Empa
Materials Science and Technology

Braking Forces in the Assessment of Road Bridges

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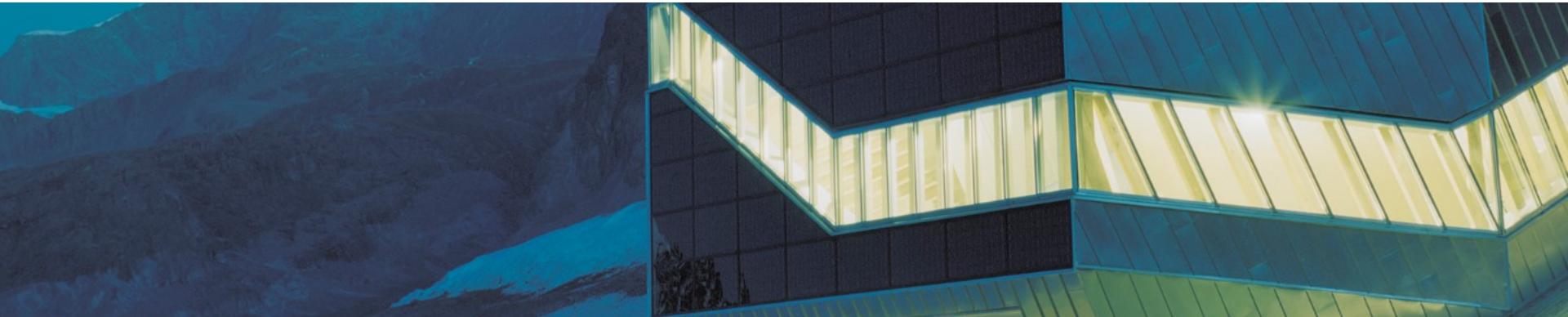
Empa's Structural Engineering Research Laboratory (Department 303)

Empa's Structural Engineering Research Laboratory (Department 303) is actively involved in research focusing on new advanced materials and technologies, timber engineering and innovative manufacturing processes. Its quest for knowledge aims to improve the reliability and robustness of structures, with the ultimate goal of reducing waste and CO2 emissions.



The Laboratory's approach includes research into extending the service life of structures.

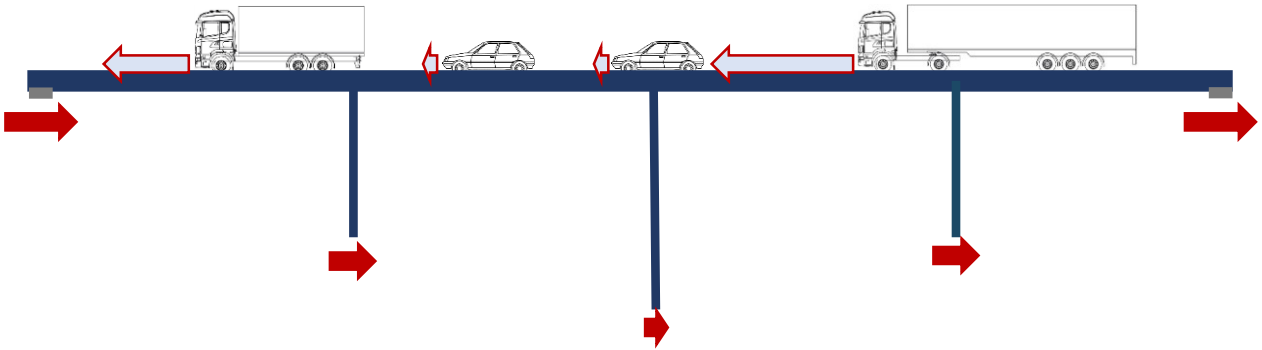
This is pursued by:

Retrofitting or strengthening existing structures

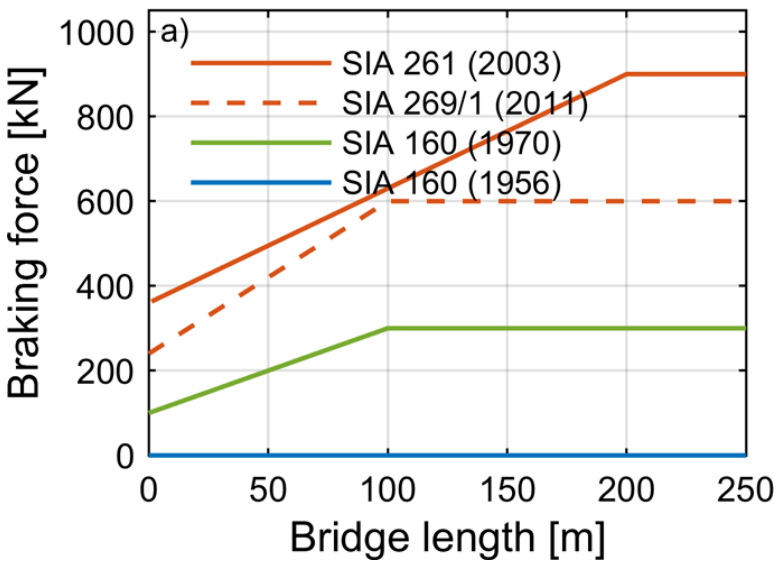
The refinement of load and structural resistance models

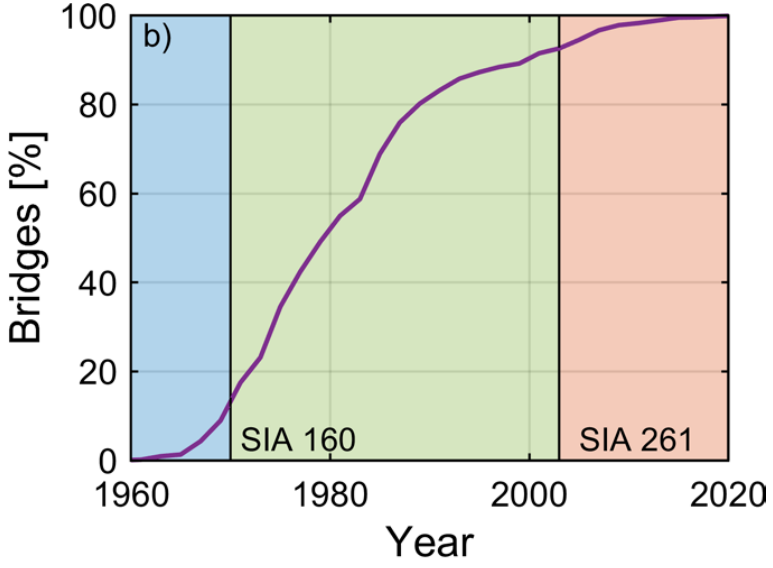
Braking forces

- Bridges designed to withstand forces induced by braking heavy vehicles
- Force induced by braking vehicles is transient ➔ Dynamic motion of the bridge (floating articulation)
- Braking force: Force transmitted to the underground by piers and supports
- Bridge motion (inertial force) increases forces of braking vehicles (dynamic amplification)

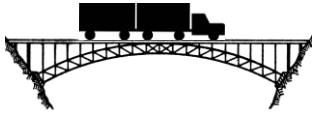


Braking forces on bridges from a Swiss perspective

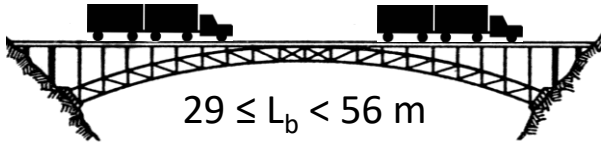




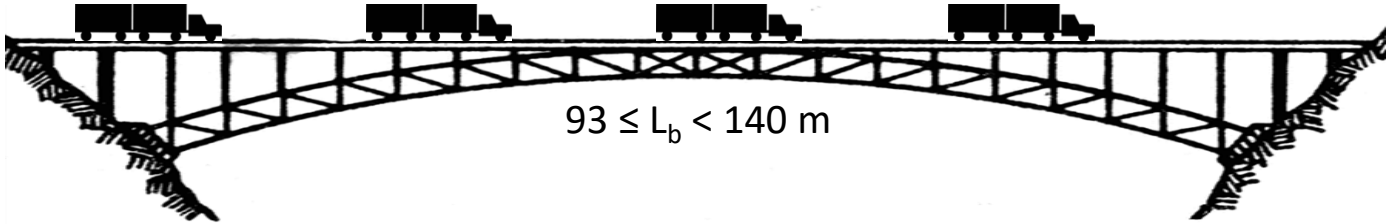
Deterministic Model



$12 \leq L_b < 29$ m



$29 \leq L_b < 56$ m



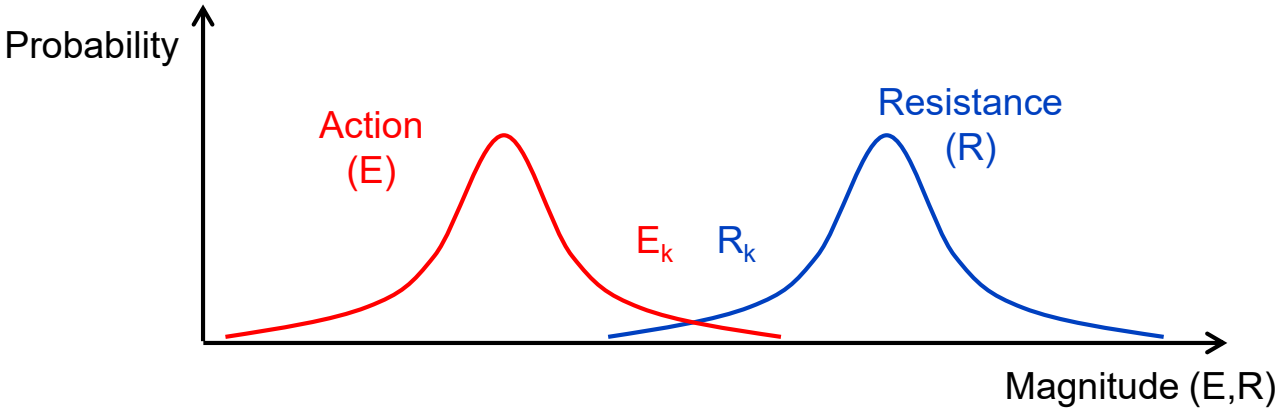
$93 \leq L_b < 140$ m

Merzenich, G., Sedlacek, G., 1995, Hintergrundbericht zum Eurocode 1 – Teil 3.2: "Verkehrslasten aufStraßenbrücken", Bundesminister für Verkehr, Abt. Straßenbau, Bonn-Bad Godesberg, Germany.

Experimental determination complex and expensive

Problem of the deterministic model

- Modern building standards are based on concepts of reliability theory (probability of failure)



- Deterministic braking forces do not allow the probability of failure to be estimated

Stochastic model for estimating braking forces (1)

- Stochastic model based on :
  - Traffic data (site-specific or data-oriented)
  - Recorded braking profiles (safety-critical events)

- takes into account:
  - Braking kinematics
  - Randomness of the phenomena
  - Bridge dynamic in the longitudinal direction
  - Return period

Monte Carlo Simulations of braking events➔ Probability distribution of braking forces

Original formulation: (1) Martins J, Feltrin G., Beyer K. AGB 2011/003 Updated braking forces for the assessment of road bridges, 2016, Forschungsbericht ASTRA.

Swiss Traffic data (Automatic vehicle counting stations)

- Information to vehicle class, speed, length, distance, etc.

