Bicycle Braking Performance

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Structure and Concept – Bicycle Deceleration Performance

- Brake Performance of Vehicles with Independent Brakes
- Ideal Brakeforce Distribution
- Test Results – Rear Brake Application
- Parameter Variations
- Conclusion

Brake Performance of Two-Wheelers

- Challenge #1:

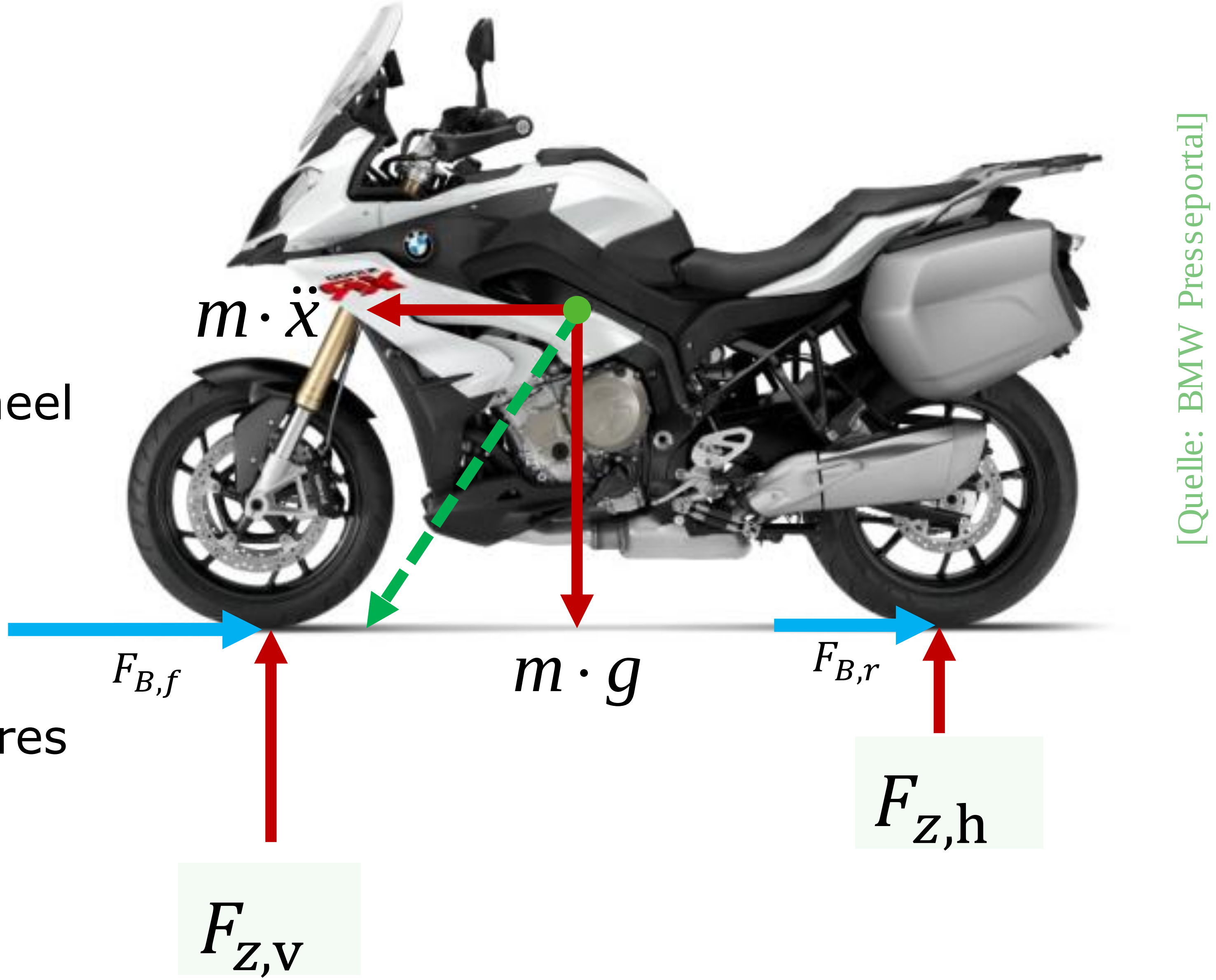
  Maintaining vehicle stabilty requires a rotating front wheel

- Challenge #2:

  Avoiding rear-wheel liftoff

- Challenge #3:

