Influence of road condition on electric vehicle energy consumption

LiRA annual seminar 2021

Asmus Skar
Work Package Leader
Assistant Professor at DTU
asska@byg.dtu.dk

PhD, Natasja Ringsing
Specialist at Vejdirektoratet
nrn@vd.dk

Outline

- Measured energy consumption
- Energy consumption and physical modelling
  a) Vertical system
  b) Horizontal system
- Analysis framework
- Modelling of energy loss
- Isolating rolling resistance (utilizing a simple physical model)

Measured energy consumption

- Traction consumption measured by the car

→ the traction power, $\boldsymbol{P_t = F_t V}$

- $\boldsymbol{F_t}$: the traction force generated by the electric motor
- $\boldsymbol{V}$: velocity of vehicle

- Energy trip consumption

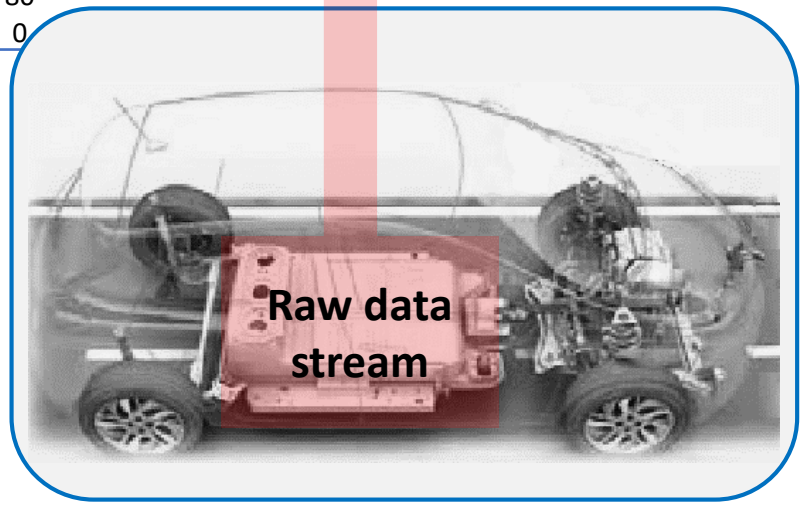
→ $\boldsymbol{E_{trip}} = \int_0^{t_{end}} P_{bat}\ dt$

- $P_{bat} = P_t + P_{aux}$

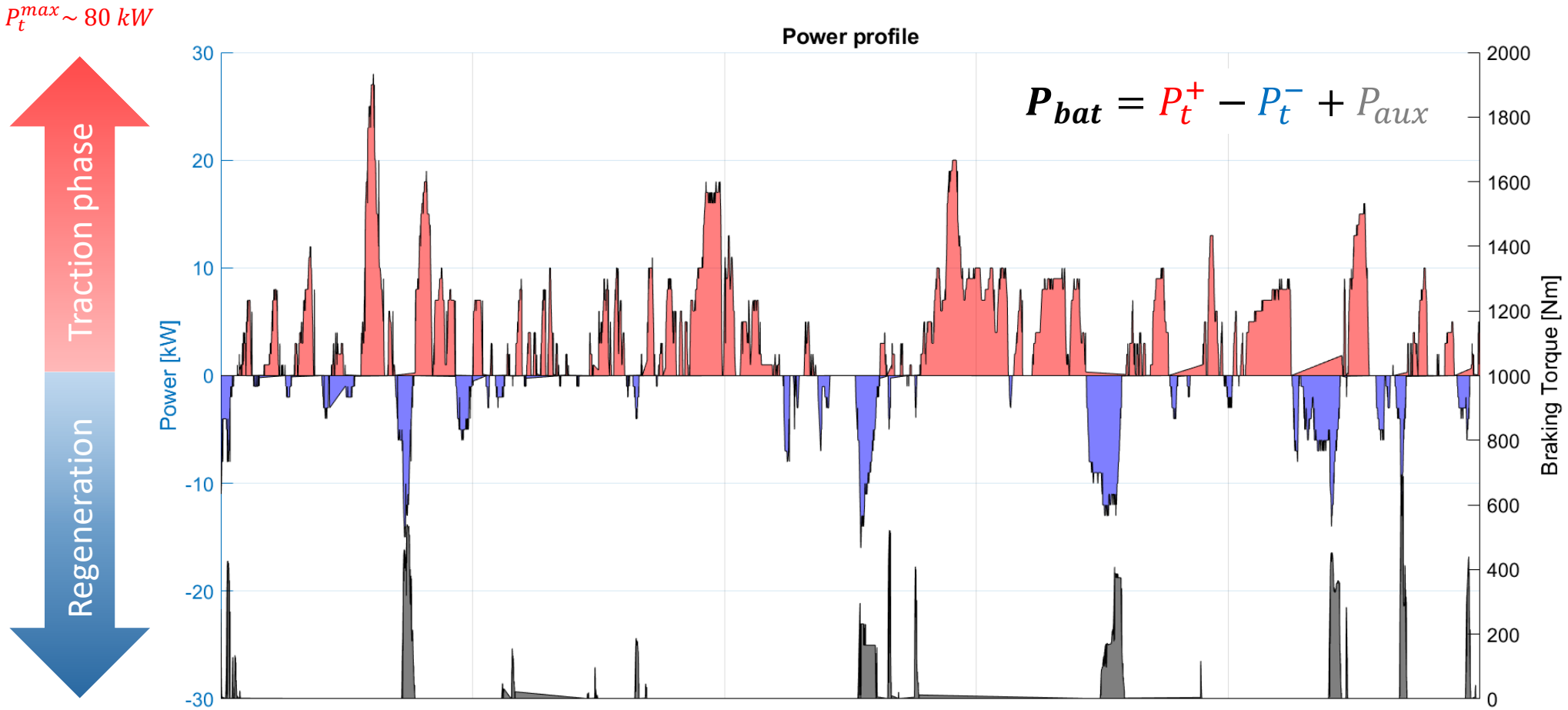
Library

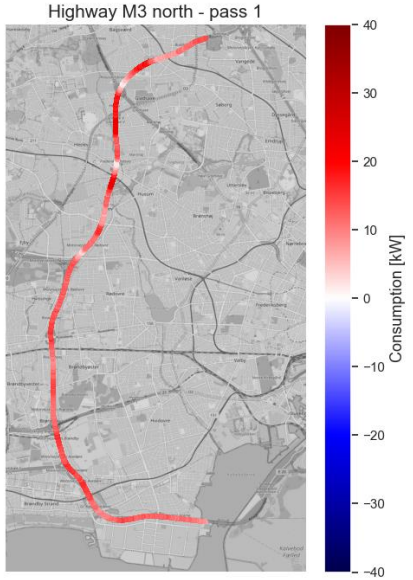
ID (hex)	**638**
definition	**Traction Instant Consumption**
unit	kW
elements	1
startBit	0
endBit	7
resolution	1
offset	80
decimals	0

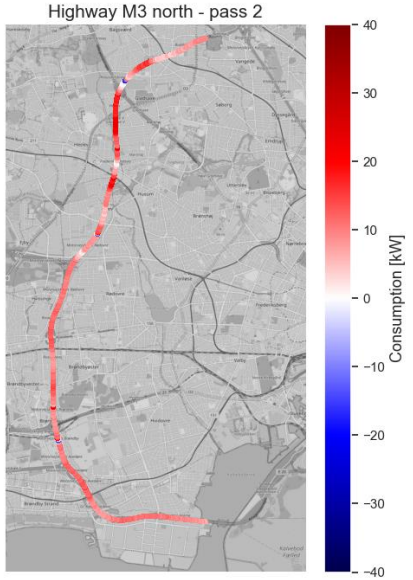
354#0000000000000000
18A#FFF000064000
1F6#DE00001D00FFFFFF
638#50FFBFE0000000
1F8#FC04FFEFFE00060D
212#FE3D406C0000
511#04A160AA8B493C

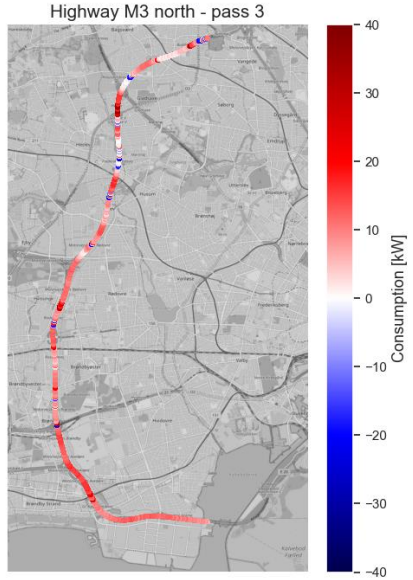


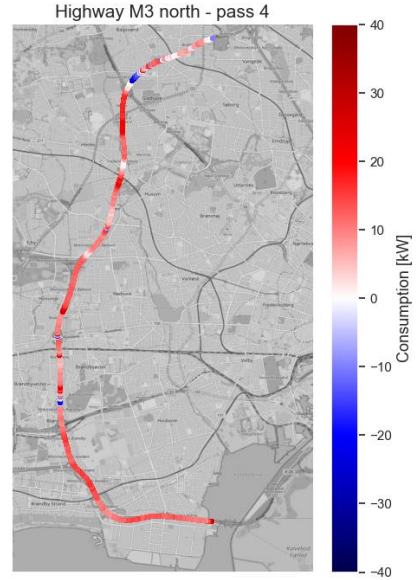
Measured energy consumption

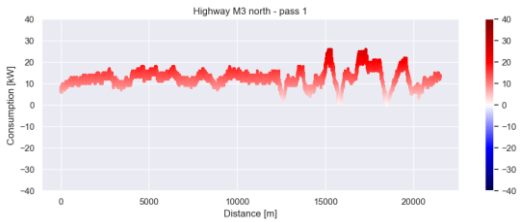


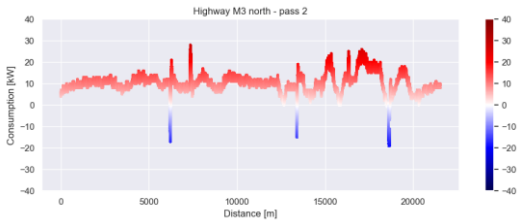

Highway M3 north - pass 1
Consumption [kW]
40
30
20
10
0
−10
−20
−30
−40

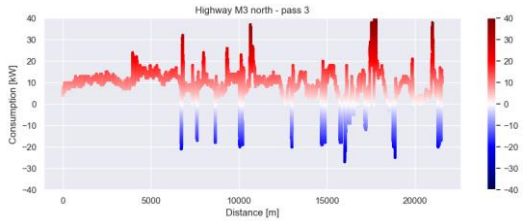

Highway M3 north - pass 2
Consumption [kW]
40
30
20
10
0
−10
−20
−30
−40

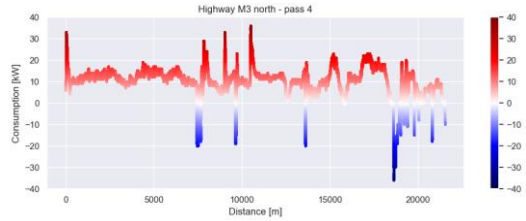

Highway M3 north - pass 3
Consumption [kW]
40
30
20
10
0
−10
−20
−30
−40

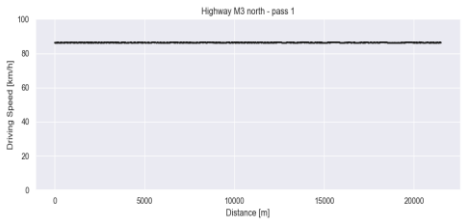

Highway M3 north - pass 4
Consumption [kW]
40
30
20
10
0
−10
−20
−30
−40

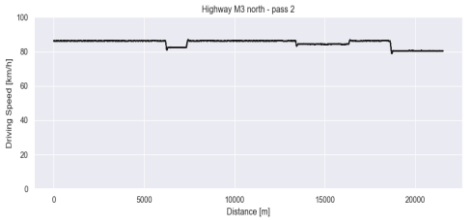

Highway M3 north - pass 1
Consumption [kW]
Distance [m]
0
5000
10000
15000
20000

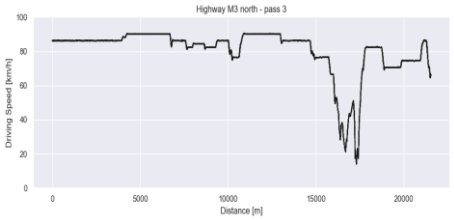

Highway M3 north - pass 2
Consumption [kW]
Distance [m]
0
5000
10000
15000
20000

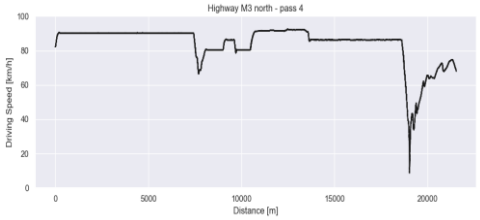

Highway M3 north - pass 3
Consumption [kW]
Distance [m]
0
5000
10000
15000
20000

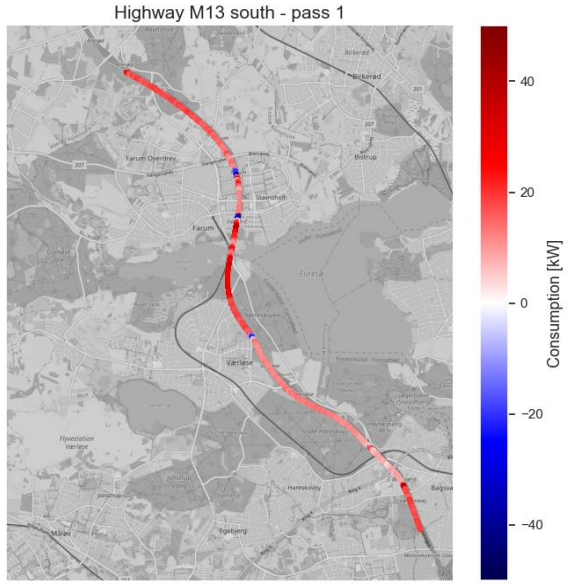

Highway M3 north - pass 4
Consumption [kW]
Distance [m]
0
5000
10000
15000
20000

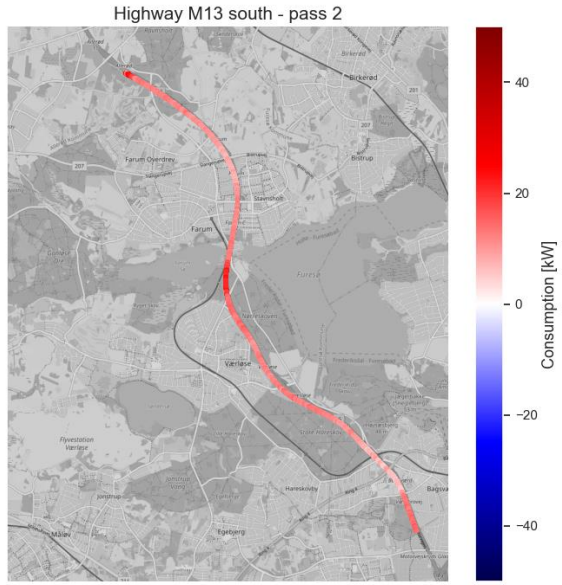

Highway M3 north - pass 1
Driving Speed [km/h]
Distance [m]
0
5000
10000
15000
20000