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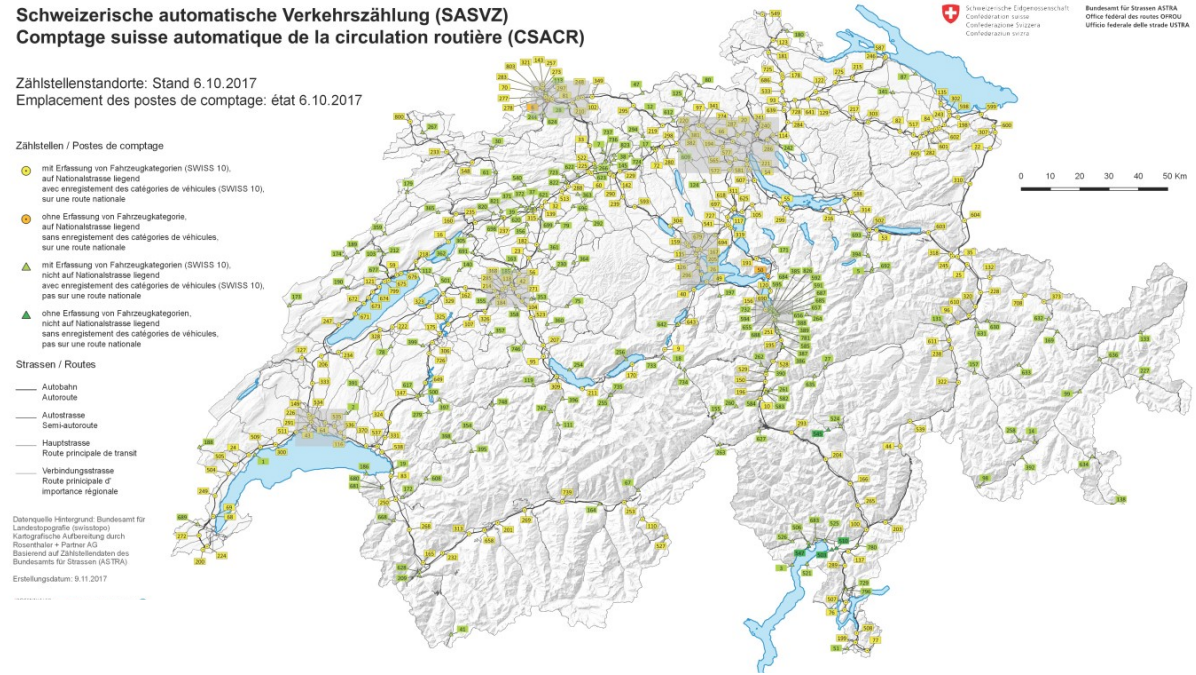
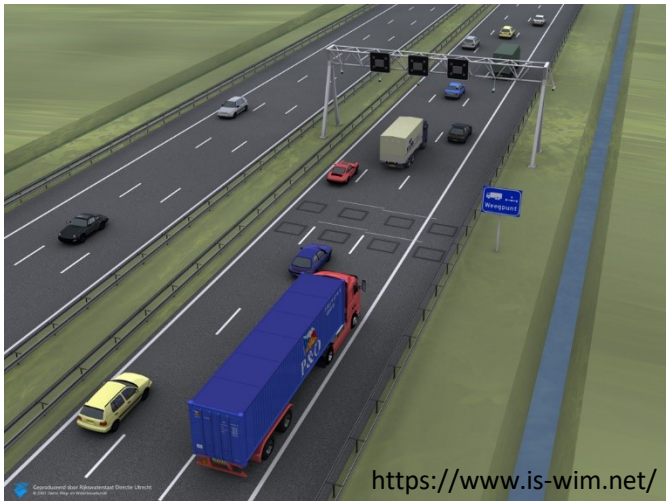
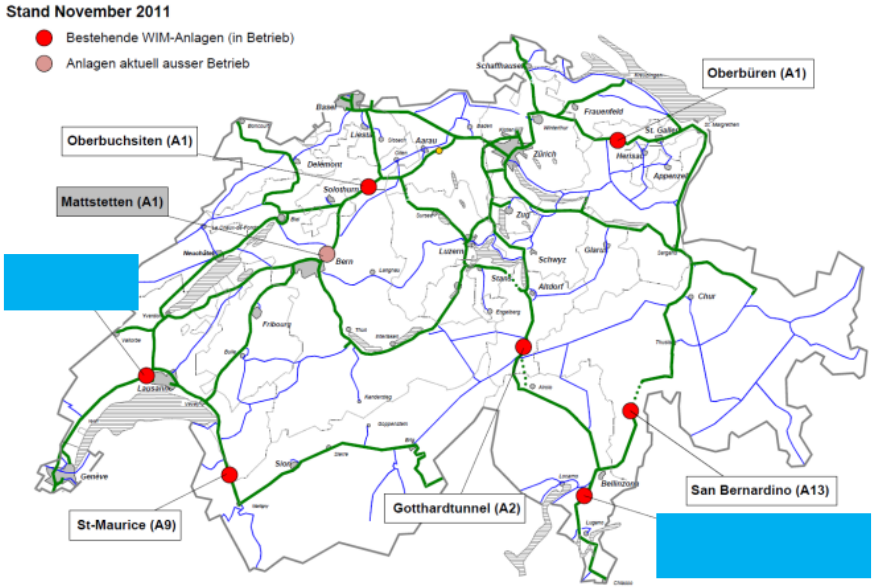


Swiss Traffic data (Weigh in motion station)

- Weigh in motion (ASTRA)
- Information on vehicle class, speed, **weight**, axle weight, etc.

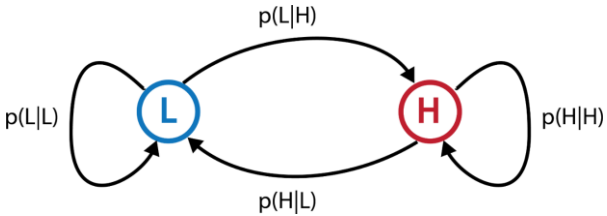




Synthetic traffic

- **Step 1:** Markov chain model, it provides the basic structure of the synthetic traffic by generating a sequence of light vehicles and heavy vehicles. Markov chain model to construct a sequence of vehicles

  A Markov chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event (Wikipedia)

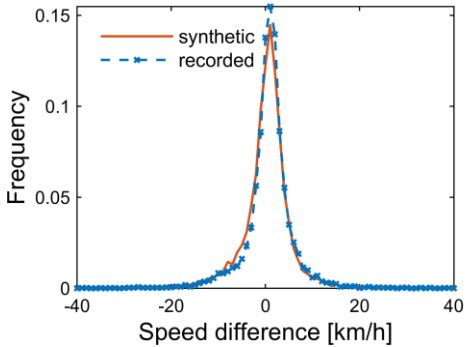


H: truck (heavy vehicle)
L: car (light vehicle)
→ transition probabilities

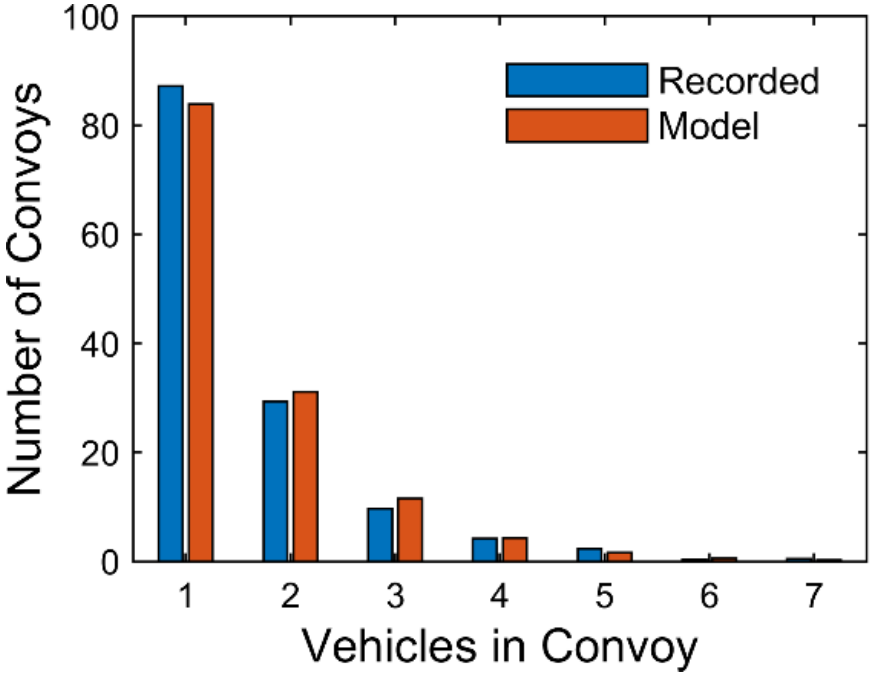
- ***Step 2:*** Vehicle speed model modeled as a random process

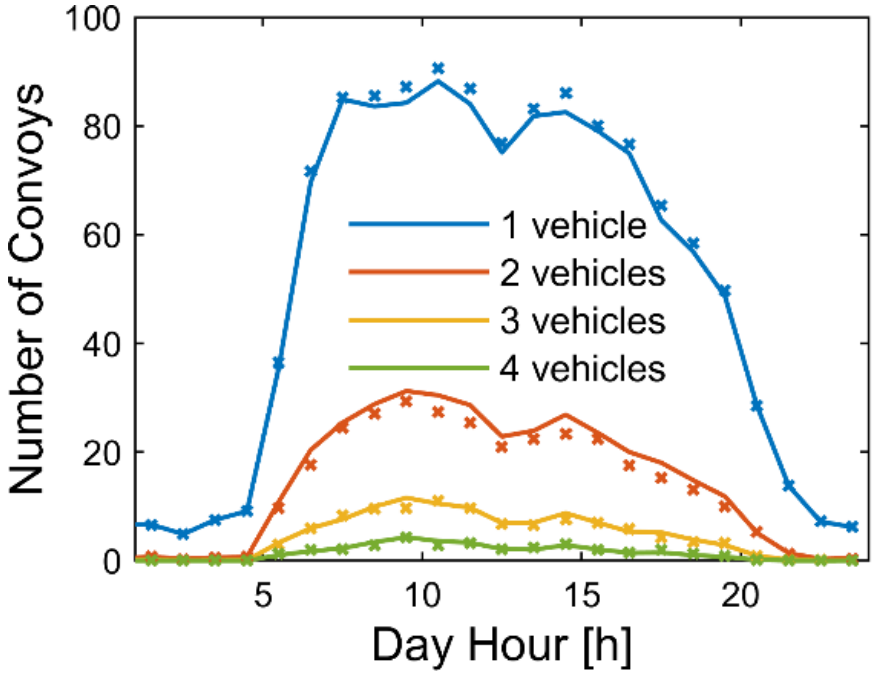
$$\upsilon_{i+1} = a(\upsilon_i - \overline{\upsilon}) + \overline{\upsilon} + \varphi_{i+1}$$

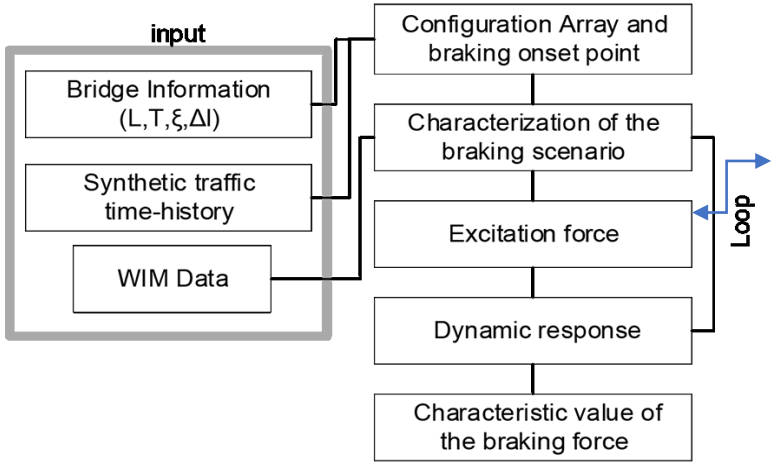
deterministic component stochastic component

