BMW GROUP

INSIGHT INTO PARTICLE FORMATION IN FRICTIONAL CONTACTS OF DISC BRAKE SYSTEMS

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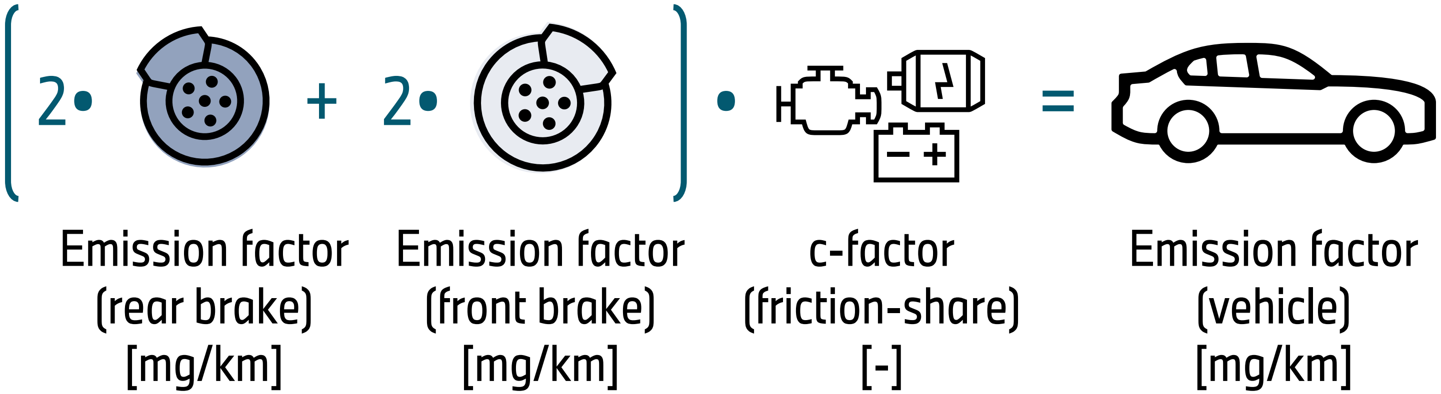
CONTENTS

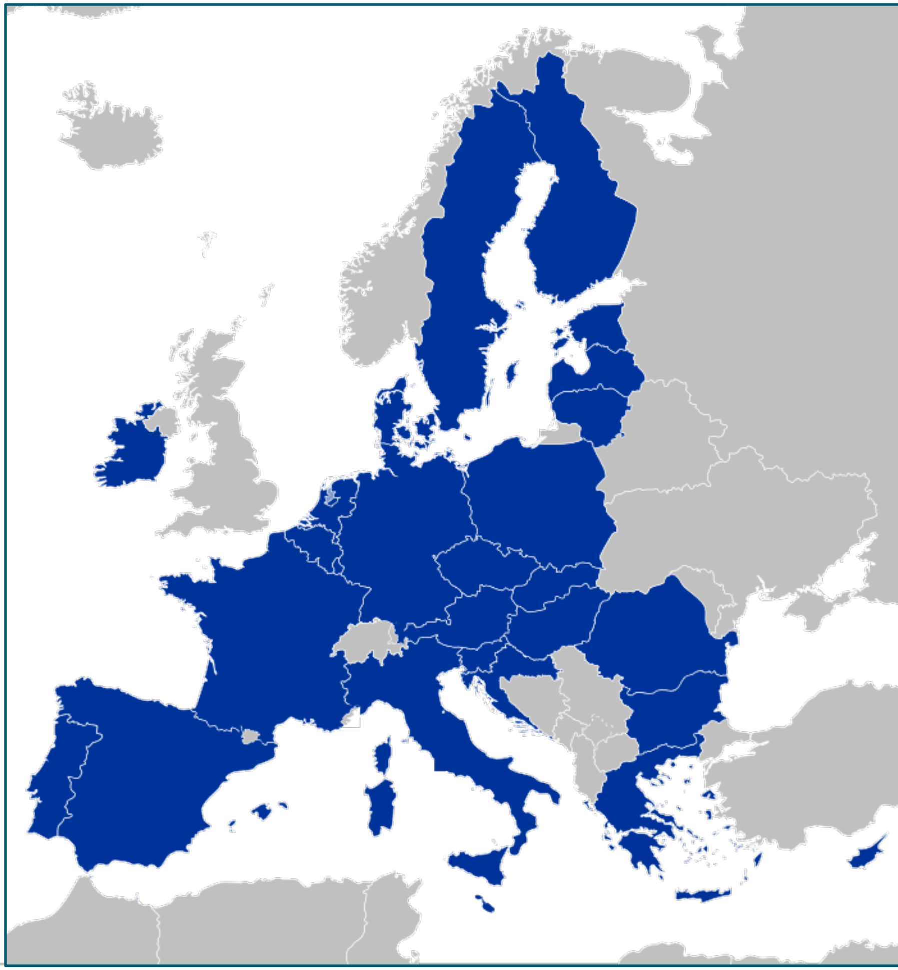
INTRODUCTION

- Implementation of legal limit for brake emissions on vehicle basis for light-duty vehicles (LDV/LCV)
  EURO 7: November 2026: new vehicle types
  November 2027: all vehicle types

- Vehicle emission factor is determined based on two single brake emission factors and the non-friction braking capability of vehicle family parent