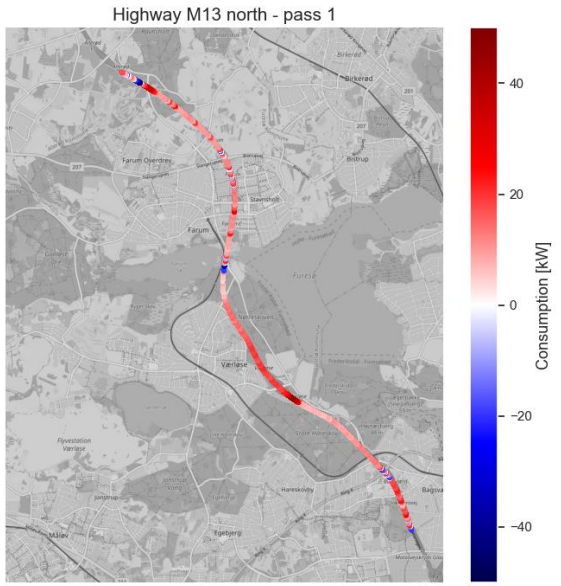

Highway M3 north - pass 2
Driving Speed [km/h]
Distance [m]
0
5000
10000
15000
20000

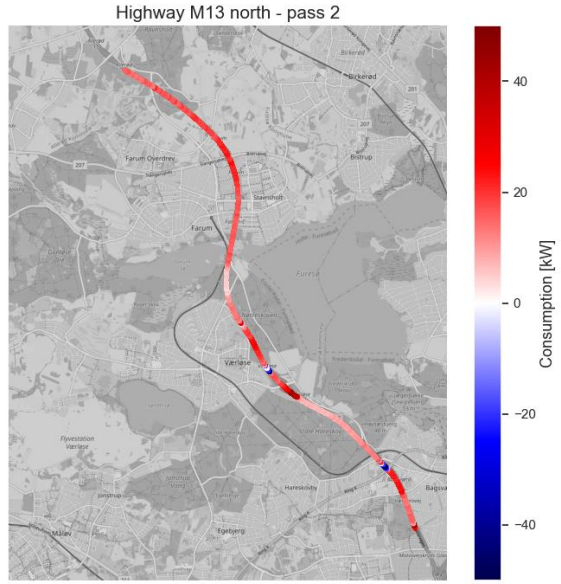

Highway M3 north - pass 3
Driving Speed [km/h]
Distance [m]
0
5000
10000
15000
20000

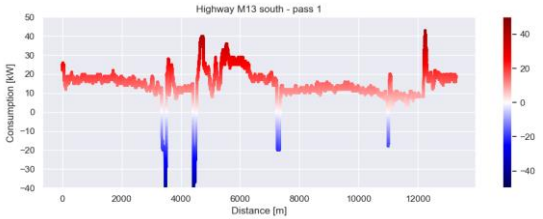

Highway M3 north - pass 4
Driving Speed [km/h]
Distance [m]
0
5000
10000
15000
20000

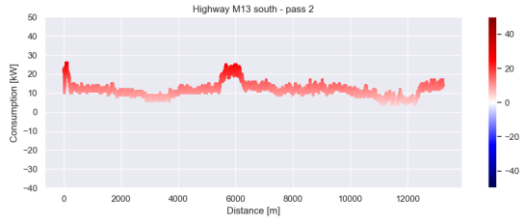

Highway M13 south - pass 1
Consumption [kW]
40
20
0
−20
−40

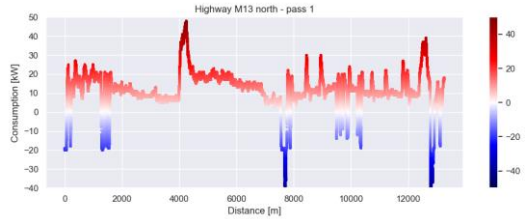

Highway M13 south - pass 2
Consumption [kW]
40
20
0
−20
−40

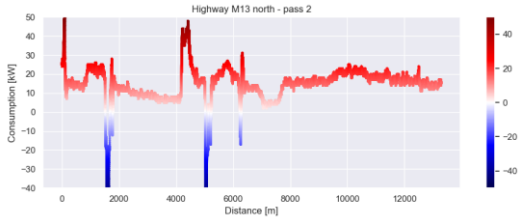

Highway M13 north - pass 1
Consumption [kW]
40
20
0
−20
−40

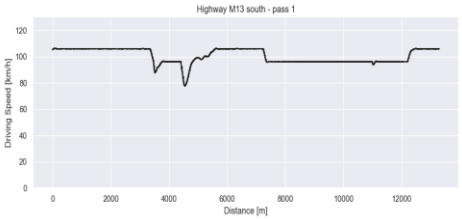

Highway M13 north - pass 2
Consumption [kW]
40
20
0
−20
−40

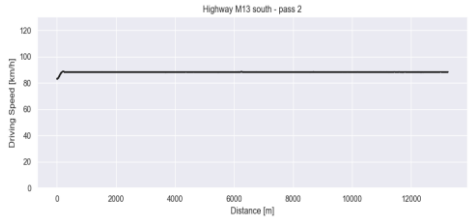

Highway M13 south - pass 1
Consumption [kW]
Distance [m]

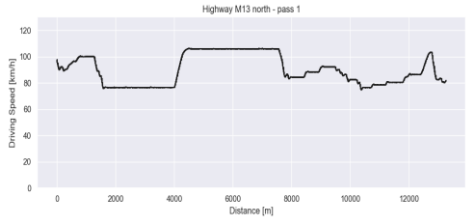

Highway M13 south - pass 2
Consumption [kW]
Distance [m]

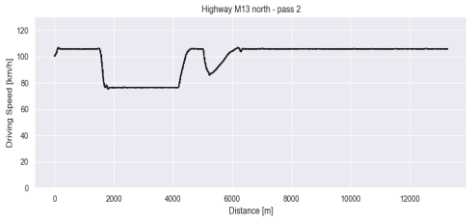

Highway M13 north - pass 1
Consumption [kW]
Distance [m]

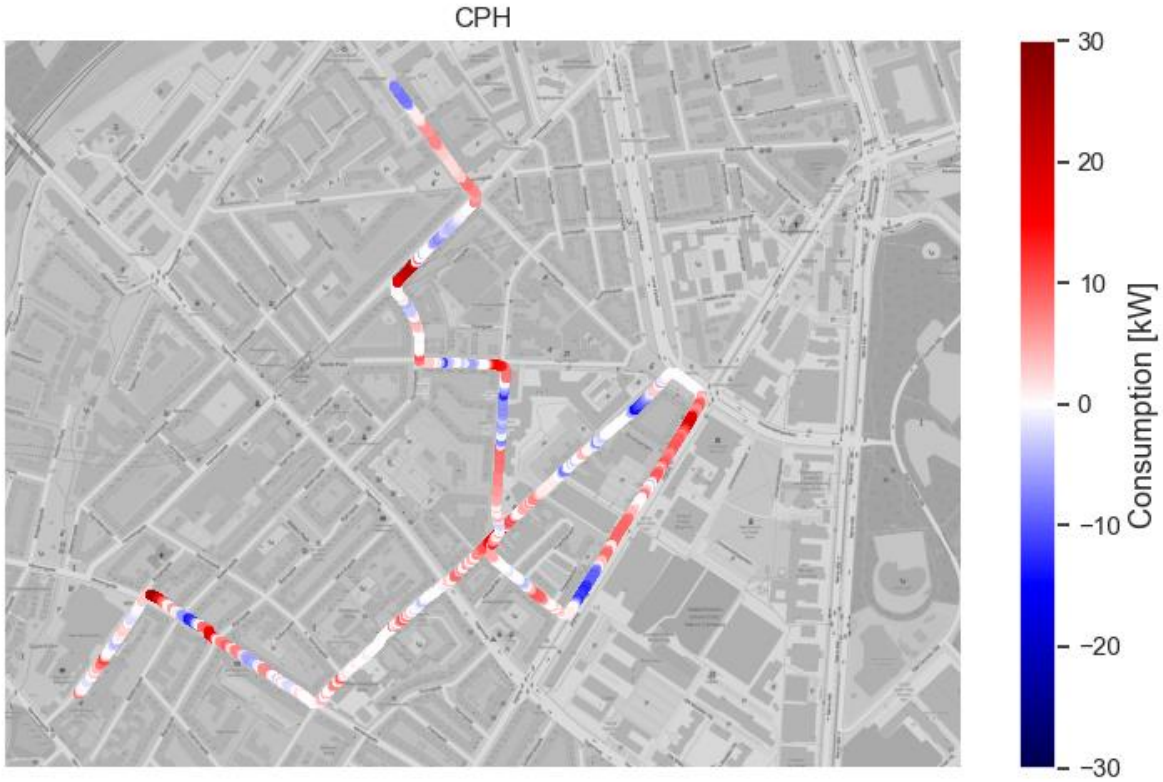

Highway M13 north - pass 2
Consumption [kW]
Distance [m]

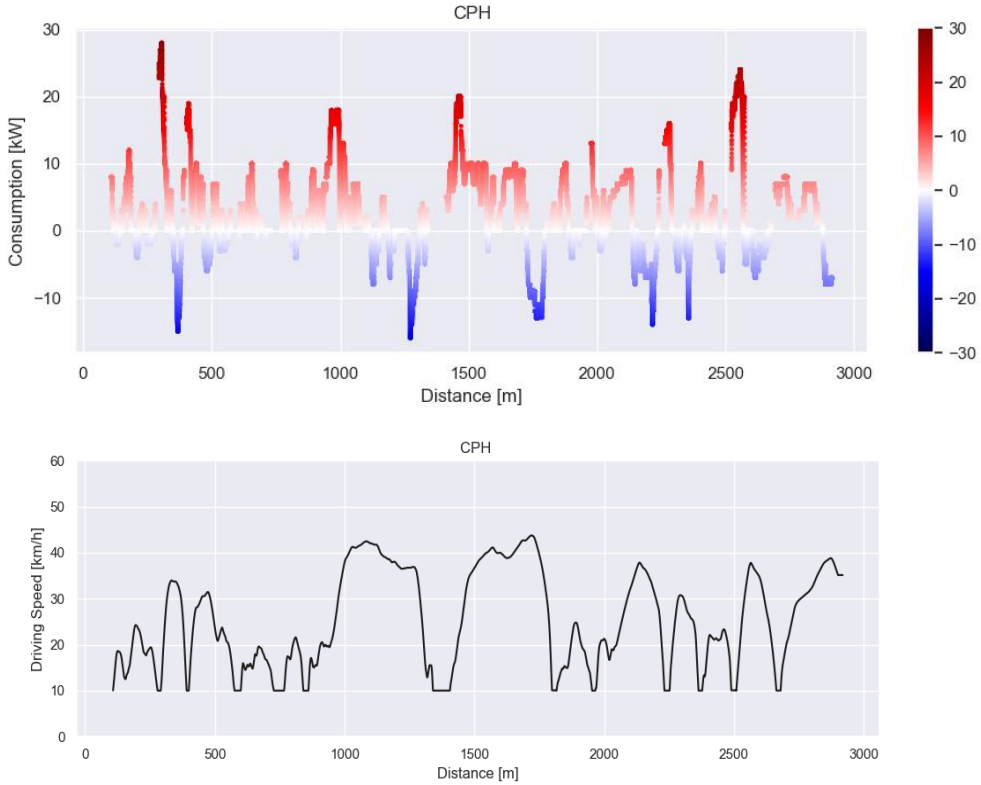

Highway M13 south - pass 1
Driving Speed [km/h]
Distance [m]


Highway M13 south - pass 2
Driving Speed [km/h]
Distance [m]

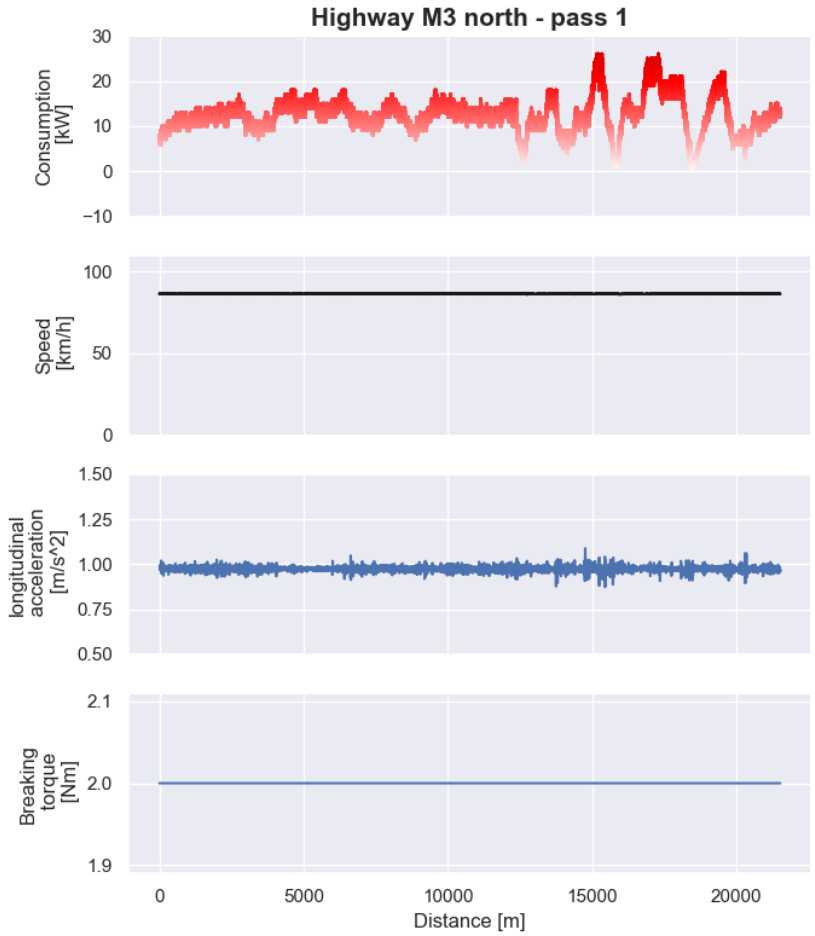

Highway M13 north - pass 1
Driving Speed [km/h]
Distance [m]