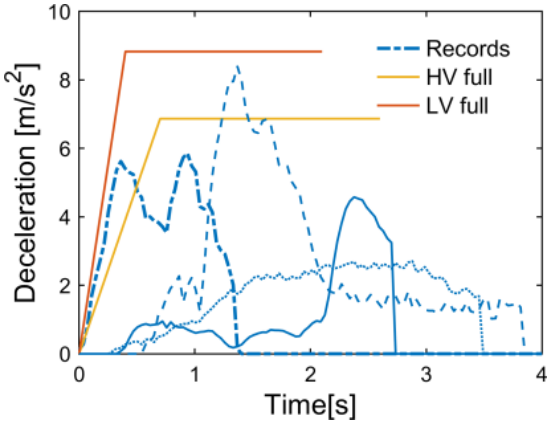


Synthetic traffic: Spontaneous clustering of heavy vehicles

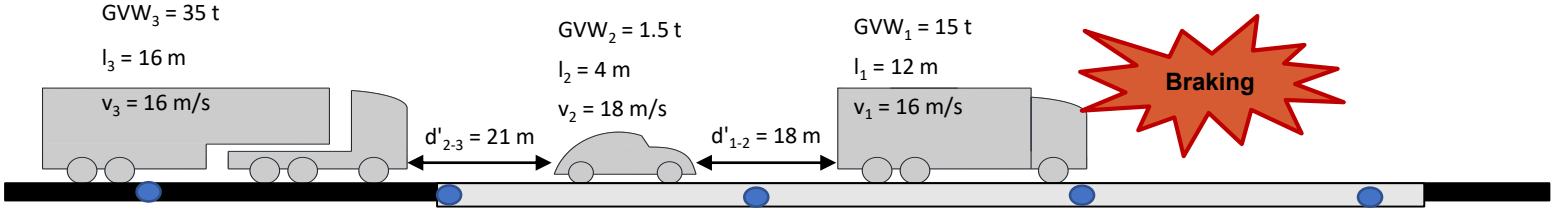




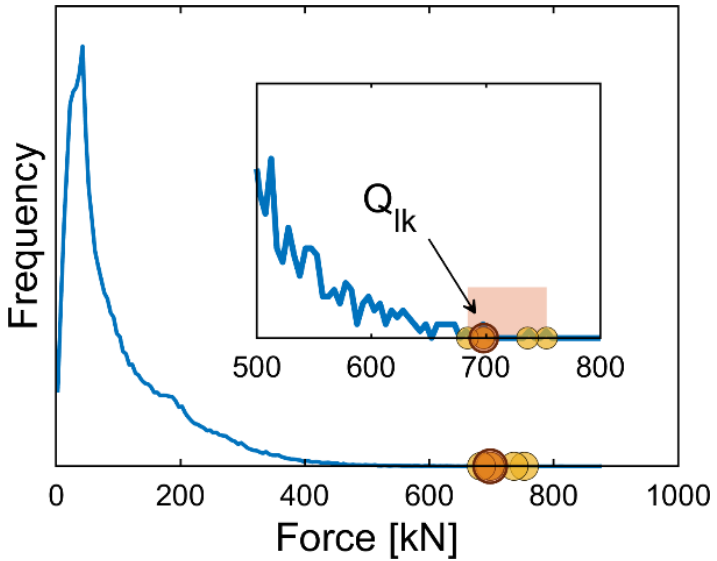


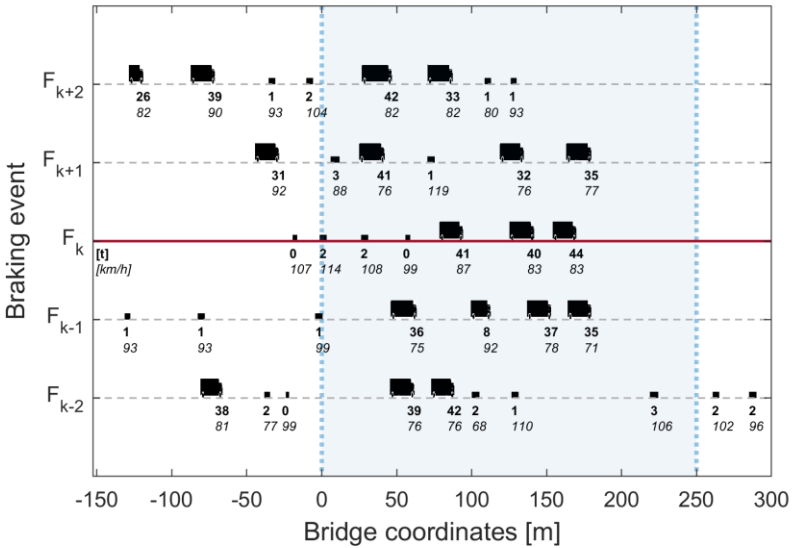


Acc.profiles form: Dingus et al. (2006)



Braking characteristic value





Rate of braking events (R)

- The model requires a parameter that describes how often braking events occur, this can be expressed in “hard braking event per travelled unit distance” (3 event every 1000 km travelled)
- Dingus et al. 2006 → 7.1×10^{-8} $(veh\cdot m)^{-1}$ threshold: 4 m/s^2
- Olsen et al. 2009 → $6.5\times10^{-7}(veh\cdot m)^{-1}$ threshold: 2 m/s^2
- Martins et al. 2016 → $7.0\times10^{-7}(veh\cdot m)^{-1}$ threshold: 4 m/s^2 Based on Dutch AOS study on accident prevention

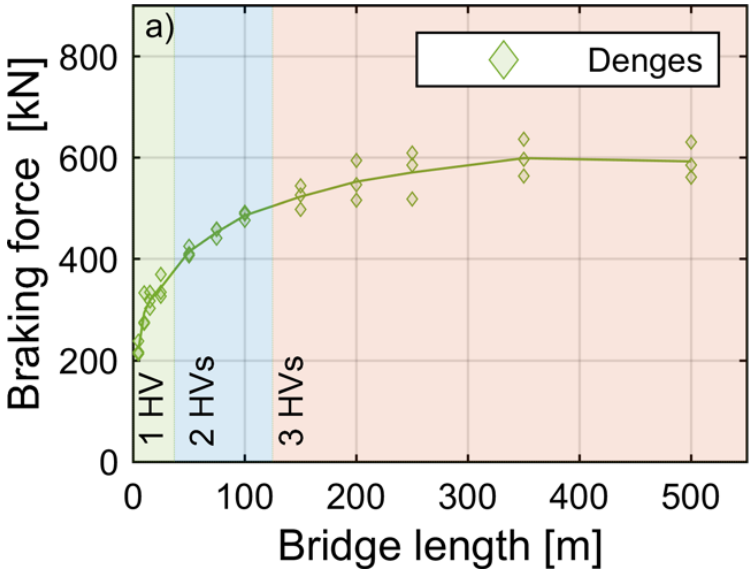
Actual period of time covered by the simulations

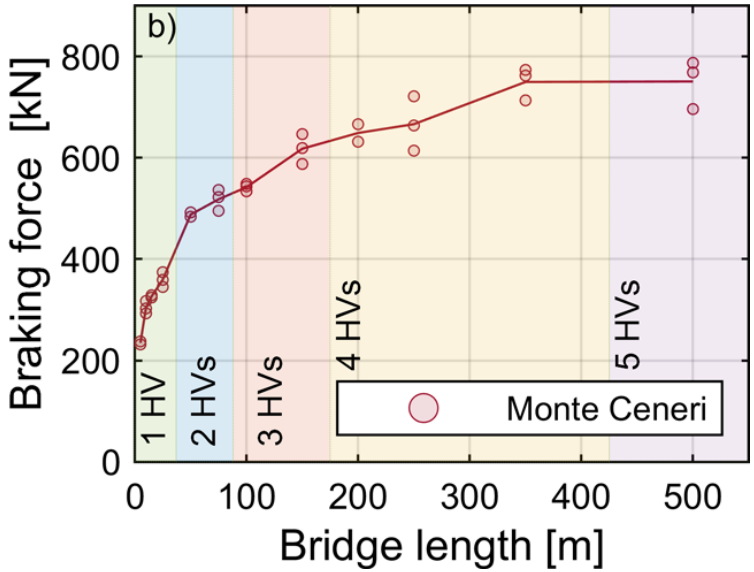
$$k \approx \frac{\Delta t_{eq}\left(\Delta l, \Delta t_{\mu}\right)}{(PR)\cdot R}$$

Return period

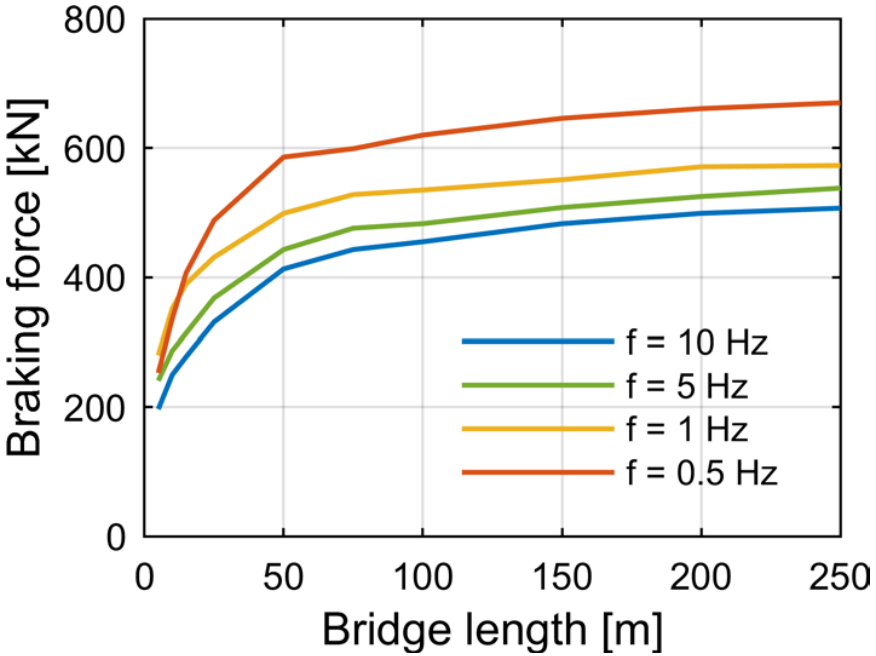
A supervised learning classification algorithm was developed to compute the distance travelled per road type (motorway, regional and local roads), from the speed profile only.

Results

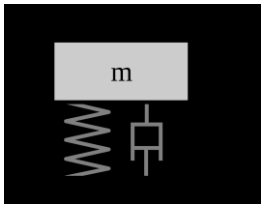

a)
Denges
Braking force [kN]
0
200
400
600
800
1 HV
2 HVs
3 HVs
0
100
200
300
400
500
Bridge length [m]

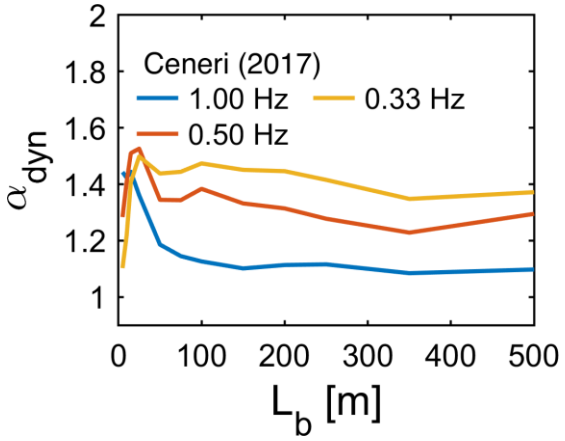

b)
Braking force [kN]
0
200
400
600
800
1 HV
2 HVs
3 HVs
4 HVs
5 HVs
Monte Ceneri
0
100
200
300
400
500
Bridge length [m]

Impact of natural frequency on characteristic value of the braking force

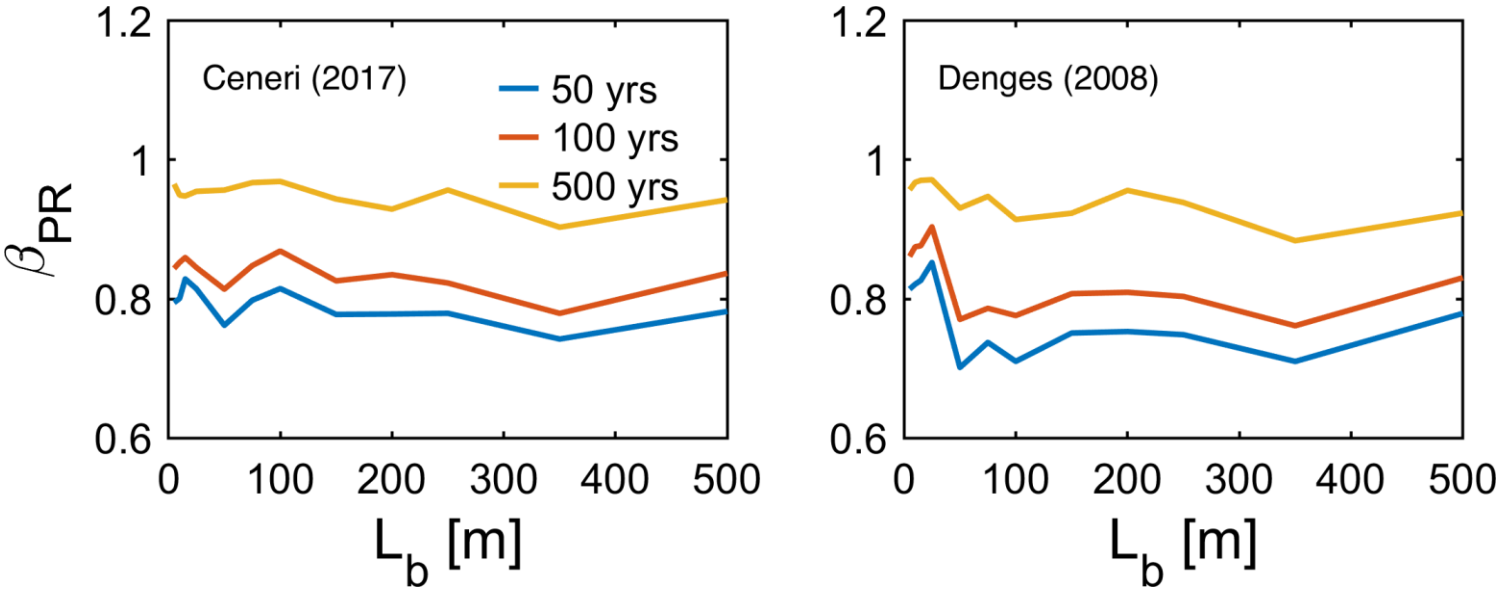


- Dynamic amplification increases with decreasing natural frequency of longitudinal bridge mode (linear SDOF model)