  Ideal brake operation requires two-channel brake control



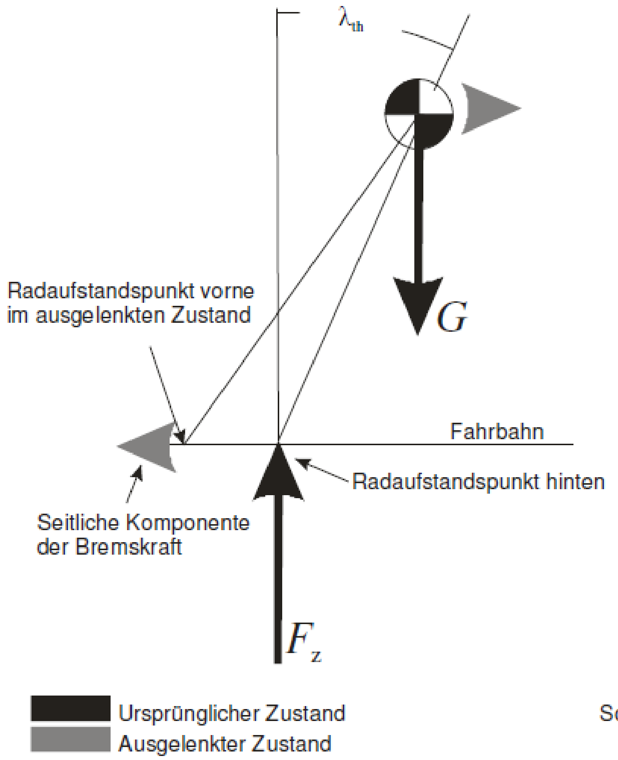
Assumptions - Behavior

- High deceleration values require experience and control
  - Avoid front wheel lock
  - Avoid tip-over
  - Two-channel: Decreasing rear wheel force while increasing front wheel force
- It should probably not be assumed that typical riders are able to reach the physical limits
- The safest method for emergency braking on a two-wheeler is rear wheel only

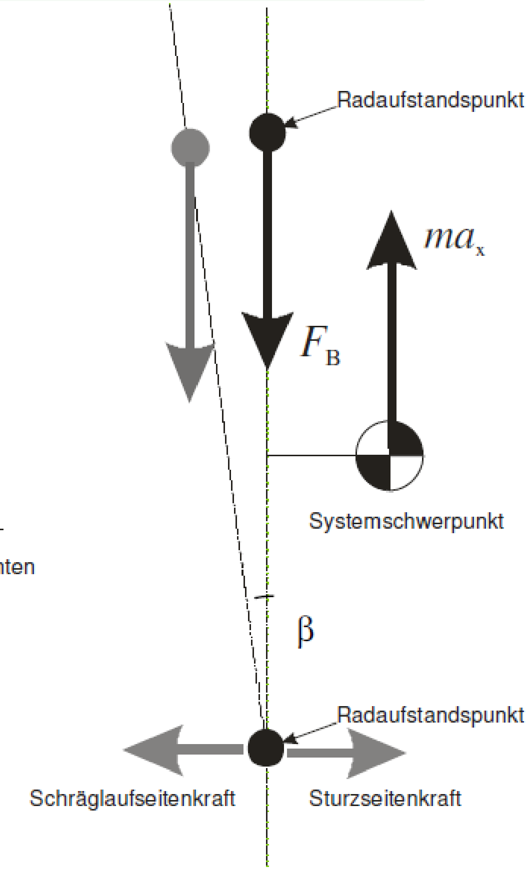
Front Wheel Lock – Capsize Mechanism

- A locked front wheel cannot take side force, friction opposed to moving direction
- Vehicle is unstable in roll and yaw motion
- Small disturbances would lead to immediate capsize