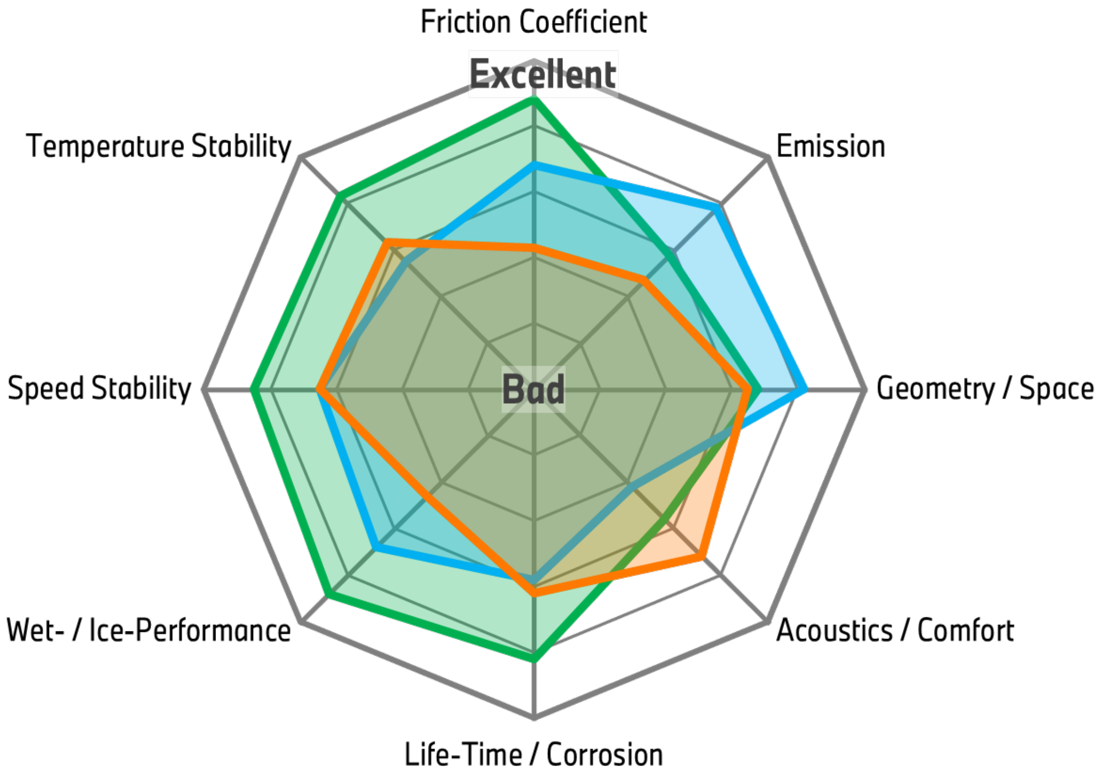
- Additional markets / countries to follow soon (ideally based on same legislative basis: UNECE GTR 24)



CONFLICT OF GOALS AND CHARACTERISTICS IN BRAKE DESIGN

Brake design and development is not an easy task:

- Vehicles may be equipped with braking different technologies (e.g. front: disc brake & rear: drum brake)
- Identical brakes may be used in different vehicles (e.g. same rear brake for ICE, Hybrids, BEV)
- Character of the vehicle or target market require different performance focus



Brakes have significantly shorter life-time than vehicle:

- After-sales market parts are of high relevance (e.g. test procedure and conditions should be vehicle independent)

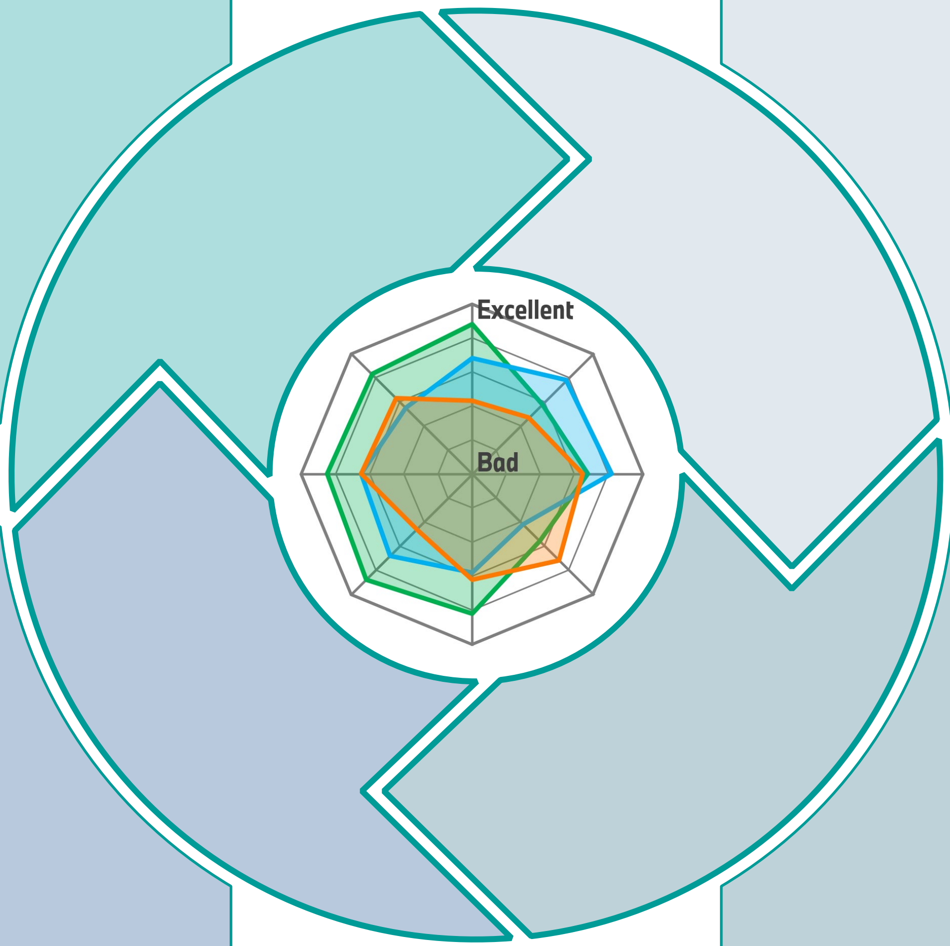
Emission testing of brakes appears to be simpler, but more topics come into play that are less relevant for exhaust

Complexity does not result from emission testing but from boundary conditions of use