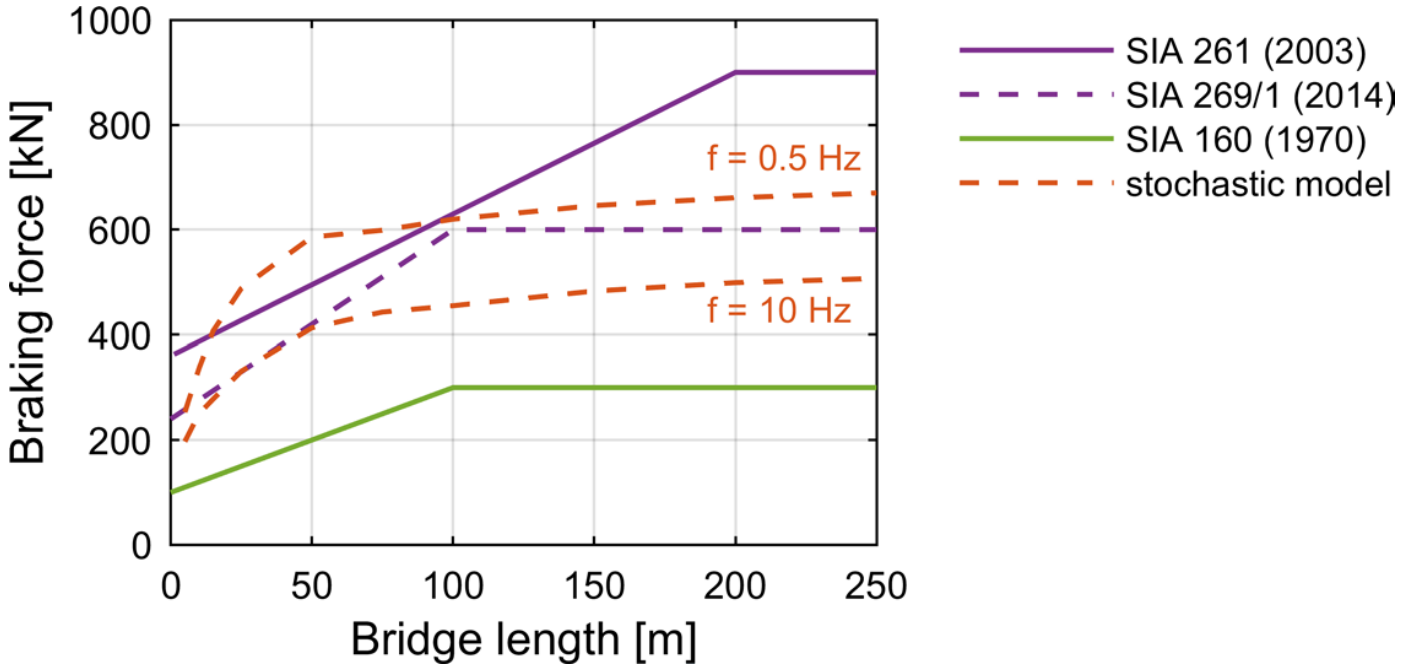




Impact of return period on characteristic value of the braking force



Comparison of characteristic value of the braking in codes in Denges/Préverenges



Findings I

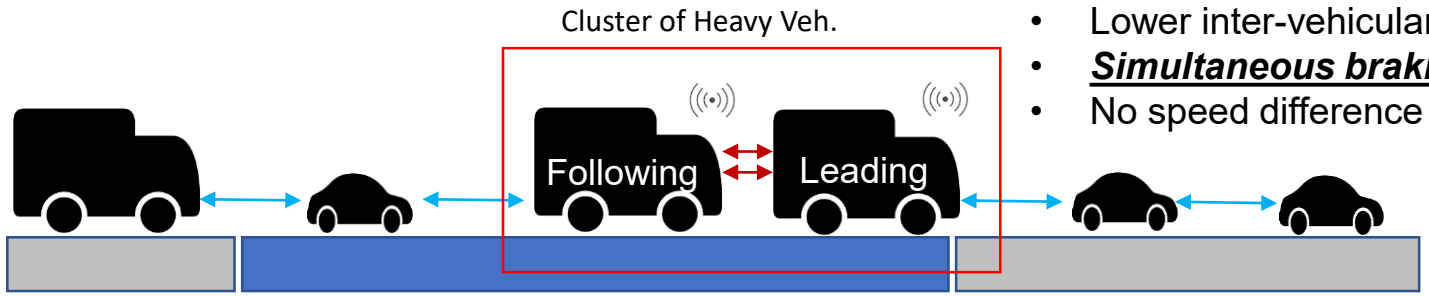
- The usage of traffic data and data recorded on instrumented vehicles combined with stochastic simulations allows designing the action for a specific bridge.
- The code model for existing bridges (SIA 269/1) fits reasonably well with the braking force of the stochastic model.
- However, the quality of this action depends very much on the quality of data.
- Since the data concerning the braking of heavy vehicles is still scarce, further investigations are necessary to improve data quality and, consequently, the quality of the estimated braking forces.

Platoons of heavy commercial Effects on braking forces (2)

Platoons of heavy commercial → Higher braking forces Effects on bridges ?

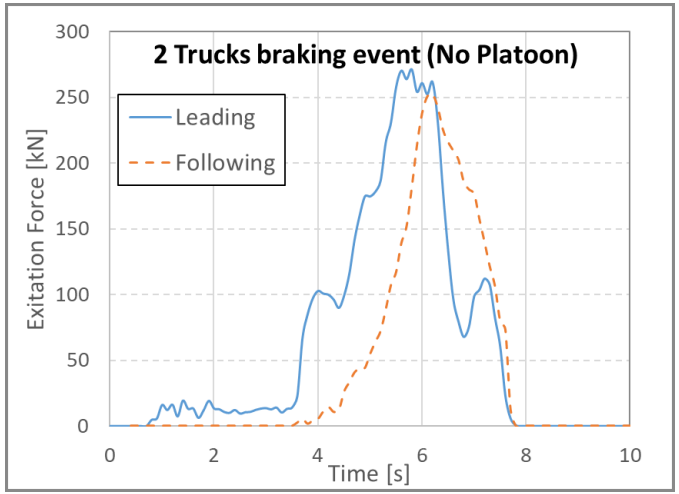
(2) Matthew S, Nussbaumer A, Breveglieri M, Glauco F. AGB 2017/004 Impact of heavy vehicle platooning on Swiss bridges. 2022, Forschungsbericht ASTRA.

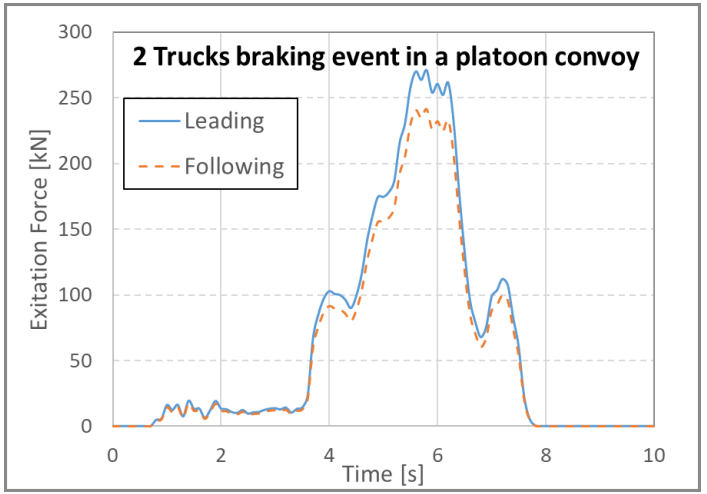
Braking forces induced by truck platoons



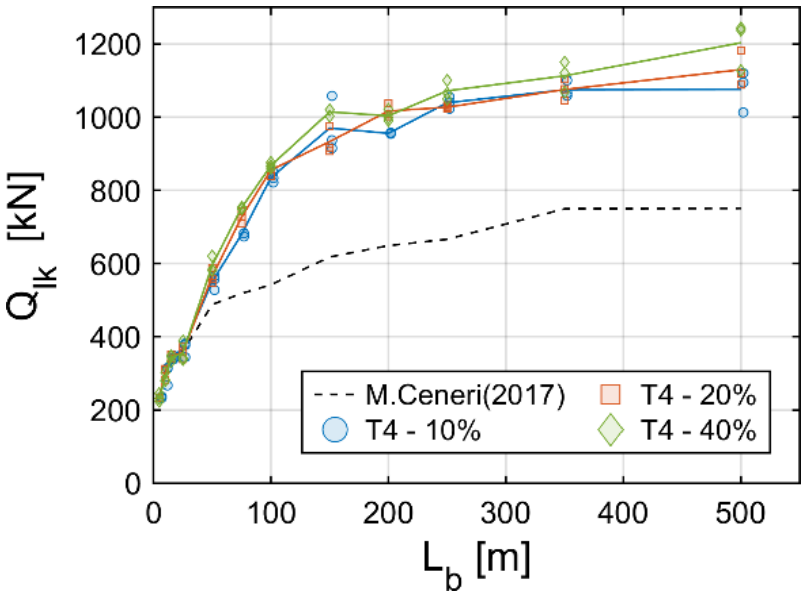
- Lower inter-vehicular distance
- ***Simultaneous braking***
- No speed difference

Bridge [L (length), T (peridod) , ξ (damping)]





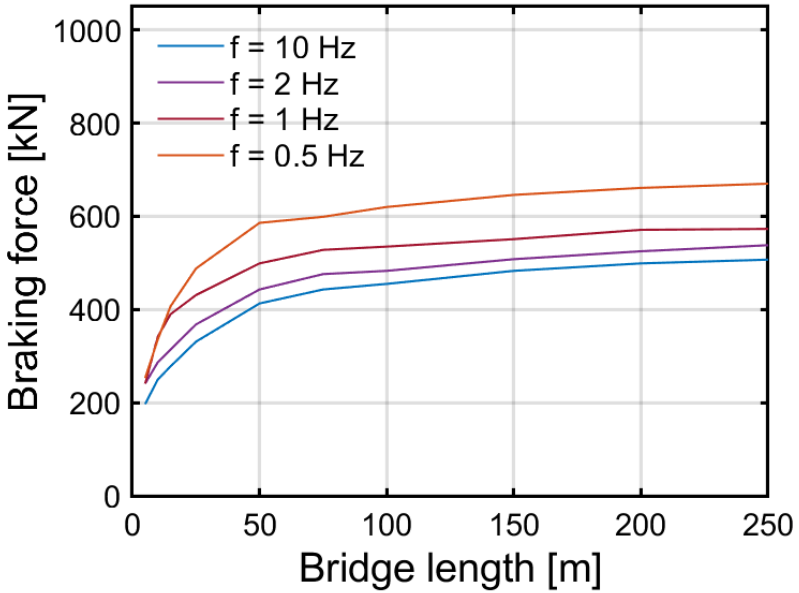
Findings II

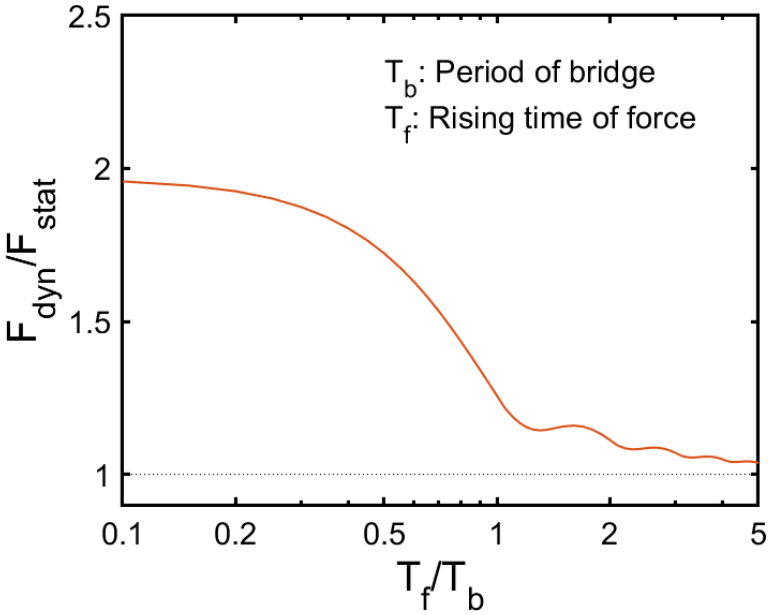


- Braking forces on highway bridges will certainly increase with the deployment of platoons.
- The platoon size turns out to be the most important factor.
- The impact of 2-truck platoons is generally rather limited. 4-truck platoon traffic can almost double the value of the characteristic value of the braking force.
- Furthermore, the penetration rate has a small impact on braking force.