Seen from rear

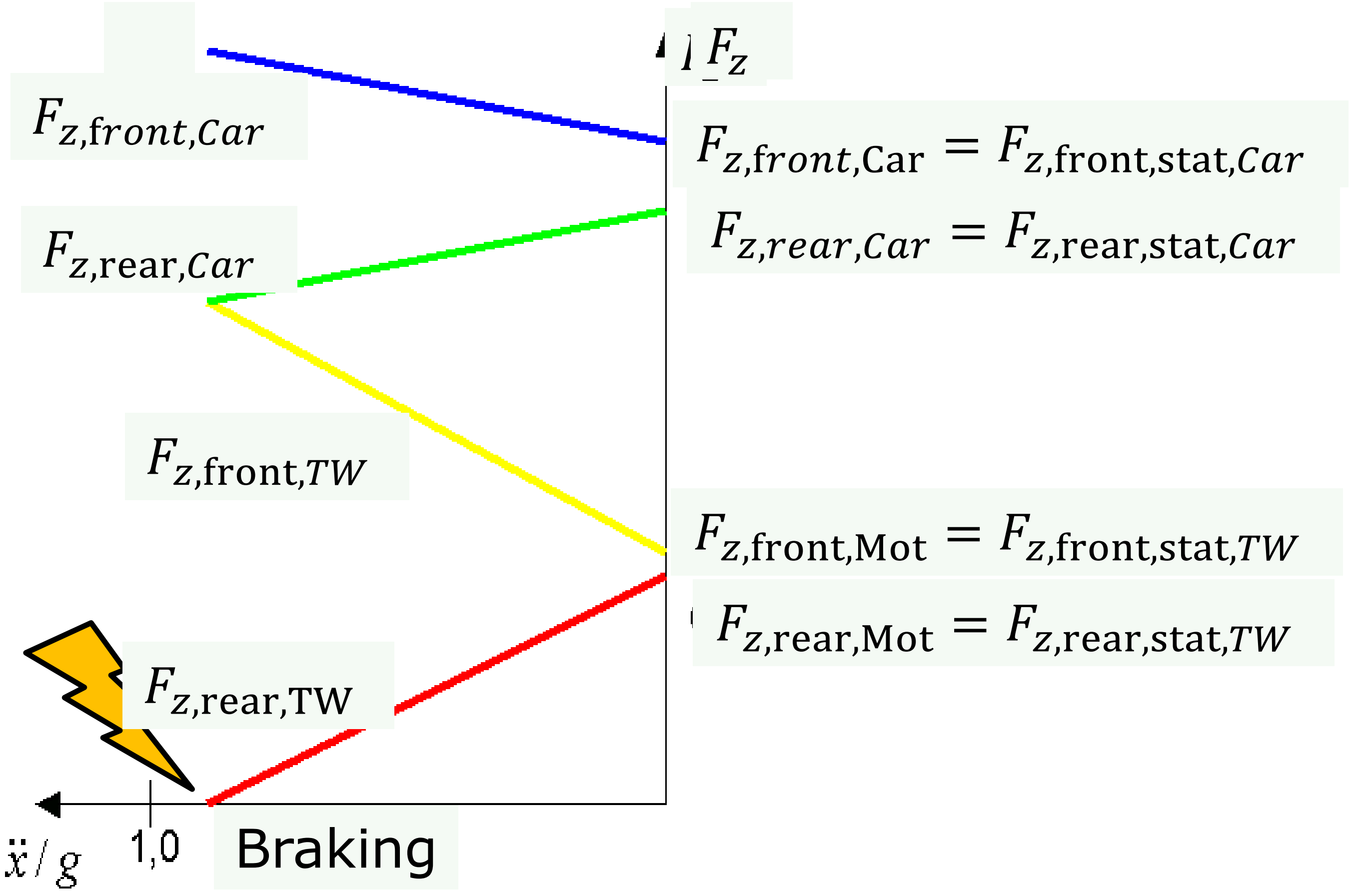


Seen from top



Wheel loads for car and two-wheeler during deceleration

- Center of gravity high
- Wheelbase short
- Deceleration transfers wheel load from rear to front
- Wheel load of rear wheel might become zero
- For increased deceleration, vehicle (TW) tips over



Ideal Brakeforce Distribution

- Brake force per wheel: $F_{B,i} = \ddot{x} \cdot F_{z,i} \leq \mu \cdot$
- Wheel load for deceleration ($\ddot{x}$<0!)
  - $F_{z,front} = \frac{l_h}{l} \cdot m \cdot g - \frac{h_s}{l} \cdot m \cdot \ddot{x}$, increases during braking
  - $F_{z,rear} = \frac{l_v}{l} \cdot m \cdot g + \frac{h_s}{l} \cdot m \cdot \ddot{x}$, decreases during braking
- Brake force per wheel:
  - $\frac{F_{b,front}}{m \cdot g} = \frac{l_h}{l} \cdot \ddot{x} - \frac{h_s}{l \cdot g} \cdot \ddot{x}^2$
  - $\frac{F_{b,rear}}{m \cdot g} = \frac{l_v}{l} \cdot \ddot{x} + \frac{h_s}{l \cdot g} \cdot \ddot{x}^2$
- Both equations lead to brakeforce distribution diagram:

Exact Calculation of Maximum Deceleration for Rear-Wheel Brake Application

- Eq. of Motion: $m \cdot \ddot{x} = F_{B,rear,max} = \mu \cdot F_{z,rear}$ ($\ddot{x} \geq 0$ for braking)
- Wheel load: $F_{z,rear} = \frac{l_v}{l} \cdot m \cdot g - \frac{h_s}{l} \cdot m \cdot \ddot{x}$
- Maximum possible deceleration:

$$m \cdot \ddot{x} = \mu \cdot \frac{l_v}{l} \cdot m \cdot g - \mu \cdot \frac{h_s}{l} \cdot m \cdot \ddot{x}$$

$$\Leftrightarrow \ddot{x} + \mu \cdot \frac{h_s}{l} \cdot \ddot{x} = \mu \cdot \frac{l_v}{l} \cdot g$$

$$\Leftrightarrow \ddot{x} = \frac{l_v}{\frac{l}{\mu} + h_s} \cdot g$$

Front Wheel: ($\ddot{x}$ >0 for braking)

- Wheel load: $F_{z,rear} = \frac{l_v}{l} \cdot m \cdot g + \frac{h_s}{l} \cdot m \cdot \ddot{x}$
- Maximum possible deceleration case 1:

$$m \cdot \ddot{x} = \mu \cdot \frac{l_v}{l} \cdot m \cdot g - \mu \cdot \frac{h_s}{l} \cdot m \cdot \ddot{x}$$

$$\Leftrightarrow \ddot{x} + \mu \cdot \frac{h_s}{l} \cdot \ddot{x} = \mu \cdot \frac{l_v}{l} \cdot g$$