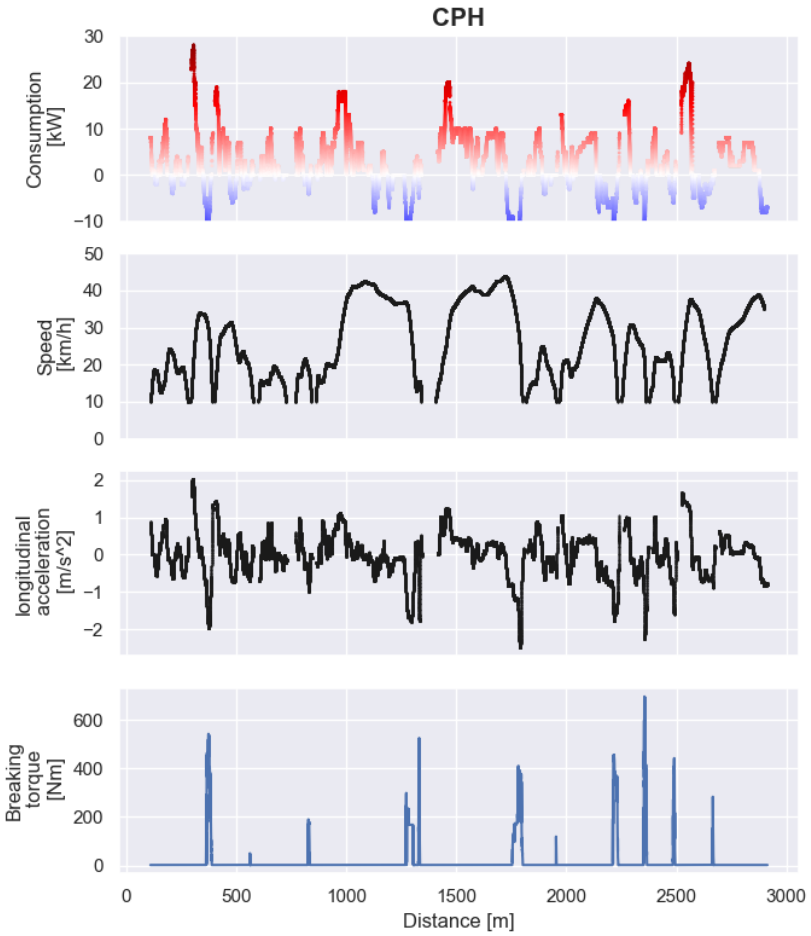

Highway M13 north - pass 2
Driving Speed [km/h]
Distance [m]


CPH
30
20
10
0
−10
−20
−30
Consumption [kW]

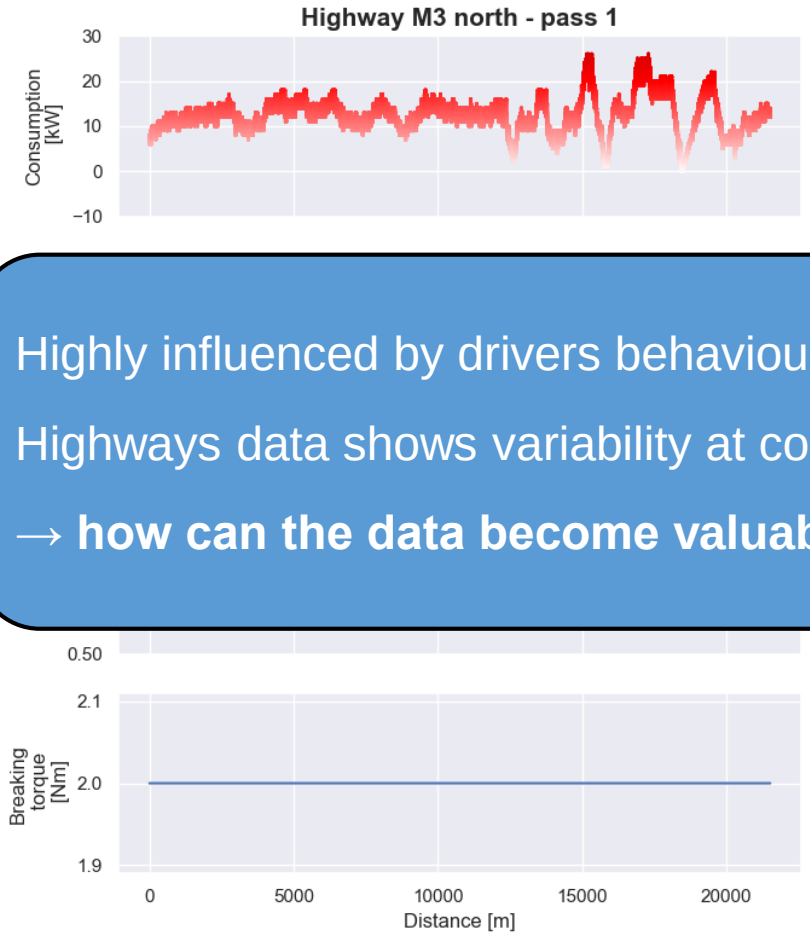

CPH
Consumption [kW]
Distance [m]
CPH
Driving Speed [km/h]
Distance [m]

Measured energy consumption





Measured energy consumption



Highly influenced by drivers behaviour, traffic flow in urban environment

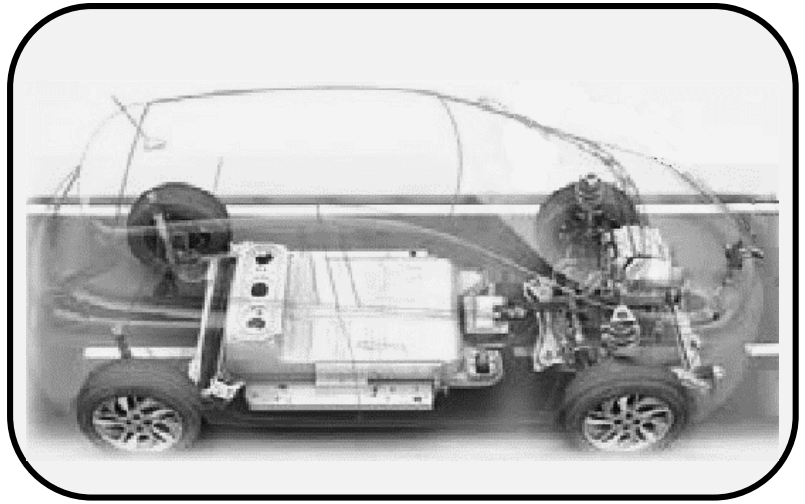
Highways data shows variability at constant speed

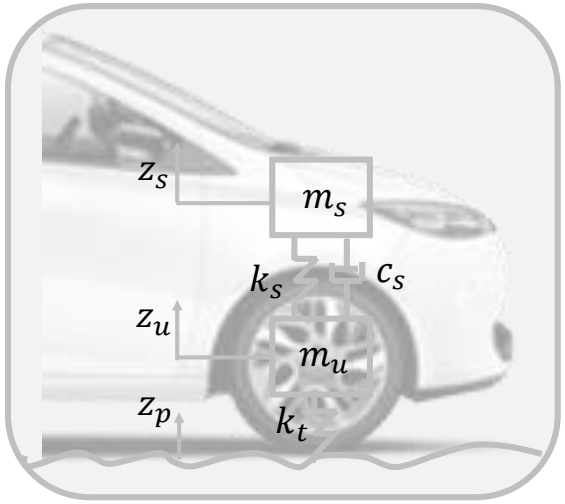
→ **how can the data become valuable information to road asset owners?**

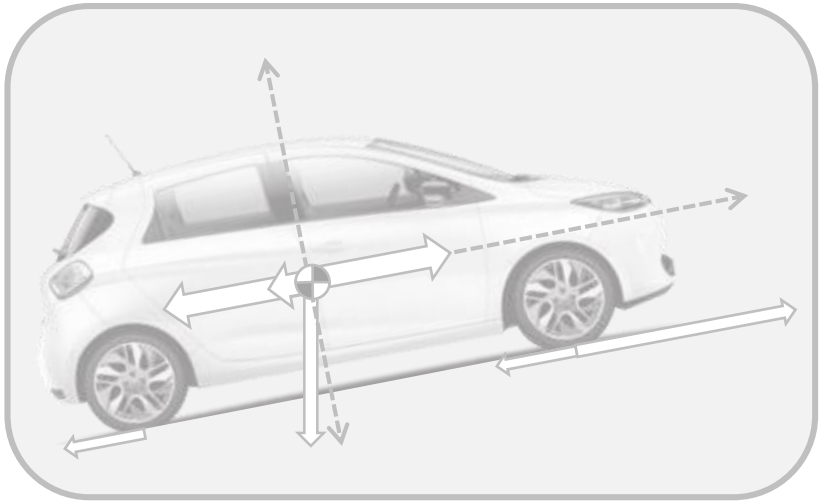
Analysis framework

- Highly influenced by drivers behaviour, traffic flow, road geometry in urban environment
- Highways data shows variability at constant speed

→ **how can the data become valuable information to road asset owners?**



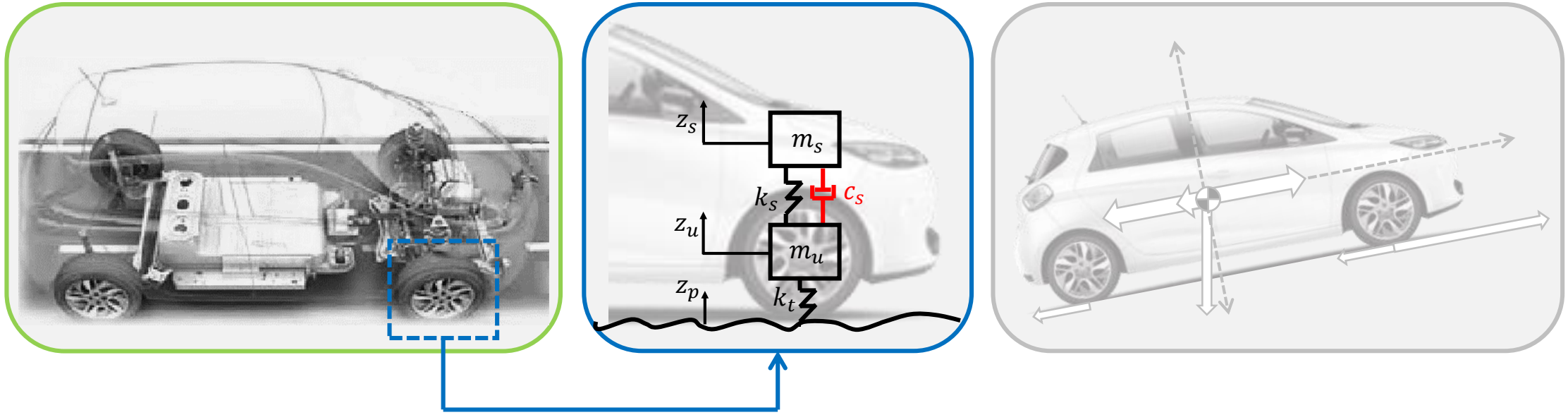




Analysis framework

- Energy lost in the suspension system

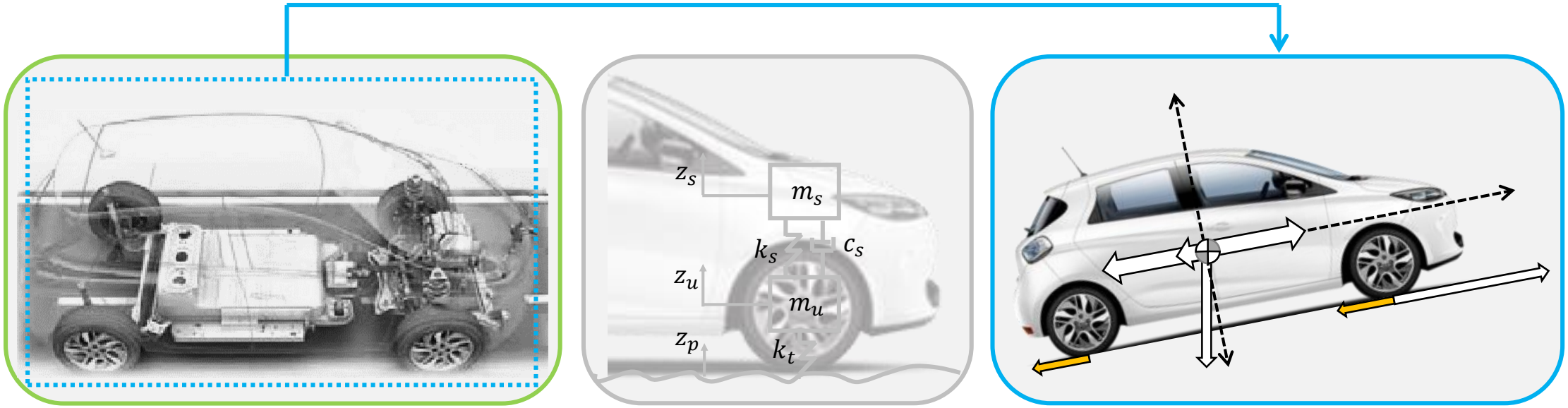
→ simulated energy loss in dashpot (heat generation)



