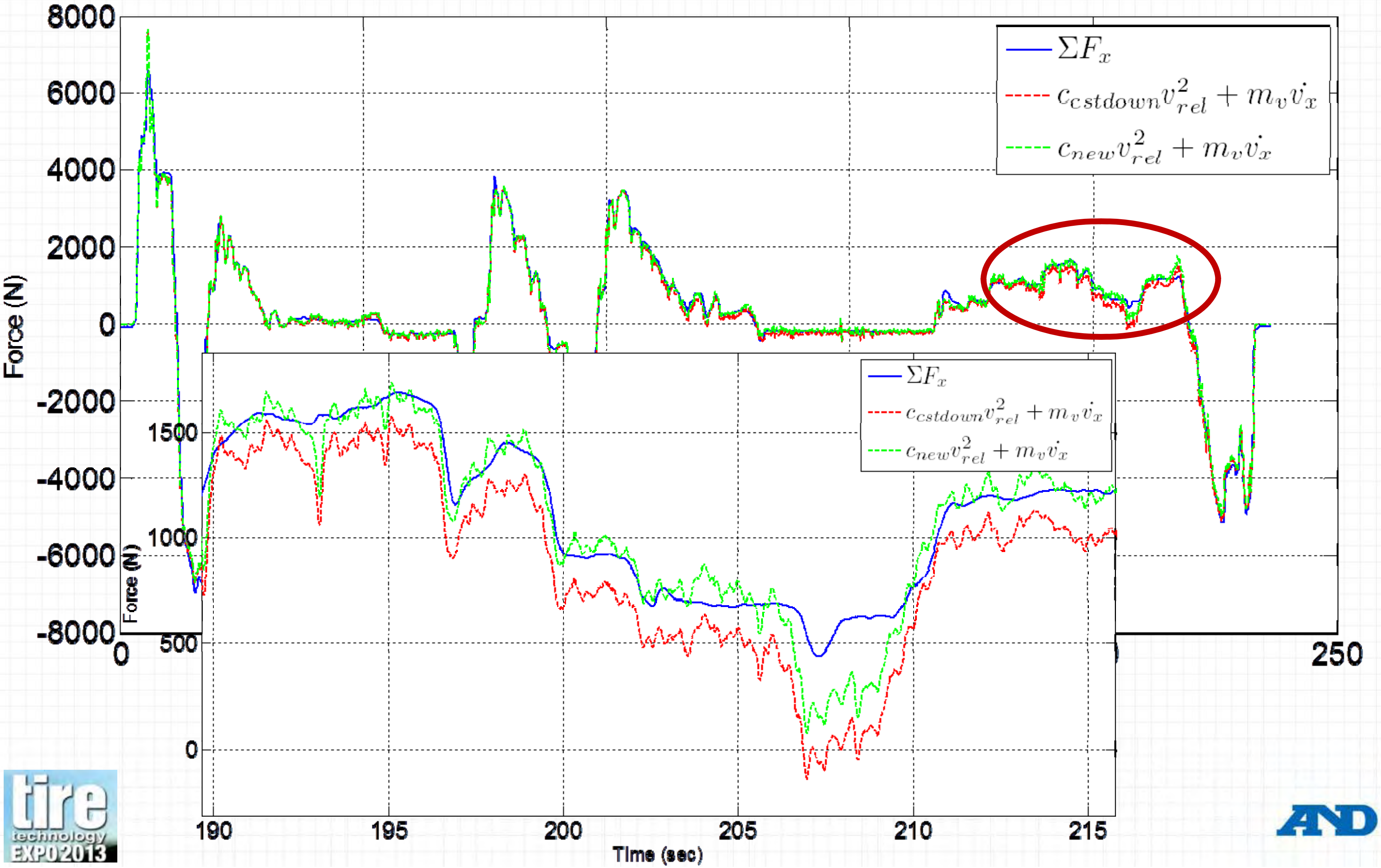
Comparison of Coast-down & Force Method