$$\Leftrightarrow \ddot{x} = \frac{l_h}{\frac{l}{\mu} - h_s} \cdot g$$

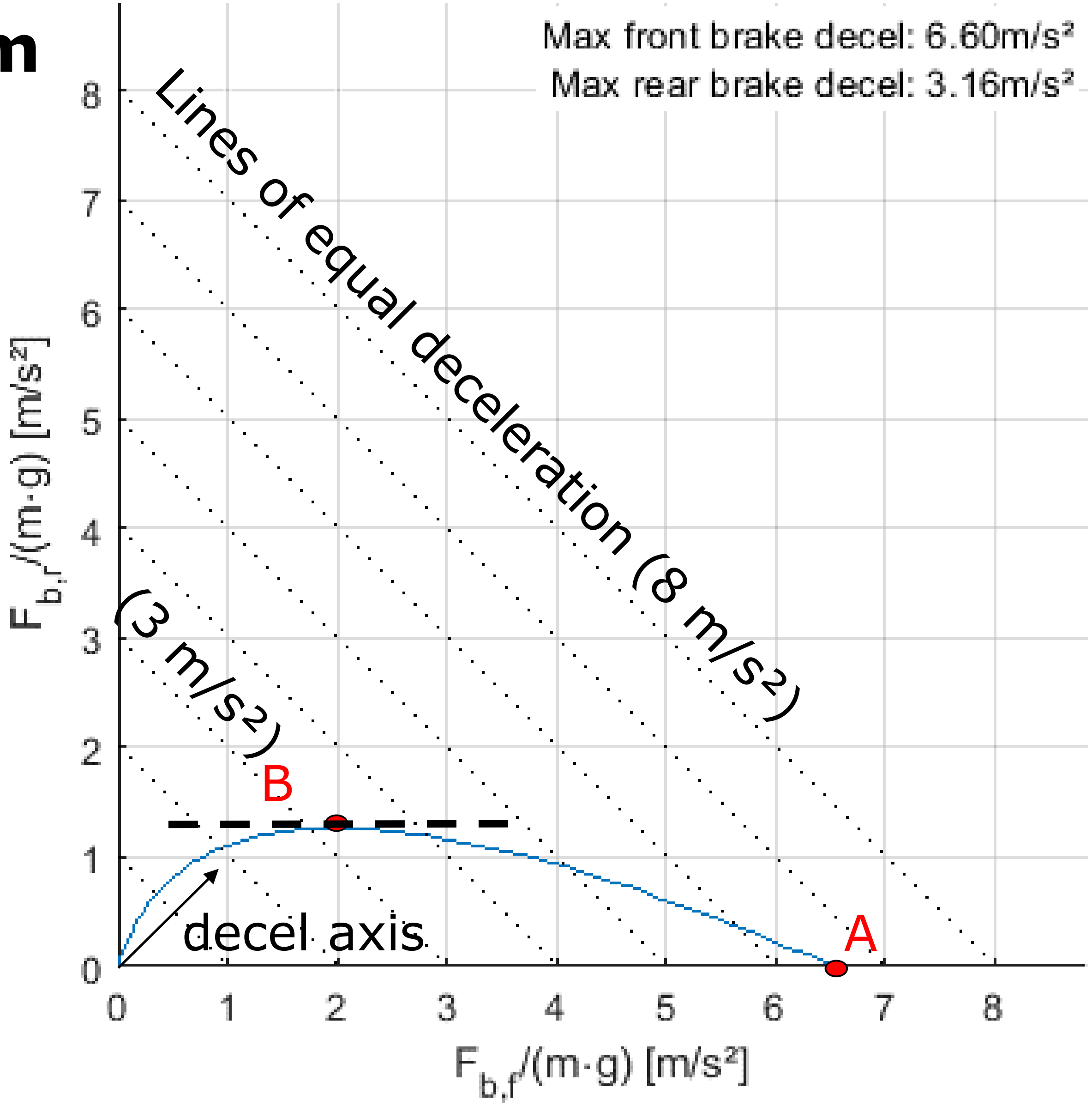
- Maximum deceleration case 2: Rear wheel load = 0, tipping over

$$0 = \frac{l_v}{l} \cdot m \cdot g - \frac{h_s}{l} \cdot m \cdot \ddot{x}, \rightarrow \frac{l_v}{h_s} \cdot g = \ddot{x}$$

- Maximum front wheel deceleration: $\ddot{x} = \min\left(\frac{l_v}{h_s} \cdot g; \frac{l_h}{\frac{l}{\mu} - h_s} \cdot g\right)$