Analysis framework

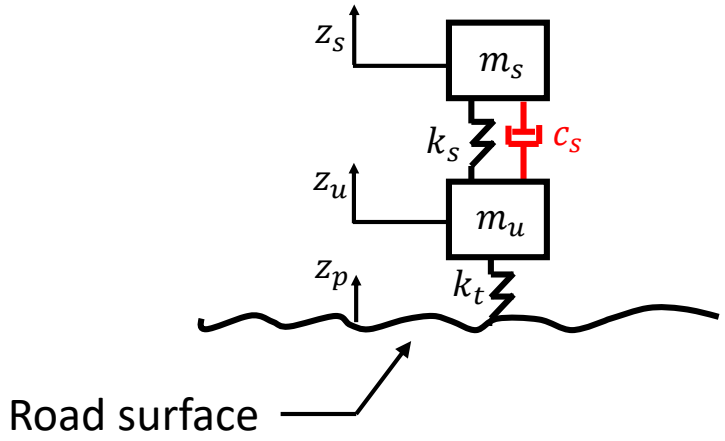
- Longitudinal dynamics of the vehicle

→ Isolate the force from rolling resistance from the total horizontal force

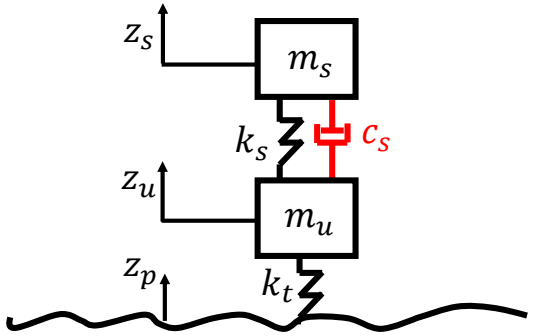


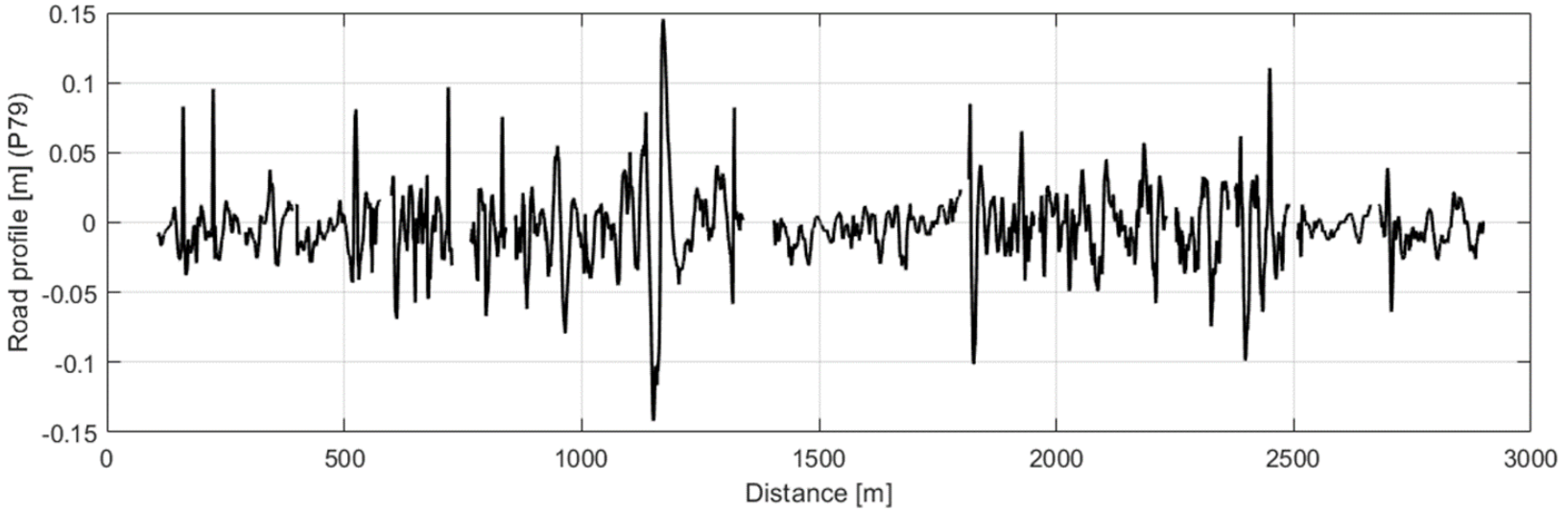
Modelling of energy loss

- Simulate the dissipated energy in the suspension system

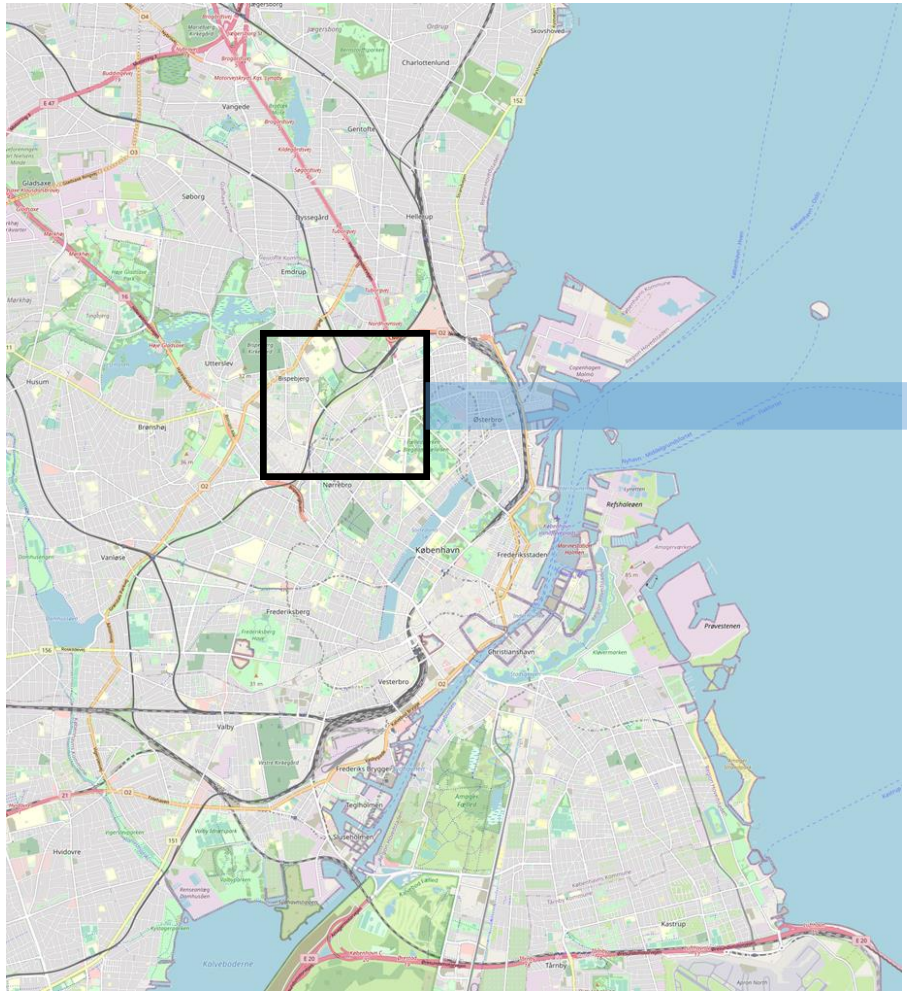


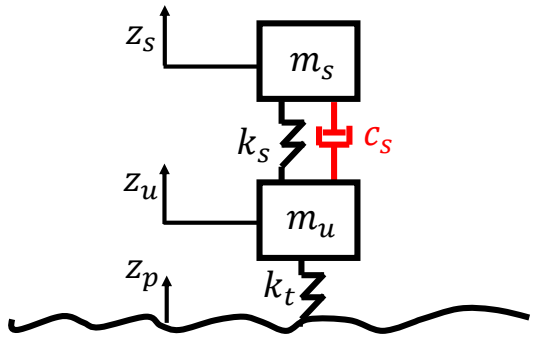
Modelling of energy loss



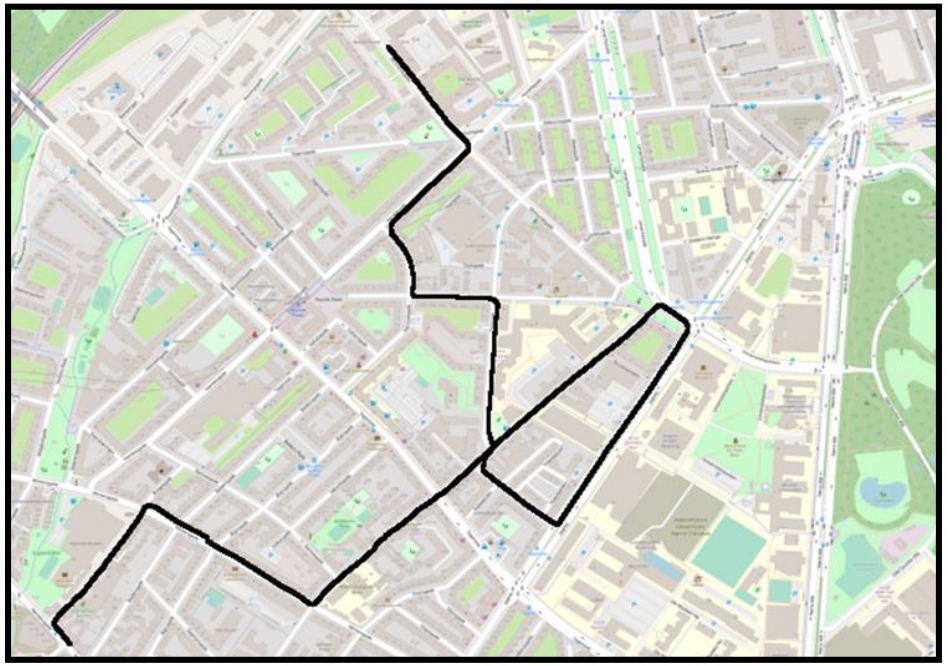


Modelling of energy loss

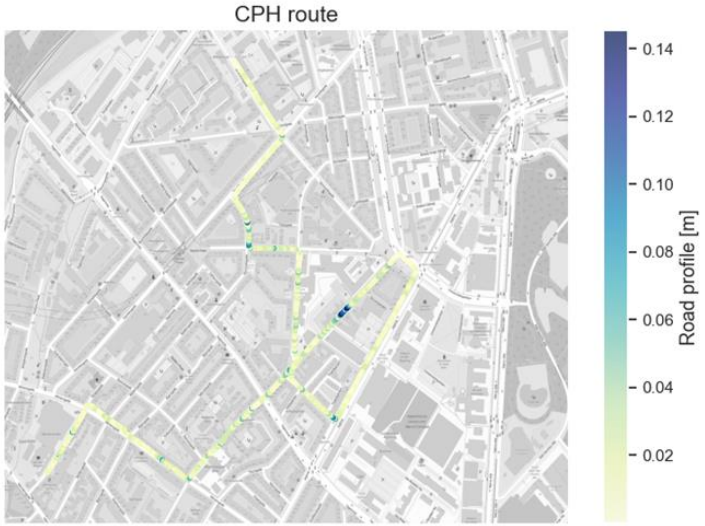


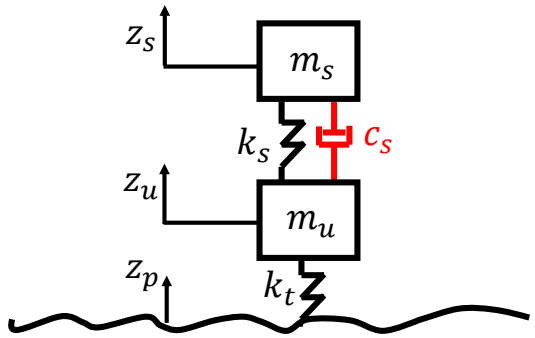


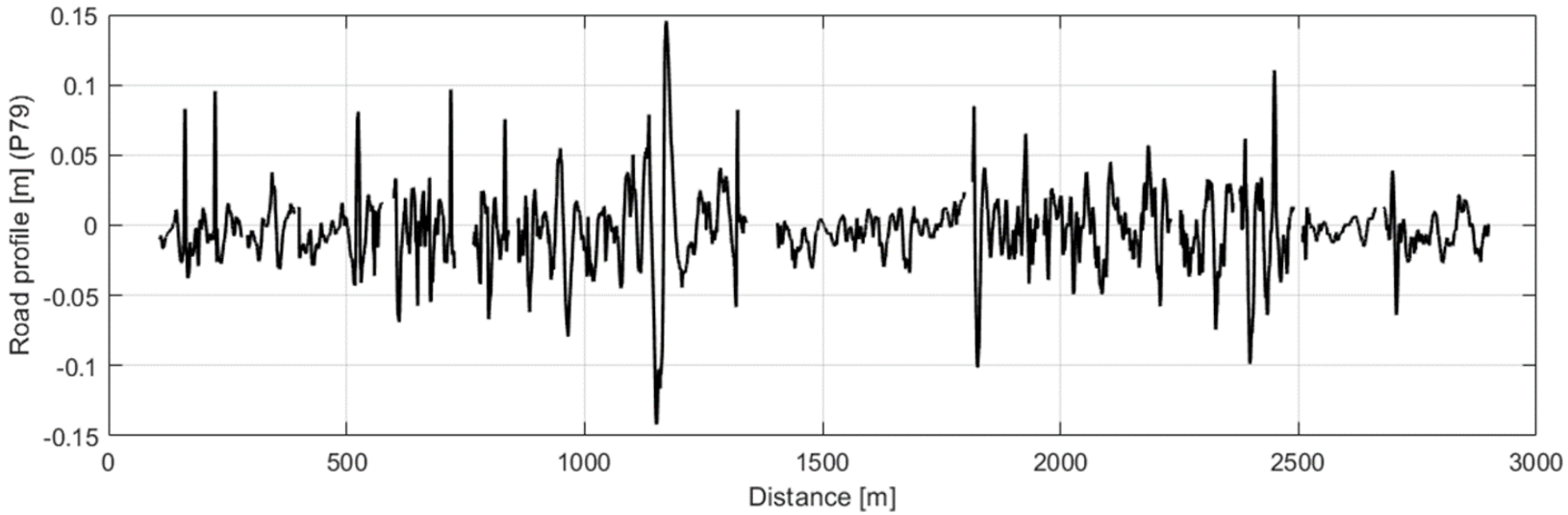
CPH route