SIMPLIFIED DESIGN AND TESTING PROCESS (MAIN FOCI)

evaluation of braking behaviour (**safety first**)

evaluation of emission behaviour **(legal limit)**



evaluation of NVH (acoustics) behaviour

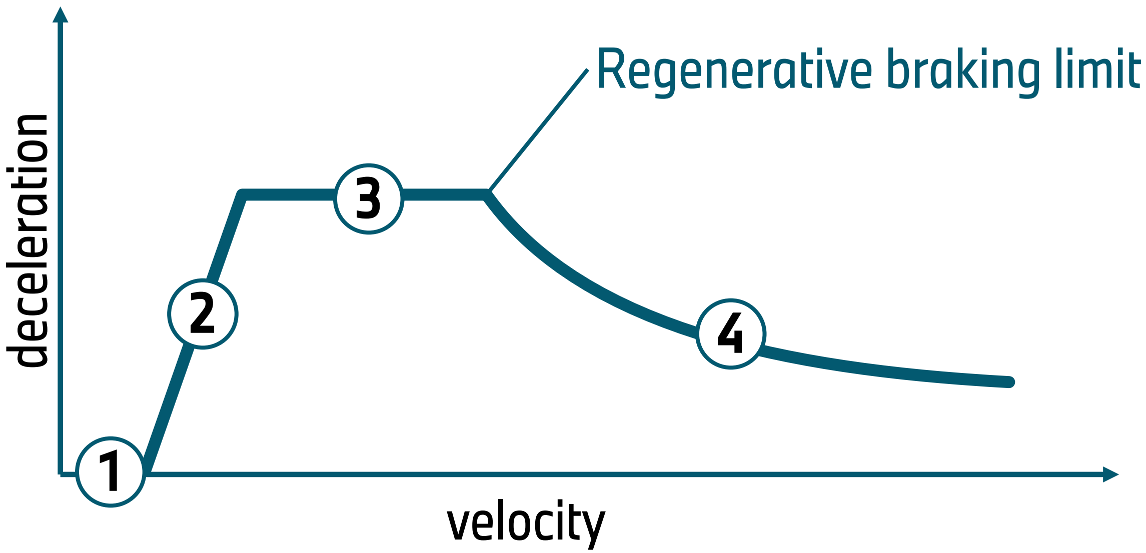
evaluation of life-time / corrosion behaviour

Complexity of requirements and impossibility of combined testing requires an iterative and time-consuming development process

TWO MAJOR FIELDS OF OPTIMIZATION OF EMISSION PERFORMANCE

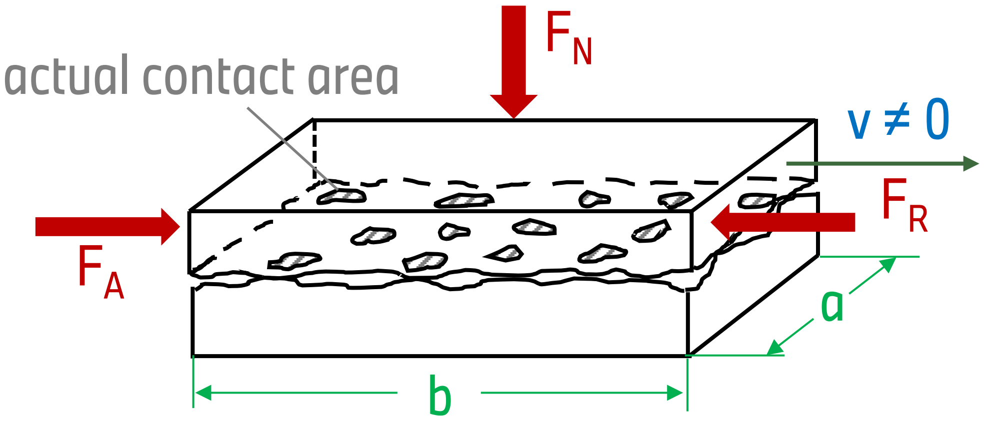
Optimization of "non-friction braking"

Taking into account the relevant boundary conditions, optimization of "non-friction braking" is directly linked to power-train and vehicle characteristics

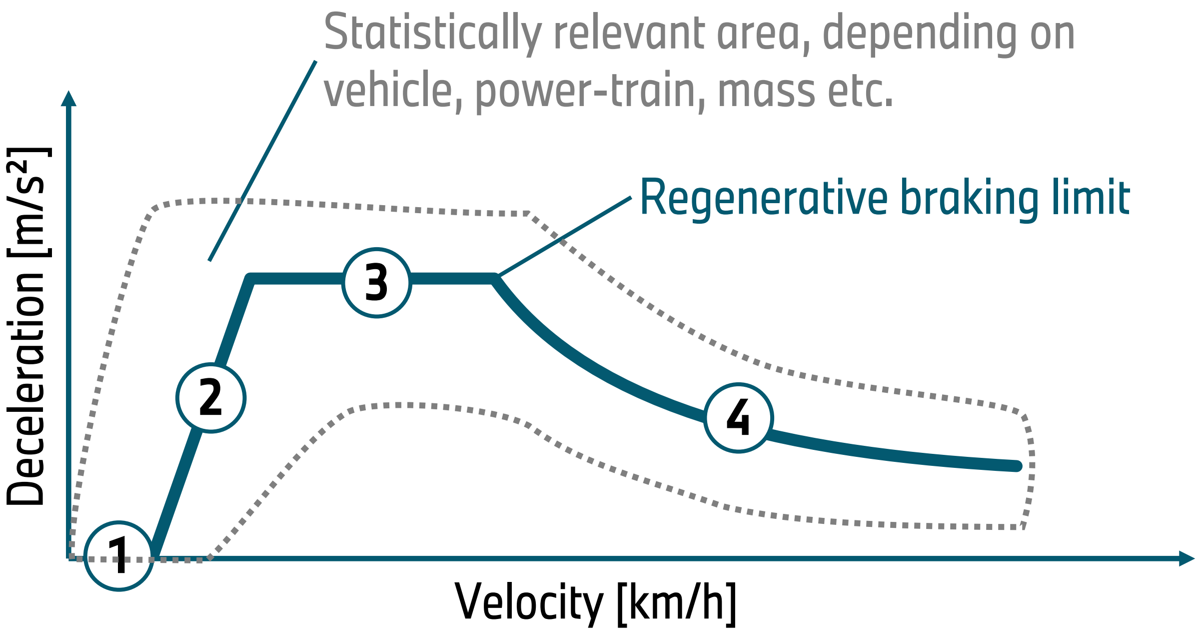


Optimization of brake system friction contact

Taking into account the relevant boundary conditions, friction contact can be optimized for emission behaviour



