**Hochschule Karlsruhe**
University of
Applied Sciences

Institut für
**Energieeffiziente Mobilität**

# Approach to a Holistic Modelling of Cycling Dynamics

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# Yannick Rauch M.Sc.

**Education and Experience:**

- Master‘s Degree in Automotive Systems Engineering from Karlsruhe University of Applied Sciences
- Research Assistant at Institute of Energy Efficient Mobility

**Research Interests:**

- Modelling and Simulation of Cycling
- Energy Management Systems for Electric Vehicles
- Energy Prediction and Management for E-Bikes/Pedelecs

# Motivation and Use-Cases

**Promoting Cycling as Part of New Mobility Strategies**

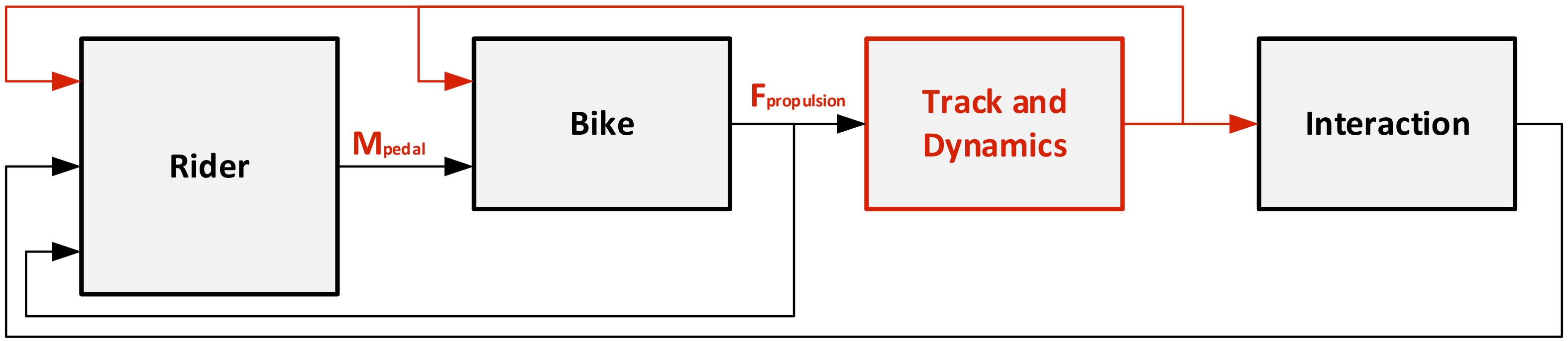
<u>Potential Use-Cases:</u>
A-priori simulation based quality evaluation of cycling infrastructure
→ Focusing on physical aspects with relevance to the cyclist

*Usage of Model-Based Methods*

**(Increased) Technologisation of Cycling → E-Bikes/Pedelcs**

<u>Potential Use-Cases:</u>
- model-based development of components or functions
- increased energy demand prediction for E-Bikes