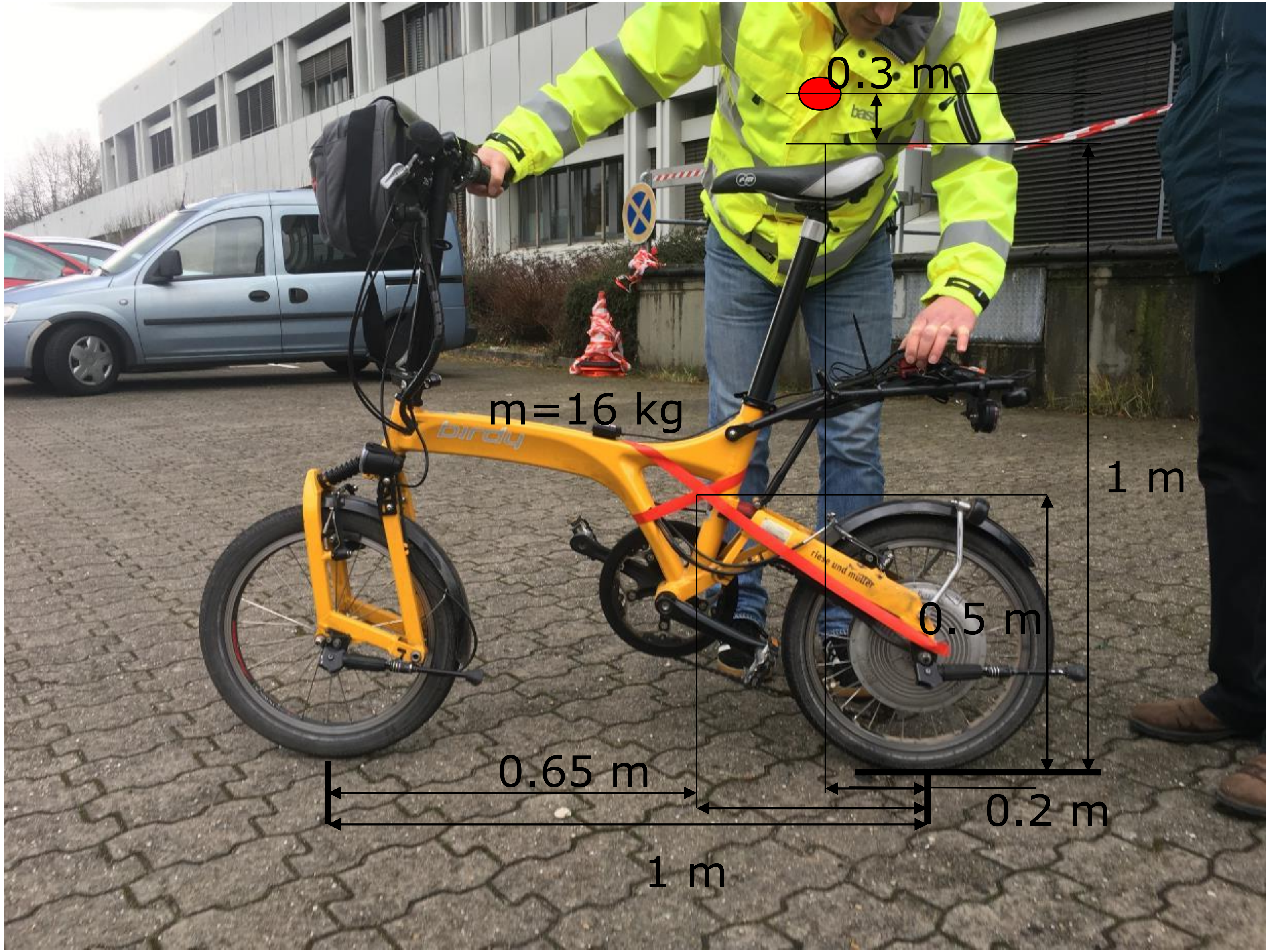
Brakeforce Distribution Diagram

- Ideal brake force distribution as function of
  - CG Position
  - Wheelbase
- A: Maximum deceleration with front wheel brake
- B: Maximum deceleration with rear wheel brake