OPTIMIZATION NON-FRICTION (REGENERATIVE) BRAKING



Limitations of development:

1. V_{min} for regenerative braking
2. Driveability / comfort / safety
3. Vehicle stability / physical boundaries (e.g. wheel load)
4. Power / capacity limitation of electrical system

Optimization of interaction between friction brake, regenerative braking capabilities and power train

Documentation of functions and interaction of systems

Vehicle based testing and simulation

DETERMINATION OF REGENERATIVE BRAKING CAPABILITY OF VEHICLE **(FRICTION BRAKING SHARE COEFFICIENT ACCORDING TO GTR 24)**

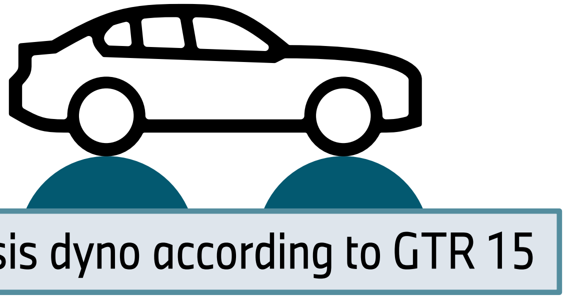
- To allow minimization of testing effort GTR 24 contains Table 5.3, defining c-factors, depending on power-train configuration of the vehicle

Table 5.3.
Friction braking share coefficients for all vehicle electrification types

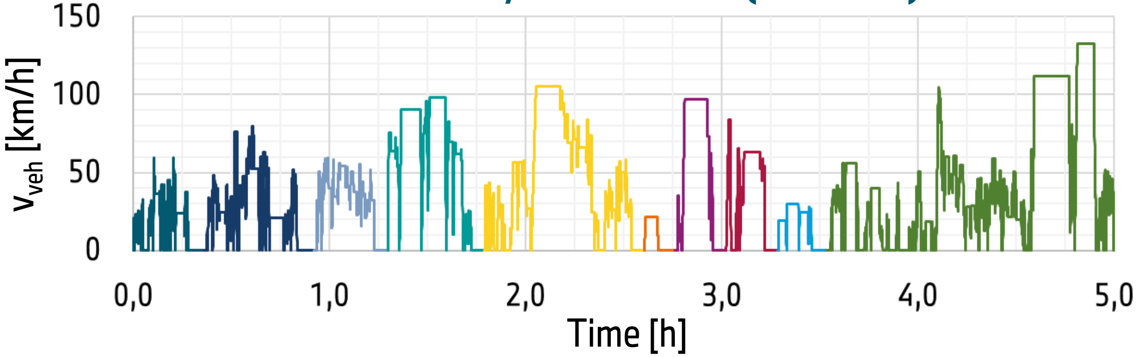
Brake type	*Vehicle Electrification Type*	*Friction Braking Share Coefficient (c)*
Full-friction braking	ICE and other vehicle electrification types not covered in the non-friction braking categories in this Table	1.0
Non-friction braking*	NOVC-HEV Cat. 0 **	0.90
	NOVC-HEV Cat. 1	0.72
	NOVC-HEV Cat. 2	0.52
	OVC-HEV	0.34
	PEV	0.17

**Note*: Testing facilities may use vehicle-specific friction braking share coefficients measured and calculated according to Annex C of this UN GTR.
***Note*: NOVC-FCHV and OVC-FCHV vehicle electrification types shall be considered as NOVC-HEV Cat. 0 for the purpose of this table.

- Alternatively, the c-factor may be derived on a chassis dynamometer by measurement of brake torque or pressure