**Stand-Alone Simulation of the Cycling Process**



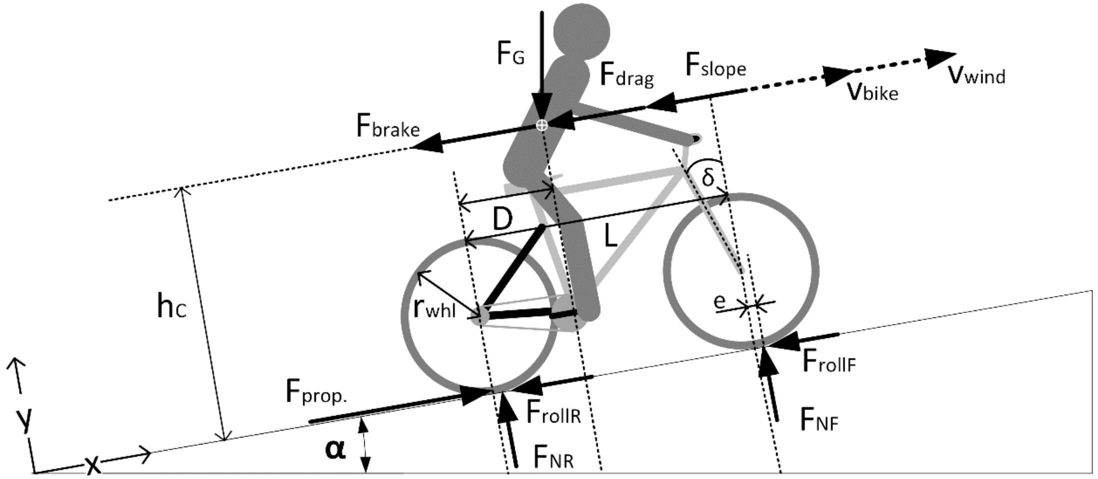

→ **Resulting dynamics define the physical model structure of bike and rider subsystems**

# Modelling Cycling Dynamics

Longitudinal Dynamics

**Given as a-priori knowledge:**

- trajectory of the cycled path
- further route properties (e.g. slope, wind)




**Description of Longitudinal Dynamics:**

$$m\,a = F_{prop.} - F_{brake} - F_{roll} - F_{slope} - F_{drag}$$

$$v(t) = \int a(t)dt$$

**Slope Resistance:**

$$F_{slope} = F_G\ \sin(\alpha) = m\,g\,\sin(\alpha)$$

**Drag Resistance:**

$$F_{drag} = \frac{1}{2}\,\rho_{air}\,c_W\,A\,(v_{bike} - v_{wind})^2$$

**Roll Resistance:**

$$F_{roll} = F_N\,f_R = F_G\ \cos(\alpha)\,f_R = m\,g\,\cos(\alpha)\,f_R$$

($f_R$ *representing tyre flexing-, roll off- and surface-resistance*)

**Transient Resistance:**

Longitudinal and rotational inertia represented in

**Resulting Dynamics description:**

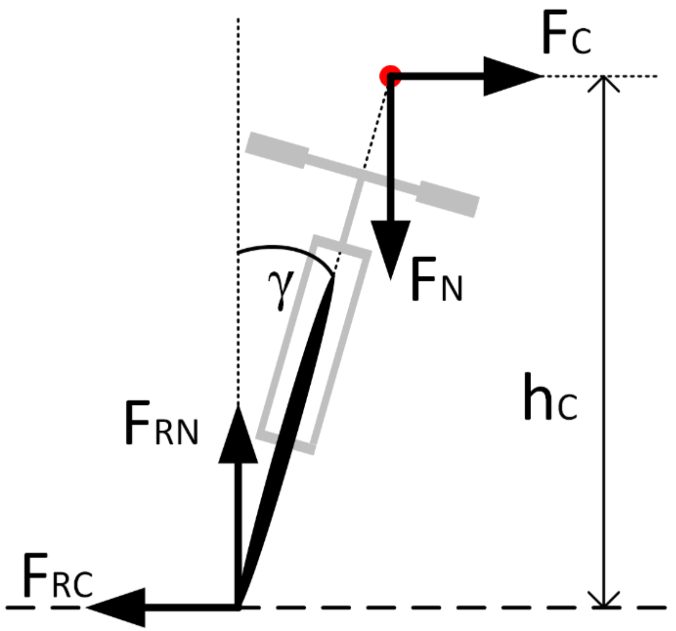
$$\lambda\,m\,a = F_{prop.} - F_{brake} - F_{roll} - F_{slope} - F_{drag}$$

# Modelling Cycling Dynamics

Lateral Dynamics – Bicycle Balance

**Modelling Conditions and Assumptions:**

- given trajectory of the cycled path
  ➔ given steering curve radius ($r_c$)
- stability of the bicycle is given
- ideal curve is assumed