How accurate is a linear SDOF model?

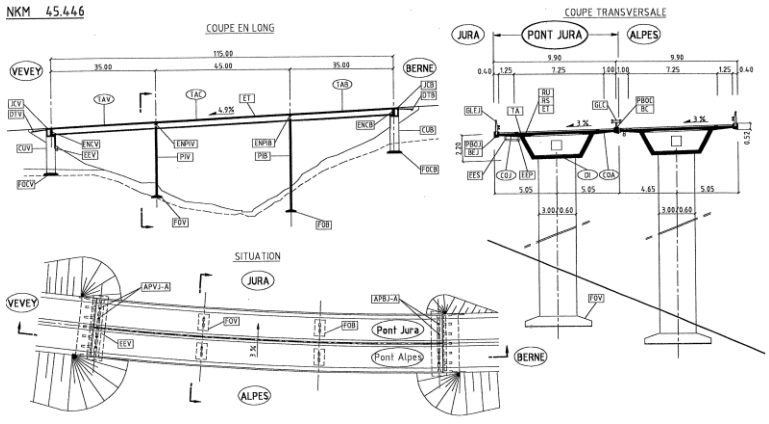
- Force induced by braking vehicles is an impulsive force





Model Validation: Bridge test (3)

- Motorway bridge “Viaduc de Matran” (1968-1970)
- 3 span box girder bridge with floating articulation: Reinforced concrete piers monolithically connected to box girder, abutment with elastomeric supports
- Design braking force: 204 kN



(3) Feltrin G. AGB 2017/002 Validation of the model for computing the dynamic action of the braking force on road bridges, 2021, Forschungsbericht ASTRA.

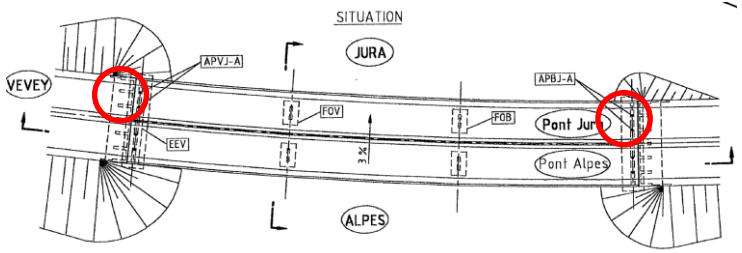
Bridge instrumentation (displacement transducer)

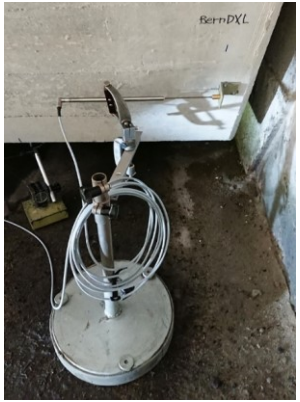
- Each abutment:

2 longitudinal displacements (relative to abutment)

1 lateral displacement (relative to abutment)

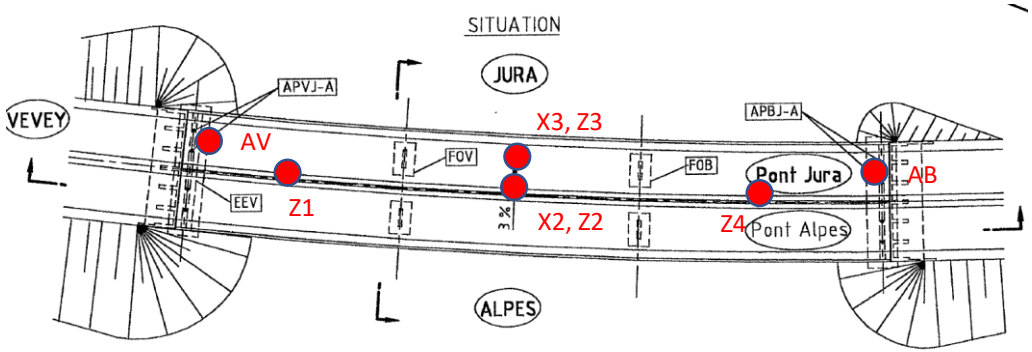
3 vertical displacements (relative to abutment)





Bridge instrumentation (accelerometers)

- Longitudinal vibrations of bridge deck (X2 und X3)
- Bending and torsional vibration of bridge deck (Z1, Z2, Z3 und Z4)
- Longitudinal vibrations abutments (AB und AV)

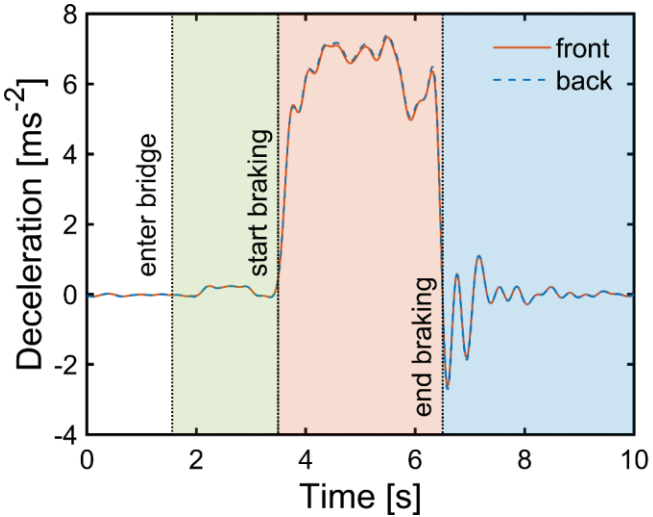


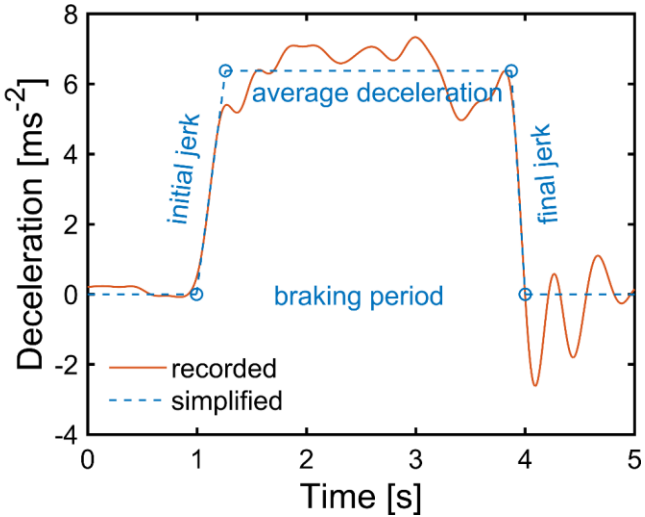
Vehicle instrumentation

- GPS antenna (position and speed)
- 2 capacitive accelerometer (deceleration)
- 2 capacitive accelerometer (vertical vibrations)

Vehicle deceleration

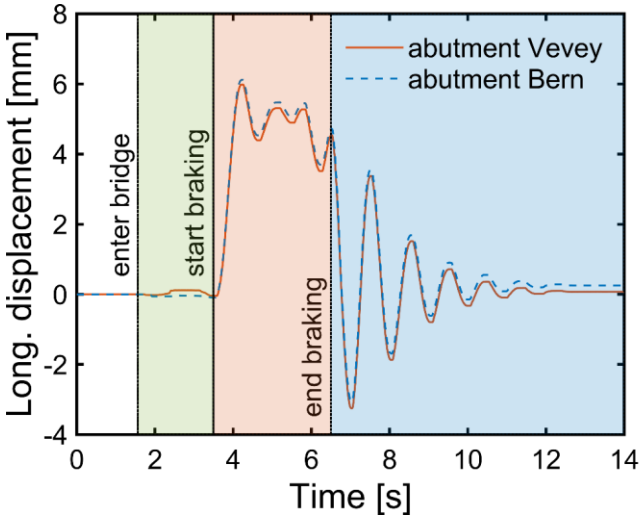
- Rapid increase of deceleration when starting to brake (initial jerk)
- Period of high deceleration
- Rapid decrease of deceleration shortly before vehicle stop (final jerk)
- Longitudinal vehicle oscillation after vehicle stop

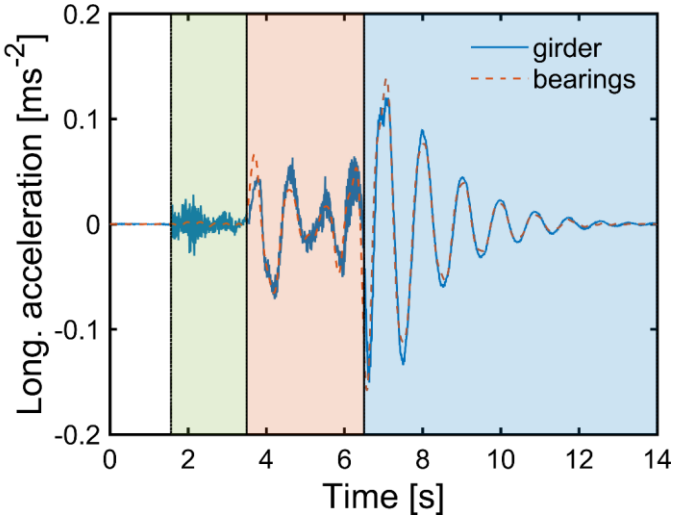




Longitudinal bridge motion

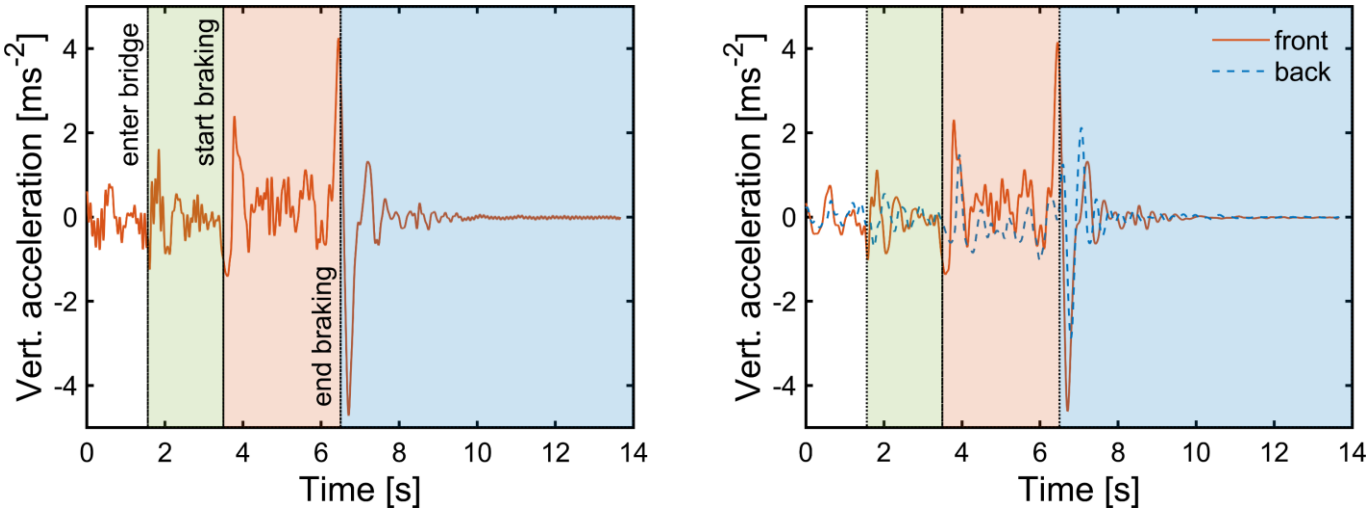
- Longitudinal displacement similar to vehicle deceleration during braking phase
- Strong vibrations after vehicle stop
- Vibration decay due to structural damping
- Acceleration derived from longitudinal displacement agree with recorded acceleration