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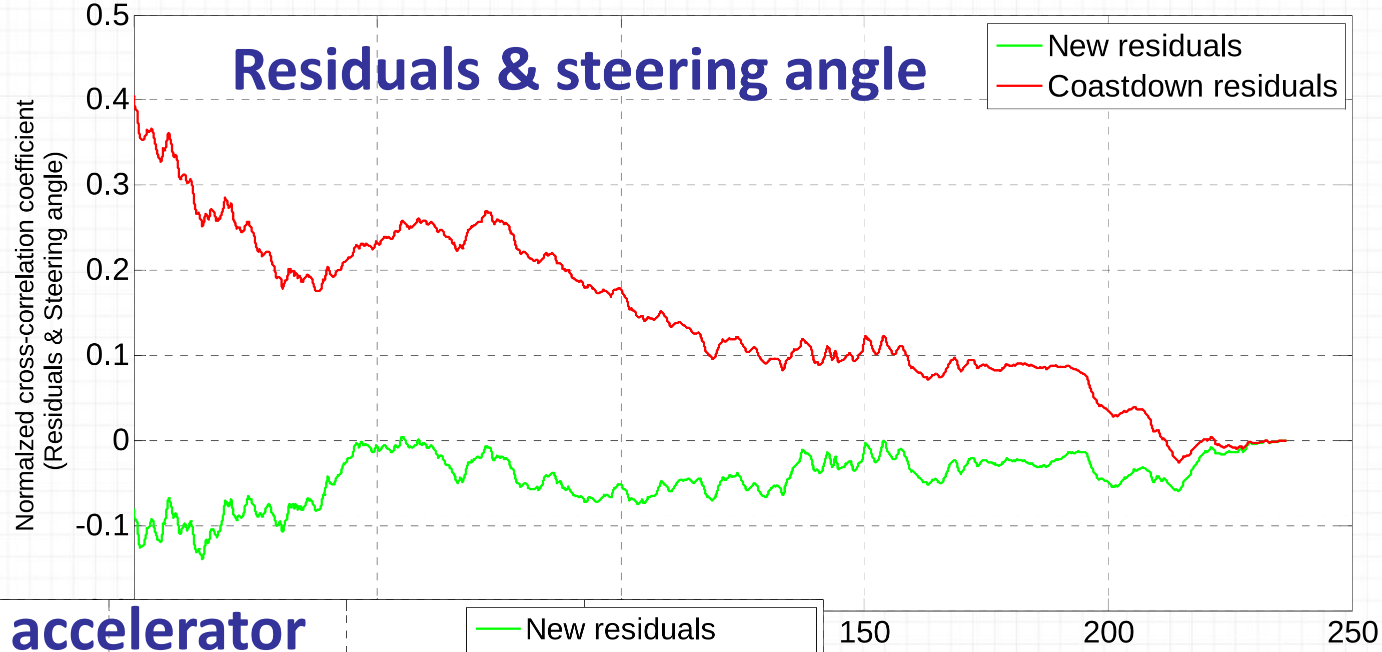