<u>Representing the tilt angle ($\gamma$) of the bicycle caused by deflection of the centre of gravity in relation to the point of contact:</u>

- determination by ratio between centrifugal ($F_C$) and normal force ($F_N$):

$$F_C = \frac{m\,v^2}{r_c}$$

- **condition for stable cornering:**

generation of equal torque by normal and centrifugal force

$$F_G\,h_c\,\sin(\gamma) = \frac{m\,v^2}{r_c}\,h_c\,\cos(\gamma)$$

➡ **Resulting tilt angle:**

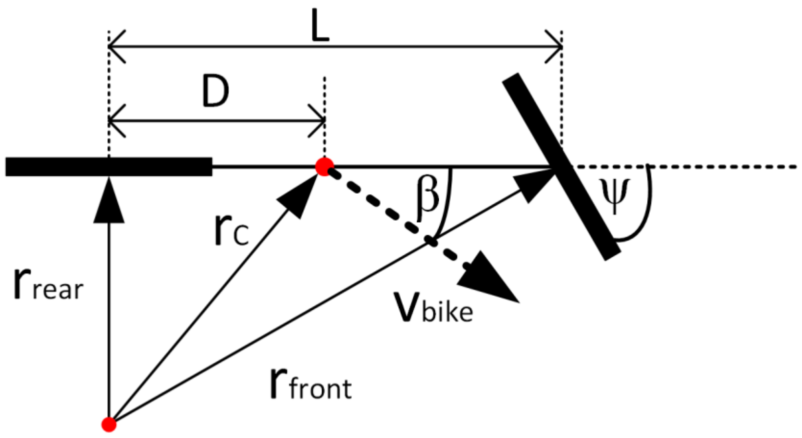
$$\tan(\gamma) = \frac{v^2}{g\,r_c}$$

# Modelling Cycling Dynamics

Lateral Dynamics – Bicycle Steering

**Modelling Conditions and Assumptions:**

- given trajectory of the cycled path
  - ➔ given steering curve radius ($r_c$)
- ideal curve is assumed




Calculating the turn angle ($\theta$) of the handlebar:

- calculating yaw angle ($\beta$) around the centre of gravity

$$\sin(\beta) = \frac{D}{r_c}$$

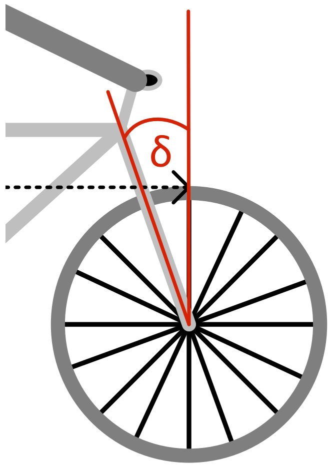
- calculating front wheel angle ($\psi$)

$$\tan(\psi) = \frac{L}{D}\tan(\beta)$$

**Calculating turn angle of the handlebar ($\boldsymbol{\theta}$)**

(assuming a small head tube angle ($\delta$))

$$\boldsymbol{\tan(\theta) = \frac{\psi}{\sin(\delta)}}$$



# Modelling Cycling Dynamics

Braking Dynamics

**Dynamic limitations of cycling occur primarily during braking**

*Fairly low propulsion force doesn‘t cause spinning wheels*

Intensive braking quickly exceeds friction limits

→ *wheel lock up*

Calculating maximum braking force using static friction force:

$$F_{B_{max}} = F_S = \mu_s \ F_N = \mu_s \, m \, g \ \cos(\alpha)$$

Considering static and dynamic normal force distribution:

$$F_{N_{front}} = \frac{F_N \, D - m \, a \, h_s}{L} \text{ and } F_{N_{rear}} = \frac{F_N \, (L-D) - m \, a \, h_s}{L}$$