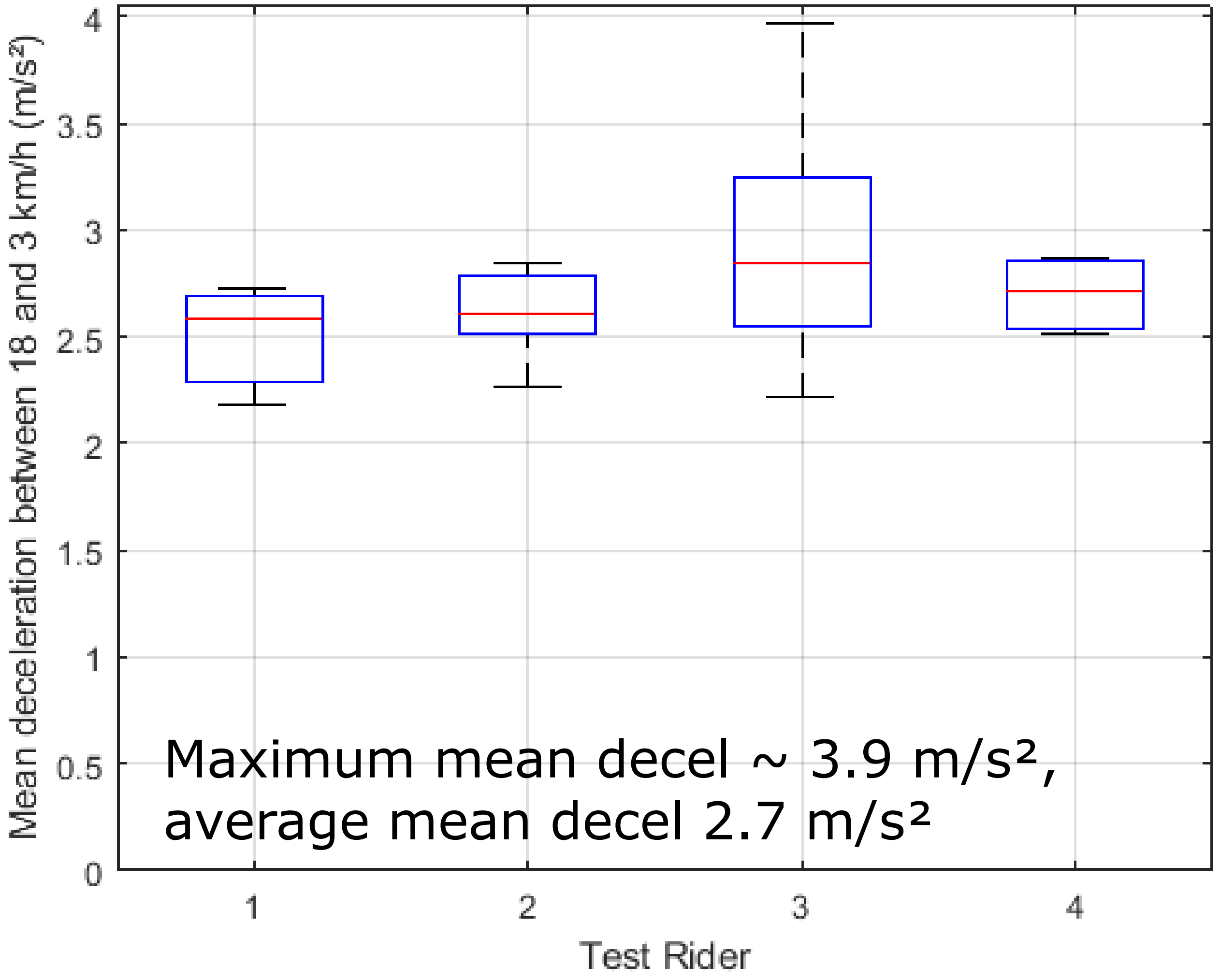


Experiment Bicycle

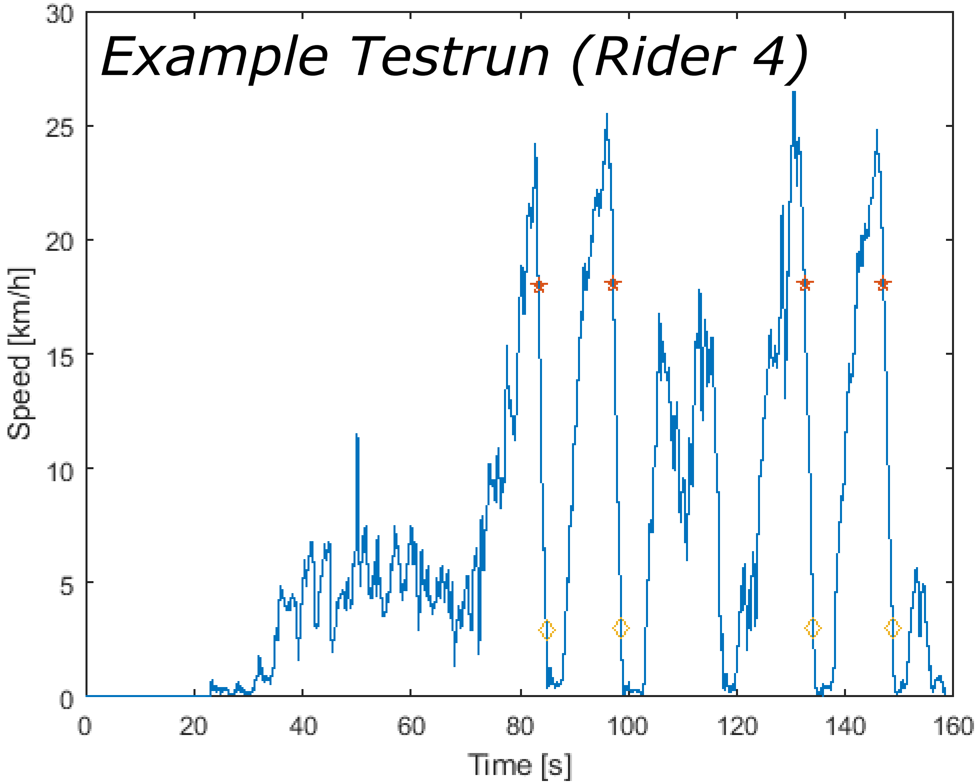
- Rear-heavy bike
- Equipped with deceleration and speed logger
- Application of rear wheel only
- 4 riders, masses known



Measurement Results (1)



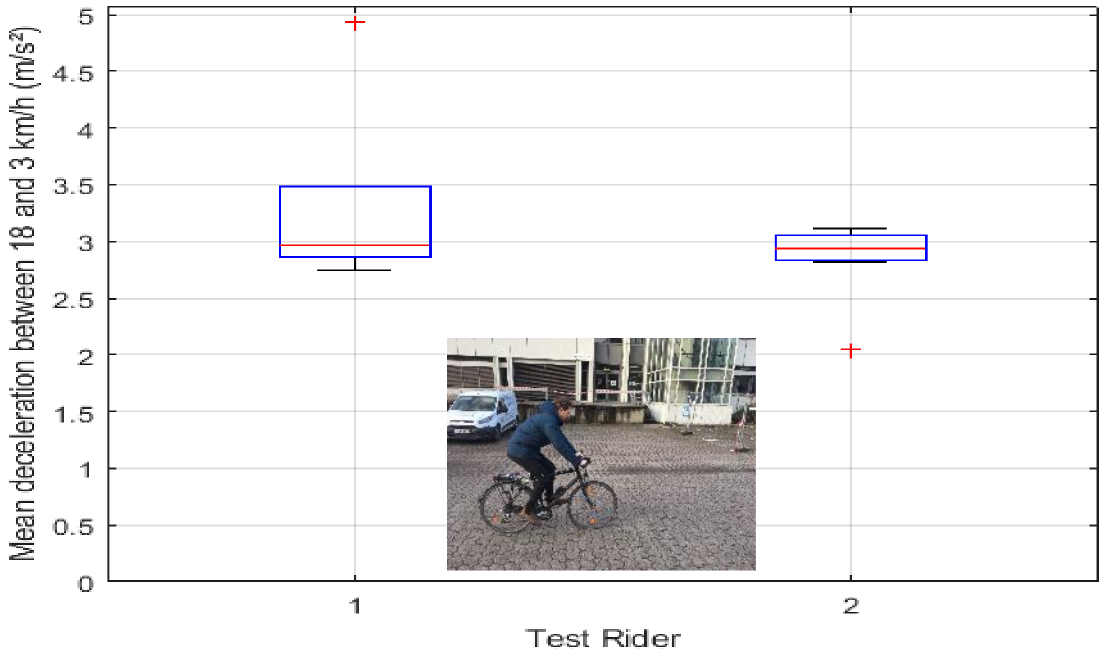
Maximum mean decel ~ 3.9 m/s²,
average mean decel 2.7 m/s²