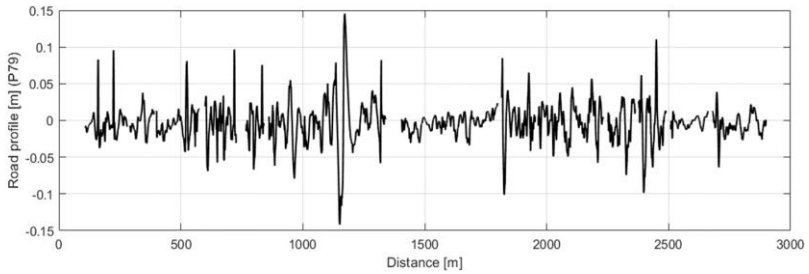
Modelling of energy loss

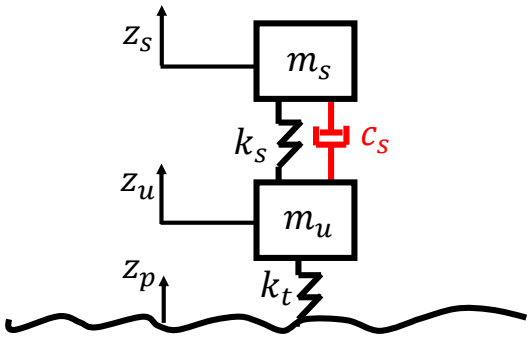


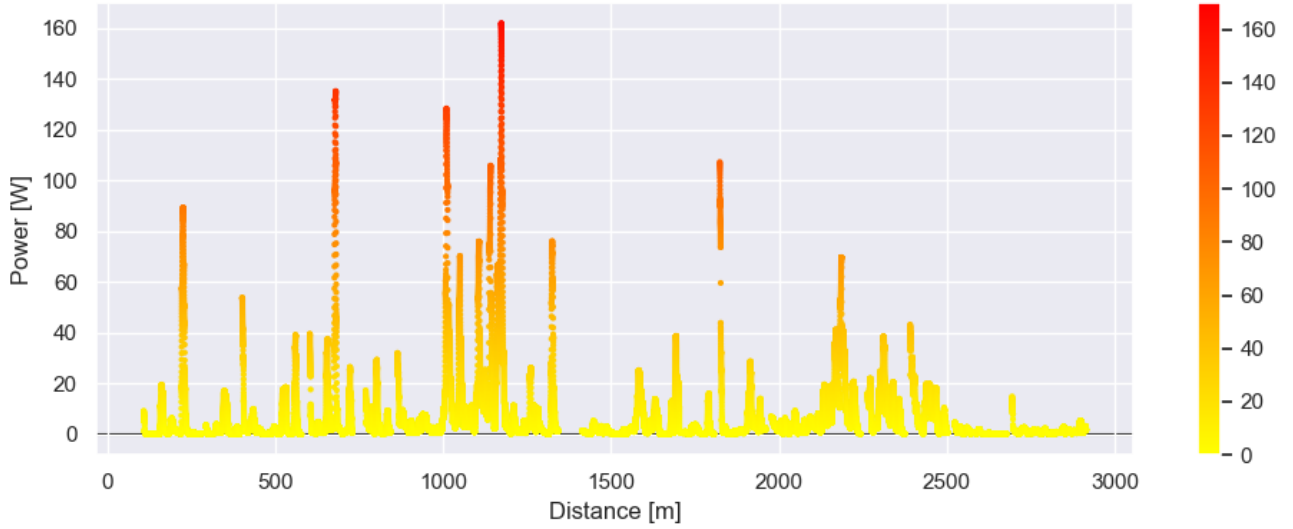




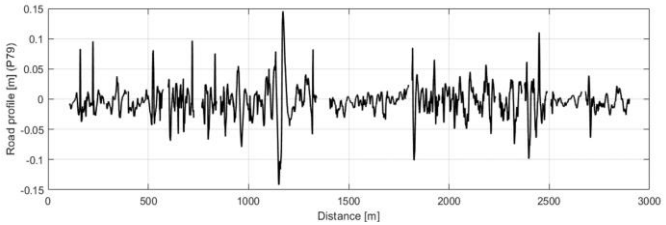
Modelling of energy loss

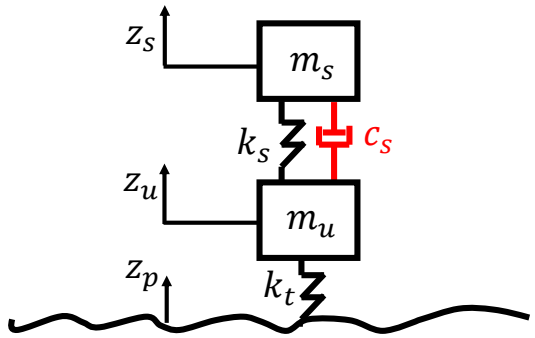


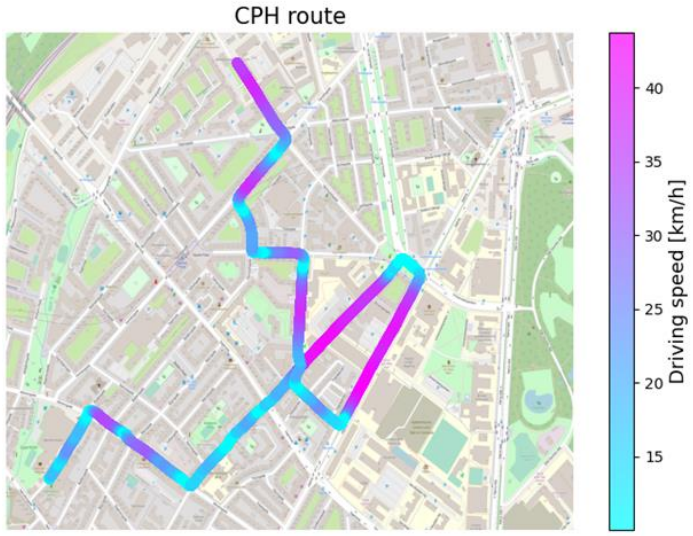


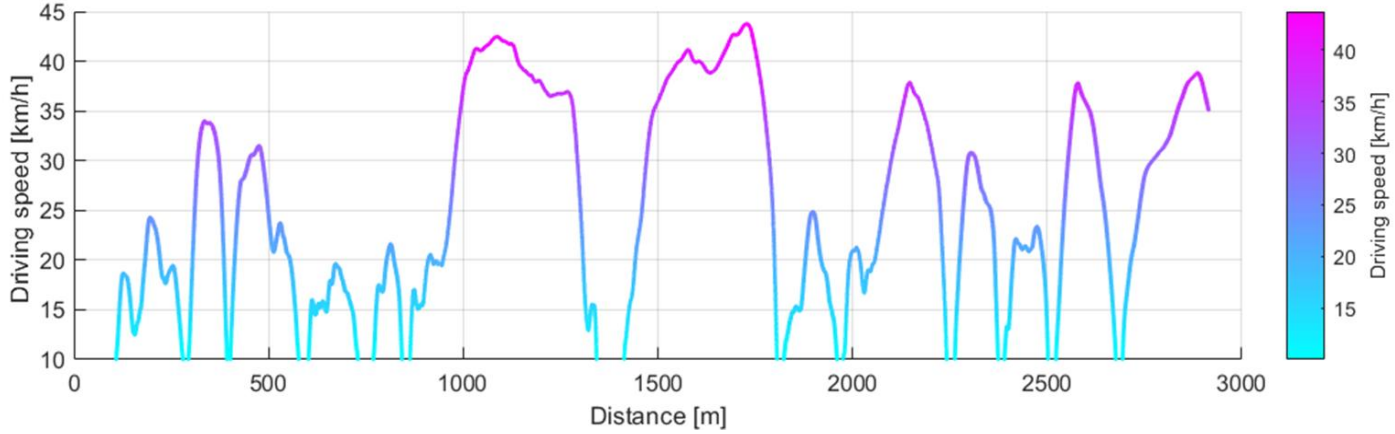


Modelling of energy loss

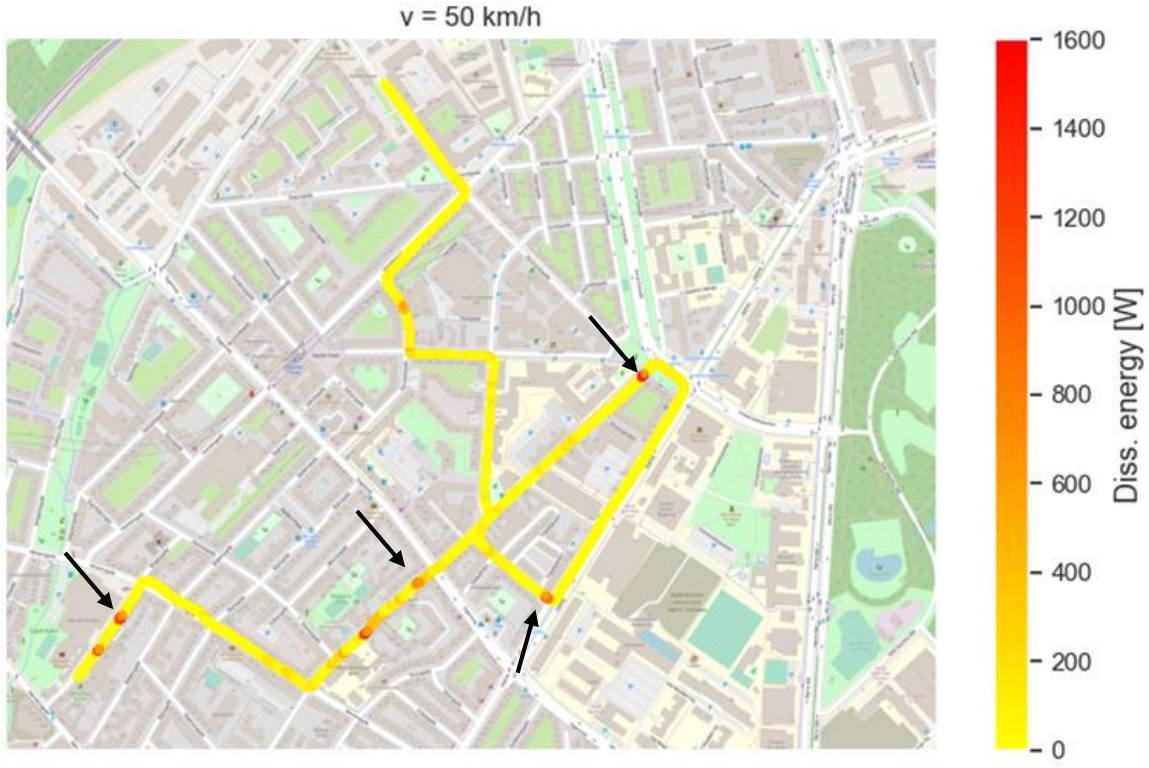


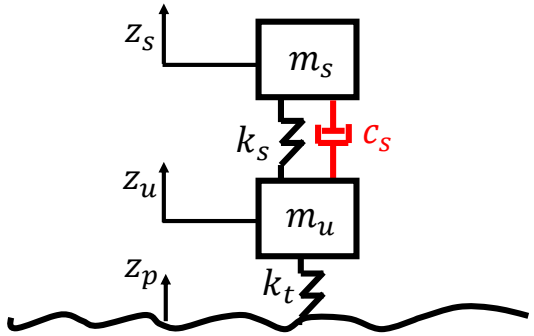


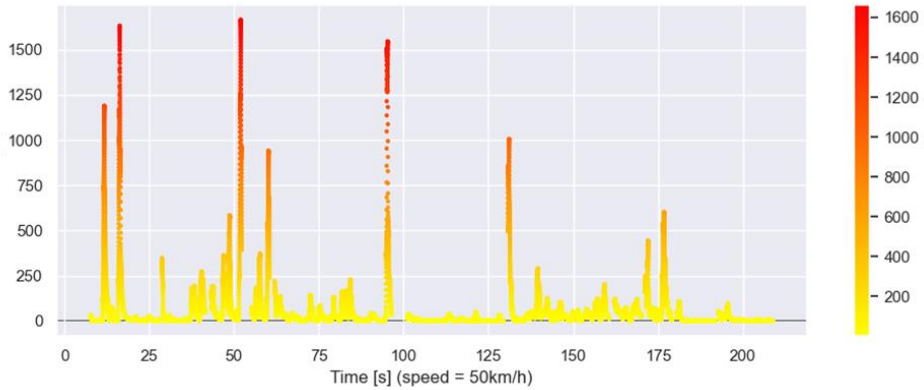




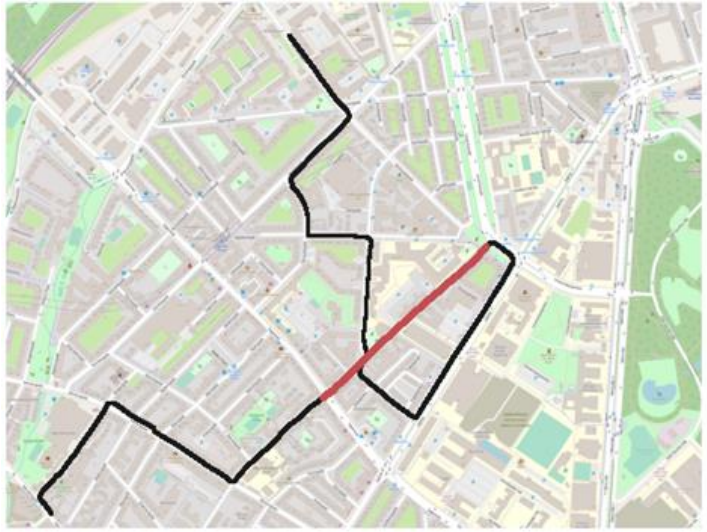
Modelling of energy loss







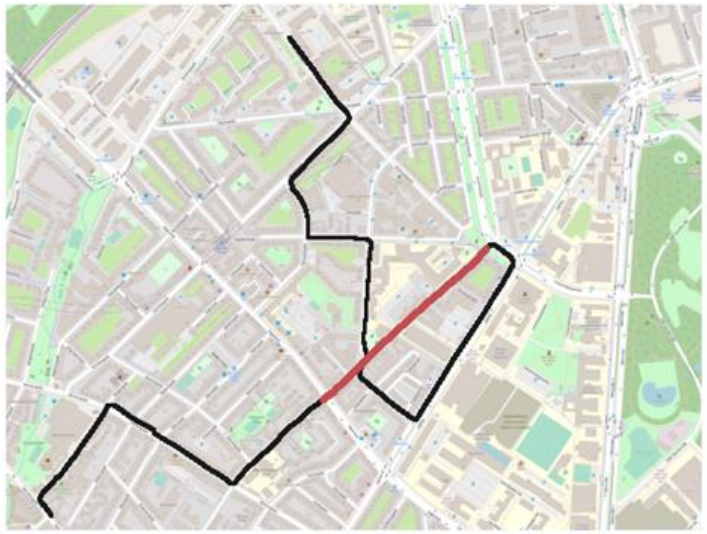
Modelling of energy loss



What features on the road causes spikes in power?