➔ **different maximum braking force on front and rear wheel**

**Braking in Curve Situations:**

- maximum braking force is decreased
- static friction also used for lateral traction

$$\Rightarrow F_{B_{max}} = \sqrt{F_S^2 - F_C^2}$$

*centrifugal force used as lateral guidance force*

Calculating resulting centrifugal force on front and rear wheel:

considering speed, curve radius and weight distribution

$$F_{C_{front}} = \frac{m \, D \, v^2}{L \sqrt{r_C^2 - D^2 + L^2}} \text{ and } F_{C_{rear}} = \frac{m \, (L-D) \, v^2}{L \sqrt{r_C^2 - D^2}}$$

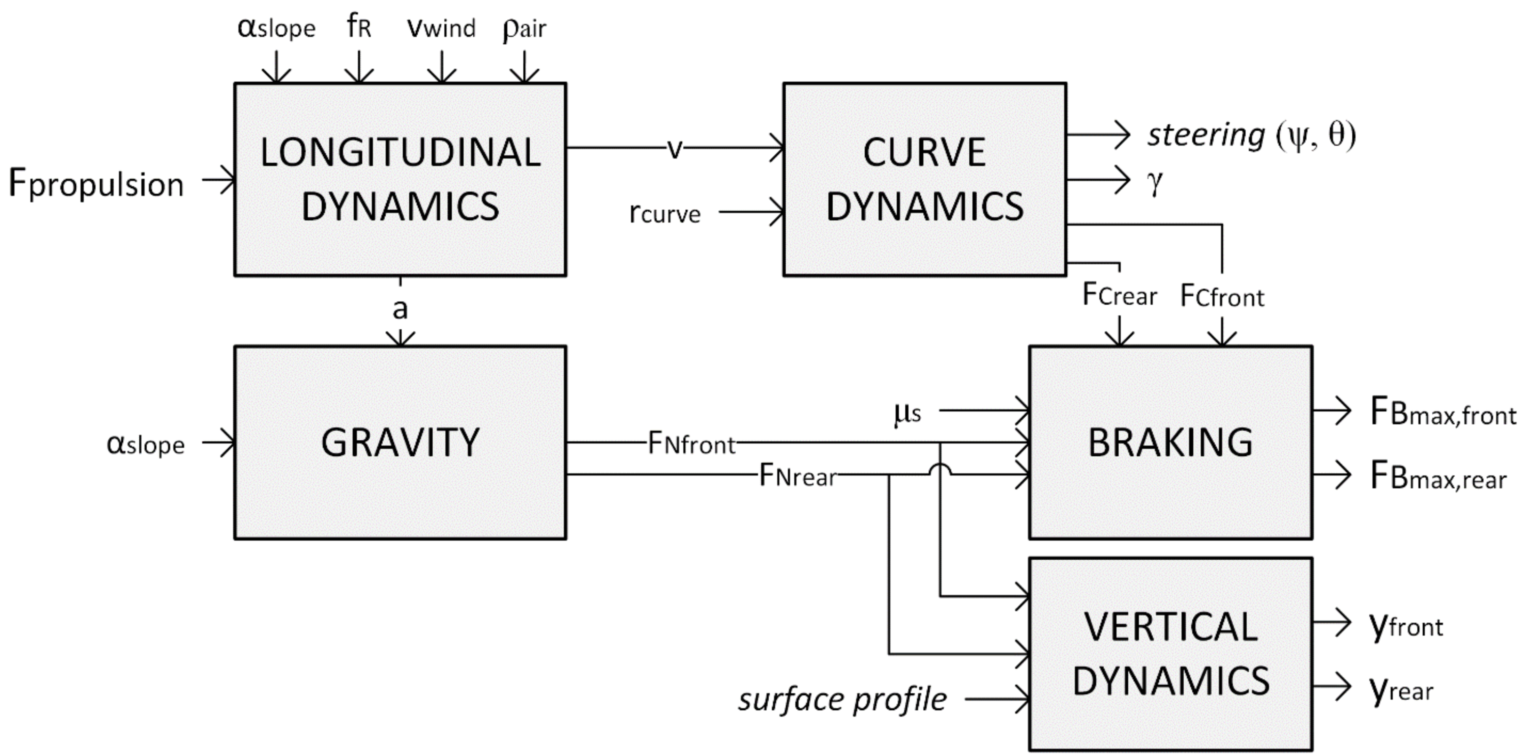
# Implementation

Resulting Model

**Physical equations derived by the dynamics description of cycling implemented in MATLAB/Simulink**

**Generated a-priori knowledge by pre-processing:**

- $\alpha_{slope}$: slope angle
- $f_R$: roll resistance factor
- $v_{wind}$: wind speed
- $\rho_{air}$: air density
- $r_{Curve}$: curve radius
- $\mu_S$: static friction coefficient
- surface profile