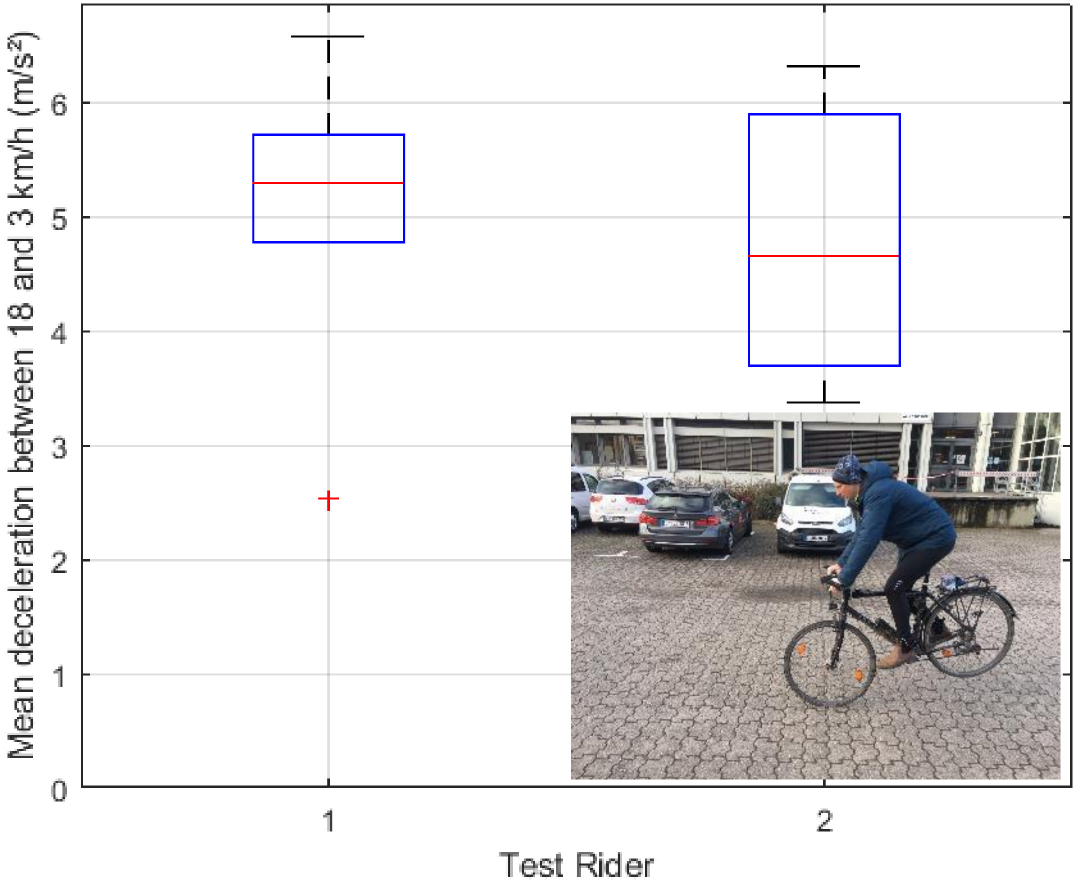


Other Bikes

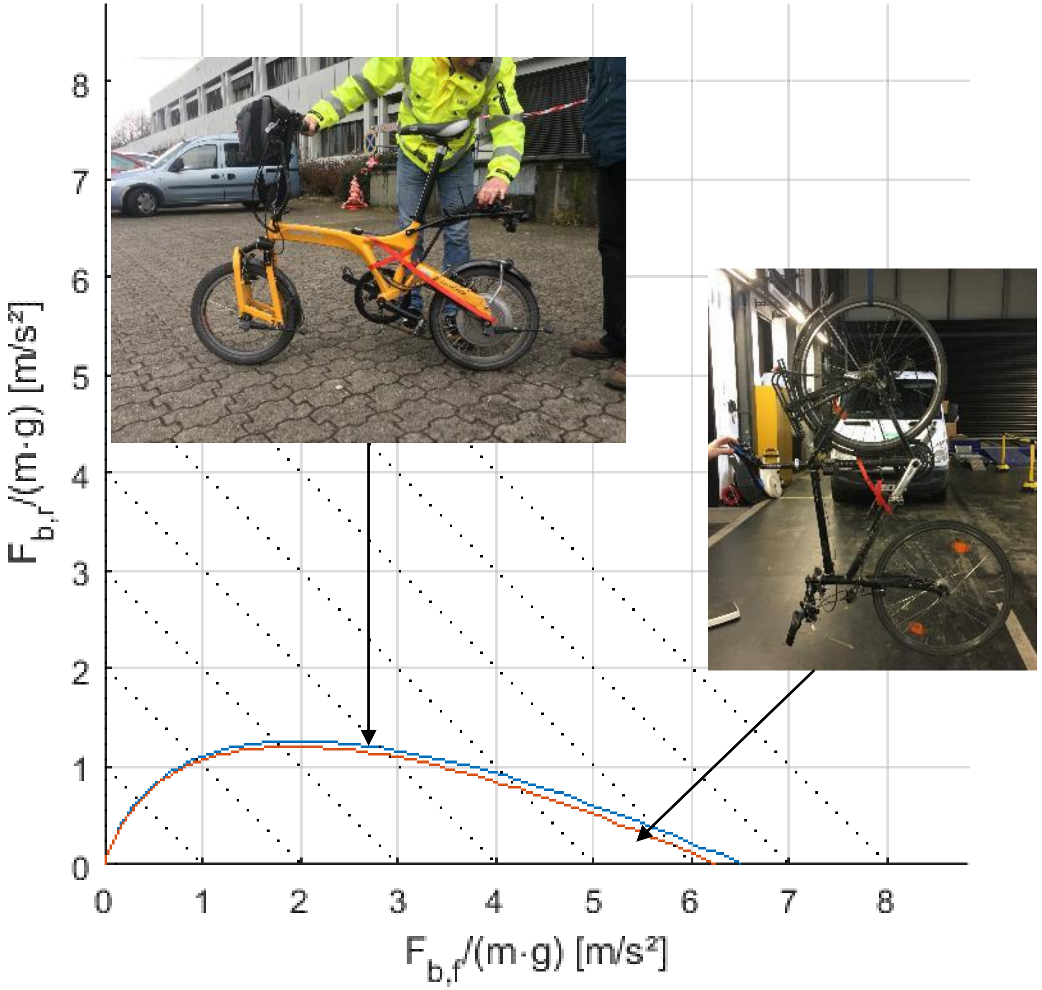
- Geometry of saddle – CG – wheelbase comparable to other bikes