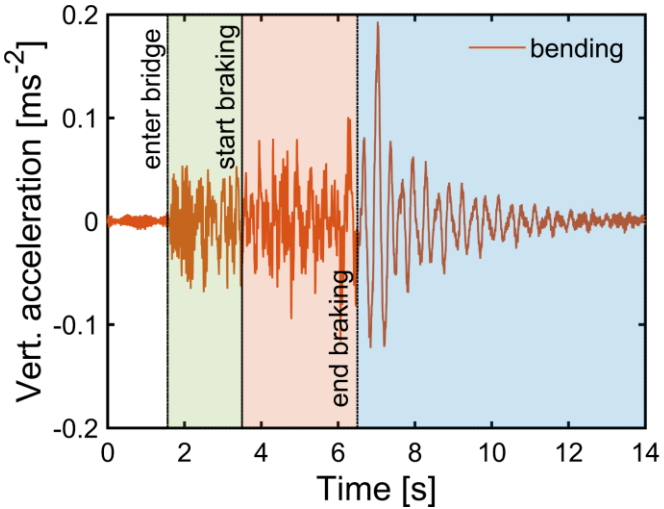
Vertical acceleration of vehicle

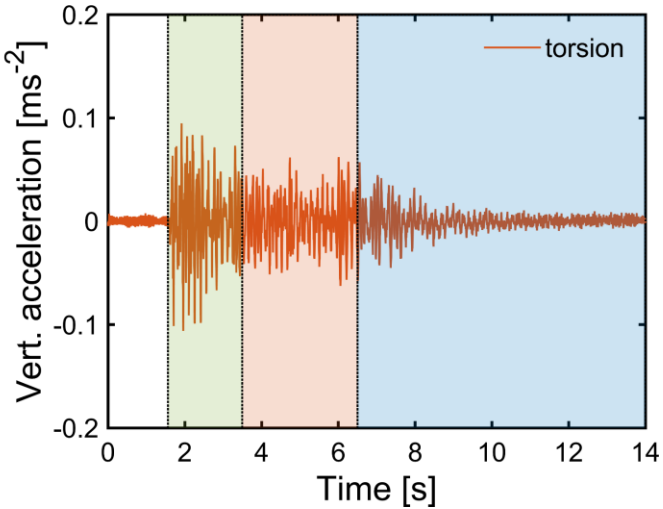
- Strong vertical accelerations at start and end of braking phase
- At end of braking phase much stronger than at start
- Front part of vehicle had higher accelerations than end part



Bending and torsional vibrations of bridge

- Strong bending vibrations at the end of brake (1st bending mode, 3.03 Hz)
- Any torsional vibrations at the end of brake (1st torsional mode, 7.04 Hz)





Findings III

- The bridge behaved non-linearly and much stiffer than expected
- The dynamic response of the bridge was depending on driving direction
- Strong non-linear behavior (stiffening) of the bridge increases the dynamic amplification

- A linear SDOF bridge model is a good approximation for determining dynamic amplification, provided the non-linear behavior remains moderate. However, it underestimates the longitudinal deformations

- Further tests need to be done to better understand the dynamic effects

How to improve the model: The quality of the model depends on the quality of the provided data [4]

- Collection of data on braking events

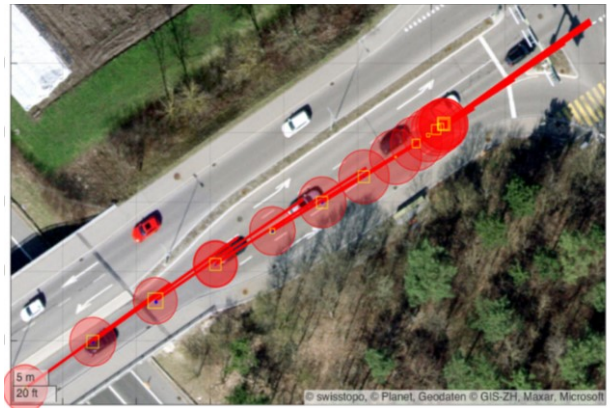
How often do you brake hard?

Where do you brake hard?

How much deceleration is applied?

- Very little data available:

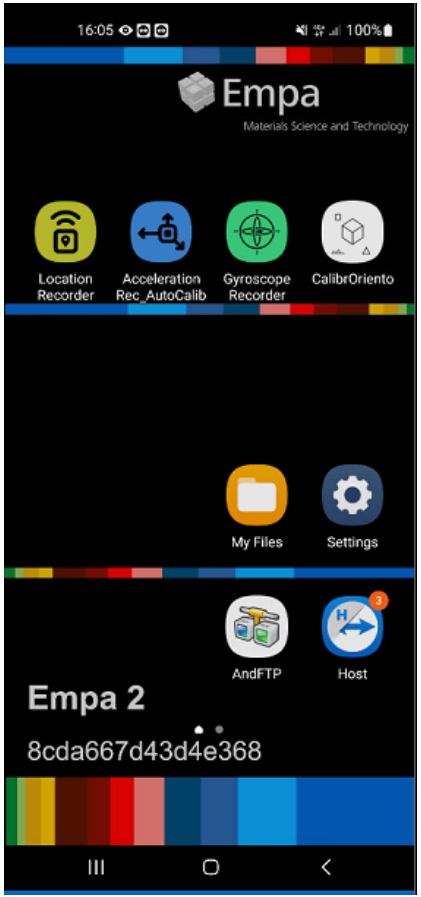
Field tests with instrumented vehicles
The 100-Car Naturalistic Driving Study (USA)
AOS Field Operational Test (Europe)



[4] Feltrin G.,Breveglieri M. BGT_20_02D_01 Monitoring of braking events of heavy vehicles for determining braking forces on road bridges, 2024

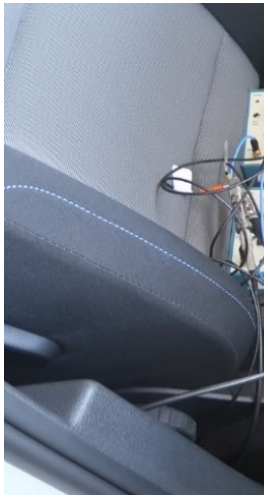
Monitoring of braking events

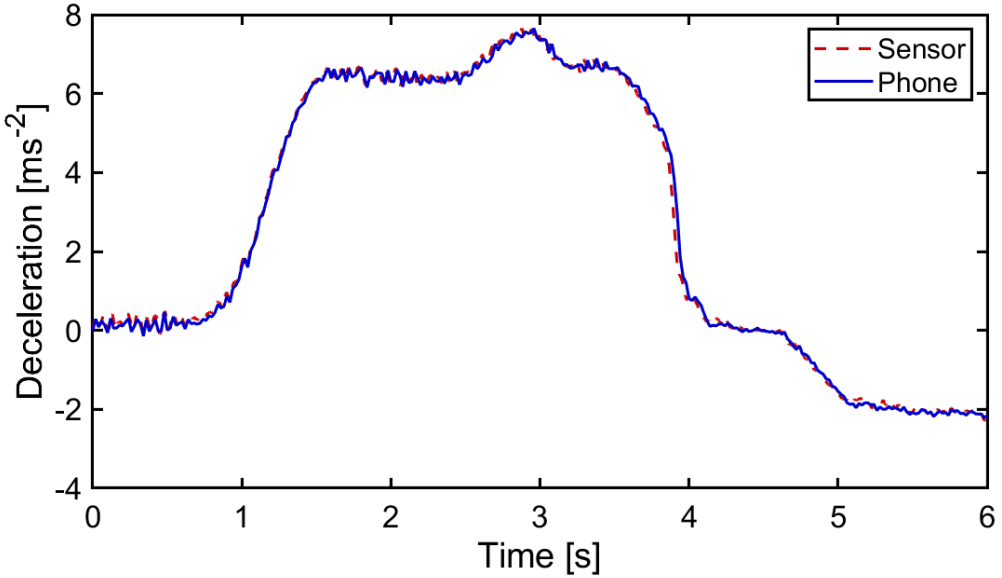
- Smartphone as a sensor
- Cheap monitoring and communication device
- Apps recording
  - Vehicle position (GPS)
  - Vehicle deceleration (Accelerometer)
  - Vehicle angular velocity (Gyroscope)
- Automatic data upload to server
- Remote maintenance (TeamViewer)

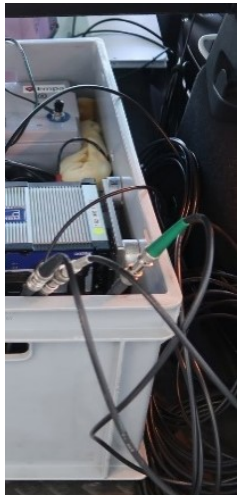


Deceleration record with smartphone

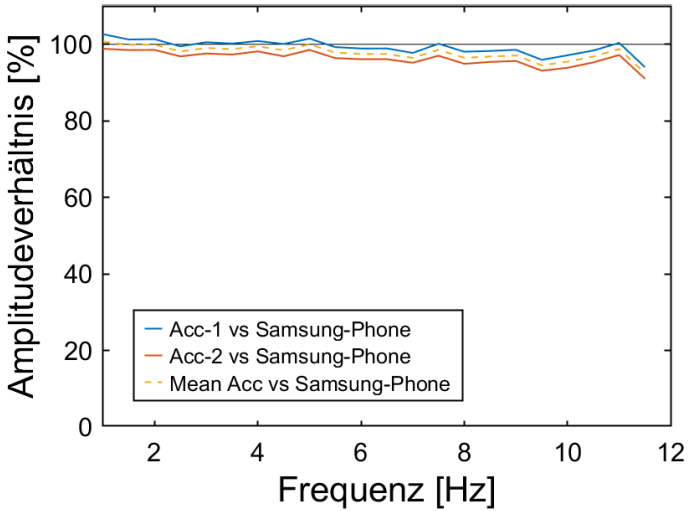
- Comparison with high accuracy sensor and data acquisition device