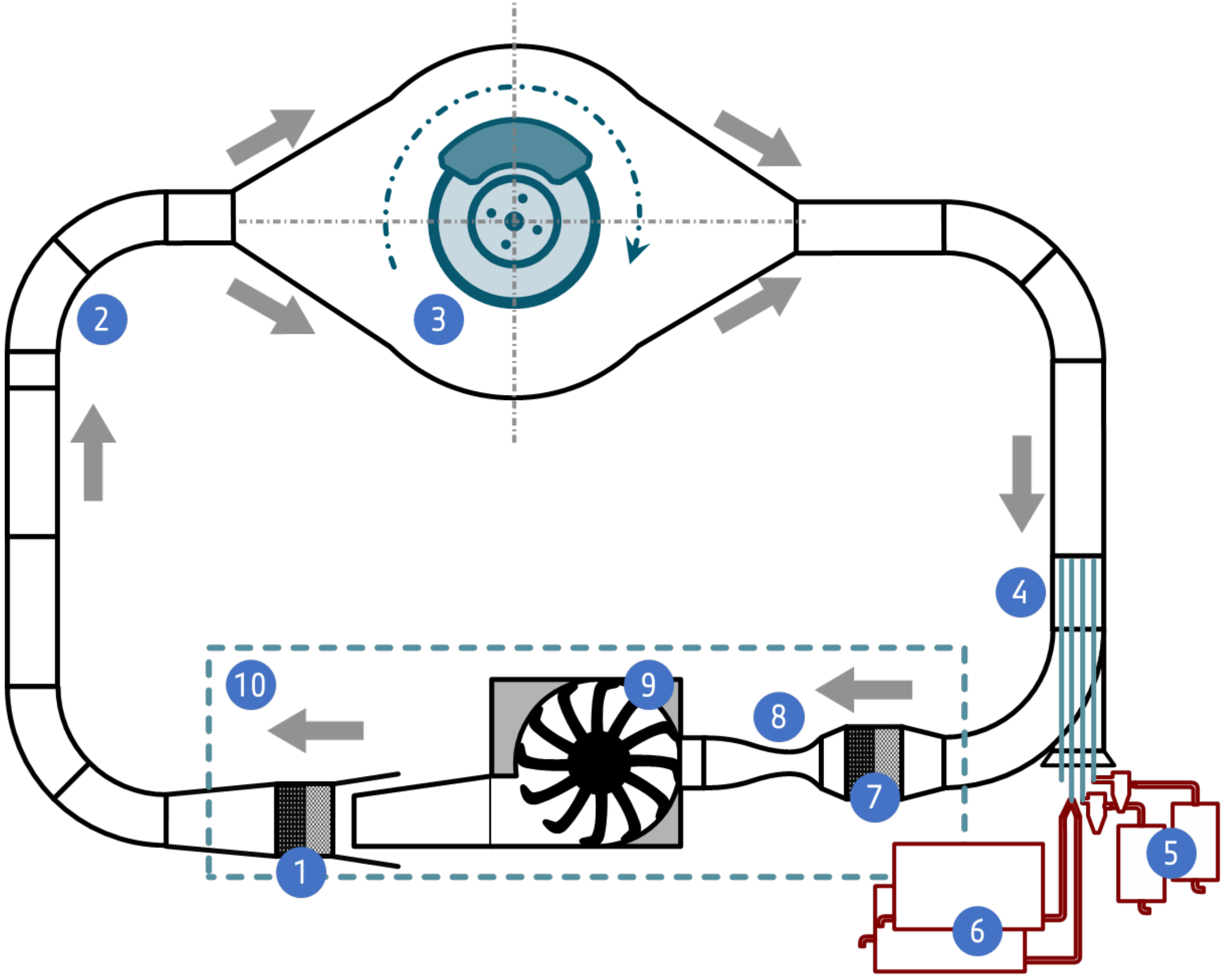


WLTP Brake Cycle ≠ WLTC (exhaust)



$$c = \frac{W_{brake}}{W_{ref}} = \frac{\text{Friction work dissipated in the friction brake system of the vehicle}}{\text{Normalized work of the reference cycle, subtracted by 13\% (accounting for driving resistances)}}$$

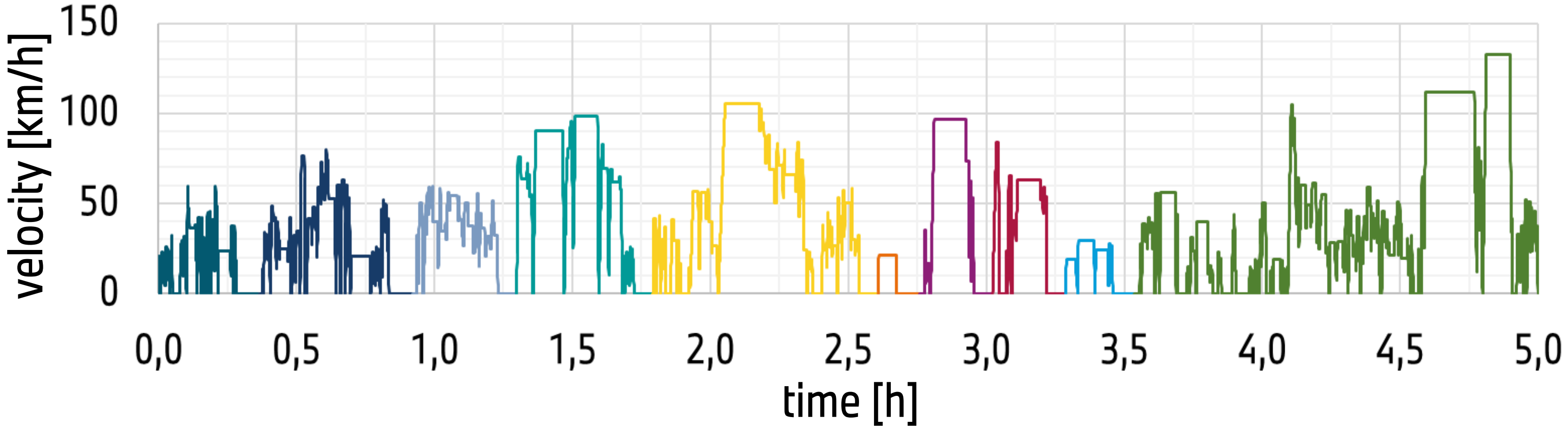
DETERMINATION OF PARTICLE EMISSIONS ACCORDING TO GTR 24
(BRAKE EMISSION FACTOR FOR FULL-FRICTION BRAKING)



1. HEPA (and charcoal) Filter
2. Cooling Air ducting
3. Brake enclosure
4. Isokinetic sampling system
5. PM-Sampler to collect PM_{10} and $PM_{2.5}$
6. Counting systems for SPN & TPN
7. Optional air filter
8. Air-flow control
9. Blower and differential pressure control
10. Air conditioning (T, rH)

DETERMINATION OF PARTICLE EMISSIONS ACCORDING TO GTR 24
(BRAKE EMISSION FACTOR FOR FULL-FRICTION BRAKING)

Same database as WLTC (exhaust) but different characteristics and focus.



Additional cooling sections between trips (not displayed)

Brake emission test, 3 sections, new brake systems

Assembling / disassembling of brake

Fully-automated test run

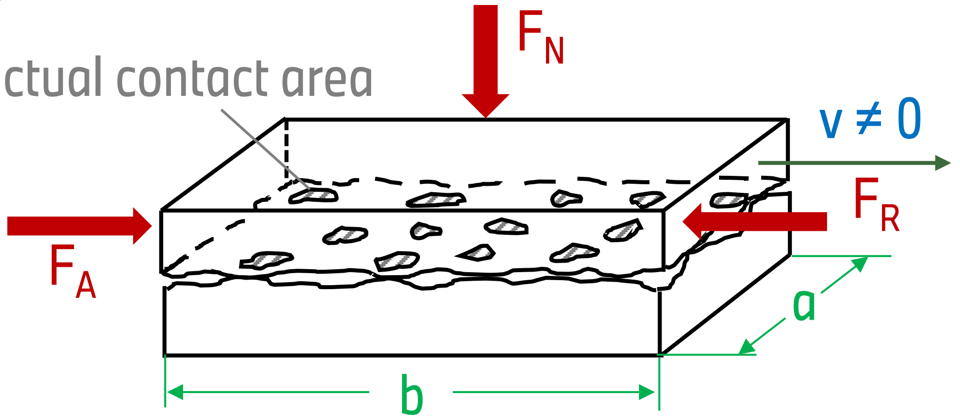
1. Cooling Air Adjustment (Trip 10)
2. Bedding (5x WLTP-Brake)
3. Emission Measurement (1x WLTP-Brake)