# Implementation

## Modelling Parameters

**Characteristics of**

**Bicycle** | **Rider** | **Route**

### Ride Constant Parameters

**For generic bicycles: rule-based derivation of parameters**

- in dependence of the bicycle type and rider‘s physique:
  *$c_W$-Value, frontal Area, centre of gravity position*
- in dependence of the bicycle type:
  *head tube angle, wheelbase, spring-damper-parameters*
- in dependence of the tyre type:
  *vertical dynamic tyre properties*

**For specific bicycles:**

- technical documentation
- experimental determination, e.g. coasting experiment

### Distance Dependent Parameters

**Synthetic routes:**

Required to self define all properties

**Routes based on real infrastructure:**

Self-developed route data generation algorithm, enables calculation of:

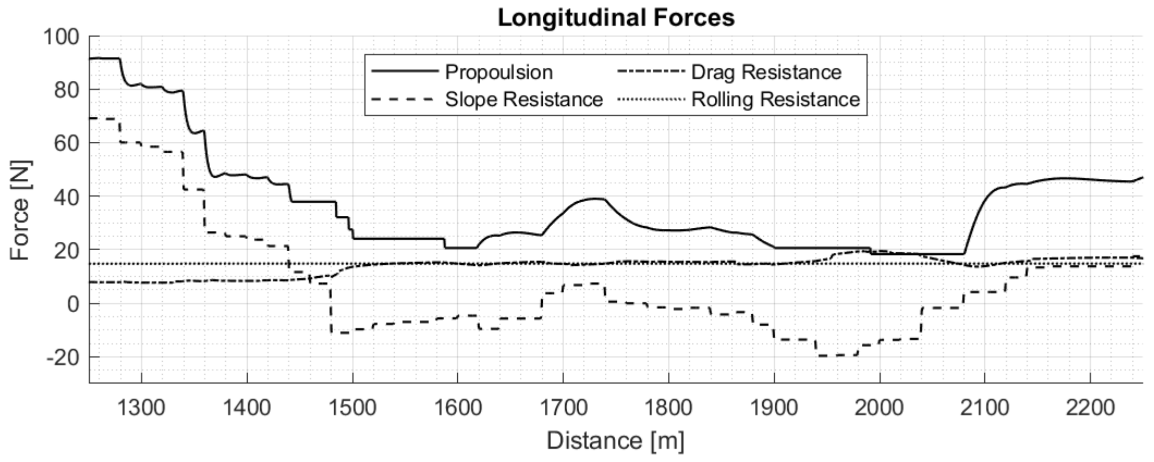
- *curve radius* based on route trajectory
- *slope angle* based on altitude
- *air density* based on altitude, air pressure, humidity and temperature
- *resulting wind speed* based on wind speed and direction
- *rolling resistance factor* and *static friction coefficient* based on underground as well as tyre type and pressure