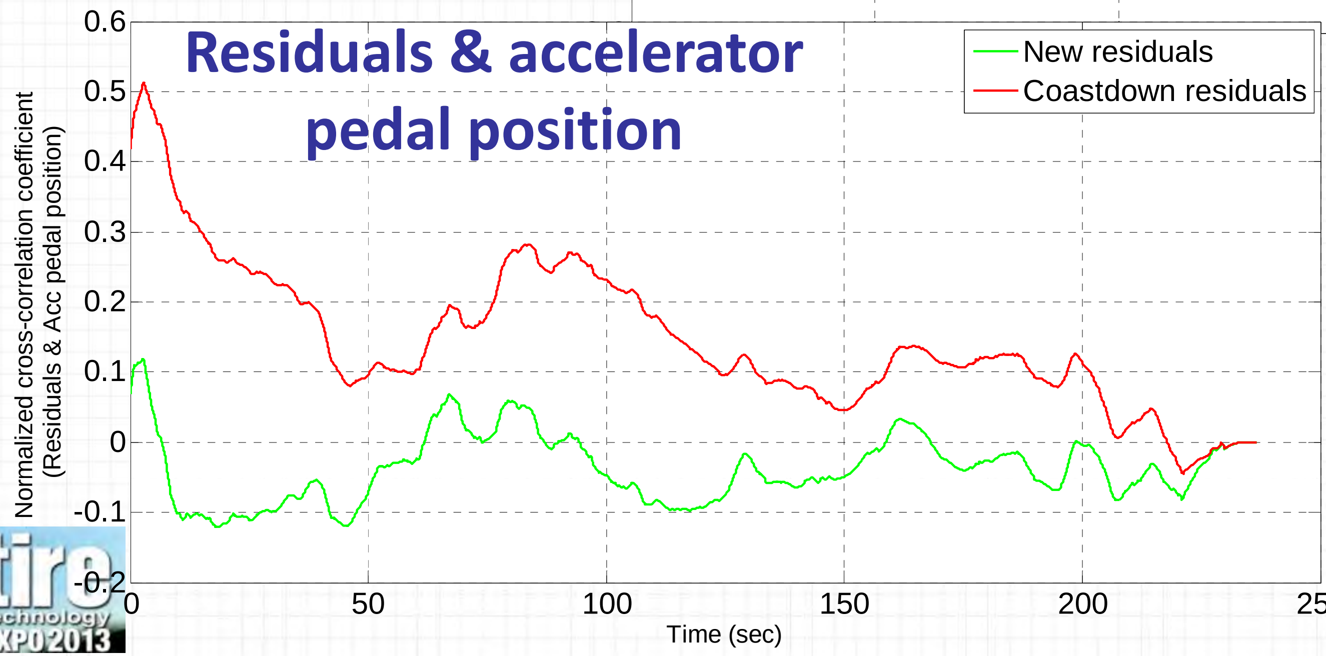
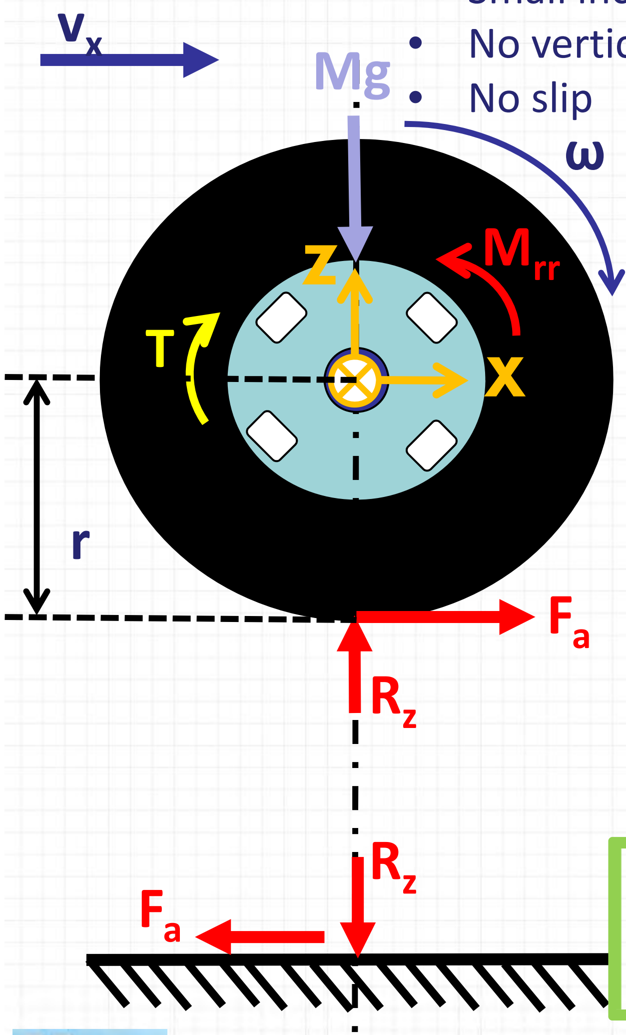
AND