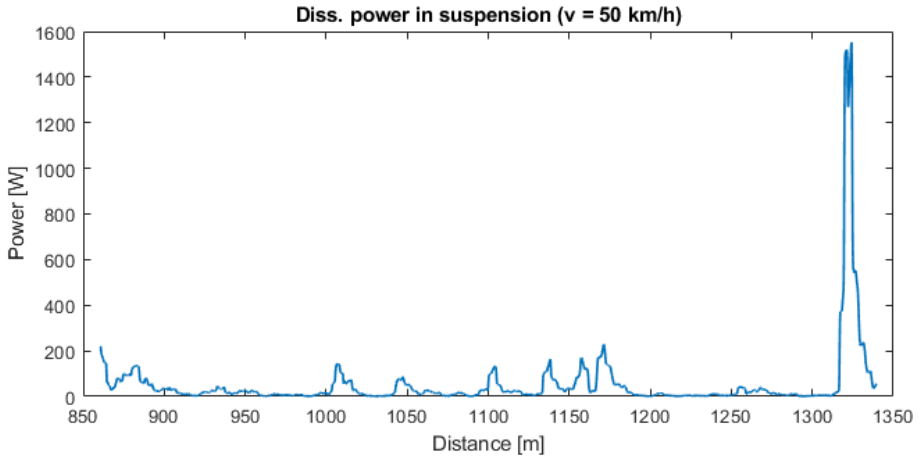
- Zoom in on a section

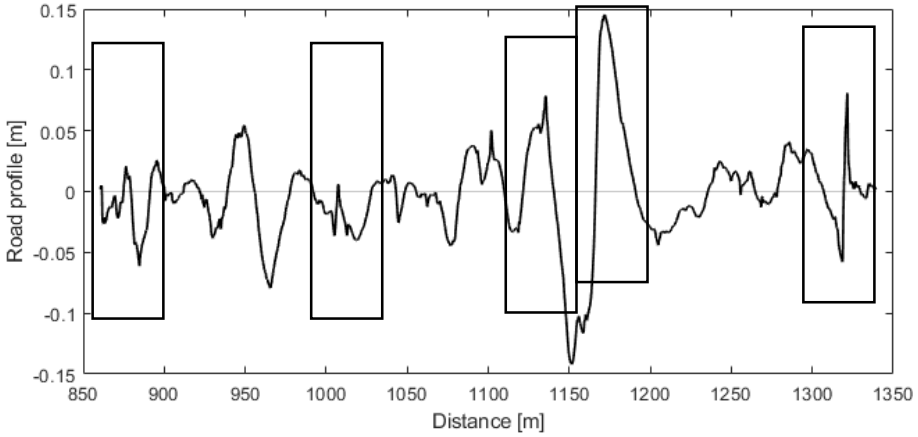
Modelling of energy loss



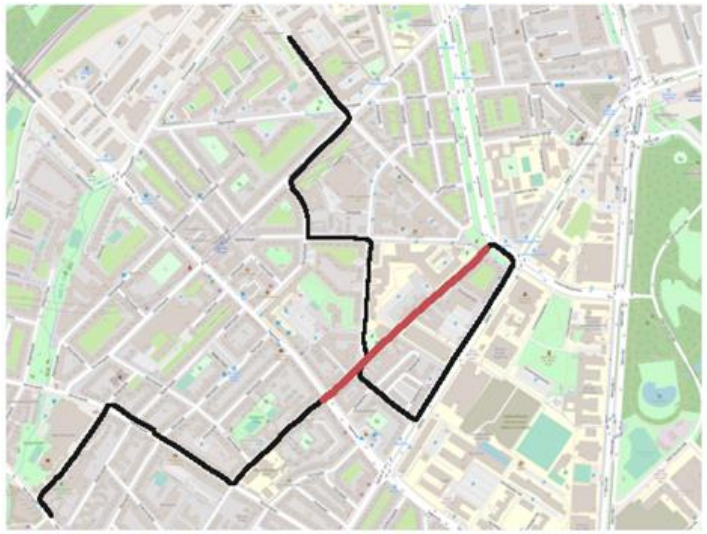
What features on the road causes spikes in power?

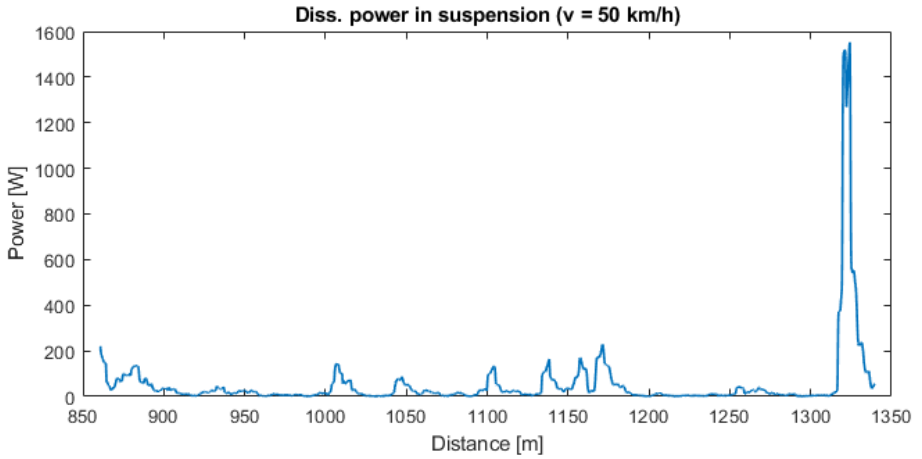
- Zoom in on a section
- Not all road features influence the dissipated power

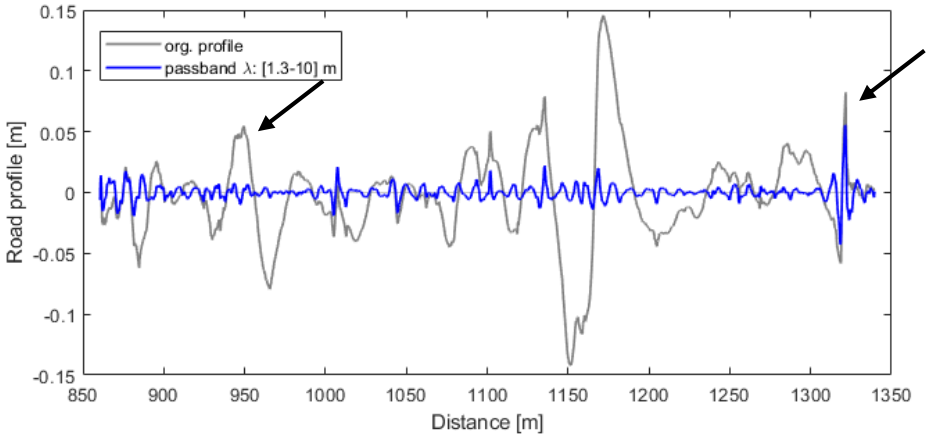




Modelling of energy loss







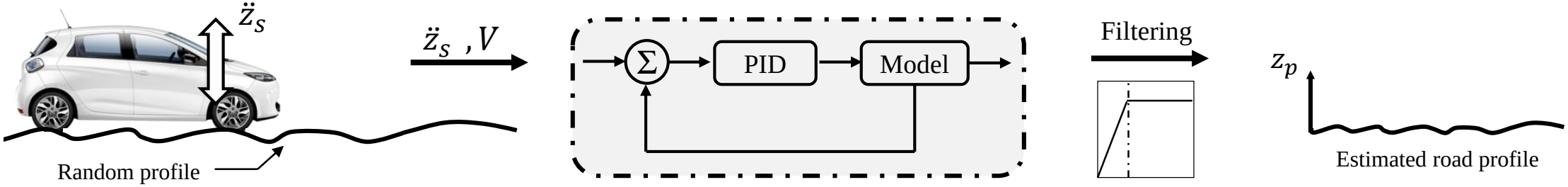
What features on the road causes spikes in power?

- Zoom in on a section
- Not all road features influence the dissipated power
- Relevant wavelengths: λ:[1.3 m –10 m]

Modelling of energy loss

Future work

- Add damping in tire
- Combine with the road profile inversion
- Investigate more data!

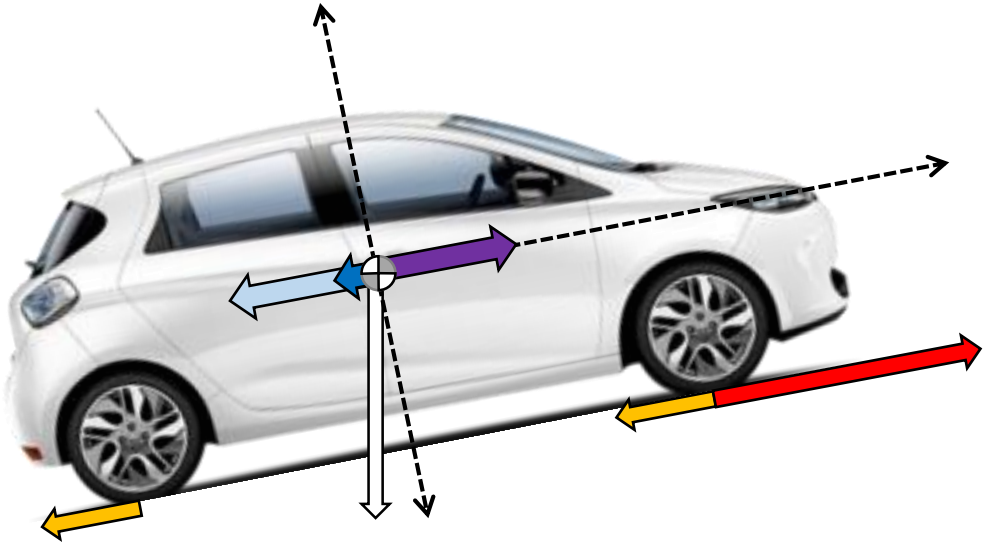


Isolating rolling resistance

- Newton's second law for the longitudinal dynamics of the vehicle

$$F_t = F_{hc} + F_{aero} + F_i + F_{rr}$$

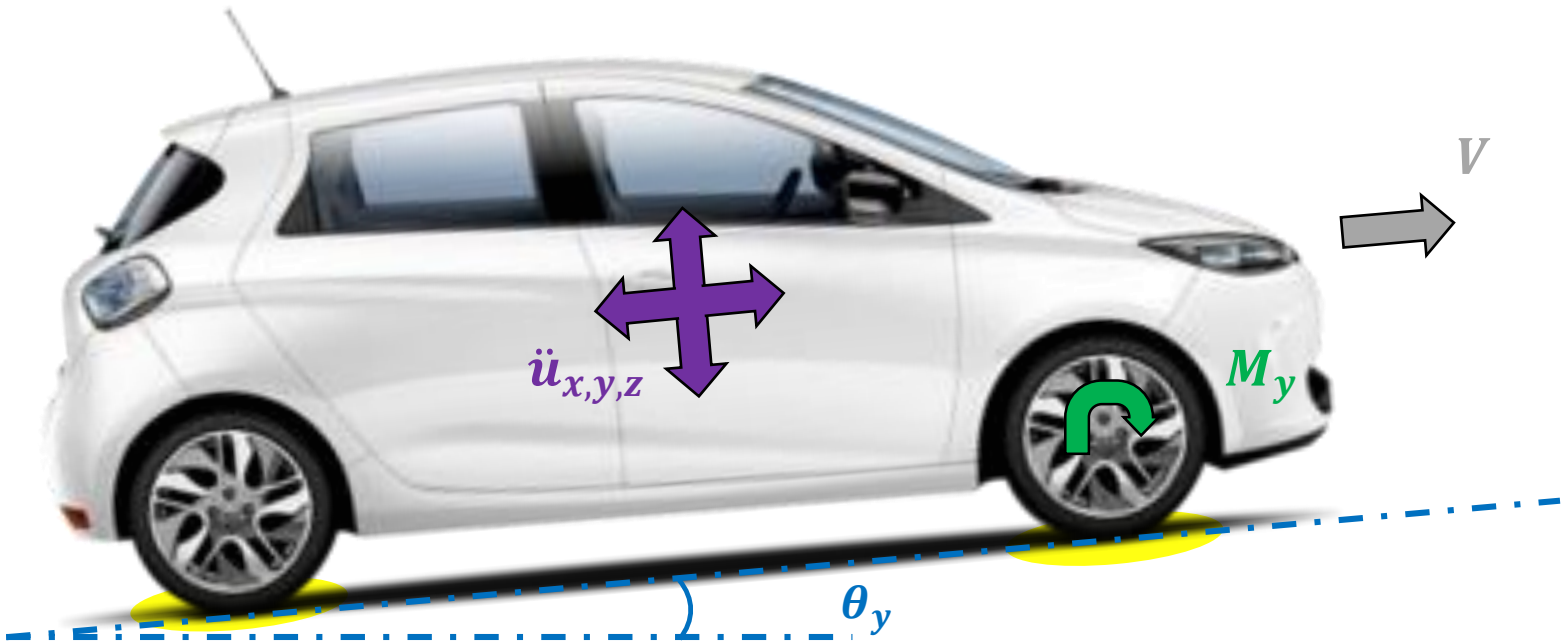
- Traction force, $\boldsymbol{F_t}$, generated by the electric motor, must overcome the sum of all resistive forces
  - the hill climbing force, $\boldsymbol{F_{hc}}$ (which is the component of the vehicle weight, $\boldsymbol{F_g}$, that acts along the slope);
  - the aerodynamic drag, F_{aero};
  - the inertial force, $\boldsymbol{F_i}$, and;
  - the rolling resistance force of the wheels, F_{rr}.