Key figures of cycle and test:

- Distance: 192 km
- Brake events: 303
- Trips: 10
- Max. velocity: 132,5 km/h
- Max. deceleration: 2,2 m/s²
- Cycle duration: 5-8 hours
- **Test duration: ~2 days**

OPTIMIZATION OF FRICTION CONTACT (FOR DISC BRAKES)

The magic happens between the surfaces of the rotating brake disc and the brake pads



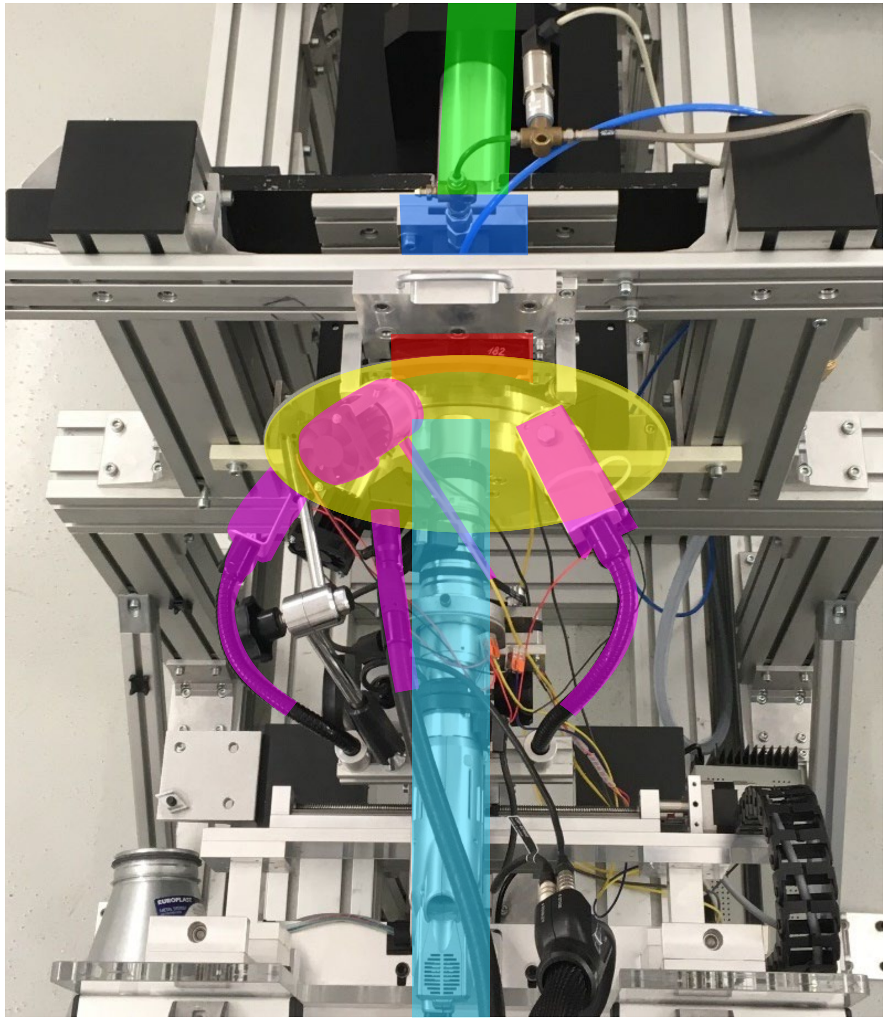
$A_0 = a \cdot b$

$A_R = \sum A_{R,i}$

F_A = wheel force
F_N = normal force
F_R = friction force
v = velocity
A_0 = geometrical contact surface area
A_R = actual contact surface area

- Tribological processes in frictional contact are responsible for particle formation and frictional behaviour
- Many theories of processes and relationships in frictional contact are derived from ex-situ investigations of friction partners
- Innovative approaches are required to better understand tribology of modern friction partners
- Simulation of "global behaviour" is difficult due to heterogenous mix of several materials in the pad

INVESTIGATION OF FRICTIONAL CONTACT



Drive train of test rig

Brake pressure actuator

Brake pad

"Brake" disc (made of glass)