Cross-correlation of Residuals





Traction & Braking Scenarios



Assumptions:

- Small inclination and side-slip angles
- No vertical displacement of the tire
- No slip

m: Mass of tire wheel assembly
J: Polar moment of inertia of tire-wheel assembly about the center of wheel hub
T: Applied torque at wheel hub
F_a: Tire-road friction force

$$J\dot{\omega} = T - F_a r - M_{rr}$$

$$F_a = \frac{T - J\dot{\omega} - M_{rr}}{r} = \frac{T - J\dot{\omega}}{r} - R_x$$

Let WFS measurements be represented as F_x, F_z and M_y

Then,

$$T = M_y, r = \frac{v}{\omega}$$

v → From laser Doppler sensor
ω → From encoder

$$F_x = F_a - m\dot{v}_x = \frac{M_y - J\dot{\omega}}{r} - R_x - m\dot{v}_x$$

$$R_x = \frac{M_y - J\dot{\omega}}{r} - F_x - m\dot{v}_x, \quad RRC = \frac{R_x \times 1000}{F_z}$$

J, m: Determined before the experiment

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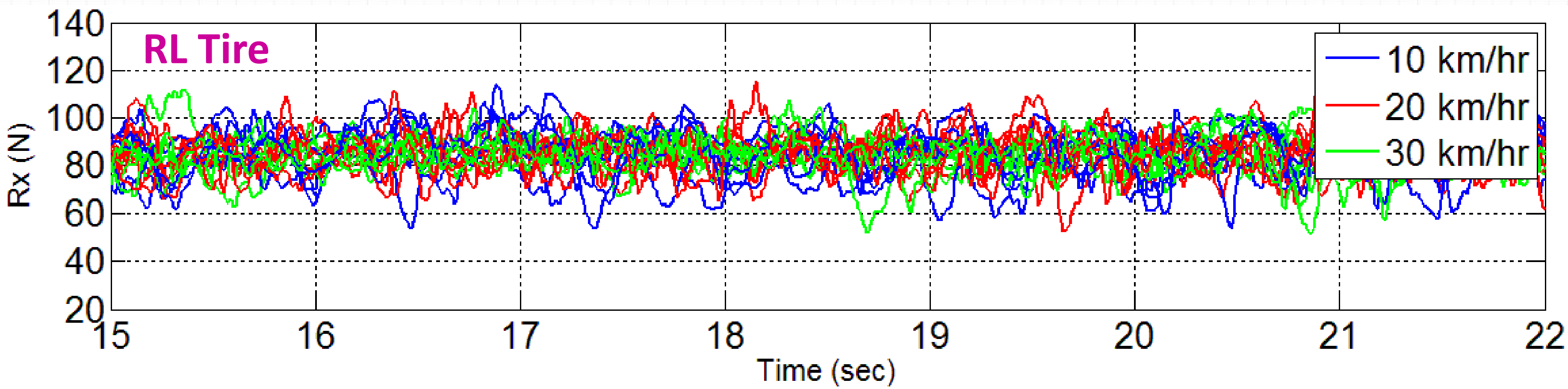
Calculation of 'a' from Force Method