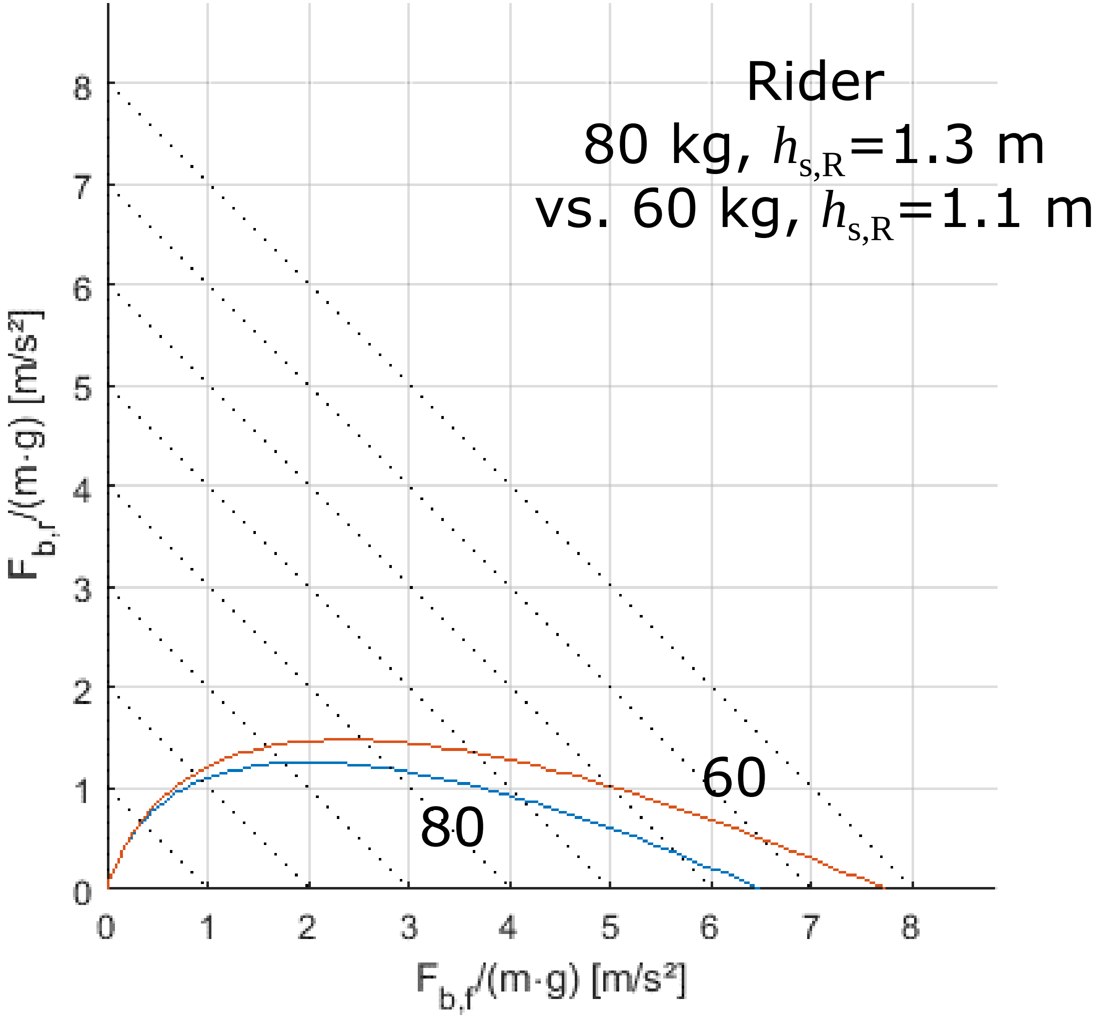
Measurement Results (2)





Comparison of Bicycles and Riders





Speed Reduction for Braking at PoNR

v Bicycle [km/h]	a Bicycle [m/s²]	t PoNR [s]	s PoNR [m]	v avoidance [km/h]
10	3.5	0.58	1.46	21.18
15	3.5	0.72	2.72	30.15
20	3.5	0.88	4.59	41.06
25	3.5	1.06	7.03	52.75
30	3.5	1.25	10.04	64.83

Conclusions

- Rear wheel brake application considered as safest variant for emergency brake
- Typical bicycles in theory allow approximately 3.5 m/s^2
- Measurements show: Maximum MFDD ~ 3.9 m/s^2, average 2.7 m/s^2
- Effect of 3.5 m/s^2 on required speed reduction:
  - TTC for Braking → 0.72 s
  - Avoidance Speed → 30 km/h