Isolating rolling resistance

Sensors and known parameters:

- Wheel torque, M_y
- 3-axis accelerations, $\ddot{u}_{x,y,z}$
- Velocity of vehicle, V
- Road slope, θ
- Tire pressure
- Wheel rpm
- Car metadata
- Weather



Isolating rolling resistance

$$P_t = F_t V$$

$$F_t^p \begin{cases} F_{hc} = (m_{car} + m_p) g \cdot \sin(\theta) \\ F_{aero} = \text{sign}(V + V_{wind}) \frac{1}{2} \rho A C_d (V + V_{wind})^2 \\ F_i = C_{i0} (m_{car} + m_p) \ddot{u}_x \\ F_{rr} = \text{sign}(V) (m_{car} + m_p) g \cdot \cos(\theta) \cdot C_{rr} \end{cases}$$

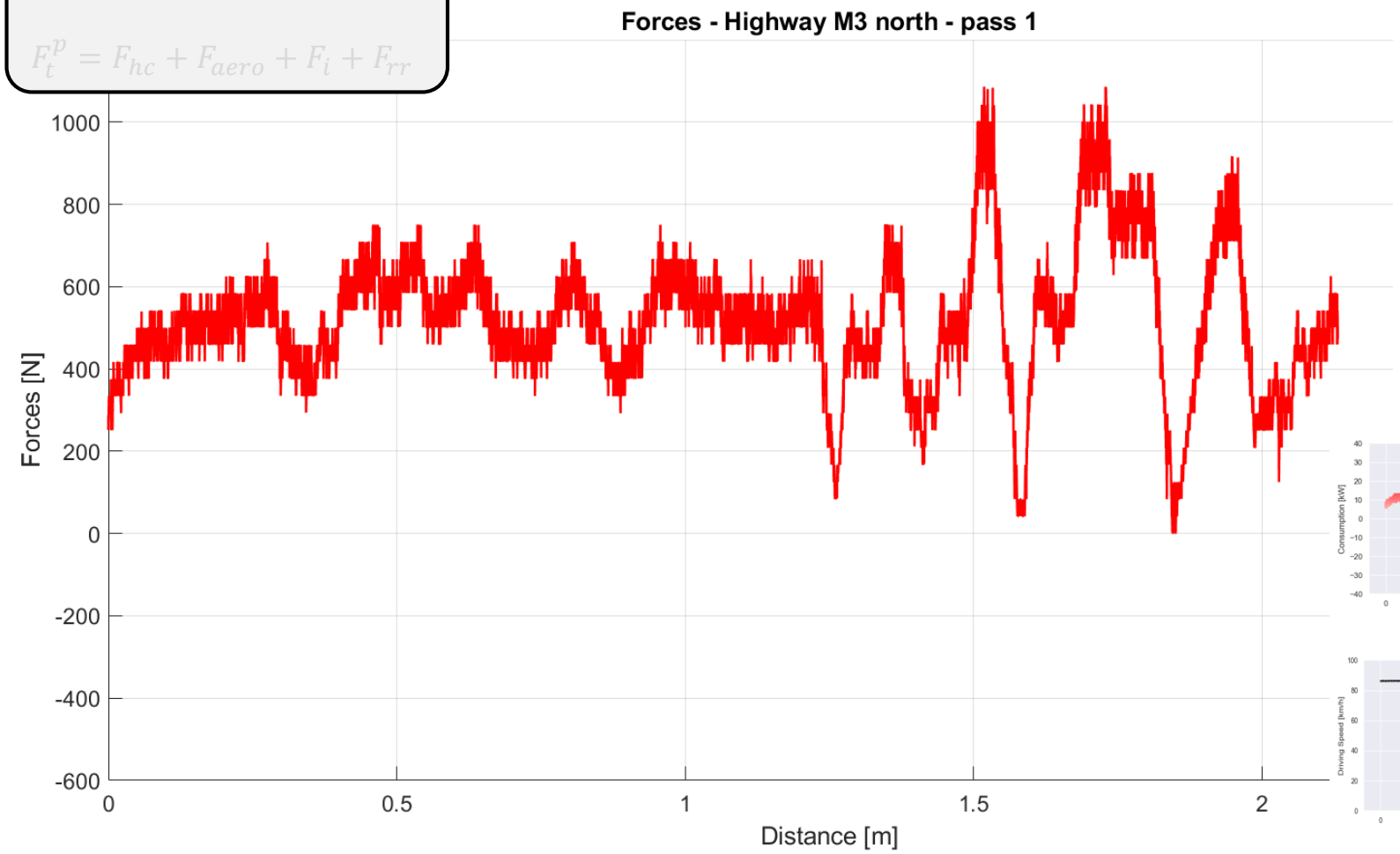
Rolling inertia coefficient	C_{i0}	–	0.05
Rolling resistance coefficient	C_{rr}	–	$0.01\left(\frac{1+V}{100}\right)$
Air drag coefficient	C_d	–	0.29
Density of air [kg/m3]	ρ	kg/m^3	1.225
Gravitational acceleration	g	m/s^2	9.81
Velocity of wind	V_{wind}	m/s	0
Cross-sectional area of car	A	m^2	2.33
Mass of car	m_{car}	kg	1966
Mass of passengers	m_p	kg	80

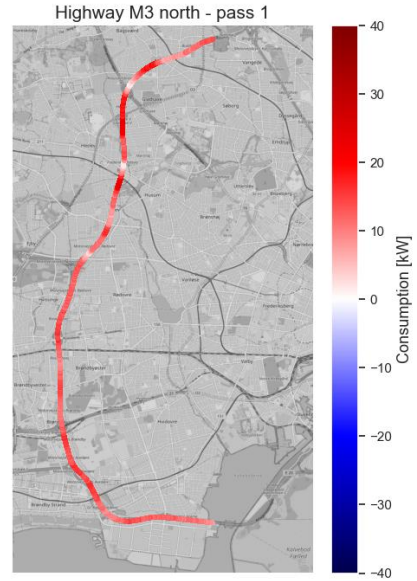
C_{rr} function of tire pressure, temperature, the road **surface type**, **the road conditions**, the vehicle tire type and the velocity

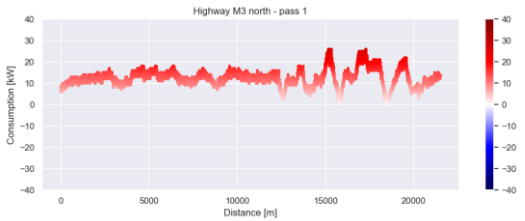
Isolating rolling resistance

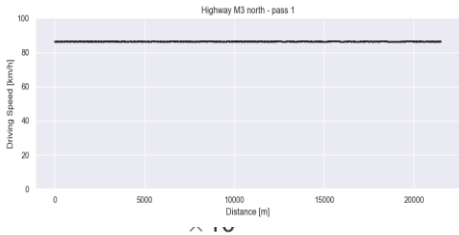
$$F_t^m = P_t / V$$

$$F_t^p = F_{hc} + F_{aero} + F_i + F_{rr}$$





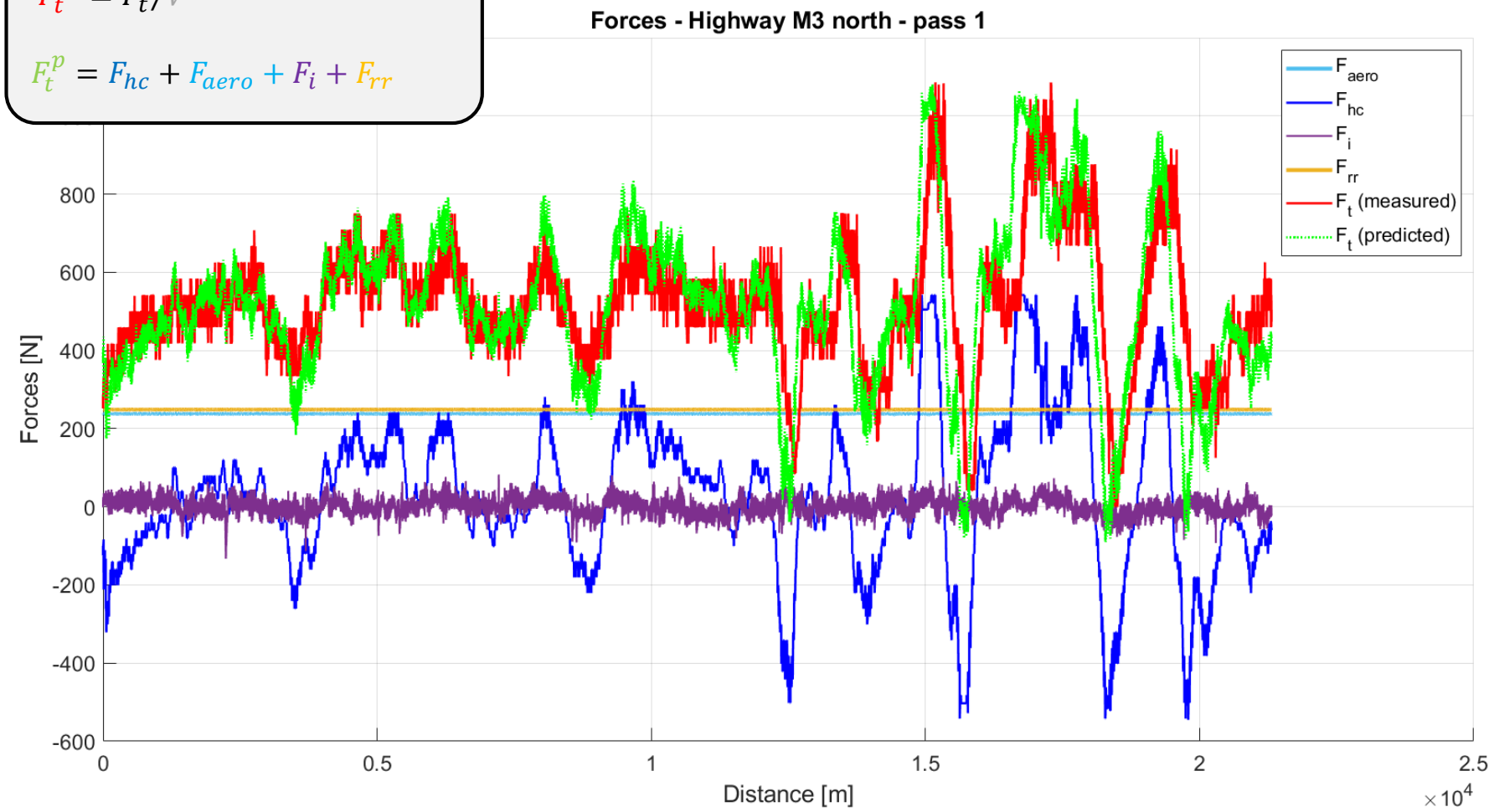




Isolating rolling resistance

$$F_t^m = P_t / V$$

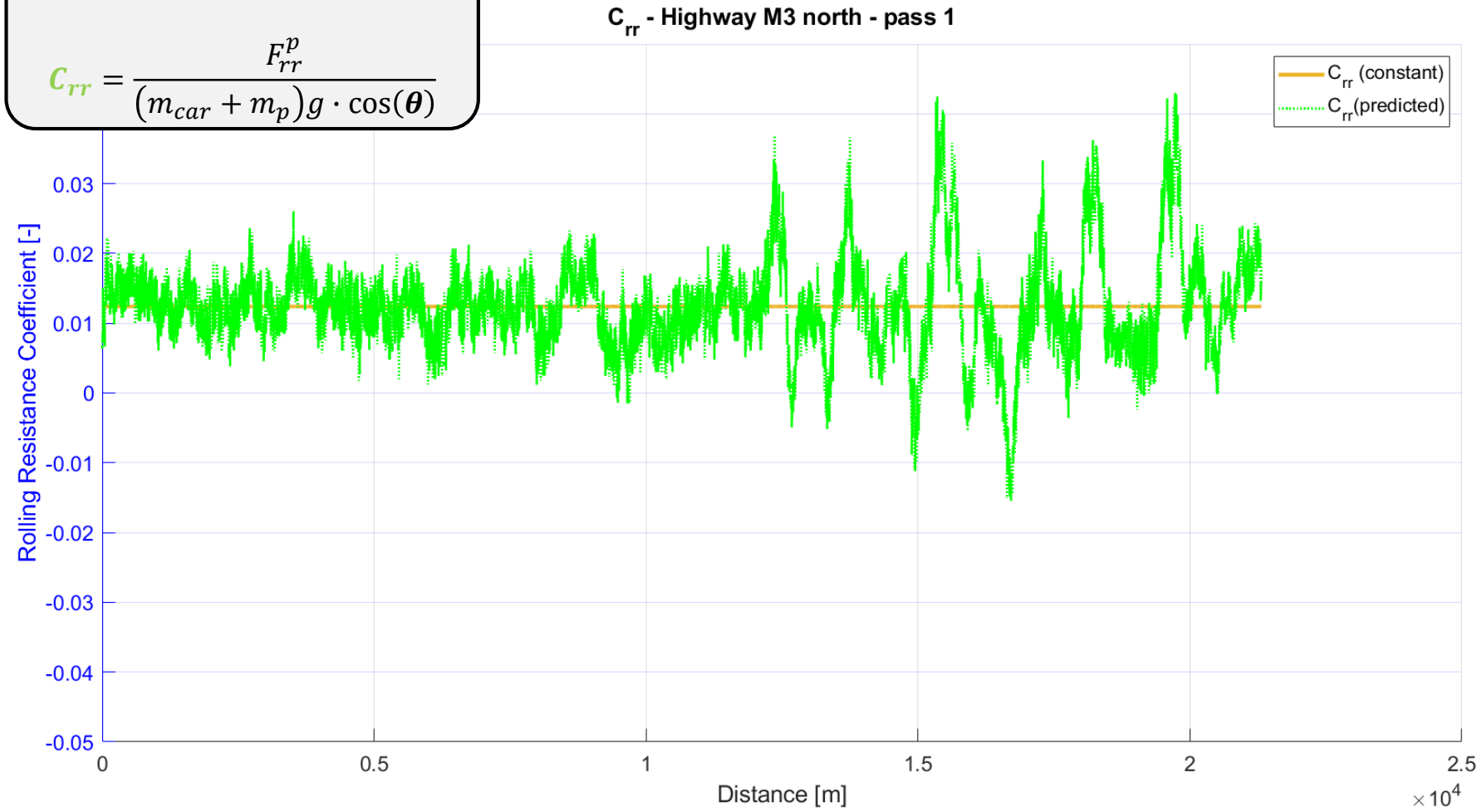
$$F_t^p = F_{hc} + F_{aero} + F_i + F_{rr}$$