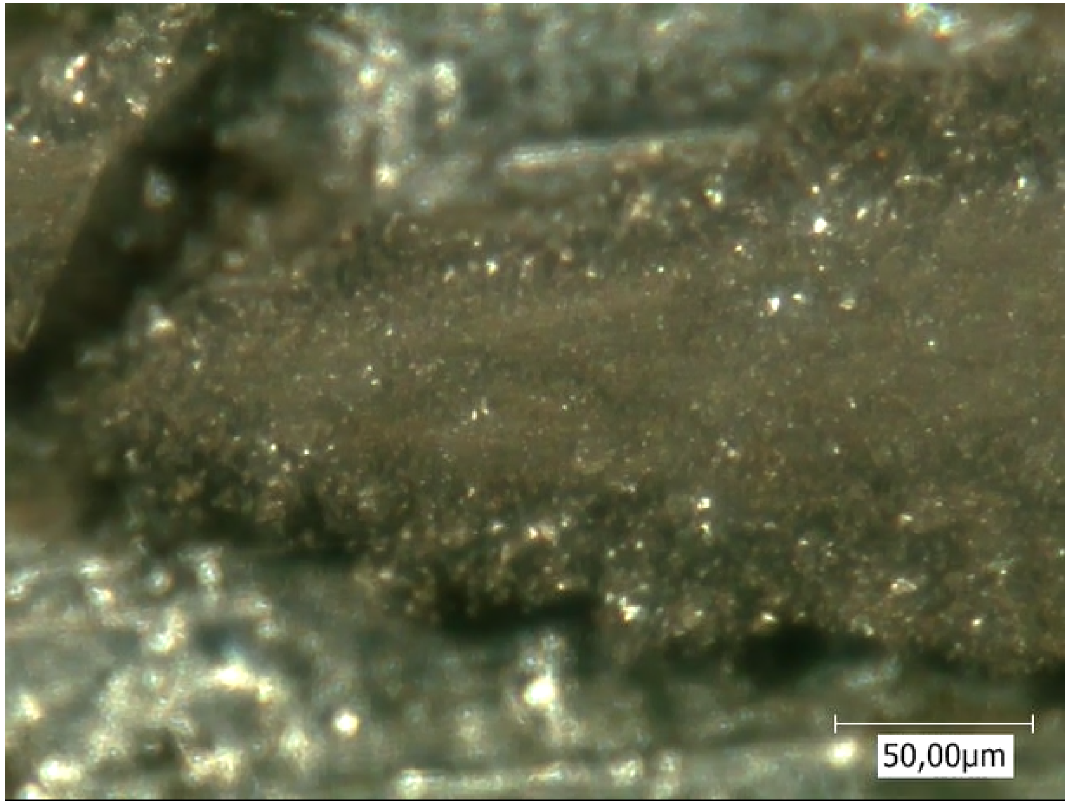
LED light sources

Optical system

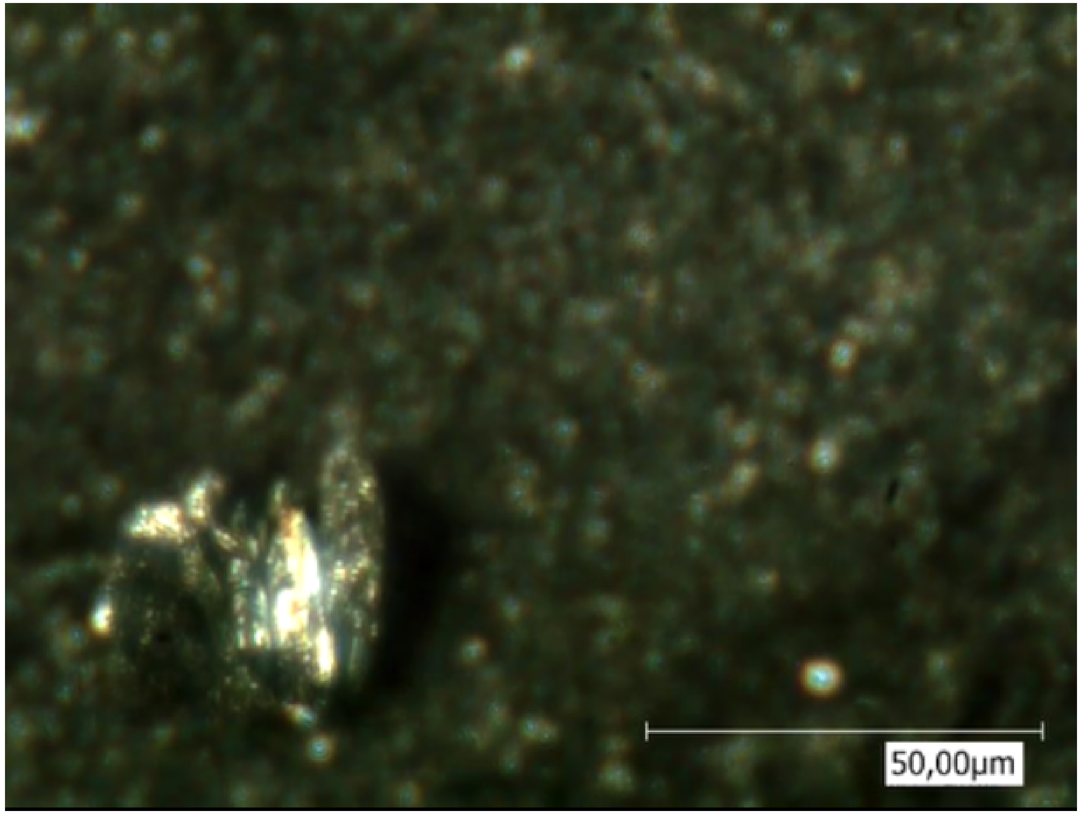
- Frictional force is independent of nominal geometric area, but relationship between frictional force and real contact surface is assumed
- The use of a glass disc instead of a grey cast iron disc enables direct optical observation of the frictional contact
- But: Glass disc shows significantly higher emission than grey cast iron
- But: Limited operational range, due to temperature and pressure resistance of glass

- Investigation of the tribological mode of action
- Learn more about interactions of typical base materials (resin matrix, abrasives, lubricants, metals)

EXAMPLES OF VISIBLE MOVEMENTS IN MICROSCOPIC SCALE



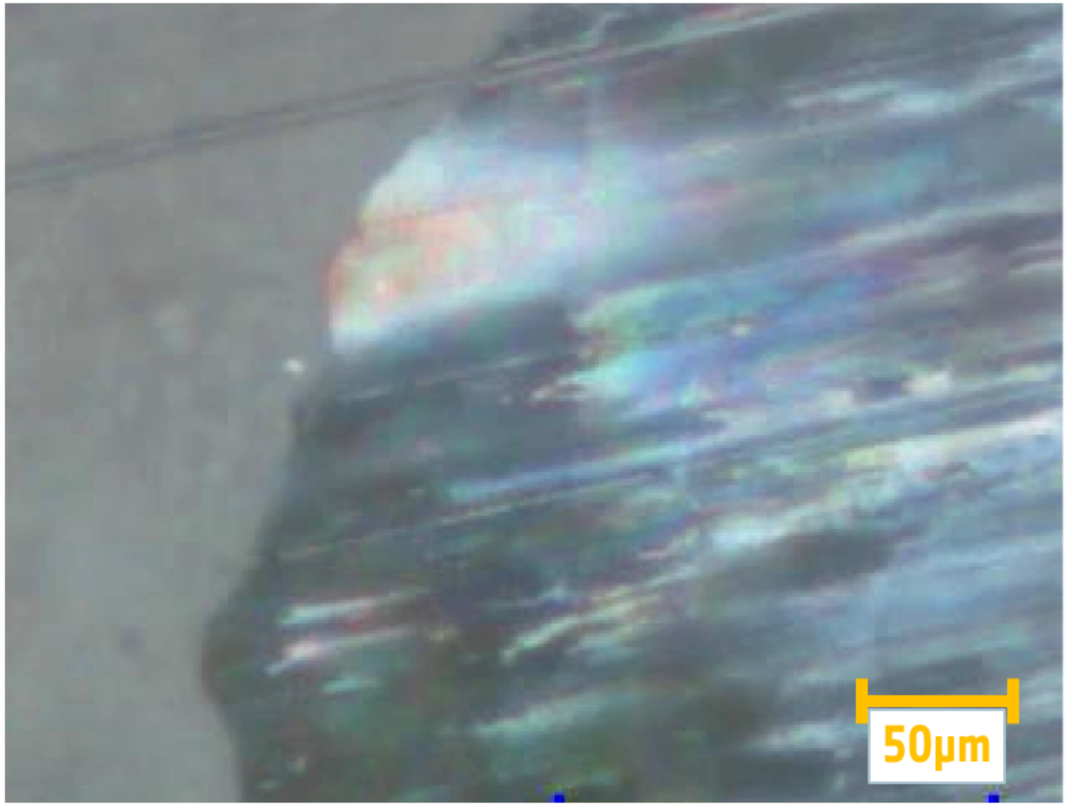
Agglomeration of particles close to patch