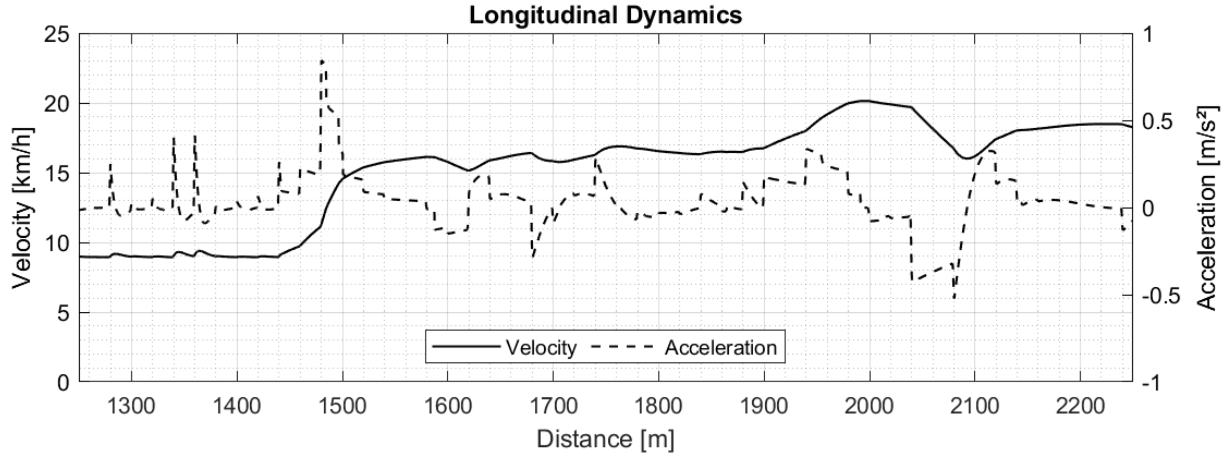
# Simulation and Results

Longitudinal Dynamics

**Simulation of cycling on a forest road**

- ➢ starting with an uphill section → significant slope resistance results in lower speed ✔
- ➢ end of uphill section → increased speed ✔
- ➢ increased velocity → drag resistance ✔
- ➢ constant rolling resistance → due to no change of underground ✔