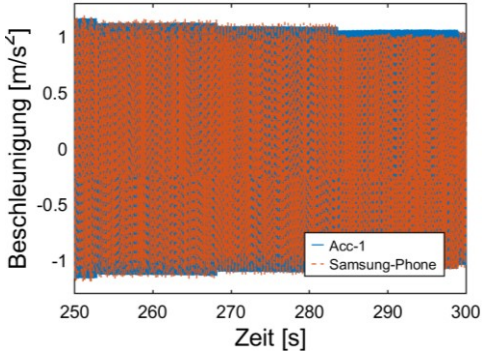


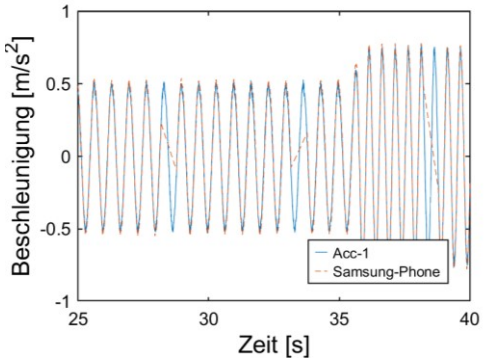




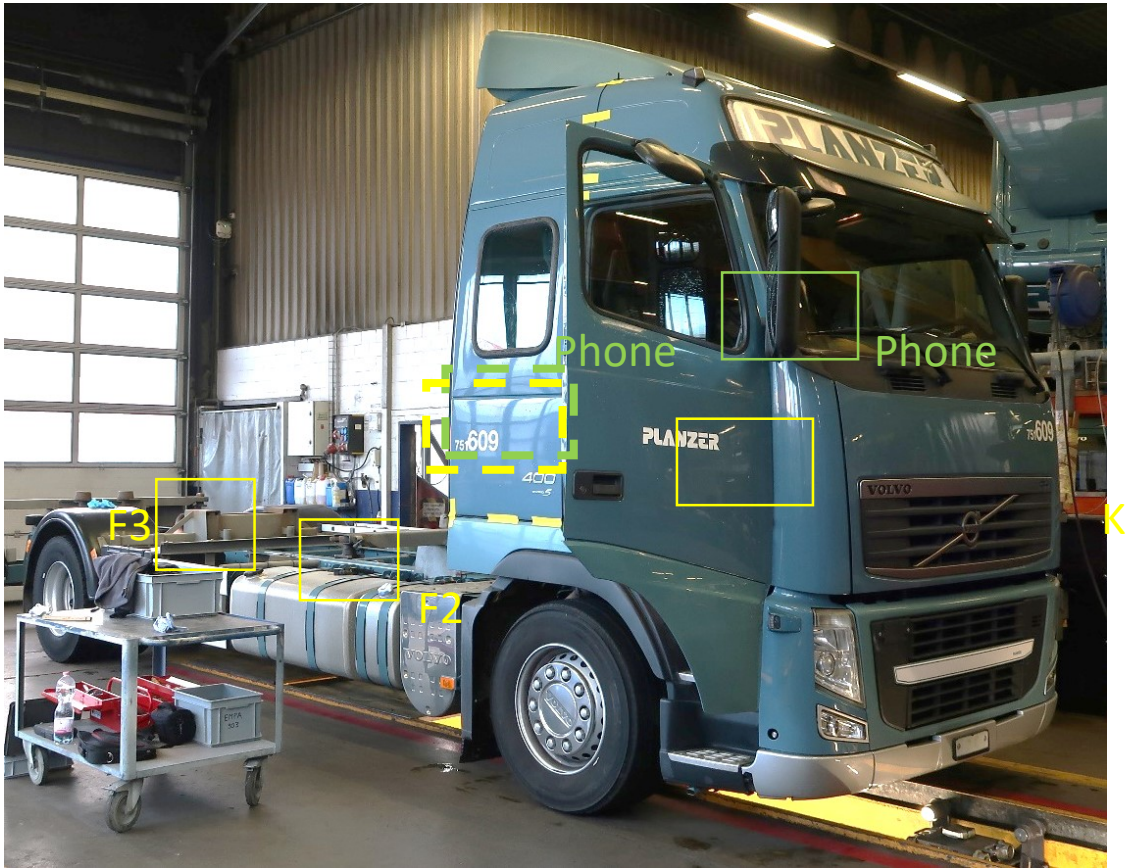
Experiment with shaker

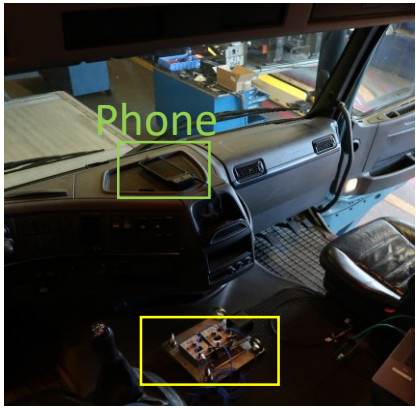




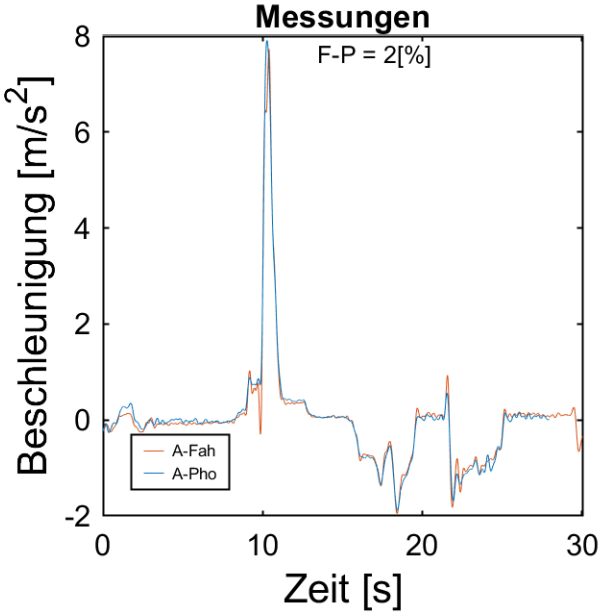


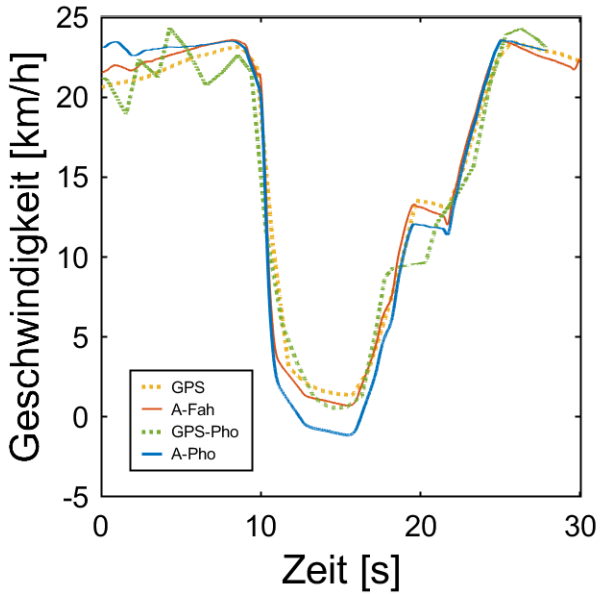
Accuracy data braking events with smartphone test





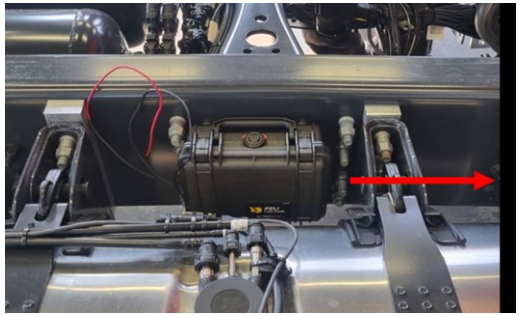
Correction with transfer function





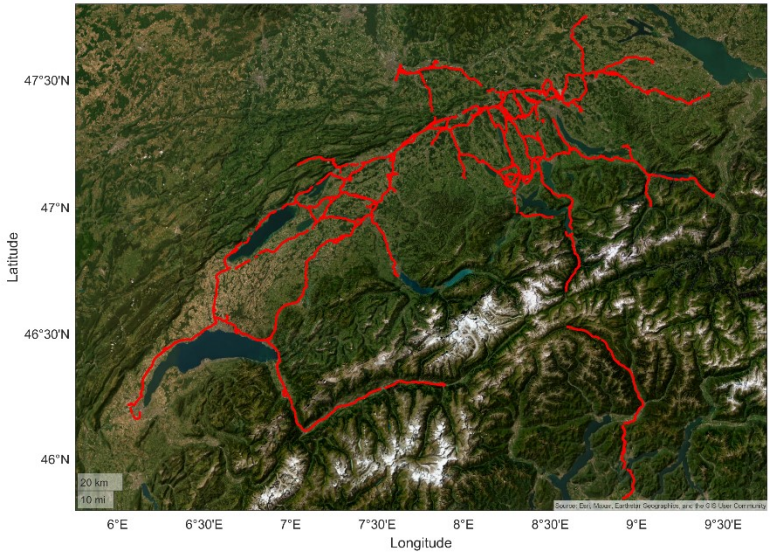
Numerical correction→ Characterisation of the transfer function between chassis and smartphone location

Mounting of smart phone on trucks



Pilot Test with one Truck

- Checking the reliability of the smartphone
- Checking the connection between smartphone and data server
- Development of additional analysis programs
- Tests for app management and solving potential problems (app crash)

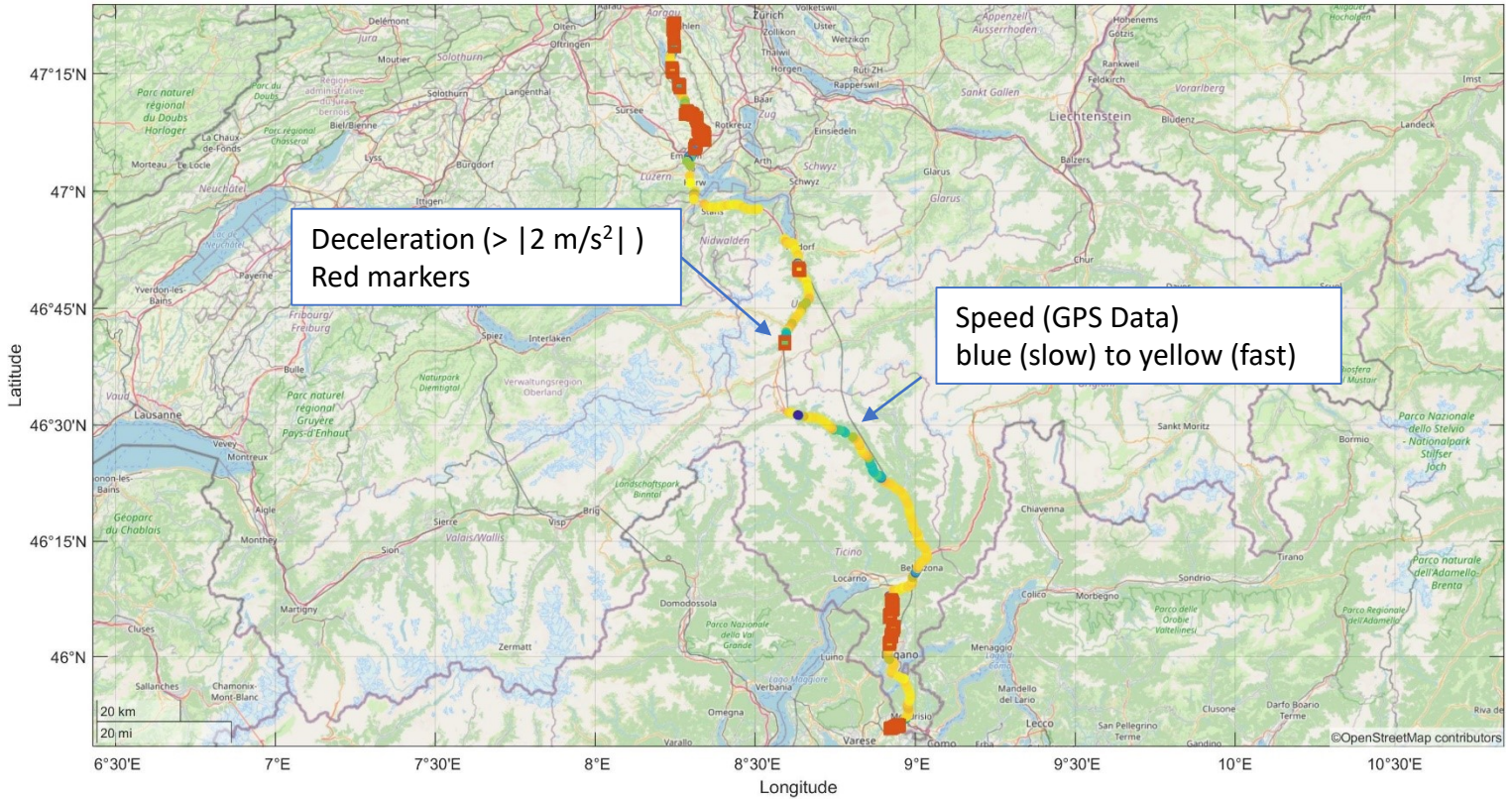


06.03.2023 bis 28.05.2023 → 20’936 km

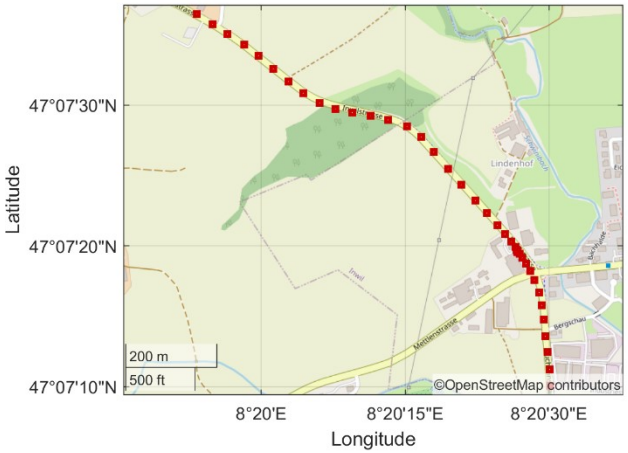
Test Phase
in cooperation with Planzer AG

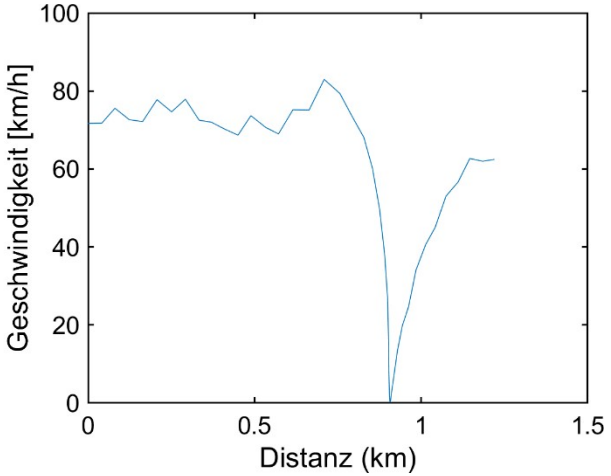
A fleet of 22 trucks will be driving across Switzerland for a period of 6 to 9 months. Various types of truck are being employed on the main routes.