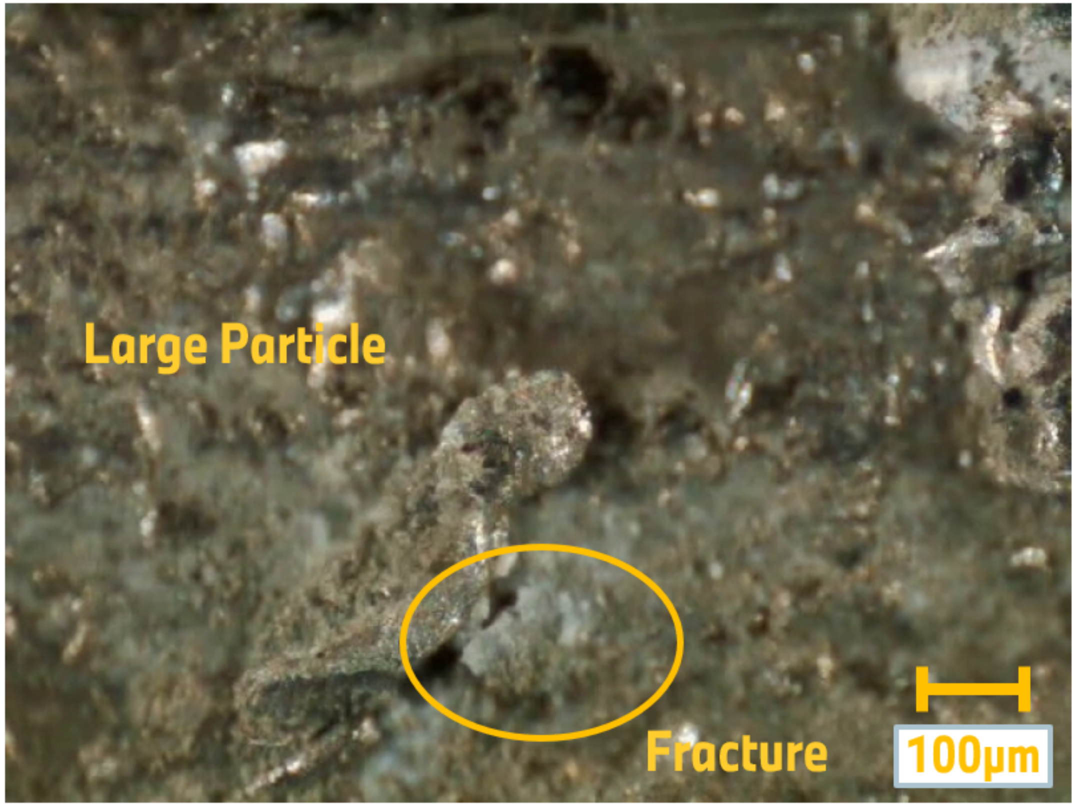
Irregularities on surface with moving and changing patch

Average speed of particles is depending on their size and geometry, topological effect between disc and pad, phenomena occurring “along the way” and the local balance of forces. Their speed is far below the rotational speed of the disc

EXAMPLES OF PHENOMENA AND PROCESSES IN THE FRICTION LAYER



Movement of material on patch



Removal of peak in "roughness"

- Visible movement of the smallest particles on the surface of secondary patches → Not the entire surface is in contact with disc
- Generation and decomposition of big particles, which are not necessarily relevant for PN/PM but for wear due to their large size
- Grinding effects (of these big particles) on disc and pad with destruction of particle-binding structures

SUMMARY

- **Basic insight to UNECE GTR 24 as the first implemented legislation for testing of brake emissions**
  - It is expected to be the basis for world-wide (harmonized) brake emission testing
  - The regulation of brake emissions based on a <u>vehicle-specific limit</u> creates several challenges
    → Regulation of After-Sales-Part-Market
    → In-Service-Compliance or "brake life-time"
    However:
    → Focussing on "brake only" would not <u>take into account the significant potential of regenerative braking</u>

- **Basic insight in the design process for vehicles and brake**
  - Challenges in finding an optimum solution for vehicle performance
  - Requirements in terms of operational time and driving distance to address all important topics
  - Conflict of engineering goals for regenerative braking as well as for brake system design

- **Basic insight in the formation of particles on the friction surface**
  - Limited operation window (low loads and speeds) due to testing setup and boundary conditions
  - Input data for simulation design and improved modelling
  - Better understanding of processes and design of friction surfaces

CONCLUSION

- Biggest challenge at the moment is the time schedule of the regulation and missing details on type approval requirements for authorities and manufacturers
- Vehicle optimization is complex and cannot be done by using one single test rig or vehicle
- Friction contact is still an important and interesting field of scientific work
- Brake components create different challenges in terms of air-quality, safety and brake life-time etc.
- Different climatic conditions may also impact performance of brake systems
- Combination of vehicle chassis and brake dyno testing appears to be the best solution at the moment:
    - Regenerative potential of vehicles is taken into account
    - After-Sales-Part suppliers are able to perform tests without detailed vehicle data or actual vehicle testing
    - Most relevant driving situations are taken into account
    - Other testing procedures may be considered in future, but several open topics need to be addressed first (e.g. background correction, different brake systems per vehicle, braking in traffic situations on the road)

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