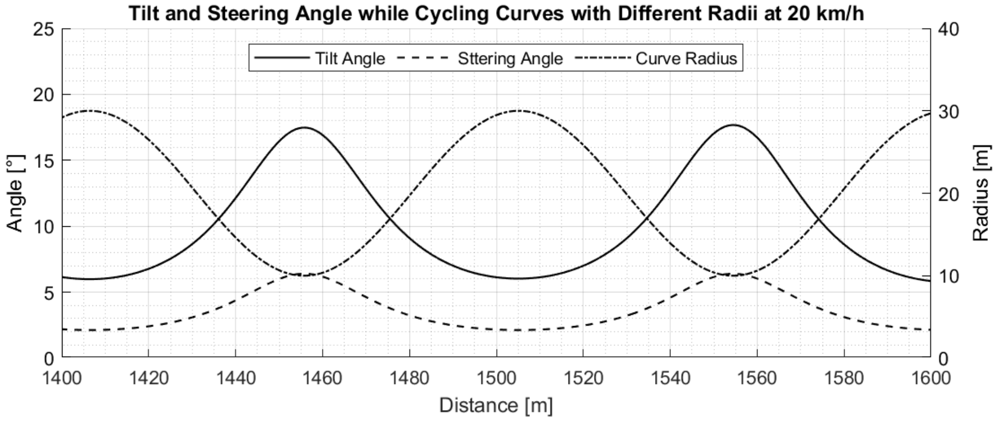



# Simulation and Results

Lateral and Braking Dynamics

**Periodically cycling curve radius**

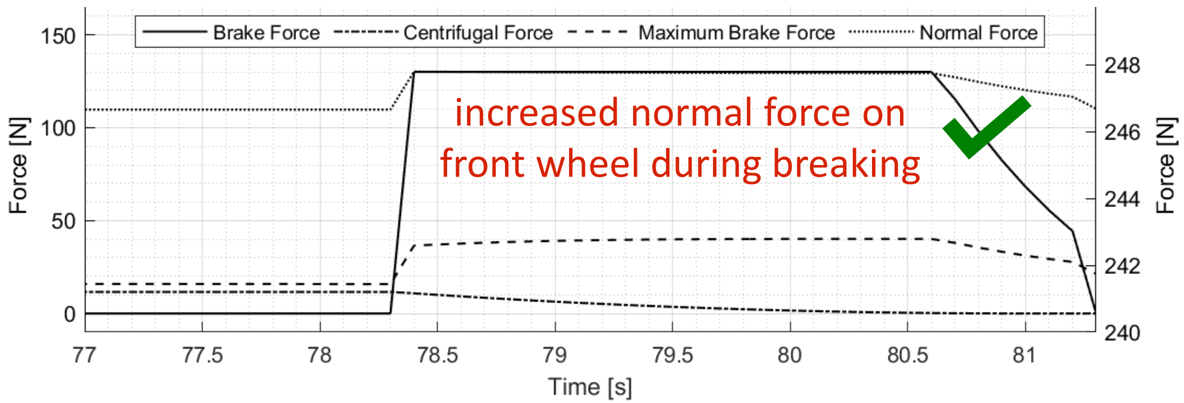
**between 10 to 30 meters at 20 km/h**

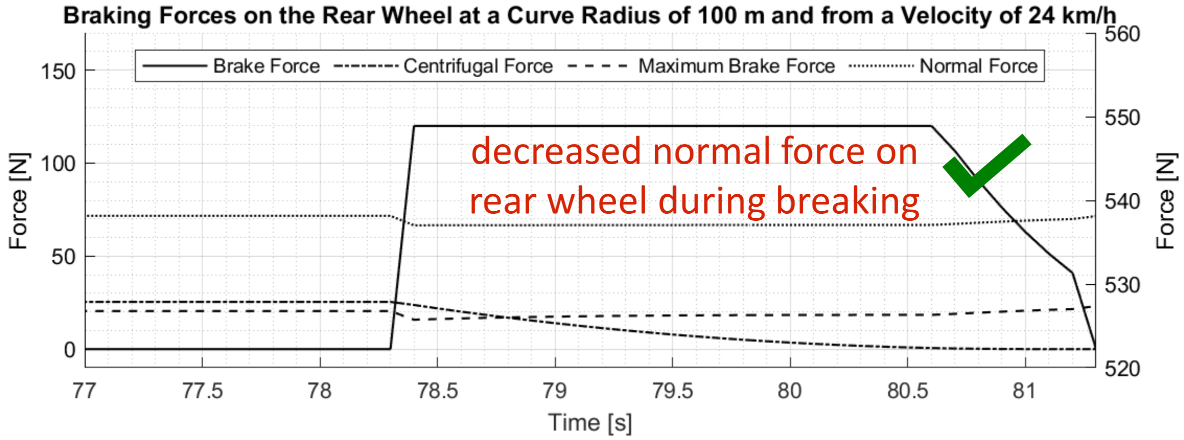



narrower curves/smaller curve radius

➔ increased steering and tilt angle

**Braking at a curve radius of 100 m and from a speed of 24 km/h**




➔ decreasing centrifugal force leads to increase of maximum braking force

# Conclusion and Future Work

**Conclusion:**

- Approach towards a holistic model of cycling dynamics to be used in standalone simulation of cycling
- Longitudinal, lateral and vertical dynamics as well as dynamic limitations are described as function of a propulsion force, trajectory and route properties
- Simulink implementation of achieved dynamics description
- Verification shows that model is capable of plausibly representing the required cycling dynamics

**Future Work:**

- Qualitative evaluation of the model → further literature research and experiments for determining parameters
- Evaluation of the dynamics model – especially in comparison to real cycling situations
- Extended consideration of vertical dynamics description
- Further optimisation and continuous development according to given requirements from the model environment or given use-cases

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# Thank your for your Attention

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