6 constant speed tests for each speed, 18 tests total



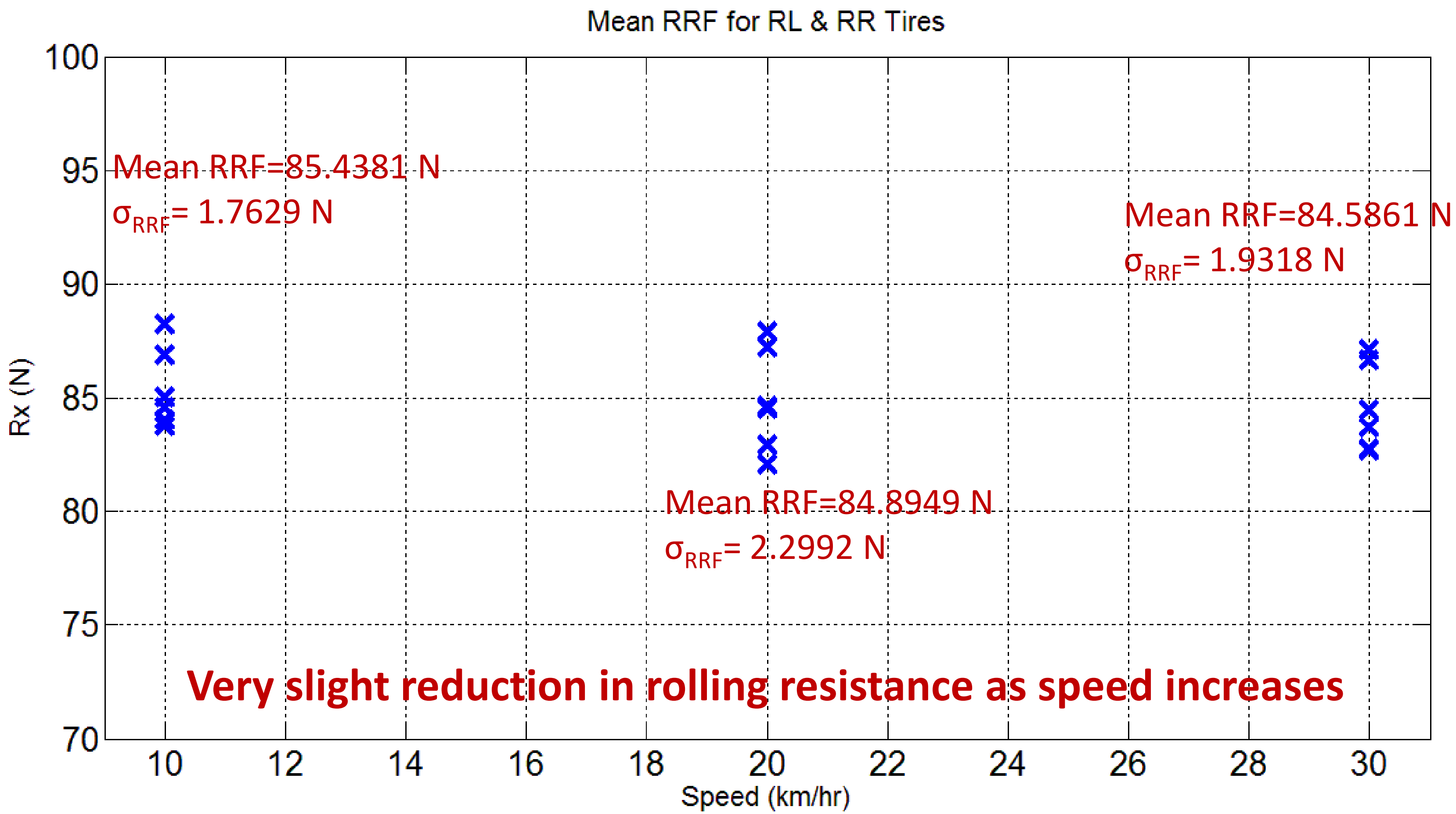
Assuming that wheel well aerodynamic losses are negligible at low speeds, calculate

$$a = \Sigma R_x$$

a = 271

Note: Measured value of rolling resistance is much higher than what standardized tests predict [11]

Calculation of ‘b’ from Force Method



$$b = \frac{\delta(\Sigma R_x)}{\delta(\Sigma v_x)}$$

$b \approx 0$

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Summary

Coast-down Method

a = 191.69, b = 2.54, c = 0.41

- **R^2** = 0.9280
- Estimate variance is higher
- Estimation only over coast-down; road load is under-estimated for non-coast-down conditions
- Residuals are correlated with driver inputs
- Changing the tire changes ‘c’ substantially
- Influence of drivetrain losses is included
- Less instrumentation is needed
- Less distortion of vehicle aerodynamic

Force Method

a = 271, b = 0, c = 0.5371

- **R^2** = 0.9926
- Estimation based on physics; variance is very low
- Estimation can be carried out during all conditions
- Correlation is significantly reduced
- Changing the tires preserves ‘c’ very closely
- Influence of drivetrain losses is NOT included
- More instrumentation required
- Vehicle aerodynamics are modified to a greater extent

Acknowledgements

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  - Hiroki Yamaguchi
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- Dr. Michael Smith, A&D Technology, Ann Arbor

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