Record of a day



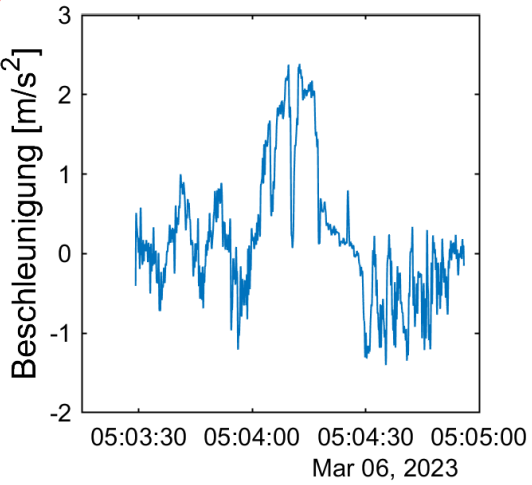
Braking event





GPS Data

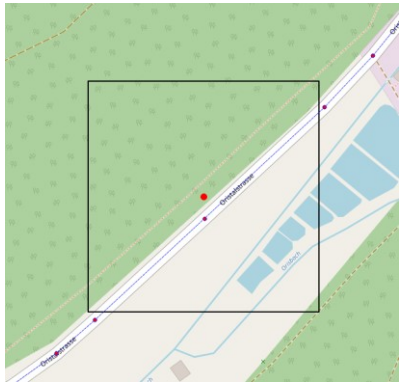
(+) Deceleration

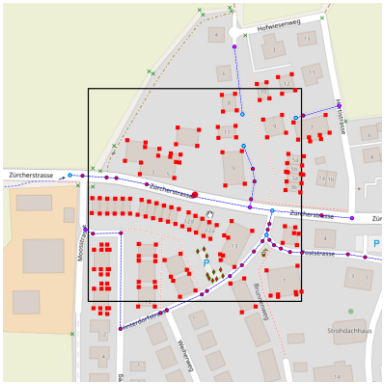


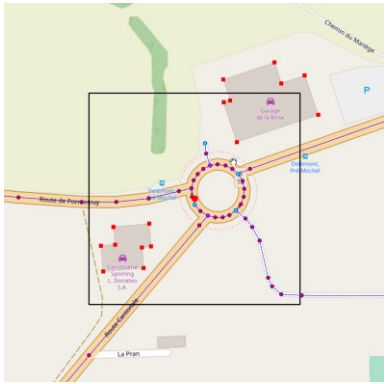
Acceleration-Data

Analysis of braking events

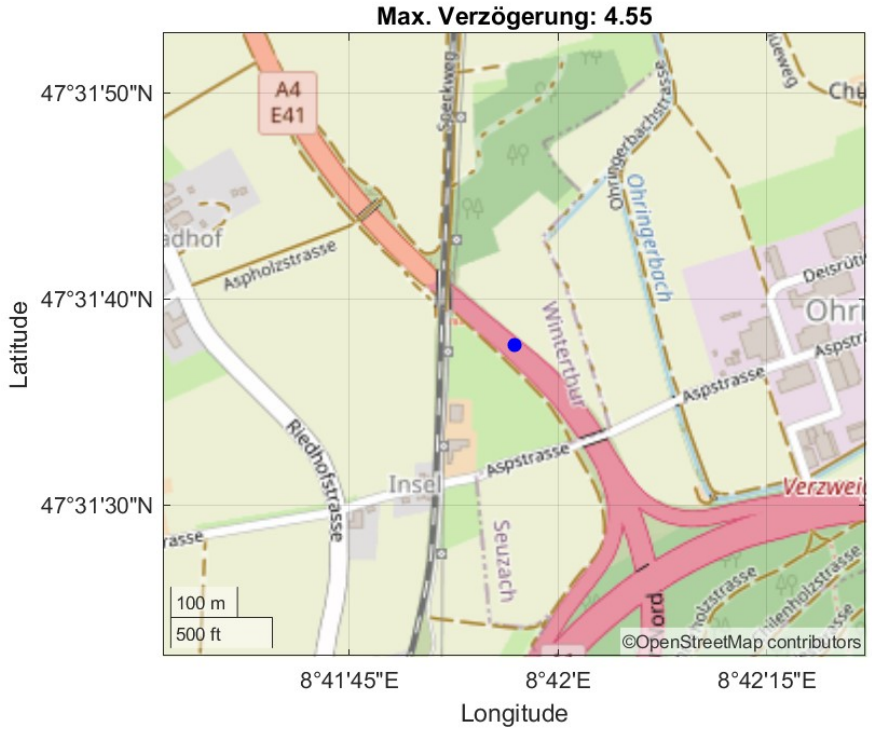
- Rate of braking events for each road category and situation
- Classifying braking events combining recorded vehicle data with road network and geographic data (OpenStreetMap)
  - Road course (straight section, bend)
  - Road morphology (driveway, intersection, roundabout)
  - Settlement density (urban, suburban, non-urban)
- Autonomous classification







Geolokalisierung: Strassenklasse



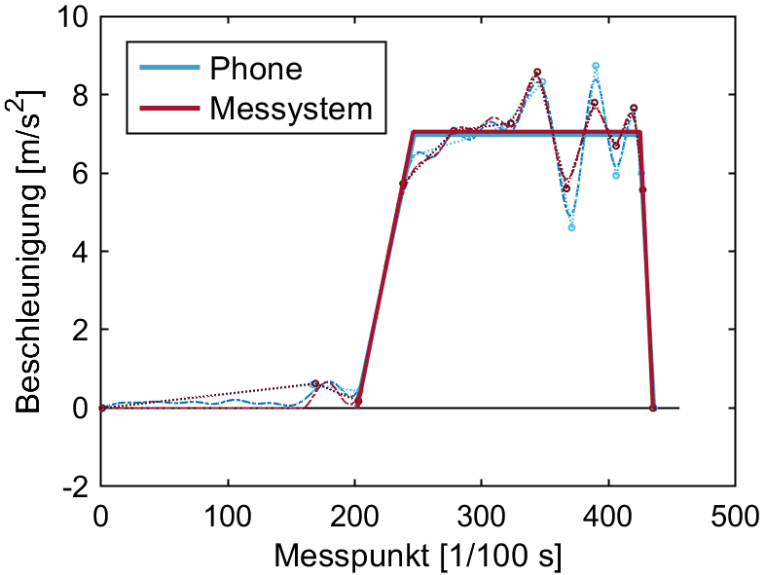
<u>Klasse 1: Autobahn</u>
Klasse 2: Hauptstrassen
Klasse 3: Nebenstrassen

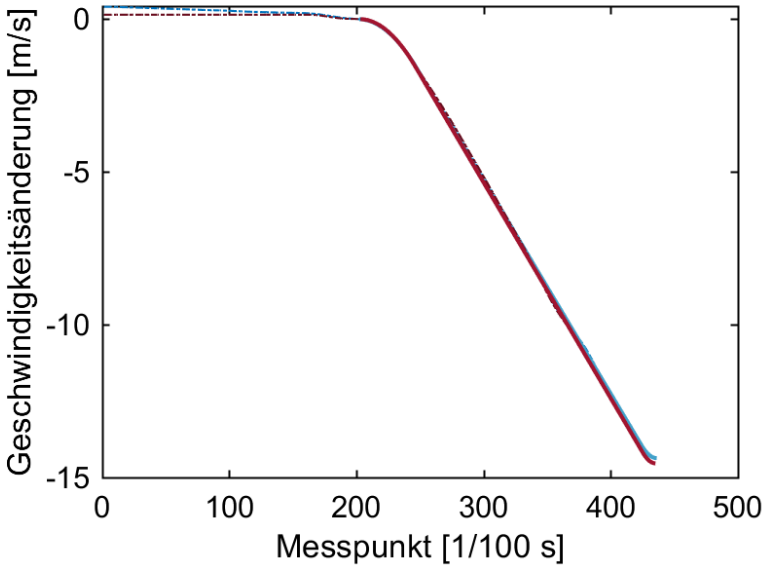
Geolokalisierung: Strassenklasse

Klasse 1: Autobahn
Klasse 2: Hauptstrassen
Klasse 3: Nebenstrassen

Parameters for characterizing a deceleration profile

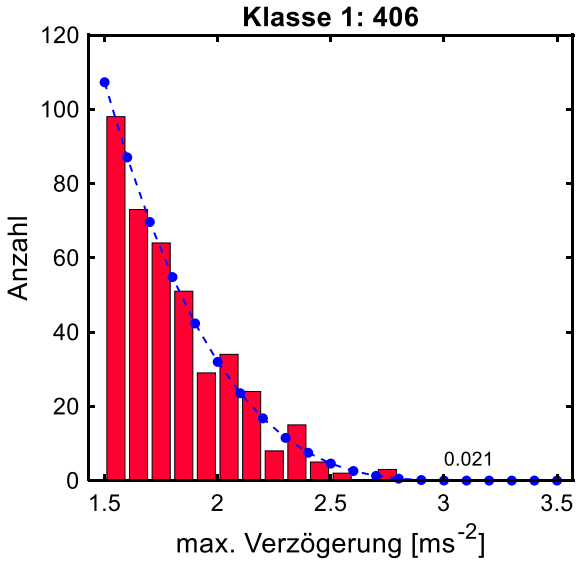
- Maximum acceleration, plateau acceleration, maximum jerk, minimum jerk, time to braking, time to peak, time over a threshold, change in speed

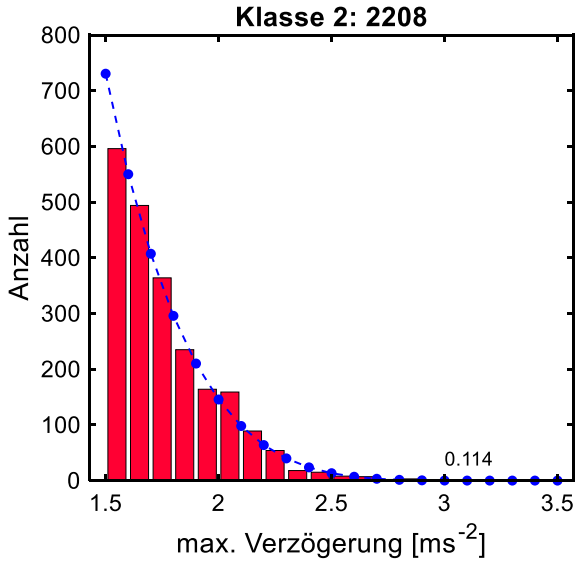


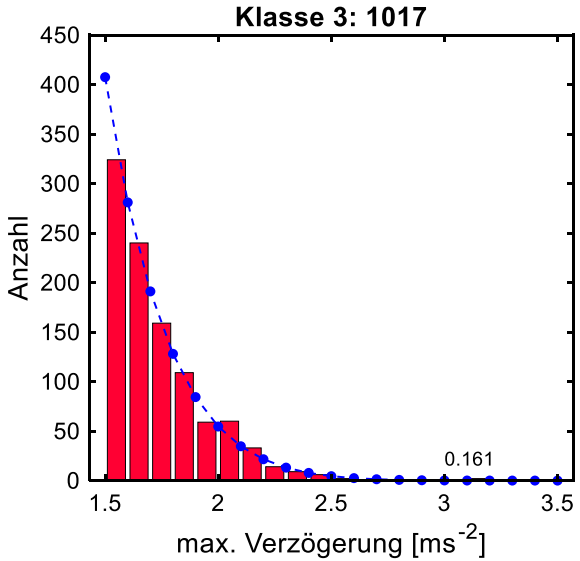


Braking events
Daten Planzer AG – Fleet Box

- ca. 40’500 km
- 3631 Events mit max. Deceleration > 1.5 ms^{-2}
- 260 Events mit max. Deceleration > 2 ms^{-2}
- 1 Event mit max. Deceleration > 3 ms^{-2}







Outlook

- Goals
  - Collect broad and detailed information on hard braking events on the Swiss road network
  - determine specific occurrence frequencies of braking events for different road categories and road network topologies
  - verify the characteristic values of the braking forces developed in the project AGB2011/003 "Updated Braking Forces for the Assessment of Road Bridges".
  - determine the characteristic values of braking forces for specific sections of a motorway (open sections, sections with entrances and exits and sections with service stations).

Empa
Materials Science and Technology

Thank you for your attention

Planzer AG deserves special thanks

08.11.2023

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