Isolating rolling resistance

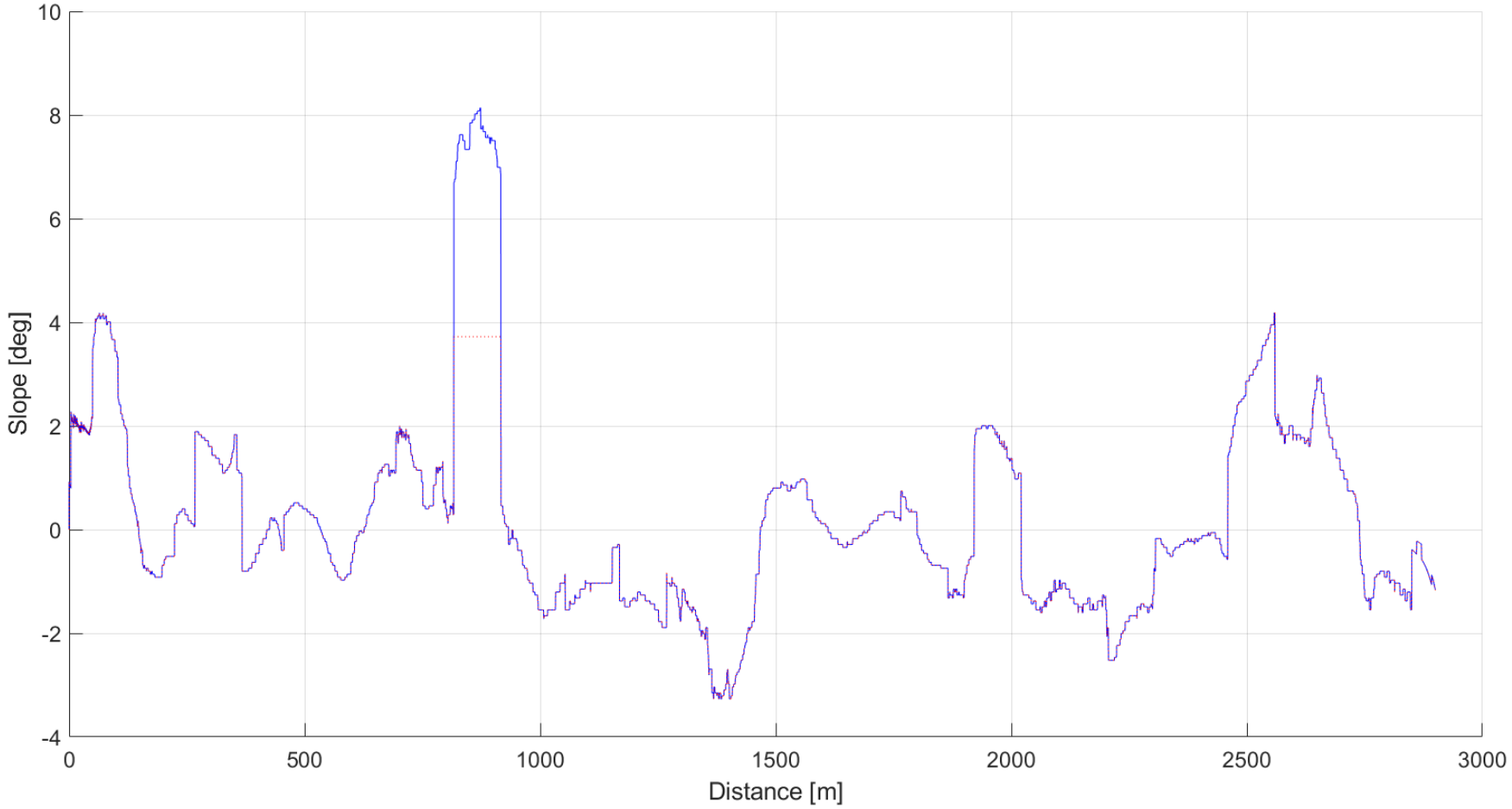
$$F_{rr}^{p} = F_{t}^{m} - (F_{hc} + F_{aero} + F_{i})$$

$$C_{rr} = \frac{F_{rr}^{p}}{(m_{car} + m_{p})g \cdot \cos(\boldsymbol{\theta})}$$

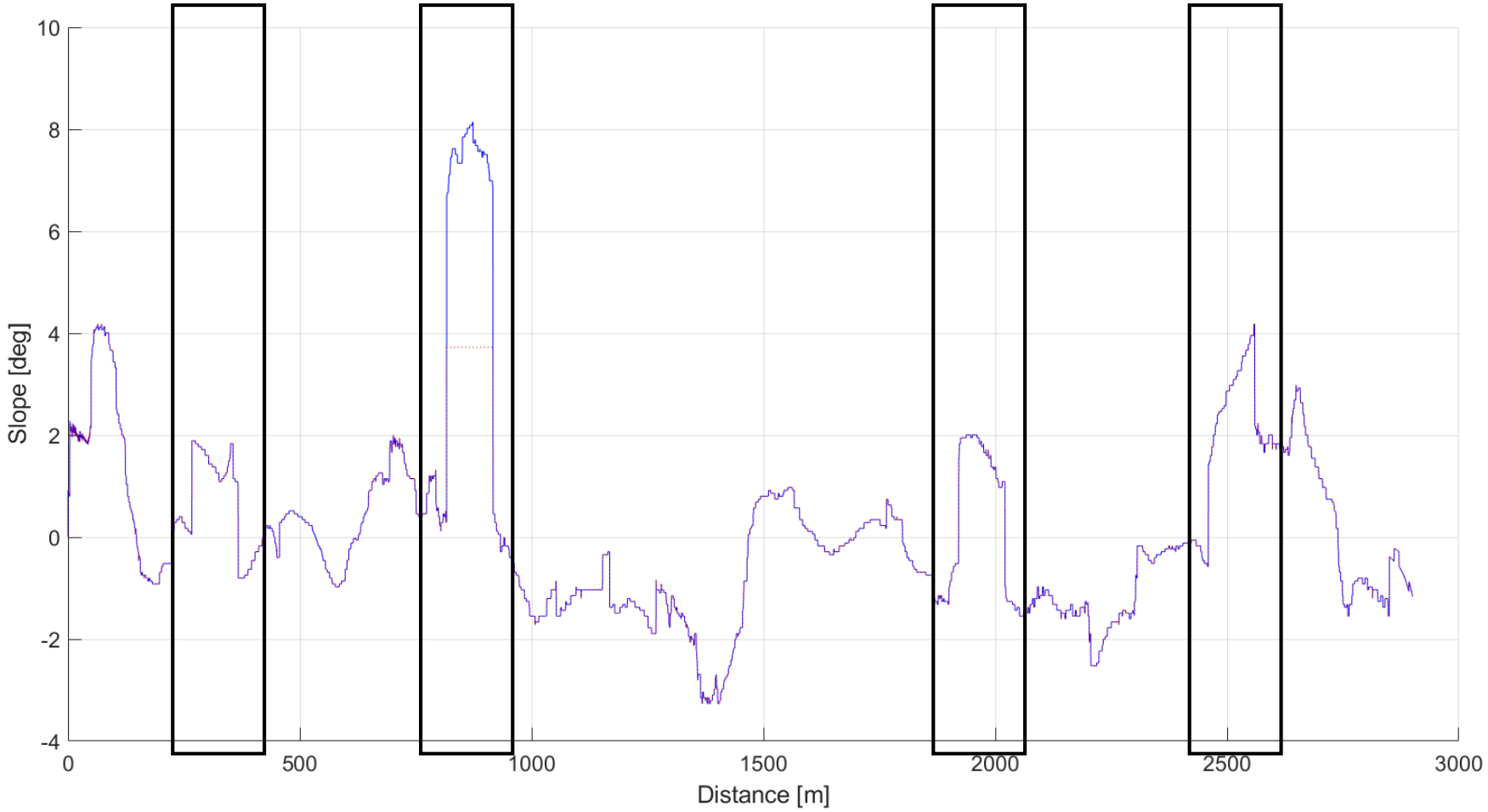


Isolating rolling resistance

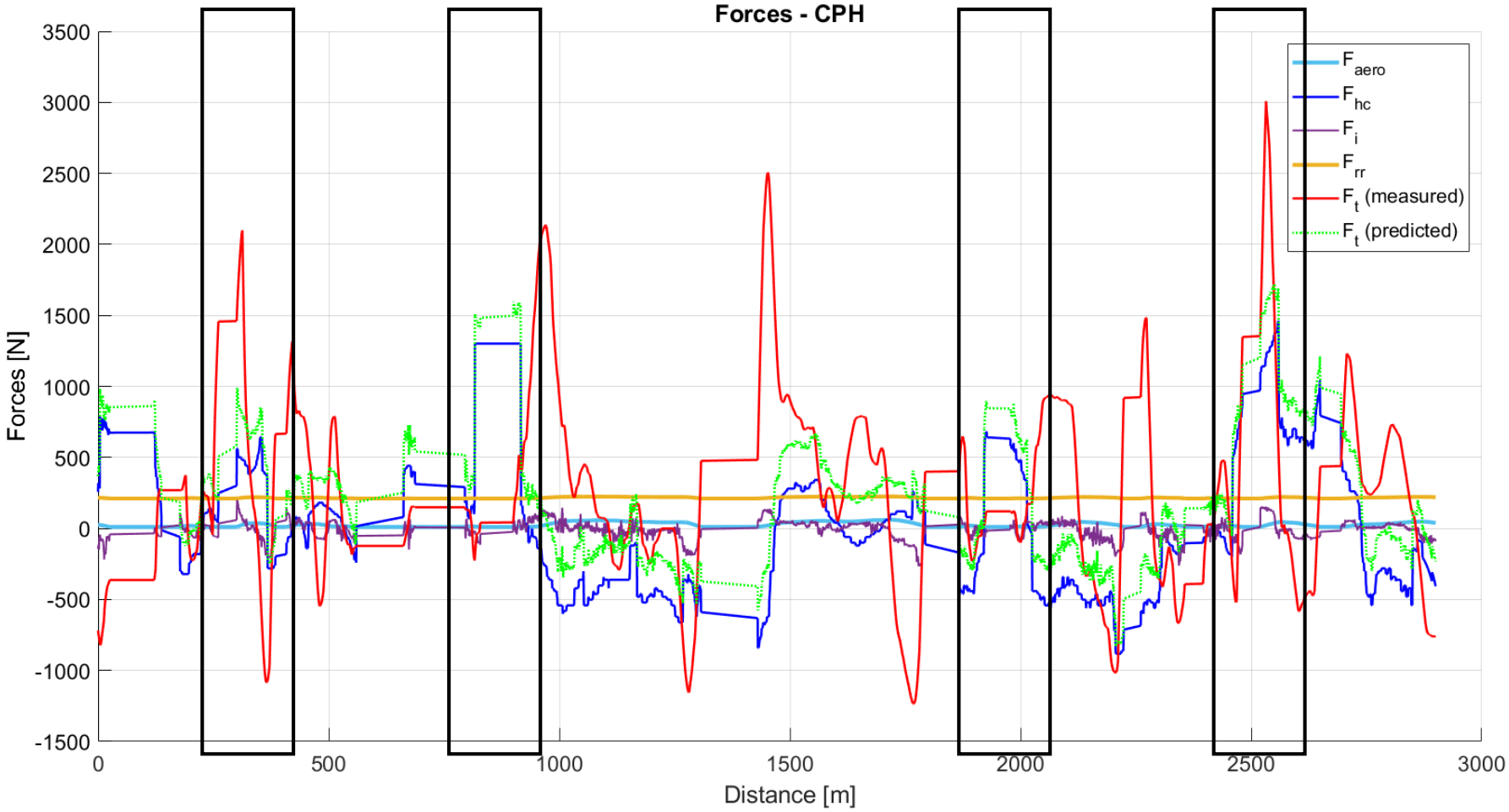
Isolating rolling resistance



Isolating rolling resistance



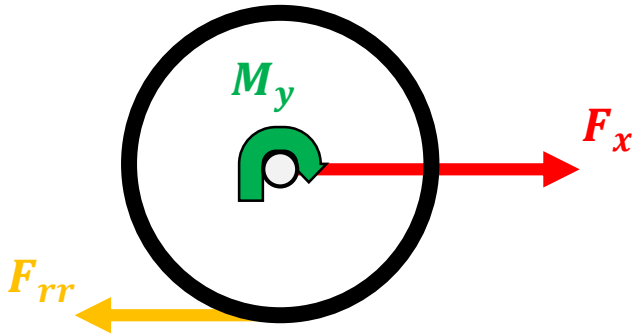
Isolating rolling resistance



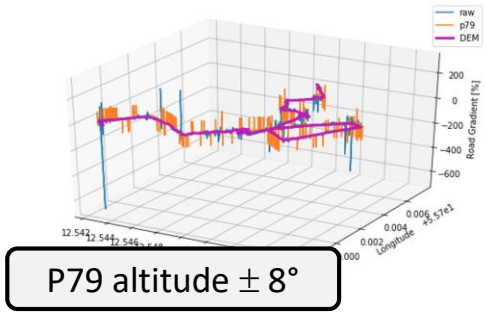
Isolating rolling resistance

Future work

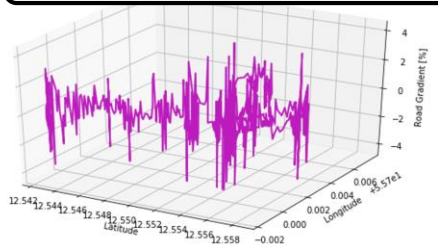
- Modification and improvement of physical model
- Prediction of C_{rr} / F_{rr}
  - analyse data at constant speed
  - different road surface types and conditions
  - different weather conditions
- Improve data quality:
  - Slope – implement altitude data from other sources
  - Weather – implement data from weather stations
- Analyse more data



$$F_{rr} = \frac{M_y + m \cdot r_t^2 \cdot \dot{\omega}\,(\mathrm{rpm, t})}{r_t} - F_x$$



P79 altitude ± 8°



Danmarks højdemodel ± 3°